Optimization of a water treatment process with respect to coagulation and sedimentation process of a conventional water treatment plant.

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Declaration

I the undersigned **Ramawela Lefa (518712)** hereby declare that the work contained in this dissertation has been produced by me without any collaboration with other students, staff or third parties aside from those acknowledged in this report. I have not engaged in any acts of plagiarism and to the best of my knowledge, I have recognized all information obtained from other authors' work. This work is being submitted for the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Ramawela Lefa
15th day of November 2022

Abstract

The coagulation-flocculation mechanism has been increasingly investigated by many researchers in water treatment. A wide variety of chemicals are used for the treatment of raw water with the aim to remove suspended and dissolved particles in raw water. Known conventional water treatment methods that used coagulants such as silica and high lime have been reported to have high operating costs due to the high coagulant consumption and large sludge volume generation. Therefore, there is an urgent need for the investigation of the coagulant and flocculation process with a primary objective of improving removal efficiency, while reducing chemical costs and achieving acceptable final water quality with lower sludge production. Taking this background into account, this study utilized the jar test methodology to establish an alternative treatment regime that can solve the above-mentioned challenges. In this study, two well-defined treatment regimens were investigated. Regime 01 was characterized by the usage of polyelectrolyte known as Zeta-Floc, while regime 02 was characterized by the usage of Zeta-Floc as a primary coagulant and lime as a coagulant aid. The source water for both regimes was abstracted from Vaal Dam with an initial turbidity of 62.4 NTU, the sample was collected in the winter season of the year 2018, and the average turbidity of that season was 63.4 NTU.

The study revealed that Regime 02 can be preferred over Regime 01 as it proved to promote the agglomeration lager-sized particles which settle much faster. At optimal pH of 8.3 and the optimal coagulant dosage of 6 mg/l, it was established that the measured residual turbidity of regime 01 and regime 02 were found to be 4.1 NTU and 2.8 NTU respectively. These were achieved under the rapid mixing of 100 rpm and the flocculation intensity of 30 rpm. Regime 02 proved to yield the lowest residual turbidity and improved physicochemical properties of the treated water as compared to Regime 01, this was due to the addition of low lime as a coagulant aid. Regime 02 archived performed better than the current, which achieved a turbidity of 6.3 NTU. The results obtained from this study highly recommend the usage of regime 02 in the treatment of raw water, it has been proved to reduce chemical cost and does not generate high large volumes when compared to the current high lime regime.

Keywords: Coagulation, colloidal, flocculation, Turbidity, physicochemical, Settling velocity.

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My heartiest tribute to Rand Water, for giving me a diverse exposure in the field of Water Treatment design, research and development as well as operations of bulk water treatment works. Without your financial support, would not have had a chance to peruse my Master’s Degree.

Dedications

I would like to dedicate this work to my hard-working father Erick Ramawela and my loving mother, Julia Ramawela, for their continuous support throughout this journey. Even though you did not acquire any form of formal education, you still encouraged me to do engineering; you have always been a source of inspiration to me and I must be honest that no words can express my gratitude.

I must say that I was lucky enough to find myself among very loving and carrying sisters, Conny, Lesedi, and Mapula Ramawela. I would like to share my achievement and joy with all of you.

To my brother Mark Ramawela, you told me that you want to become an engineer when you grow up, I am dedicating this dissertation to you as an indication that everything is possible if you work hard towards your dreams.

To my two beautiful daughters, Bohlale and Rorisane Ramawela, one day you will grow up, and I will tell you that: “school starts from Grade R and finishes at Ph.D., if you quit anywhere in between you have dropped out”. I strongly believe in you guys, and I know the world is not ready for your greatness.

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Furthermore, I cannot end without mentioning that this work is also dedicated to those who have lost hope but still found a purpose to keep them going.

Danko means thank you!!!

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List of Abbreviations

BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DWS	Department of Water and Sanitation
NEMA	National Environmental Management Act
NEMWA	National Environmental Management Waste Act
TSS	Total Suspended Solids
PAC	Powdered Activated Carbon

Chapter 1 : Introduction

1.1 Research Background

Water is an essential commodity of our everyday life. Recently, it has become apparent that water is indeed not an unlimited resource, as much as it is responsible for life on earth; it is very much important to note that water is not an infinite resource. It is essential to note that water is not readily available as potable (drinkable) water; water treatment processes need to be employed to ensure that raw water is converted into potable water for human consumption and use.

It is also critical to note that water is unevenly distributed in most parts of the world, because of this uneven distribution it requires proper management to sustain life on earth. Likewise, it is said that 70% of the Earth's surface is covered with water and about 97% of this water is salty water, which is unfit for human consumption, moreover, such waters are expensive to treat due to the operational cost associated with the process of removing the suspended and dissolved salt from the salty water (Balasubramanian, 2015)**.** Most of the 3% that is usable is not readily available, about 2 % exists as ice caps and glaciers; hence we are compelled to find sustainable ways to transform this finite commodity such that it becomes available and usable (Saleh *et al.*, 2020). Figure 1.1 depicts the percentage distribution of the earth's water.

For many years mankind has relied on the most visible forms of waters that are referred to as surface water, this includes run-off water as well as water that is found in lakes and dams. Freshwater is mostly found underground in aquifers rocks (Abdelhafez *et al*., 2021). Both ground and surface water may require further processing, depending on the level of contamination associated with the water. Different water treatment processes have been developed over time to treat water to attain specific desired quality.

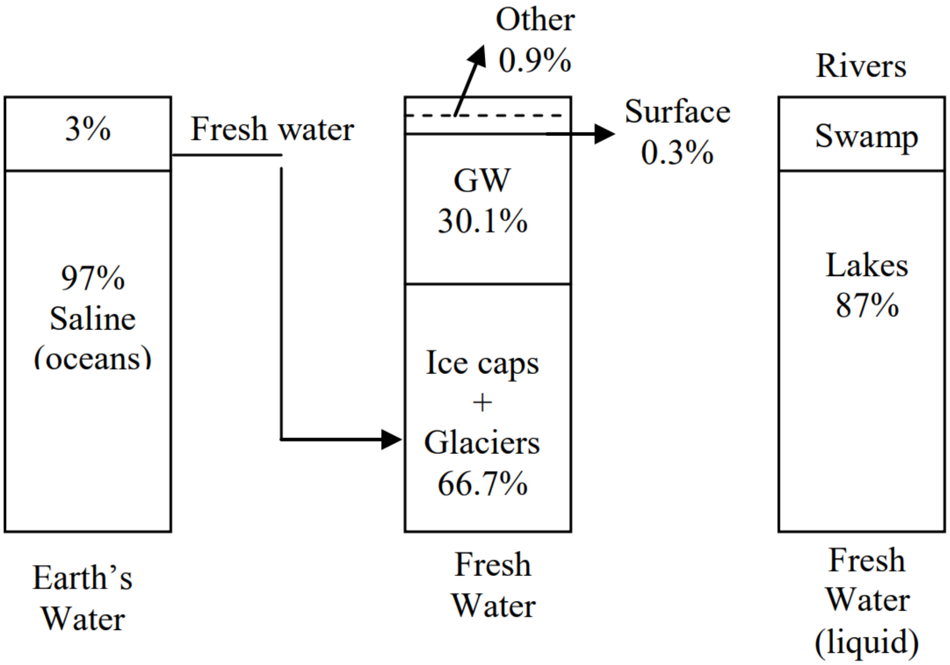

Figure 1. 1: The distribution of the earth 's water body (Balasubramanian, 2015)

The exponential increase in population and industrial activity has subsequently led to an increased demand for water. Over the years, scarcity of water has been observed in most parts of the world. This scarcity is further aggravated by uncontrolled pollution due to industrialization and poor domestic waste management systems (Leal Filho *et al.*, 2022).

According to the Institute for Security Studies (ISS), South Africa is considered a water-scarce country; it was mentioned that over 60 % of South Africa's rivers are currently being overexploited and only one-third of the country's main rivers are in good condition (Mema, 2010). Furthermore, the same authors mentioned that the 2015 drought followed the three consecutive years of below-average rainfall, marking the most severe and prolonged drought since 1940. The rapid increase in South Africa's population has led to pressure being put on the insufficient sources of water in the country; the current population of Johannesburg is 5,926,668 according to the World Population Review (Hashan *et al*., 2021).

Gauteng as a province is known to have no water sources that could sufficiently accommodate such a large population. As such, Gauteng gets its water from the Vaal Dam, which also gets feed from the Lesotho Highlands Water Project developed in partnership between the South African and the Lesotho Government. The Lesotho Highlands Water Project provides 25% of the water distributed by the Vaal River system (Mokonyama & Schalkwyk , 2017).Water in Gauteng and the surrounding provinces is being supplied by Rand Water, which abstracts raw or untreated water from the Vaal Dam and converts it to potable water using its robust treatment technology.

Rand Water possesses the biggest water treatment facility in sub-Saharan Africa with a maximum treatment capacity of over 4000 megalitres per day, which always operate to not less than 80 % of its capacity on daily basis. The major contaminants of the water from the Vaal dam are suspended solids, dissolved solids, and microbiological species (Plessl *et al.*, 2019). A considerable amount of the suspended material present in untreated water is present in the microscopic and sub microscopic range. Particles smaller than 1 µm (1x10-3 mm) are referred to as colloids (Shehab *et al.*, 2020). This type of particles is inherent to untreated raw water.

Particles in this colloidal size range and smaller can retain a dispersed or dissolved state because of inherent properties that promote their stability. Stability here refers to the capacity of particles to remain independent entities within a dispersion. In most cases, the stability of colloids in dispersions is determined by their surface effect, which is a result of mutual repulsion between particles. Most of the particles are negatively charged, and the charge can be determined using electrophoretic methods (Guppy *et al*, 2017). For many years, scientists and engineers have been on a quest to model and optimize bulk water treatment plants, with an objective to make them more effective and less costly.

1.2 Research rationale and motivation

With so much water in demand because of the rapid increase in population in Gauteng and the surrounding provinces, the treatment capacity of the current water treatment works proved to be under a great deal of stress. To avoid tight restrictions and the undersupplying of water to municipalities, Rand Water had to expand its largest treatment facility that treats a maximum of 3640 Mega litres per day by adding a system that treats an additional 600 Mega litres a day at Station 5 located in Zuikerbosch.

Coagulants, which are chemical agents are typically organic polymers that promote agglomeration of colloidal particles that are too small to be settled or filtered. These constitute a backbone of raw water treatment processes. The increase in the price of coagulants has forced Rand Water to find alternative treatment coagulants and optimum processes with an aim to lower the operational costs associated with water treatment.

This research was necessitated by the need to investigate a particular polymer of interest named Zeta-Floc with an intent to find the optimal coagulation dosing rates under well-defined operational conditions, and further determine the impact of hydraulic conditions on the coagulation and flocculation processes on the treatment of raw water from the Vaal dam.

In recent times, the sudden increase in the turbidity of the water in the Vaal dam was picked up by the Rand Water Scientific Services. The gradual increase in turbidity was partly influenced by the industrialization activity around the Vaal area, which illegally dumps their waste streams in the Vaal dam. The high Eutrophication levels in rivers around the country are also rendering the coagulation-flocculation process ineffective in removing high volumes of algae. This gradual increase in turbidity resulted in an increase in treatment cost. Jar tests on polyelectrolyte have been performed by the Rand Water Scientific services, with a sole intent to establish optimal coagulation dosage of coagulant. Their work did not focus on the influence of hydraulic factors such as the effect of initial mixing intensity and flocculation mixing intensity on the recent poly-electrolyte coagulants. This study was not only necessitated by the need to investigate the optimal dosing rates of polyelectrolyte (Zeta Floc), but it also aimed to investigate the usage of milk of lime as a coagulant aid, but to also understand the impact of hydraulic conditions throughout the coagulation and flocculation processes.

The results of this study are intended to influence the operations, design, and optimization of water treatment plants irrespective of the scale of the operation. The study was attributed to the fact that the coagulation and flocculation processes are the two utmost subsequent processes that determine the success of the entire water treatment process, as such, if these processes are achieved correctly, then the downstream processes such as sedimentation, filtration, and chlorination could be archived at great efficient levels.

1.3 Objective

The objectives of the study are as follows:

- To identify, compare and establish critical optimization parameters associated with two distinctive coagulation regimes used for the water treatment process. This regime is mentioned in Table 1.1 below:

Table 1. 1: The coagulation regimes to be investigated in this study.

Regime	Primary Coagulant	Coagulant Aid
01	Polyelectrolytes	-
02	Polyelectrolytes	Lime

- To determine the optimal coagulant dosage of each coagulant regime.
- To establish the impact of a coagulation aid agent on particle removal
- To determine the optimal treatment pH
- To identify the impact of rapid mixing and flocculation mixing during coagulation

1.4 Dissertation Outline

The outline of this Master's Dissertation is as follows:

The overall scope of the project is discussed in **Chapter 1** whereby the reasons why it is important to study coagulation, flocculation, and sedimentation process are outlined. This section outlines the executive introduction and further goes on to discuss the associate problem statement. The objective and motivation that necessitated this study are also discussed in this chapter.

In **Chapter 2**, the literature review provides information on the background of water treatment processes with great focus on coagulation, flocculation, and sedimentation of raw water treatment.

The coagulation, flocculation, and sedimentation mechanisms are thoroughly outlined in reference to the literature.

Chapter 3 outlines the experimental procedures used to obtain results. The approach used to obtain results is discussed, this chapter also illustrates processes involved in obtaining results.

In **Chapter 4** the logical reasoning and detailed justification of the results. This chapter further breaks down and discusses the performance of each coagulation regime, a comparative analysis is also conducted in this chapter with an aim to identify an efficient coagulant, and the optimal dosing conditions for each regime are discussed.

Chapter 5 summarizes the important findings of the study, it further outlines recommendations, perspectives, and future research avenues to consider on this important subject.

Chapter 2 : Literature Review

2.1 Motivation and Background

2.2 The history of water treatment.

The knowledge associated with water and wastewater treatment processes is not new to mankind, this topic has been evolving and advancing throughout the development of human history. Water treatment processes date back to as far as 2000 BC (Snyder, 2015), whereby ancient people devised different methods for water treatment. Some of the earliest documented methodologies were discovered in ancient Greek manuscripts that suggested heating water by boiling on fire before usage. It was also discussed in the manuscripts that water filtering could be achieved using coarse gravel and sand, by allowing water to percolate through a bed made of sand and gravel to remove suspended particles in water (Angelakis, 2015). Their motive in treating water had a lot to do with improving the taste of the water. Since there was no equipment and ways to tell the variation between clean and foul water at that time.

It wasn't until about 1500 BC that Egyptians discovered coagulation as a water purification system (Jones, 2017). The practice of recycling and reusing municipal wastewater has been adopted by mankind for many centuries; it has gone through different stages of development. This resulted in not only the understanding of the process, but the treatment technology associated with them too, and most importantly it has led to the eventual development of water standards.

2.3 Modern-day treatment processes

There is no question that water treatment processes have evolved over time. Direct sand filtration was first developed in the year 1885, and it was deemed ineffective at removing viruses, bacteria, suspended particles/colloids, and colour (Jonson, 2017). Colloids are very tiny particles that are suspended in solution and cannot be removed either by sedimentation or filtration processes. The struggle to remove colloidal particles and viruses in water treatment has necessitated a need for the development of robust processes in water treatment. Over the years, wide variety of water treatment processes have been discovered, these discoveries were compelled by the challenges associated with the treatment of industrial wastewater, raw water from rivers and dams as well as sewage wastewater. Wastewater treatment processes have been advanced to treat municipal effluent to potable water, while old processes could only treat water to meet river disposal standards. There is a lot of pressure to advance treatment technologies in the field of water treatment, this is due to the increasing level of contamination and pollutants coupled with the increase in water demand due to an increase in population. It has been confirmed by the "Global Water Crises facts" that more than 80% of the wastewater returns to the environment without adequate cleaning (Guppy *et al*, 2017). This is a call for innovative and sustainable methods required for water treatment to counteract this undesirable adverse effect that mankind poses to the natural environment.

2.4 Sewage Water Treatment

A typical wastewater treatment process is basically characterized by three main stages, which are primary, secondary, and tertiary treatment as outlined in Figure 2.1 below.

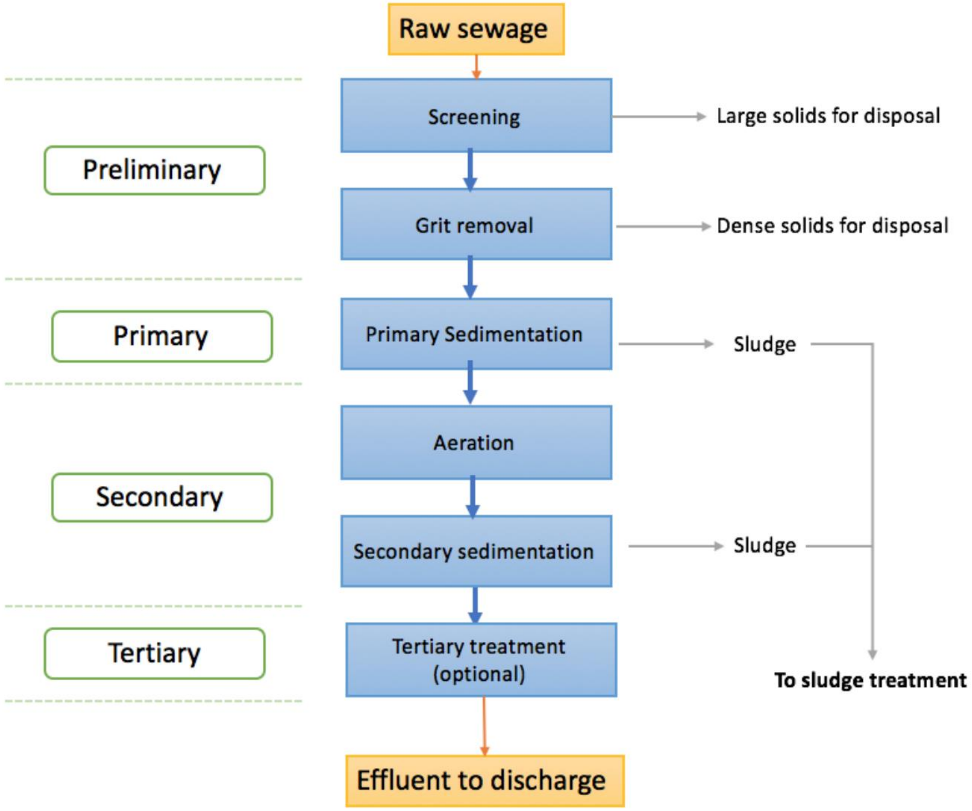

Figure 2. 1: Typical processes involved in the Conventional Wastewater Treatment (Parr, 2002)

The primary stage consists of preliminary treatment processes such as removal of large solid waste through screening to avoid them damaging the plant equipment downstream. Another importance of preliminary treatment is to reduce solids and inorganic matters through the process of sedimentation, according to (Seving *et al*., 2018) 65 % of suspended solids and 30% of BOD are removed during primary treatment. The secondary treatment stage is responsible for the removal of dissolved organic matter, which is also referred to as soluble BOD. The last stage of the wastewater treatment process could be optional, the tertiary treatment stage is responsible for the removal of nutrients such as nitrogen and phosphorus. The subsequent processes of the wastewater treatment plant are depicted in Figure 2.2 below.

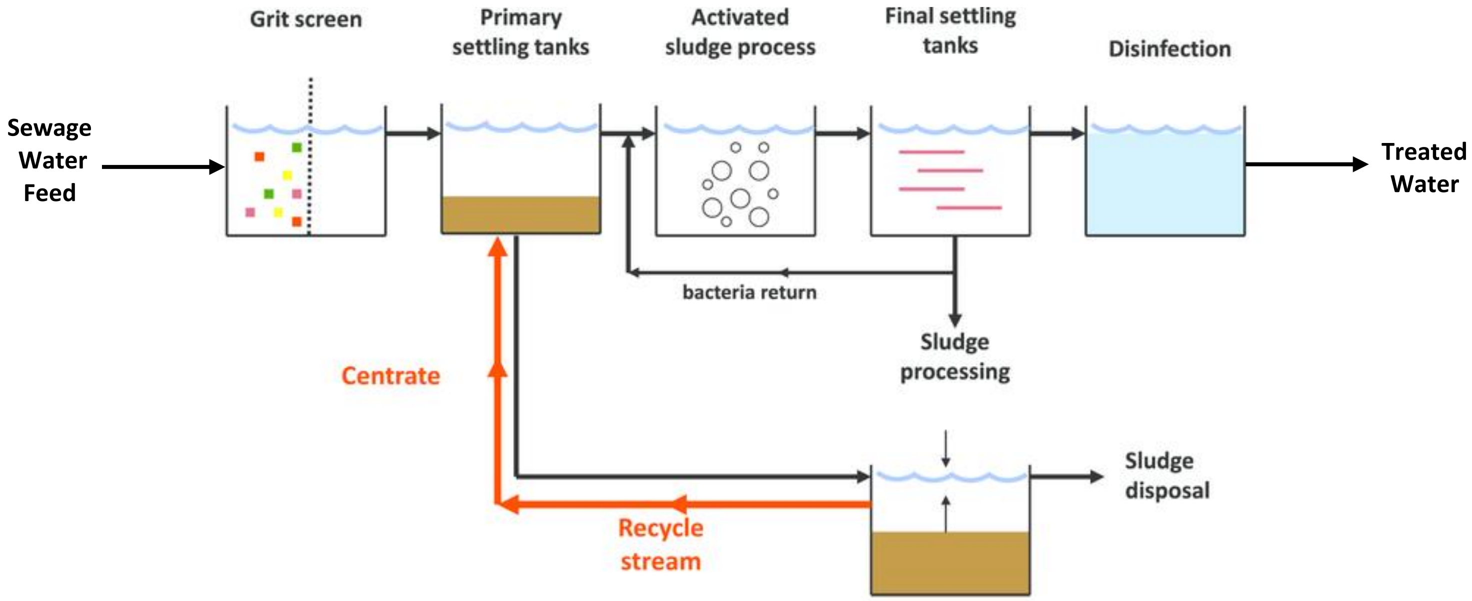

Figure 2. 2: The schematic representation of a typical sewage treatment process (Madduru, 2011).

2.5 Wastewater treatment in South Africa

There is no question that both waste and wastewater management have a direct impact on our health and the sustainability of the environment. Pollution due to poor management of wastewater in South Africa has reached apocalyptic levels. According to studies that have been conducted in recent years, pollutants have entered the water resource due to poor management and maintenance of wastewater treatment infrastructure (Edokpayi *et al*., 2017). Over the years, a high level of

E. coli proved to rise in most rivers and dams in South Africa due to poorly treated sewage water that was allowed to trickle into the water cycle (Mema, 2010).

Poor enforcement of legislature by the South African Department of Water and Sanitation (DWS), has led to poor management of sewage treatment facilities, which have been declared to release poorly treated water to rivers and dams. The current state of the sewage management systems in South Africa is by far contradicting the sewage water management requirements that were set out by the DWS which stipulates that provision of this type of services ought to be based on the principles of maximum accountability, transparency, and continued improvements. The National Environmental Management Waste Act (Act No 59 of 2008) NEMWA also condemns the poor disposal of waste into the Natural Environment.

2.6 Raw Water Treatment

The DWS is responsible for the South African water resources. Its main mission is to make sure that the quality of water resources in the country is fit for recognized water usage, such that the viability of the aquatic ecosystem is well maintained and protected at all material times (Mokonyama & Schalkwyk, 2017). To ensure that a common ground for which common water quality requirements are well-defined, the department initiated the development of the South African Water Quality Guidelines. This robust document serves as a rudimentary source of information for the determination of the water quality requirements for a wide variety of water uses, it also promotes the protection and maintenance of the health of the users.

In this context, raw water is defined as untreated water that is found from the ground in lakes, dams, and rivers. Water used for domestic, industrial, and irrigation purposes in South Africa is predominately raw water that has been treated through conventional water treatment processes. Different treatment regimens have been adopted by different water treatment bodies across the country, which are greatly influenced by the properties of raw water. All the water treatment facilities are required to treat the water to required water quality standards that are defined by the South African water quality guidelines for Domestic use as per DWS water quality standards. All the 12 water boards in South Africa are governed by these guidelines.

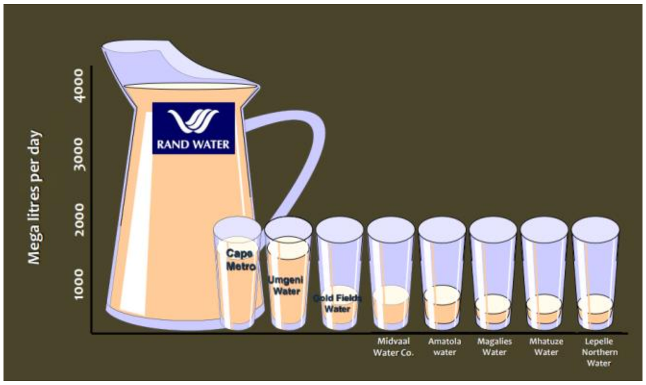

Figure 2. 3: The schematic representation of the flow capacities of major water treatment boards in South Africa.

In South Africa today, there are currently 12 water boards that are serving different municipalities with potable water. As indicated in Figure 2.3 above, Rand Water is the largest water board in terms of treated water capacity output. Rand Water covers a wide supply area, it covers predominantly the entire Gauteng province as well as peripheral parts of the surrounding provinces which are North West, Free State, and Mpumalanga province as depicted on Figure 2.4 below. Rand Water is also one of the oldest water boards, it has been supplying bulk water since 1903, and its treatment processes have been improved over time. The increase in population has obviously led to an increase in water demand, which has channelled Rand Water into scaling up its treatment facilities from time to time to catch up with the forever-changing demand.

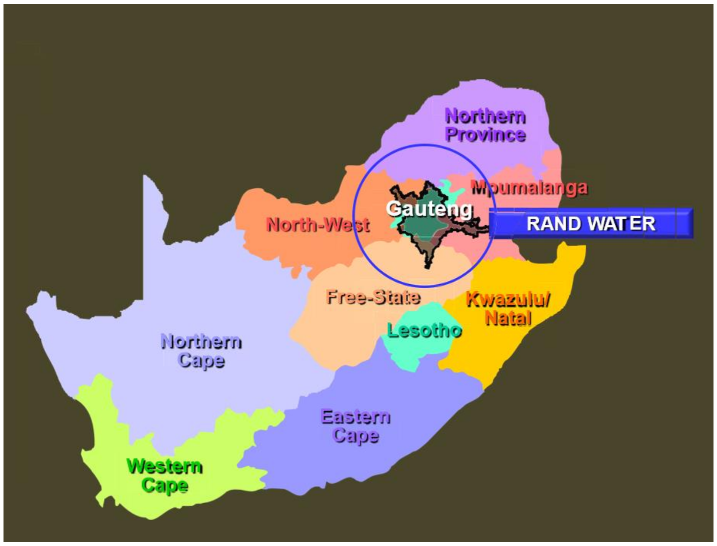

Figure 2. 4: Rand Water ‘s water supply coverage.

2.7 Water Treatment process description.

Rand Water ‘s treatment processes take place at the Vaal area in the South of Johannesburg, with two treatment plants, one located at Vereeniging and the other one in Zuikerbosch. The Zuikerbosch plant is not only the largest plant operated by Rand Water, but the biggest water treatment facility in entire Sub-Saharan Africa with a treatment capacity of 4200 megalitres per day. The abstraction point of Rand Water is the Vaal Dam, which is fed by the Lesotho Highveld project. The type of pollutants that are found within the water from Vaal Dam includes but is not limited to Total Suspended Solids (TSS), Bacteria, Viruses, BOD, and COD material. Rand Water uses a unique treatment process that has a wide range of treatment regimes depending on the initial physicochemical properties of the feed water. This treatment regime is categorized according to coagulants and coagulant aids used for specific water feed. The choice of a treatment regime is influenced by a couple of factors, with the main one being the ability to achieve the water quality as stipulated by the DWS as well as cost-effectiveness. On the Rand Water conventional treatment process, coagulation chemicals are dosed before a unique spiral flocculation system that is special to their treatment process. In recent times there have been interest in the removal of ECDs, VOCs, and DBPs in water, which are challenging bulk water treatment organizations such as Rand Water to rethink their traditional treatment processes.

Coagulation and flocculation processes constitute the backbone of a water treatment process; in the other words, the efficiency of the subsequent processes such as sedimentation and filtration strongly depend on how well coagulation and flocculation have been achieved. The physicochemical properties of the incoming water vary from season to season, this is so because during rainy seasons more pollutants are introduced to the Vaal River and dam, so during summer Rand Water sometimes introduces Powdered Activated Carbon (PAC) as part of pre-treatment chemicals in order to absorb organic metabolites of algae and organics coming from agriculture and industry to prevent the formation of algae in the downstream treatment processes. The typical water treatment process that Rand Water uses at the Zuikerbosch plant is depicted in Figure 2.5 below.

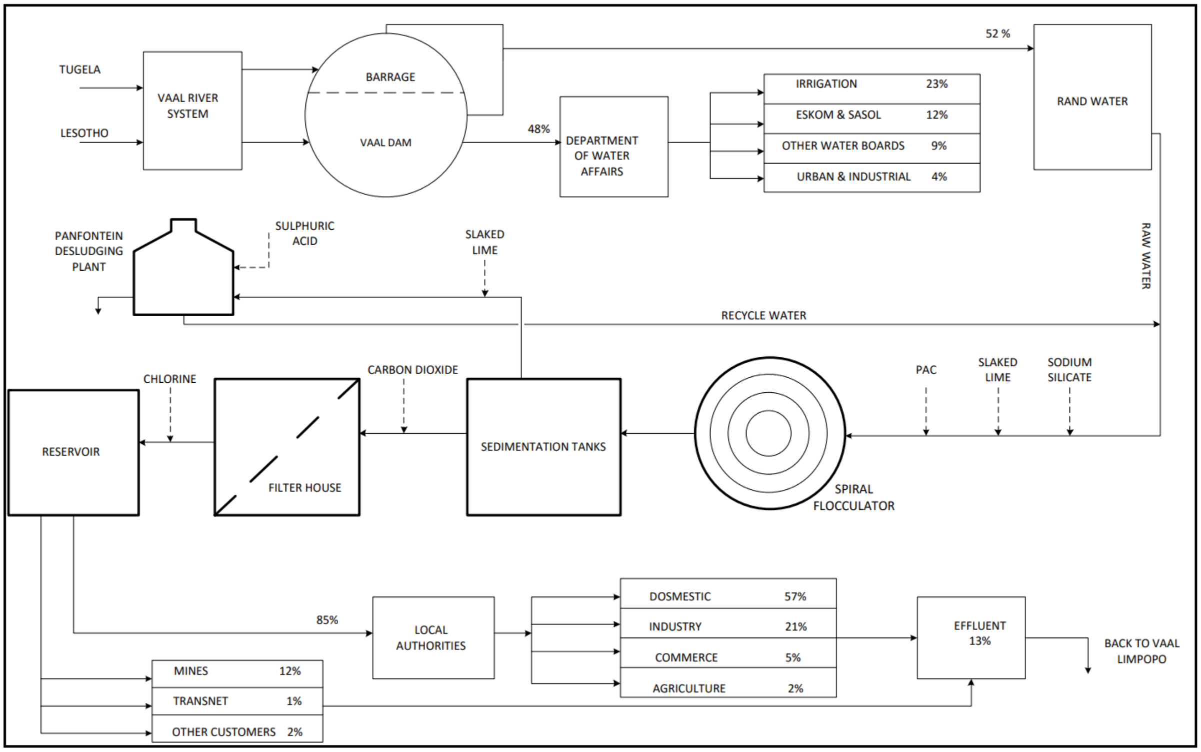

Figure 2. 5: The Zuikerbosch water treatment flow diagram (Mokonyama, Schalkwyk, 2017).

2.8 Water Quality

The term “Water quality” outlines both the physical, microbiological, and chemical properties of water. Collectively, the characteristics of the water determine the water quality and its ability to be utilized for a specific purpose. The treatment process is strongly determined by the quality requirement and the physiochemical properties of the incoming water. When considering the raw Water, the physicochemical properties will basically determine the process which must be considered for treatment.

While the water quality guidelines for domestic use by the DWS provides comprehensive information on quality aspects that are important to water treated for domestic use, the South African Bureau of Standards specification is used as an official guideline document to assess the water quality.

2.9 Chemical and Physical Water Quality

The water is a unique natural substance; it can dissolve other substances throughout the hydrological cycle which includes run-off, infiltration, rainfall, and evaporation amongst others. Throughout the hydrological cycle, water comes across different substances that may either be dissolved by the water to a larger extent or be suspended in the water (Challener, 2011). The quality of the water and its fitness for a specific usage depends on how much dissolved and suspended particles are found in the water.

The design of a water treatment facility is strongly influenced by the type of dissolved and suspended substances found in the raw water. Given that raw water will typically contain a variety of substances all at once, the treatment process cannot usually consider every substance individually, this implies that substances with similar characteristics can be treated through the utilization of the same process; these types of substances are usually grouped together for design purposes. However, there are exceptions when it comes to toxic substances, which may require specific processes and won't be particularly easy to group.

A wide variety of substances could to some greater or lesser degree be dissolved by water. Such substances range from gases such as carbon dioxide, ammonia, and oxygen to list a few. Water can also dissolve organic and inorganic substances such as humic acids and sodium chloride (NaCl) respectively. The typical example of the dissociation of salt in water is depicted in Figure 2.6 below. Over the years dissolved substances have proved to be difficult to remove from water as compared to suspended particles, this is so because such particles must either be converted to solids through processes such as precipitation or converted to gas through processes such as oxidation. In recent years, advanced techniques such as reverse osmosis and activated carbon adsorption have been developed to enhance the cost-effective way of removing dissolved substances. Most organic pollutants such as PCBs, phenols, herbicides, pesticides aliphatic and heterocyclic compounds are involved in wastewater. Chemical, physical and biological removal methods have been given much attention in recent years. Some of the known inorganic pollutants include Iron, manganese, chromium and arsenic, they usually occur in nature, and they end up in ground and surface water. A larger portion of this inorganic metals end up in our water streams due to manmade pollution, several treatment processes can be employed for the treatment this inorganic pollutants, these methods are coagulation, electrocoagulation, floatation and membrane processes.

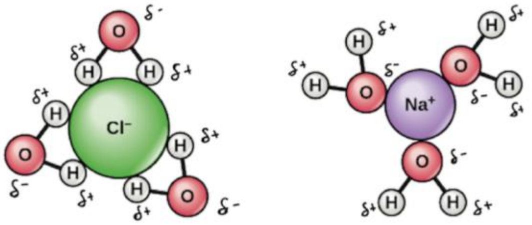

Figure 2. 6: The schematic representation of how salt dissociates into ions in water (Khan, 2011).

2.10 The characteristics of Suspended and Colloidal substances

Not all substances may dissolve in water, some substances do get suspended in water. This type of substance remains in water as a tiny, suspended particle that may be sometimes referred to as colloidal particles, depending on their size (Dayarathne *et al*., 2021). Under quiescent conditions, relatively large, suspended solids will exhibit a tendency to settle. On the other hand, fine suspended solids referred to as colloidal particles are too small to settle, and they also possess electrical charges that prevent them from settling. Until the electrical charge is neutralized, they can remain in suspension for a very long time (Fan *et al*., 2020). Colloidal particles are not categorized according to the type of substance they originate from; they are defined according to size. In water treatment terms, a colloidal particle is any particle that falls within the size range 10 nanometre (nm) to 1 micrometre (µm) (Mabvouna Biguioh *et al*., 2020). The presence of colloidal particles in the water results in high turbidity. Turbidity is defined as the cloudiness of a fluid caused by large numbers of individual particles, the measurement of turbidity is a fundamentally important measure in water engineering; this physical property of water is expressed in nephelometric turbidity units (NTU) (El Gaayda *et al*., 2021). To remove turbidity, processes such as coagulation and flocculation can be utilized. According to the SANS 241, the turbidity of drinking water should be preferably less than 0.1 NTU. Another chemical property of water that is closely monitored during the treatment process is the pH, which is basically a measure of the concentration of hydrogen ions in water; pH indicates how acidic or basic the water is. There is a wide range of water chemical parameters that need to be measured at the initial and final stage of the process to check if the treated water is complying with the defined specification, these parameters include but are not limited to hardness, chemical stability, alkalinity, and free and combined chlorine. The chemical stability of water becomes a very important subject in water treatment, as it determines whether water will be chemically stable for a specific use. An unstable waster is likely to cause diseases and result in corrosion of equipment.

2.11 Microbiological Quality of water

The determination of the microbiological quality of water is a very essential practice in water treatment. A wide array of micro-organisms can be present in water abstracted from different sources, even water that may look and taste clean could contain disease-causing pathogens (Mabvouna Biguioh *et al*., 2020). Pathogens are defined as micro-organisms that could potentially cause water-borne diseases such as cholera, dysentery, diarrhoea, and typhoid (Sadeghi, 2007). To control the microbiological properties of water, it is significant that the initial properties are measured before treatment, which is critical to guide the treatment process as far as chemical agents and process selection are concerned. The final microbiological qualities of water are measured to ensure compliance with the DWS water quality guidelines.

2.12 Coagulation and Flocculation

Even though the terms coagulation and flocculation are often used interchangeably at times, it is important to outline the fact that they define two distinctive physicochemical processes. The term coagulation, as defined by (Baghvand *et al*., 2010), is the process through which a given suspension of particles or solution is destabilized in water through the addition of a chemical agent referred to as a coagulant. The same authors further defined flocculation as the process through which discreet destabilized particles conglomerate with each other to form large agglomerates that are referred to as flocs. This destabilization process is best described in Figure 2.7 below.

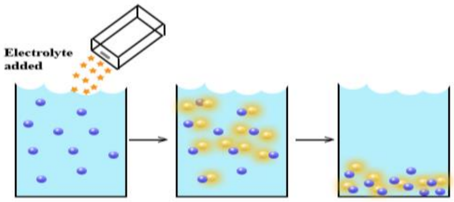

Figure 2. 7: The effect of a coagulant on the water with colloidal particles (Menjeru, 2017).

These two processes do happen naturally in river systems, lakes, and dams, which are the processes through which water naturally treats itself. In water treatment, a chemical agent may need to be added to promote the coagulation process, and such an agent is known as a primary coagulant. In some cases, a coagulant might not necessarily be enough to archive effective coagulation and flocculation, in such cases, a coagulation-flocculation aid might need to be added to the water to promote the effective formation of flocs, it is often referred to as a coagulation aid in the water treatment literature (Nyström, 2019). There is a wide array of coagulants and coagulant aids, the choice of each for a specific application will be governed by factors like the required final water quality, the initial physicochemical properties of the raw water, and most importantly the cost associated with the treatment process. These two subsequent processes can be affected by a wide range of factors, as outlined in Table 2.1 below, which shows that the coagulation-flocculation process is a function of many factors.

Table 2. 1: Factors affecting the coagulation-flocculation process (McEvoy, 1999).

Coagulant Characteristics	**Physical Characteristics**	**Raw Water Characteristics**
● Coagulant type ● Coagulant dose ● Proper solution ● Makeup and dilution ● Proper Coagulant age	● Settling time ● Mixing Intensity ● Mixing time ● Coagulant addition point ● Proper coagulant feed	● Suspended solids ● Temperature ● pH ● Alkalinity ● Presence of micro-organisms and other colloidal species ● Ionic constituent (Sulphate, fluoride, sodium, etc.)

2.13 Colloidal stability

The term colloid refers to a particle or system of discrete particles that are insoluble in water or any other liquid medium, the term is widely used in different scientific studies (de Vries *et al.*, 2022). A colloidal particle is characterized by its size rather than its mass, in defining a colloidal particle, different scientific fields use different size ranges for their definitions. In water treatment terms, a colloidal particle is any particle that falls from 10 nanometres (nm) to 1 micrometre (µm). There are a couple of interactions between the discrete colloidal particles that do contribute to their ability to stabilize in water, but the dominant one has been identified to be electrostatic repulsion (Mosley *et al*., 2003).

2.14 Basic Coagulation Chemistry

In most cases, when raw water arrives at the treatment facility, it usually displays high turbidity as a result of very tiny, suspended particles. Colloidal particles in surface water are typically negatively charged. This colloidal particle cannot flocculate together unless its charge is neutralized by a force referred to as zeta potential (Ghernaout, 2015). To neutralize colloids, a chemical agent called a coagulant is added to the treated water. Panan (2018) presented the model for ionic concentration and potential difference of a colloidal particle in water as depicted in Figure 2.8 below. For drinking water, this process must be controlled and regulated such that the process is effective, and the outgoing water is not toxic due to added chemicals. Because colloids are so small, their motion is controlled by Brownian motion (random movement), their charges must be neutralized to be destabilized.

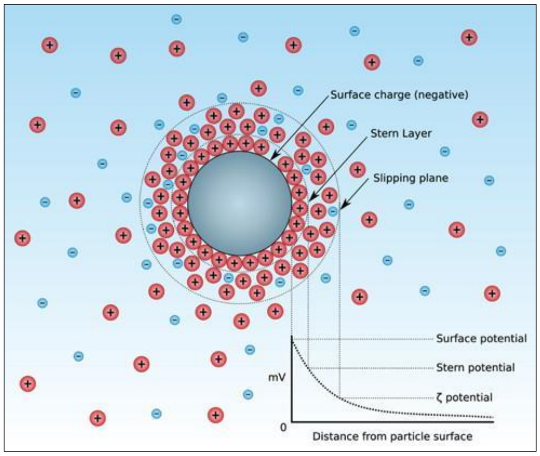

Figure 2. 8: The schematic representation of ionic concentration and potential difference of a colloidal particle in water (Pavan, 2018).

2.15 Coagulation and Flocculation Mechanism

The coagulation mechanism is defined by five main distinctive processes, which are charge neutralization, adsorption, compression of the electrical double layer, inter-particle bridging, as well as enmeshment in a precipitate known as “sweep floc” (Holm, 2019). During coagulation, colloidal particles get destabilized by the adsorption of oppositely charged particles. The coagulation mechanism occurs in such a way that, if a particle is neutralized on the surface, there will be a subsequent disappearance of the electrical double layer and as a result, the Van der Waals will make the particles agglomerate together (Prakash *et al., 2014)*. For polymeric coagulants, polymerized chains will exhibit a tendency to adsorb on a particle; and agglomerate on several sites of the polymer, this results in rapid interactions such as charge to charge, hydrogen interaction, dipole, and Van der Waals interactions (Trussell, 2012). The coagulation-flocculation mechanism is depicted in Figure 2.9 below.

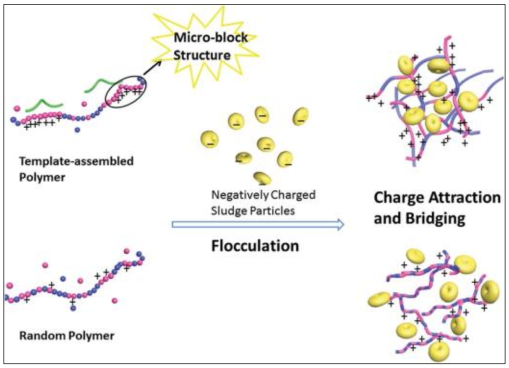

Figure 2. 9: Schematic of flocculation of charged particles with polymer (Liu *et al*., 2017).

The flocculation mechanism starts with small discrete particles which experience random Brownian motion. The Brownian motion refers to a random movement of colloidal particles in a medium, because of a persisting bombardment from other particles surrounding the fluid (Lavenda, 1985). The random movement of particles in the water will result in particle-particle collisions, as this happens particles will form larger agglomerates and eventually form larger flocs that can be settled with ease as depicted in Figure 2.10 below. According to (Trussell, 2012), these collisions happen due to velocity gradients created by stirring the water, and they are known as microscale and macro-scale flocculation (Fan *et al*., 2020).

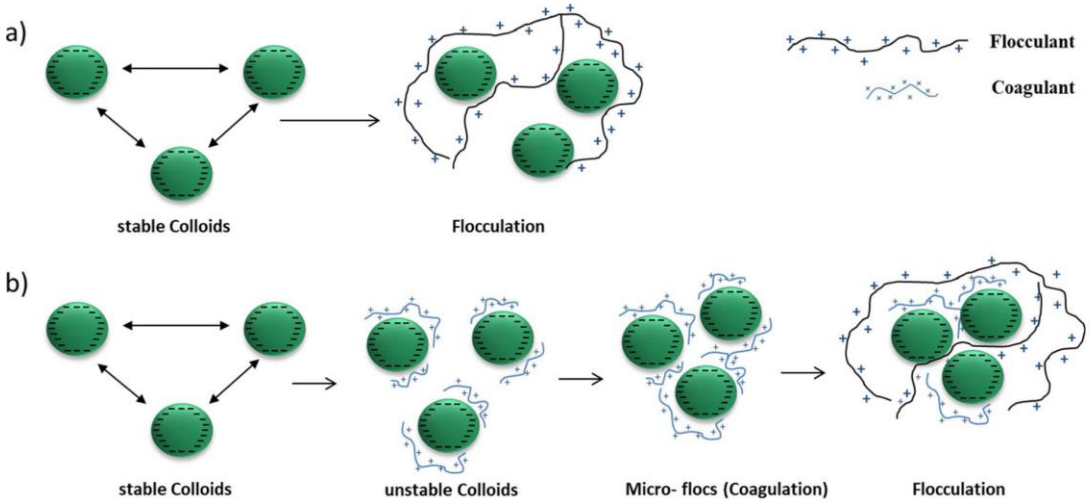

Figure 2. 10: The Schematic Representation of the flocculation mechanism (Yousefi *et al*., 2020).

As depicted in Figure 2.10, the physical models of coagulation and flocculation outline the distinctive subsequent stages that take place during these two pre-treatment processes. These processes are so instant that they almost look like they happen at the same time, the first stage after the addition of the coagulant agent, whereby the interaction between particles will be initiated; which is strongly influenced by rapid mixing. This will be immediately followed by the destabilization of the charges, which eventually results in a subsequent agglomeration of particles.

2.16 Coagulant and coagulant aids

Coagulation is a fundamentally important process in water treatment, it has been found to be the effective method to remove colloidal particles in raw water. Over the years, many researchers have effectively applied the process of Coagulation to treat turbid water of varying degrees (Prakash *et al*., 2014). Tests have been conducted on different chemicals, and it was established that different coagulants can be used for different types of source water, and this is greatly influenced by the required final water quality and the cost to achieve the desired water quality. Depending on the application, different coagulant aid agents will have their advantage and disadvantage.

2.16.1 Activated Silica as a coagulant

Activated silica is usually prepared on-site by the operator by combining sodium silicate (Na_2O_3Si) and Hypochlorous acid (HClO). Its main attribute is to keep the floc from breaking apart or shearing to guarantee a successful formation of larger flocs and consequently an effective sedimentation process, this mechanism is depicted in Figure 2.11 below. The main purpose of adding acid is to neutralize the strongly alkaline silica, this activation process results in the formation of colloidal or polymerized silica that is very essential for the removal of suspended particles in water treatment. The challenge with silica as a coagulant is that it has an isoelectric point at certain basic pH ranges, this minimizes the Brownian motion and the collision of particles from taking place, which results in ineffective coagulation (Okura *et al*., 1960). Silica is currently used by Rand Water as Activated Silica; with carbon dioxide being used as an activating agent, the challenges with this treatment regime are high cost of chemicals, as well as operational challenges that are caused by silica ‘s tendency to scale up inside dosing lines and pumps resulting in unplanned shutdowns.

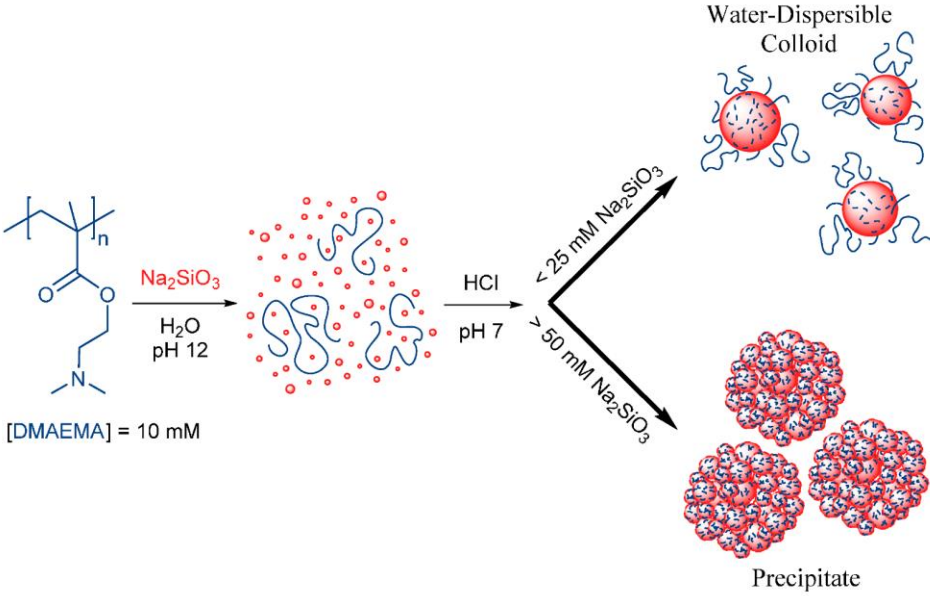

Figure 2. 11: Schematic representation of the polymerization of sodium silicate (Overton *et al*., 2016).

2.16.2 Polyelectrolytes (Polymer) as a coagulant

Polyelectrolytes coagulants are comprised of long carbon chain molecules that can produce highly charged ions when dissolved in water (Yi *et al*., 2014). They are usually classified according to the charge they possess; they can contain either a neutral, positive, or negative charge. Cationic polyelectrolytes will typically produce positive charges when dissolved in water, while anionic polyelectrolytes will typically produce negative charges when dissolved in water. The non-ionic polyelectrolytes are the ones that produce both negatively and positively charged ions when dissolved in water, in effect the charges will neutralize one another (Overton *et al*., 2016). Figure 2.12 below depicts the mechanism of coagulation using a polymer, whereby a cationic polymer is attached to an anionic stable particle to form a much bigger particle that can be settled with ease.

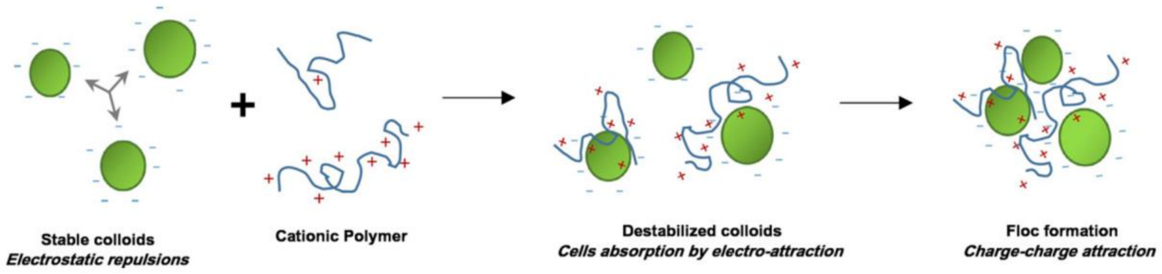

Figure 2. 12: The schematic representing the destabilization of anionic repulsive colloids by a cationic polyelectrolyte coagulant (Van Haver & Nayar, 2017).

2.16.3 Alum as a coagulant

In the quest to improve efficiency for the treatment of raw water with high turbidity, the need to utilize inorganic chemicals to achieve low turbidity has been increasing over the years. This need was not only motivated by their low cost but their abundance (Malik, 2018). Most of the particles in high turbidity waters are negatively charged, to neutralize the negative charge; a positive charge should be added (Gandiwa *et al*., 2020). The work of Schultz in 1882 discussed a couple of chemical agents that can release a cationic charge in water, this included but is not limited to potassium hydroxide which contributes the cat Ion K+, calcium hydroxide which contributes Ca 2+ as well as aluminium coagulants that give Al3+ (Malik, 2018). It has been established by the same author that the higher the charge, the better the neutralization process. Alum is the widely used coagulant in water treatment, this is so because it contains trivalent cations that hydrolyse rapidly when added to water (Xue *et al., 2021)*. The downside of using alum for bulk water treatment is that it is expensive, as such this will result in high operational costs.

2.17 Rapid Mixing

The coagulation-flocculation process performance is known to be significantly affected by mixing conditions. Rapid mixing, which is sometimes referred to as flash mixing, has been found to be an essential way to distribute coagulant species among the colloidal particles in a very short space of time to promote particle charge destabilization, which will then result in agglomeration of colloidal particles to form much larger particles (Oruc & Sabah, 2006). This implies that to achieve effective rapid mixing in a practical scenario, short but intense mixing under relatively high turbulence conditions is desirable (Kan *et al*., 2002). The greater shear rates due to rapid mixing do play a crucial part in the transportation of coagulant species, which favours the rate of adsorption between colloids and coagulant species.

2.18 Flocculation Process

Flocculation is the process of agglomerating colloidal particles to increase their size, this is the subsequent step that follows immediately after the coagulant has destabilized the colloidal particles. Unlike the coagulation process that requires vigorous agitation to ensure that mixing is thoroughly achieved between the coagulant agent and the raw water; the flocculation process requires many quiescent conditions to take place successfully. This is so because highly turbulent conditions could break the flocs that are being formed, this process is highly affected by the hydraulic conditions of the water. This type of condition needs to be considered during the design of a sedimentation tank. Some industrially used flocculators are discussed below.

2.18.1 Spiral Flocculator

The spiral flocculator is one of the flocculators that is ideal for bulk water treatment systems. One of the reasons why Rand Water is managing to run a successful bulk water treatment process is through the usage of this huge structure, through which over 250 megalitres of water per day can be successfully treated. As depicted in Figure 2.13 below, the flocculator operates such that water is fed to the centre of the flocculator under high turbulence conditions in order to promote rapid mixing with the coagulant, the water is then channelled from the centre to the periphery, whereby the flow channel area increases as you approach the outmost circumference of the spiral; this is done so to gradually slow down the flow by increasing the flow area in order to promote the formation of flocs before the water and the suspension is fed to the sedimentation basin.

Figure 2. 13: The Spiral flocculation system used by Rand Water.

2.18.2 Mechanical flocculators

The paddle type agitator, which is sometimes referred to as mechanical flocculator, is a type of flocculator that is utilized for moderate to high flow systems. It consists of pedals that are mounted to a steel bar that is rotated by a driving motor, with or without a speed regulator (Bridgeman *et al.*, 2010). The downside of this type of flocculator is that it usually requires frequent maintenance and can lead to unplanned downtimes due to rotor failure that can be instigated by accumulated sludge at the bottom of the flocculator basin. An atypical example of a pedal flocculator is depicted in Figure 2.14 below.

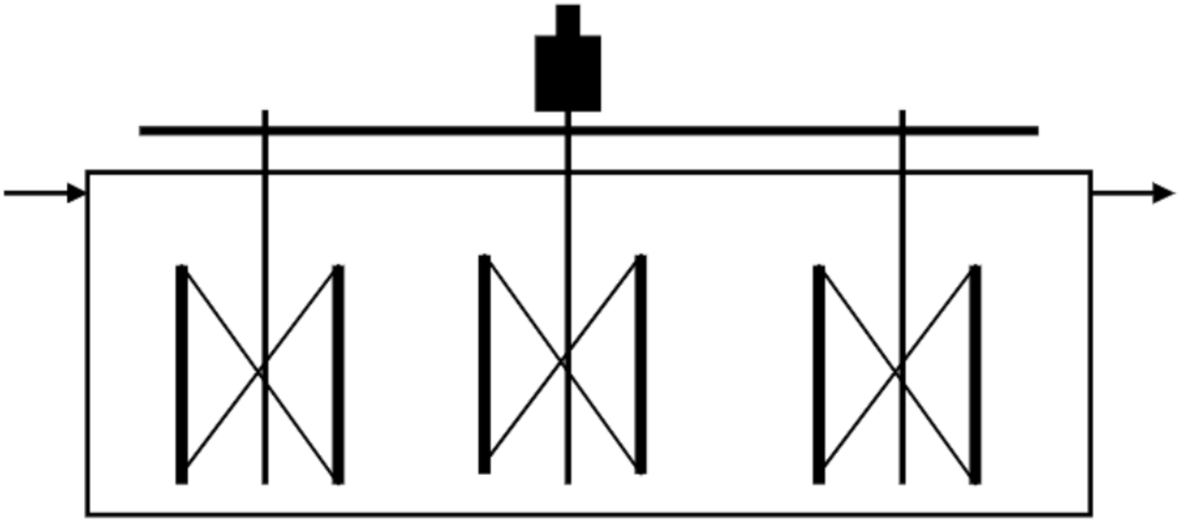

Figure 2. 14: Schematic representation of a paddle-type flocculators (Bridgeman *et al*., 2010).

2.18.3 Hydraulic flocculation

The hydraulic flocculator is a commonly used flocculator in the water treatment industry, it uses a system of baffles to instigate mixing. This type of flocculator are designed such that when the water enters the system, it turns to experience high turbulence to promote rapid mixing, and as the water flows down the channel, baffles are used to gently slow down the flow and promote floc formation. The disadvantage is that a slight head loss could significantly affect the process, since the frequency of collision between colloids is strongly dependent on velocity gradients (Bridgeman *et al*., 2010).

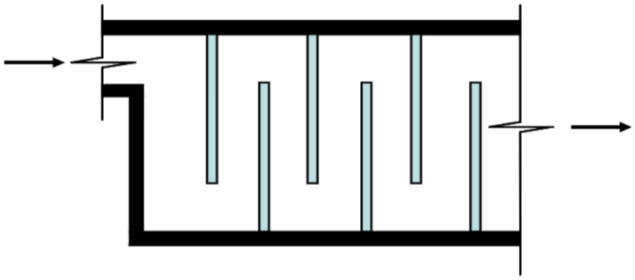

Figure 2. 15: Schematic representation of the hydraulic flocculation (Bridgeman *et al*., 2010).

2.19 Sedimentation

The sedimentation process is a fundamentally important process in water treatment, it is a solid-liquid separation process through which particles settle under the influence of the gravitational forces (Al-Sammarraee *et al.*, 2009). The sedimentation process is widely used to settle out relatively large particles that were enhanced through the predecessor process of flocculation (Al-Sammarraee *et al*., 2009). There is no question that the success of the flocculation-coagulation process guarantees a successful sedimentation process. The sedimentation process will be rendered useless if ever the flocs were not successfully formed from the flocculation-coagulation processes.

2.19.1 The significance of the sedimentation process

The sedimentation process constitutes the backbone of a water treatment process, such that if it is not performed correctly, it is more likely to adversely the upstream efforts that were put to coagulate and flocculate colloidal particles, it also affects the downstream processes such as filtration and disinfection (Zhu *et al*., 2021). It is therefore important that during the design of a sedimentation tank, a closer look is taken at factors that influence particle sedimentation.

The process of sedimentation is not only affected by the physicochemical aspects associated with the coagulation-flocculation process, but it is also affected by the hydraulic properties associated with the flow of the treated water (Al-Sammarraee *et al.*, 2009). Overlooking these properties during the design phase of the sedimentation process could lead to a poor design. A poorly designed sedimentation tank does not only lead to the waste of water in the form of sludge, but it can subject the custodians and investors to fruitless and wistful capital expenditure (Al-Sammarraee *et al*., 2009), this implies that a good understanding of hydraulic dynamics during the design of a water treatment plant is of utmost importance.

2.19.2 The Mechanism of the sedimentation process

2.19.2.1 Settling Velocities of a particle

The understanding of settling velocities is very much important when it comes to designing a sedimentation system. Settling particles are usually considered individually, there are two major forces acting upon a settling particle in a fluid, the primary force is referred to as an applied force, a typical example of an applied force is the force of gravity (Waldschläger *et al*., 2020). The other force acting on a settling particle is referred to as the drag force, which is resulted from the motion of the particle in fluid (Terfous *et al*., 2013). The interaction of these forces on a particle is depicted in Figure 2.16 below. In most practical scenarios, the applied force is typically not affected by the particle's velocity, while the drag force is highly affected by the particle's velocity (Shi *et al*., 2003).

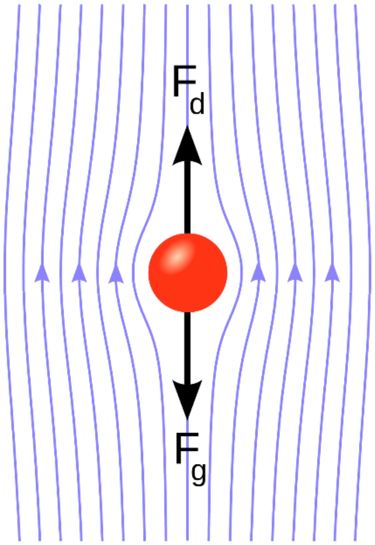

Figure 2. 16: Two major forces acting on a settling particle in fluid (Lara, 2017).

In a scenario whereby there are no other forces involved, the drag force always acts in the opposite direction of the settling particle. When the particle's velocity increases, it will approach a point whereby the applied force and the drag force are almost equal, which subsequently results in no change in the particle's velocity; under such conditions, the particle will attain what is called terminal velocity, also referred to as settling velocity of a particle (Kalman & Matana, 2022).

According to Stoke's law, larger particles will typically display greater settling velocities (Hagemeier *et a*l., 2021). By closely examining the rate at which individual particles fall, the terminal or fall velocity of a particle can be determined. The work that was done by Lv *et al*., 2021 demonstrated the measurements of settling velocities using the HD settlement shooting system as depicted in Figure 2.17 below, this work demonstrated the importance of understanding settling velocities. This analysis has added great value in the design of the sedimentation basins, as understanding the rate at which flocs settle could avoid designs that lead to flocs being carried over to the filters on the next stage of the treatment process.

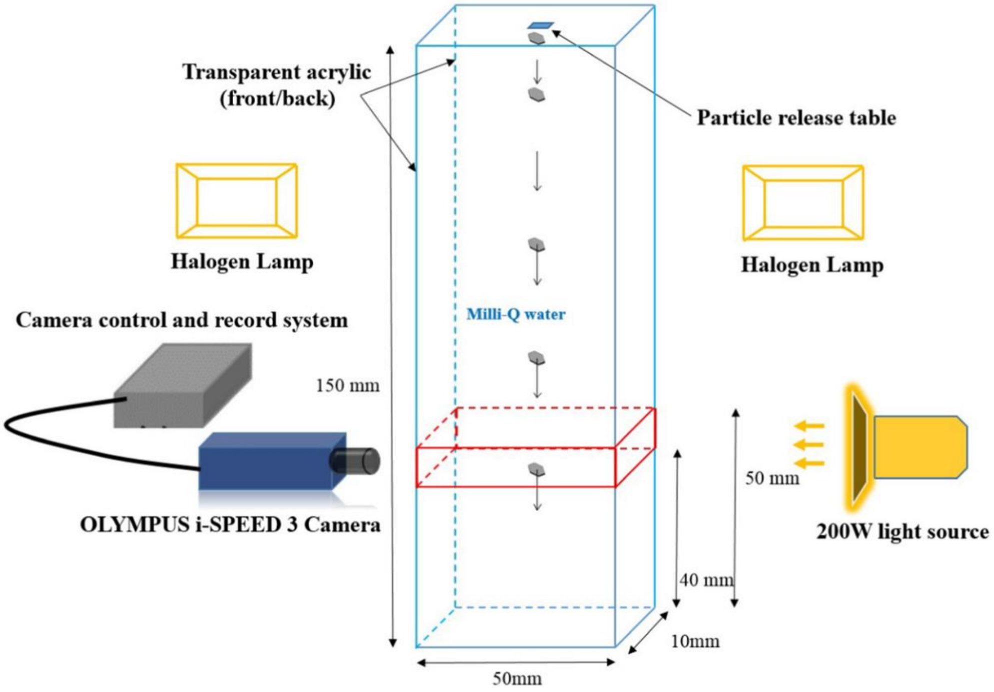

Figure 2. 17: Measurements of settling velocities using the HD settlement shooting system (Lv *et a*l., 2021).

2.19.2.2 Stoke’s Law

Stoke's law can be used to predict the settling velocity of small spherical particles in the fluid. Stoke’s law has found many applications in applied science and engineering, and it is defined as per equation 01 below.

$$v_p = \frac{2(p_p-\rho_f)gr^2}{9\mu} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where v_p symbolisms the settling velocity, $p_p$is the density of the particle, ρ_f the density of the fluid, g represents the gravitational force (applied force), r is the radius of the particle and μ denotes the viscosity of the fluid.

When applying to Stoke's law, it is important to take note that it applies under conditions whereby the Reynolds (Re) of the particle is less than 0,1 (Goossens, 2020). Stoke's law has proved to break down with an increase in Reynold's numbers due to the increase in inertia forces; under such conditions, imperial methods need to be deployed to determine the drag forces of the particles.

2.19.2.3 Effective density

One of the most critical parameters in understanding transportation as well as the movement of flocs in water is effective density. Effective density gives the relationship between a particle 's mass and its mobility, it is expressed as the ratio between the particle mass and its mobility equivalent volume (Kazemimanesh *et al*., 2021). To calculate effective density, Stoke's formula is taken into consideration, equation (2) below shows the mathematical expression for effective density.

$$\Delta_\rho = p_p - \rho_f = \frac{18\mu v_p}{gr^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Whereby, Δ_ρ denotes the effective density, and the rest of the terms retain the definition that was made on equation (1) above.

2.19.2.4 Sedimentation stages

Sedimentation is the process through which particles formed during the coagulation-flocculation process are allowed to settle to the bottom of the sedimentation tank and be removed in the form of sludge. With reference to the specific concentration of the suspended particles and the interaction between the particles, four types of settling behaviours can be outlined as follows:

- Discrete particle settling
- Flocculant settling

- Hindered settling
- Compression settling

In most cases, more than one form of settling will typically occur at the same time during the settling process, very often than not the four could occur simultaneously. Different settling mechanisms are depicted in Figure 2.18 below.

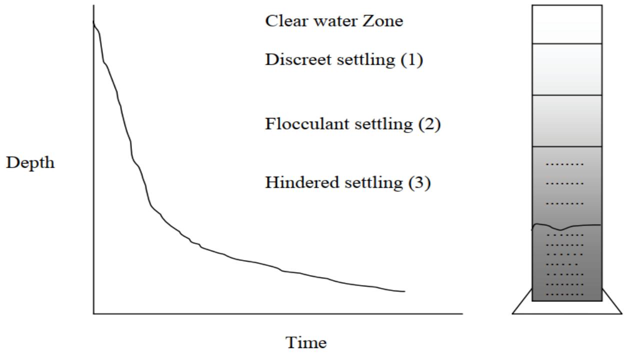

Figure 2. 18: Schematic representation of different settling types (Challener, 2011).

Table 2. 2: Different phase of the sedimentation process (Challener, 2011).

Settling Type	Description
Discrete particle	In this type of sedimentation, particles like fine sand, flocs, and fine earth deposits of low solid concentration will typically settle as individual entities with no interaction with the surrounding particles.
Flocculant	This is the type of sedimentation that occurs simultaneously with flocculation, particles will typically agglomerate together and form larger particles that settle much faster, which is typical of chemically induced flocs.
Hindered	The particles exhibit a tendency to stay in a fixed position relative to one another, and the mass of the particles subsequently settle as a unit. For this type of settling, a solid–liquid interface will form above the settling agglomerate of particles.
Compression	Refers to a type of settling through which settling particles typically form a structure, as more particles are deposited on this structure compression takes

	place due to the weight of the particles which are continually being added to the structure.

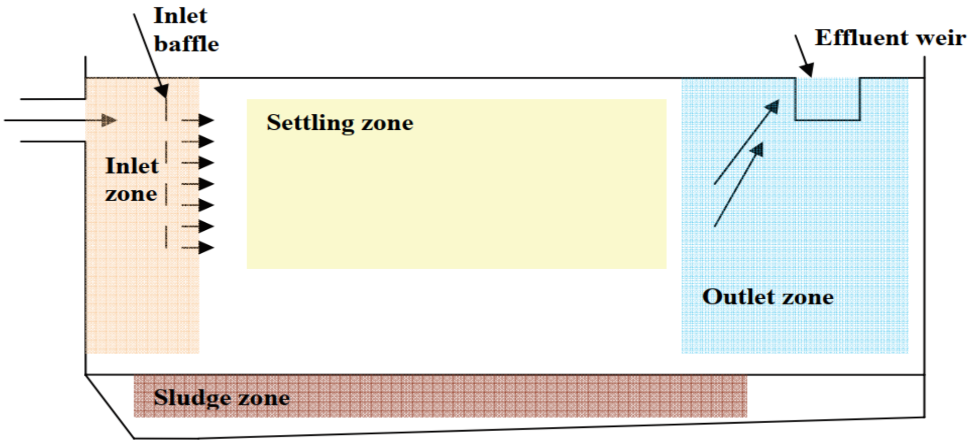

Figure 2. 19: A typical example of a sedimentation tank (Challener, 2011)

For a very long time, researchers in the field of science and engineering have been working on the design of different types of sedimentation tanks, with an intent to get the best of this critical water treatment unit operation. The universally common design is the rectangular horizontal flow sedimentation tank, with this type of tank water enters on one side of the tank and leaves on the other side. A typical example of a rectangular sedimentation tank is depicted in Figure 2.19 above. Another type of sedimentation tank is a circular tank that is characterized by a cone-shaped bottom. In this type of tank, water enters at the central point and gets distributed across the tank, and eventually gets channelled to the circumference of the tank where it leaves the tank.

Regardless of the shape and size, practically all sedimentation tanks can be divided into four zones, whereby each zone is characterized by its specific function. These zones are specified below:

- **Inlet Zone:** The function of this zone is to distribute the incoming flow and its associate suspension across the settling zone of the tank. Different designs will have different flow channelling methods such as baffles and distributors.
- **Settling Zone:** This zone constitutes the largest part of the sedimentation basin and settling of particles takes place as the water is flowing across the tank with a controlled velocity. For sedimentation to effectively take place, the settling velocity of a well-defined particle should be greater than the velocity of the bulk flow of water. This is a very important design

parameter of a sedimentation tank. If this is not done right during the design and sizing phase, there is a risk of flocs being carried over to the downstream processes, which could potentially decrease the efficiency of the process.

- **The outlet zone:** Provides a larger area through which the water leaves the sedimentation tank, this happens just before the water flows into a flume that leads to the sand filters for further treatment. The significance of using a larger area is to lower the flow velocity of the treated water, fast-moving water could potentially entrain flocs to the filters.
- **Sludge Zone:** This is the zone through which the sludge collects at the bottom of the sedimentation tank, the depth and configuration of the sludge zone depend on the method used for sludge removal. Different methods of sludge removal have been developed over time, some make use of submersible sludge pumps while some use gravity and different types of valves.

2.20 Jar Test Method

The optimization of coagulation and flocculation has been of greater interest to researchers for many years. Bridgeman *et al*., 2010, mentioned that the optimization of these two subsequent processes for a big operation is generally considered at a laboratory scale. This is achieved using the jar test apparatus and procedure. The jar test can be performed simply by adding source water to a beaker together with treatment chemicals, by simply stirring the mixture under high-intensity conditions then coagulation can take place, and by adjusting the stirrer speed to slightly lower rotations per unit time, flocculation conditions could be achieved. More involved studies that intend to investigate critical parameters that affect the coagulation and flocculation process, usually make use of this apparatus, a typical example of this apparatus is depicted in Figure 2.20 below. The apparatus consists of a series of glass vessels with a specified volume, with a mechanical agitator mounted in each vessel for the purpose of stirring the content (Dayarathne *et al*., 2021). This apparatus simulates conditions that could be scaled up with an intent to optimize a functional water treatment plant of practically any size, which is exactly what this study aims to achieve. The determination of optimal coagulation-flocculation conditions is nearly impossible without the use of this apparatus.

Figure 2. 20: Typical example of a jar test apparatus (Velp, 2021).

Numerous jar test studies using a variety of coagulant agents have been performed by different scientist and researchers over the years. In subsequent years polyelectrolytes coagulant found a great deal of application in raw water, sewage wastewater and industrial water treatment. The research focus has greatly shifted more into finding the right polymer for a specific water treatment application. For many years the Jar test has been regarded as a pilot-scale laboratory test that simulates the coagulation and flocculation processes with different reagent dosage. This method has proved to give reliable outcomes when scaled up to pilot and actual treatment plants.

Ibrahim 2021 examined the effect of utilizing the industrial coagulant of Polyelectrolyte named LT-22 comparing it with the usage of alum as a coagulant aid. After a series of jar test experiments were conducted on raw water of turbidity of 10,20,30,40,60 and 80 Nephelometric Turbidity Units (NTU). It was established upon measuring the final turbidity after sedimentation that the usage of polyelectrolyte (LT-22) and alum removed a maximum of 75% of the turbidity in each sample, which has proved to be better than the usage of polyelectrolyte (LT-22) alone, since it only achieved a maximum of 55% turbidity removal. This work also established that the usage of alum as a coagulant aid created larger and clear, easily settleable flocs, in comparison to the usage of polyelectrolyte alone. Good removal efficiency was also observed at a turbidity higher than 30 NTU.

Chapter 3 : Materials and Methods

3.1 Introduction

This chapter describes the experimental design, materials, sample preparations, experimental methods and analytical technique used in this study. The data collected from this experimental work are presented, analysed, and discussed in Chapter 04 which outlines results and discussion.

3.2 Experimental Overview

Most impurities in raw water from the Vaal dam is suspended solids referred to in water treatment literature as Total Suspended Solids (TSS), which are particles that are larger than 2 microns that are suspended in a body of untreated water (SoliSense, 2022.). Solid particles entrained by the turbulence of moving water can readily settle when the water is stationary or flowing at a slow, controlled velocity known as "settling velocity" during a water treatment process (Loubet *et al*., 2007). Suspended solids found in water extracted from the Vaal dam have been found to vary in the degree of pollution from time to time.

The water contains particles that can readily settle when the water is subjected to quiescent conditions, the water also contains very fine particles referred to as colloidal particles, which are also referred to as "difficult-to settle-particles", which are very fine and tiny particles that cannot readily settle in the sedimentation basin (Baghvand *et al*., 2010). Any particle greater than 10 µm will tend to settle given that the water is at standstill or flowing at a very controlled settling velocity, while colloidal particles of size ranging between 1 nm (0,001 µm) and 1 µm will not readily settle; with the inhibiting factor being the Brownian motion, electrostatic forces balancing the gravitational force, reaction period, coagulant type and the coagulant dose among others (Ghernaout, 2015). The jar test method has been found to be ideal for the investigation of coagulants and their efficiency in water treatment.

To optimize the coagulation-flocculation process on a large-scale continuous process, the number of critical parameters must be considered on experimental scale to establish optimum parameters that can be imposed on a large-scale water treatment process. These critical parameters are listed below:

- Coagulant dose
- pH
- Rapid mixing
- Shear rate during flocculation
- Flocculation time
- Dosing of a coagulant polymer

3.3 Objective

The main objective of this experiment is to treat raw (source) water using different coagulant regimes to archive improved physicochemical quality. The main properties of water that this experiment seek to improve are the turbidity, pH, total dissolved solids removal, and the odour of water among others. In this work, two coagulation regimes were identified and investigated in a quest to determine the most efficient coagulation method, with the aim to establish critical parameters that can be used to optimize the overall conventional water treatment process on a continuous operation. This was chosen because coagulation and flocculation constitute the backbone of all water treatment process. The following coagulation regimes were investigated:

Table 3. 1: The Coagulant regimes used in the experimental.

Regime	Primary Coagulant	Coagulant Aid
01	Polyelectrolytes	-
02	Polyelectrolytes	Lime

3.4 Experimental Design

The jar test has been known to be an effective method to determine the optimal coagulant dosing rates over the years. The results of this test are dependent on factors such as coagulant dose, pH, reaction duration, and the associate mixing energy. The jar test has been found to be an effective way to investigate the influence of these critical process parameters within a short time (Balcioglu & Durak, 2015). The jar test can also be performed for several reasons, for instance it can be performed to determine optimal coagulation pH, by varying the pH while keeping the coagulant dose constant in different vessels. It can also be performed to determine the optimal dosing rate by keeping the pH constant while varying the dosage quantity of the coagulant. The schematic in Figure 3.1 represents the coagulation experimental setup used in this investigation, whereby a series of six test beakers is lined up along a jar test apparatus, with each lined up to a stirrer that is used for content agitation purpose.

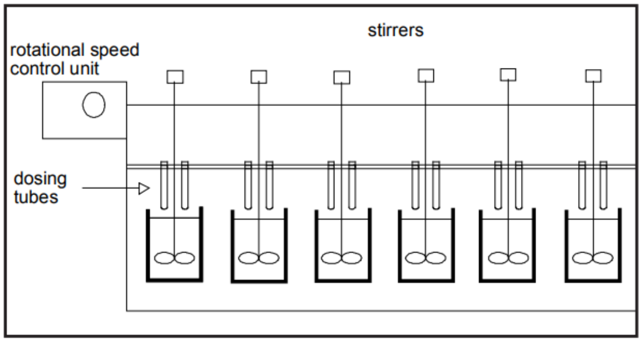

Figure 3. 1: The coagulation jar test

To optimize the coagulation/flocculation process, several process parameters need to be closely taken into consideration. For this study, such parameters include pH, coagulant dose, rapid mixing intensity, flocculation mixing intensity, dosing of coagulant coagulation aids.

3.5 Experimental Set-up for Regime 01&02

A series of experiments conducted for this study is greatly based on the theory associated with the Jar Test. The main parameters in this experiment are turbidity, coagulation dosage, pH, rapid mixing, and flocculation mixing. The experimental apparatus used in this experiment is depicted below in Figure 3.2. It is made up of six rectangular vessels of volume 2L each, all equipped with a stirrer of variable speed rated at the operational range 1-300 rpm (Revolutions per minute), which are used for agitation purposes. This agitator can be operated simultaneously at a regulated speed. As part of this study, a series of experiments were performed to determine the optimal coagulation conditions of the above-defined treatment regimes.

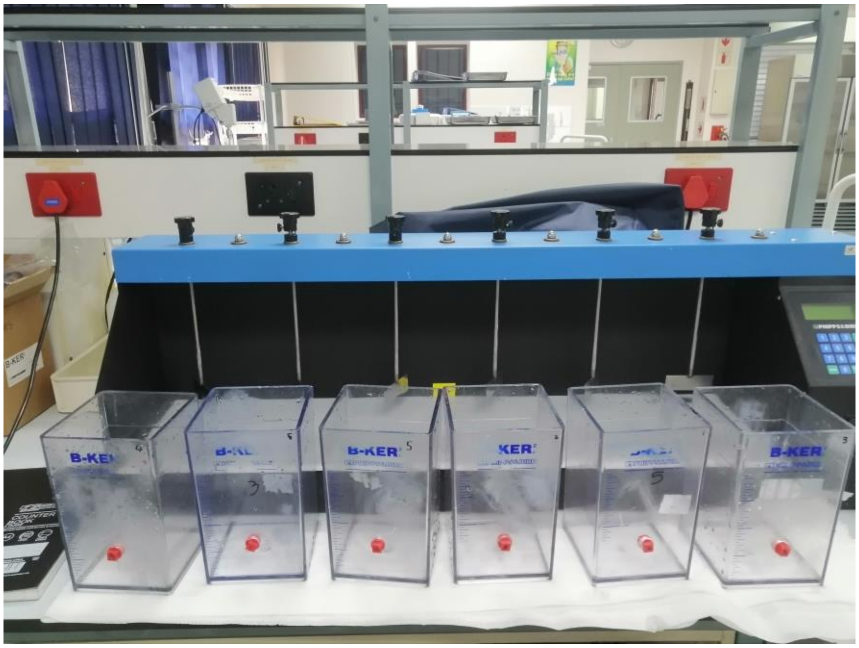

Figure 3. 2 : The Jar test apparatus used in this study.

3.6 Experimental setup and procedure

For each treatment regime, 5 sets of experiments were performed as outlined below:

1. Optimal dosing of coagulant
2. Optimal dosing pH
3. Re-determination of the optimal coagulant dose @ optimal pH
4. Effect of initial mixing intensity @ optimal pH and Optimal Coagulant dose
5. Effect of flocculation mixing intensity @ optimal pH and Optimal Coagulant dose

3.7 Chemical Reagents and Sources of Raw Water

The chemical reagents and the equipment used in this study were obtained from Rand Water Process Technology facility. The primary coagulant used in this study is polyelectrolytes (Zeta-Floc), while the coagulant-aid used is slaked lime commonly known as milk of lime; the material data sheets of these reagents were observed during this study. In this experiment, raw water collected from the Vaal dam was used as the source water for this experiment in both regimes.

3.8 Characterization of Vaal Dam water for Regime 1&2:

The initial step of this experiment was to determine the initial characteristics of the Raw Water, this was achieved using a multi-parameter photometer, which is an advanced water quality analysis tool that has 26 different programmed methodologies that are designed to measure 25 critical water quality parameters. A pH and turbidity meter were also used in this study; these water analysis tools can be seen on Appendix A. The initial properties of the source water that were of particular interest to this study were measured, and they are displayed on the Table 3.2 below.

Table 3. 2: Initial physiochemical parameters of Vaal Dam water.

Chemical and Physical Properties	Measured initial Value
pH	8.06
Temperature	20 º C
Turbidity	62.4 NTU
TSS (mg/l)	9
TDS (mg/l)	283
CaCO3 (mg/l)	79
NO3 - (mg/l)	29
SO4 2- (mg/l)	98

3.9 Reagent preparation

3.9.1 Raw Water Preparation

The initial step of this experiment was to collect the water from the Vaal Dam, which is the water that Rand Water uses as the bulk raw water feed for its continuous treatment processes. As part of reagent preparations, the water was continuously stirred for about 10 minutes at a speed of 300 rpm to ensure its composition is as consistent as possible before measuring the physicochemical properties depicted in Table 3.2.

Figure 3. 3 : The Vaal Water feed water preparation.

3.9.2 Jar Test Apparatus

The jar test apparatus depicted in Figure 3.4 below was washed with distilled water to eliminate possible foreign matter and ensure reliable results.

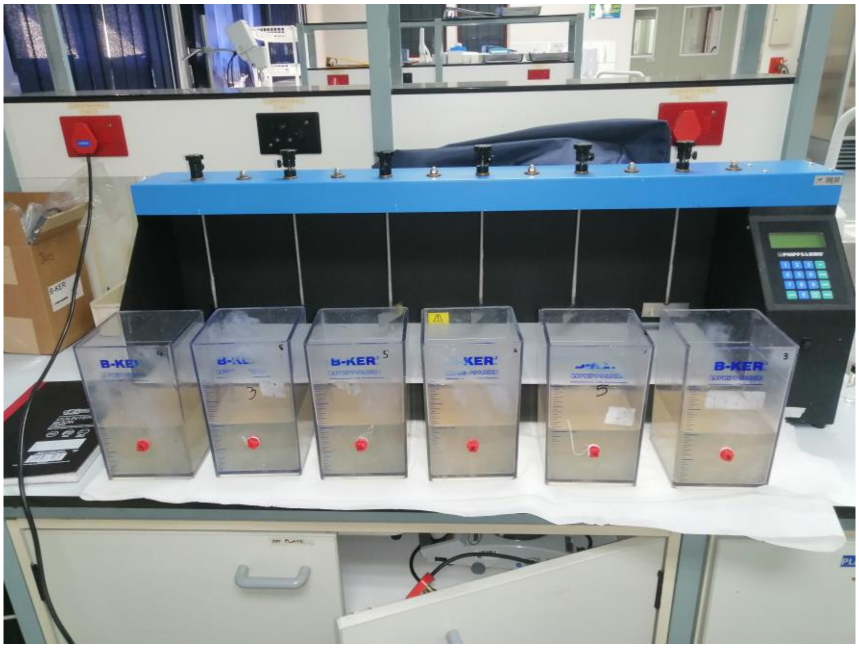

Figure 3. 4: Jars filled with 1000ml of prepared raw water from the Vaal Dam.

3.9.3 Other Equipment

A couple of equipment was used for this study for the analysis of the physicochemical properties of water and feed preparation. The apparatus used in this study are listed below:

- pH Meter
- turbidity Meter
- Weighing Scale
- Multiparameter Analyser
- Laboratory Apparatus (Beakers, Syringe, Conical flask, graduated cylinders and spatulas)

3.9.4 Poly electrolyte (Primary Coagulant) preparation

Polyelectrolytes coagulant was prepared by mixing 1g of poly with 1000ml of deionized water to promote dispersion and mixing when dozing to the jar test vessels for experimental water treatment.

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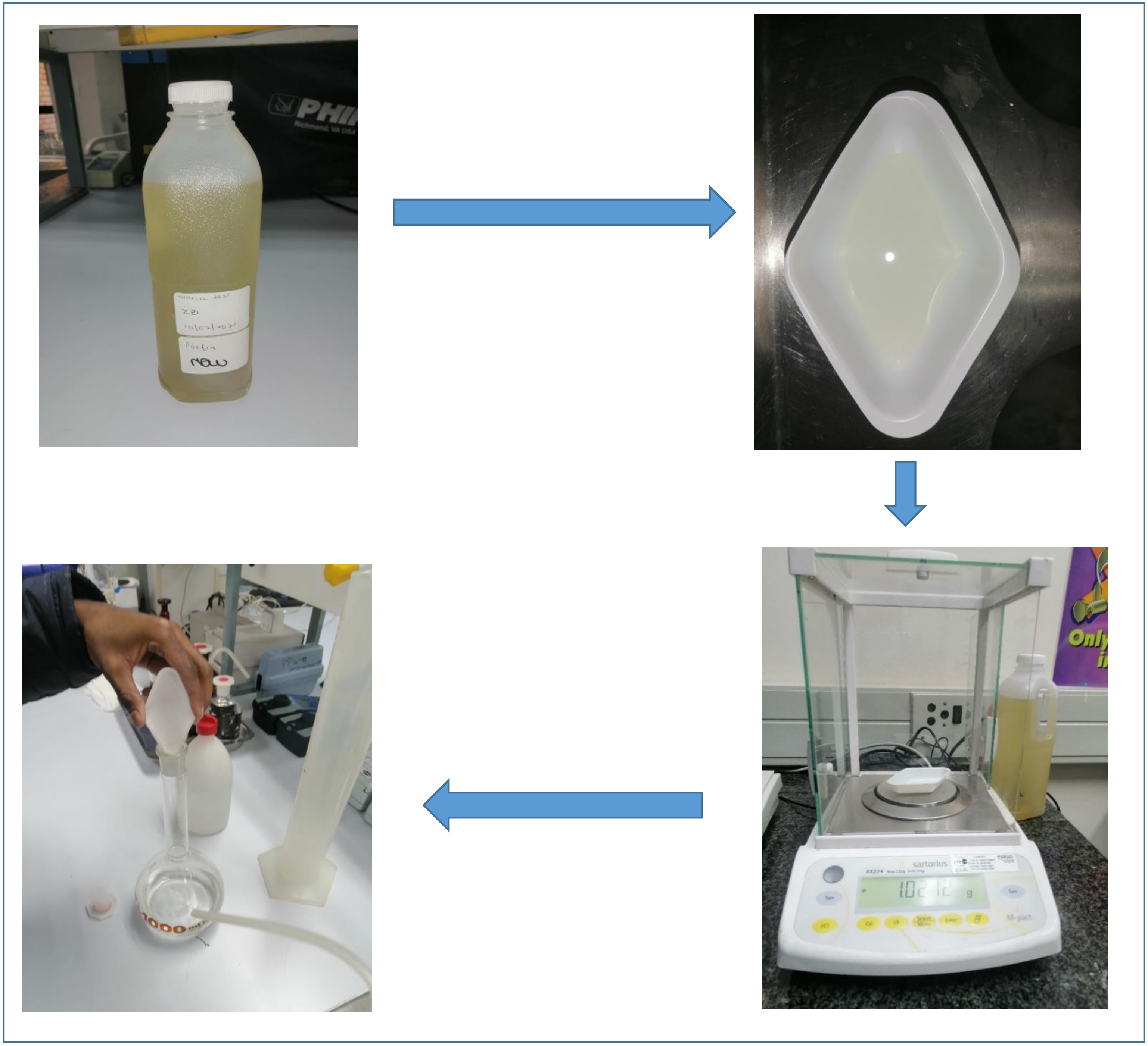

Figure 3. 5: Polyelectrolyte (Zeta-Floc) preparation sequence.

3.9.5 Milk of Lime (Coagulant Aid) preparations

Milk of lime was prepared by mixing 10 g of pulverized lime (87% Purity) with 1000 ml of deionized water to get a product called “milk of lime “which is used as a coagulant aid.

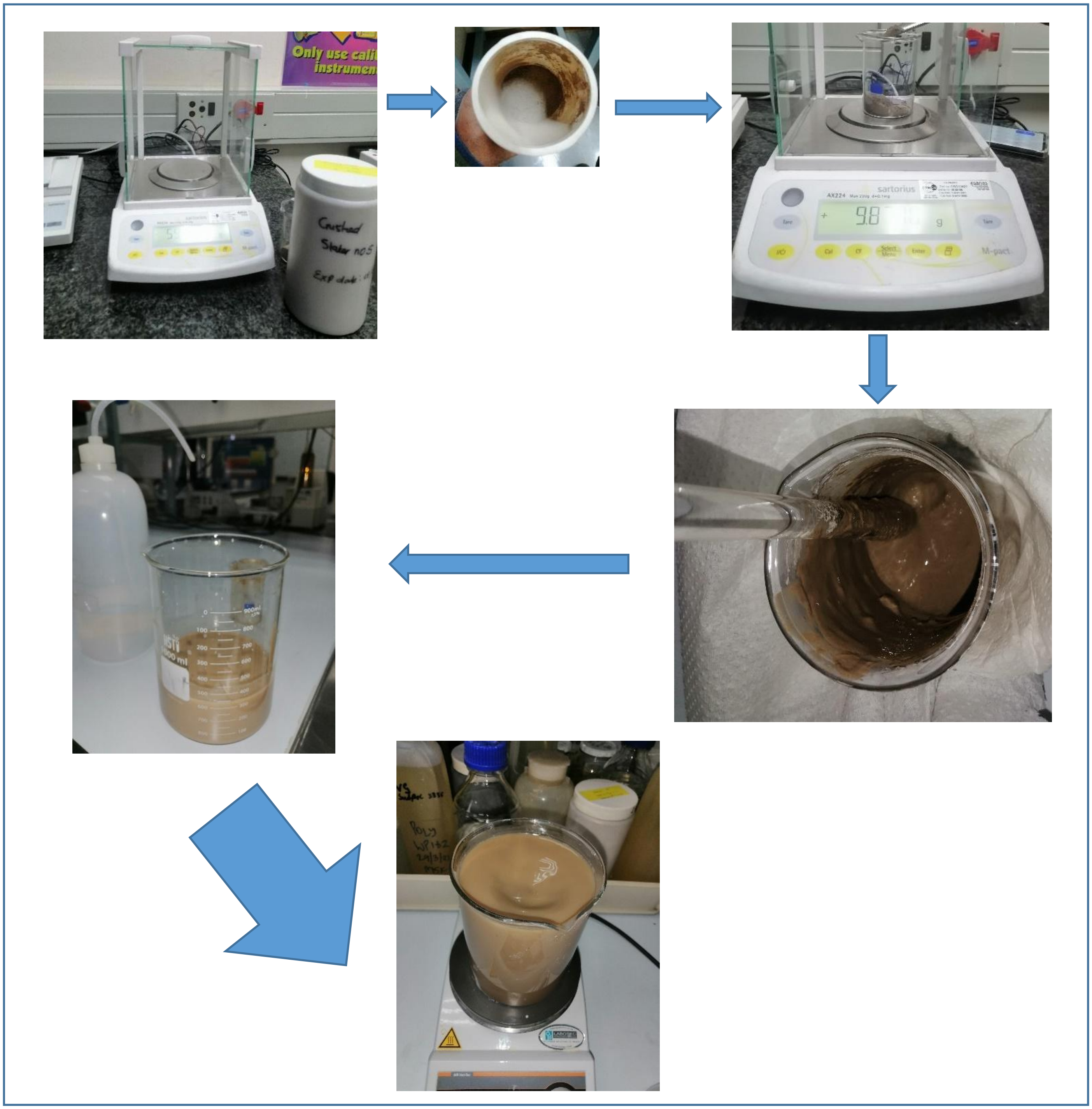

Figure 3. 6 : Milk of lime coagulant aid preparation sequence.

3.9.6 Turbidity Measurements

The initial and final turbidity in all the samples that were used in this study were measured by a turbidity meter that is depicted below. The sampling bottle was washed and rinsed with deionized water after every usage to ensure accurate results.

Figure 3. 7: Initial and Residual Turbidity Measurement with a turbidity meter.

3.10 Experiments and procedure for regime 01

3.10.1 Experiment 01: Determination of Optimal Coagulant dose

Table 3. 3: Experimental information

Characteristics	Description
Coagulant dose range	Polyelectrolyte (Zeta Floc) (1-6 mg/l)
Coagulant Aid	-
Initial Turbidity	62.4 NTU
Rapid Mixing Intensity	1 Min @ 100 rpm
Flocculating Mixing Intensity	20 Mins @ 30 rpm
Settling	20 Mins

Experimental Outline

During this investigation, the variable parameter was the coagulant dose, which was varied from a randomize range 1 mg/l to 6 mg/l as shown in Figure 3.8.

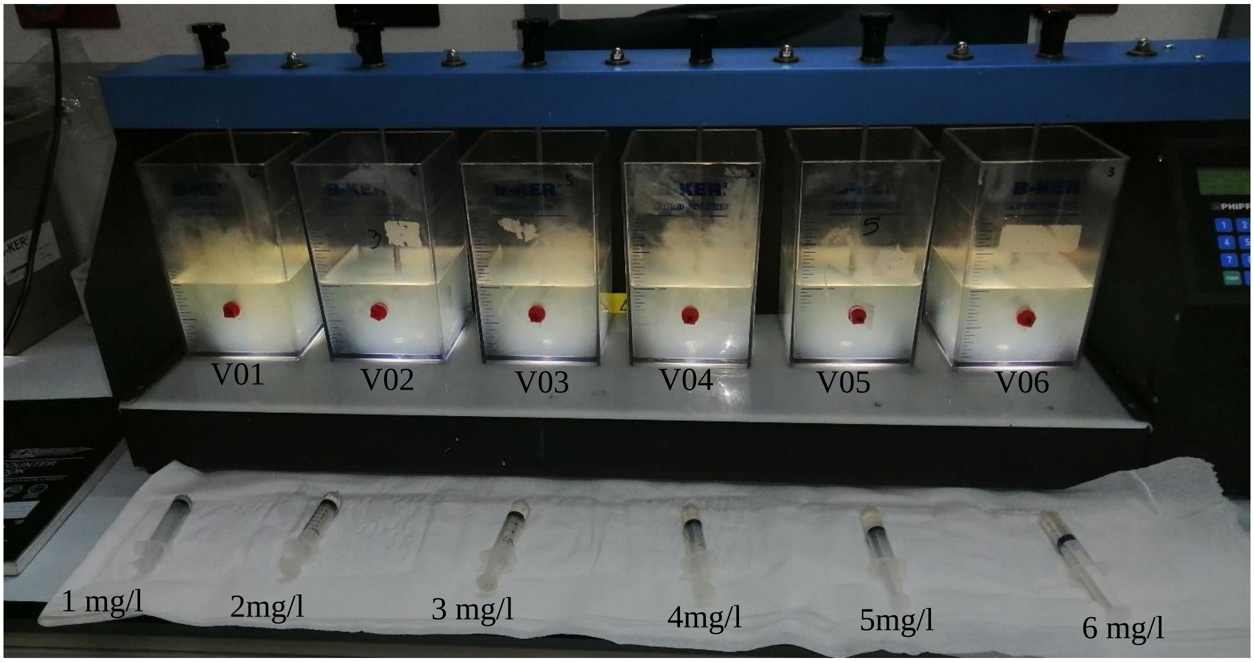

Figure 3. 8: The dosing of varying coagulant concentrations in each vessel.

As depicted in Figure 3.8 above, the vessels were labelled accordingly from Vessel (V) 1 to 6. The volume of raw water used in the experiment is 1L (1000ml) on each vessel. In this experiment the coagulant used is polyelectrolytes (Zeta Floc) and there is no coagulant aid. Coagulant dosage volume was varied across the vessels with an intent to determine the optimal dosage as depicted in Table 3.4.

Table 3. 4: Investigation of the optimal coagulant dose

Vessel Number	**1**	**2**	**3**	**4**	**5**	**6**
Sample pH	8.06					
Sample Volume (ml)	1000 ml for all					
Coagulant Aid(mg/l)	None					
Coagulant dose (mg/l)	1 mg/l	2mg/l	3mg/l	4mg/l	5mg/l	6mg/l
Coagulant Volume (ml)	10 ml	20 ml	30 ml	40 ml	50 ml	60 ml

Experimental Procedure

Firstly, the samples were lined up at the jar test apparatus with six vessels and stainless-steel stirrers submerged in each vessel for agitation purposes. The coagulant was subsequently added in the order depicted in Table 3.4 above. Each jar was agitated at 150 rpm for 1 minute to induce rapid mixing, this was done to ensure that the maximum dispersion of the coagulant is achieved. The stirrer was adjusted at 20 rpm for 20 minutes, to create a quiescent condition through which the flocculation process can occur. Lastly the vessels were removed from the equipment and put on a steady stable table to allow the sedimentation process to unfold., this process was allowed to unfold for 20 minutes; Figure 3.9 below shows the coagulation, flocculation and sedimentation processes as performed in this study.

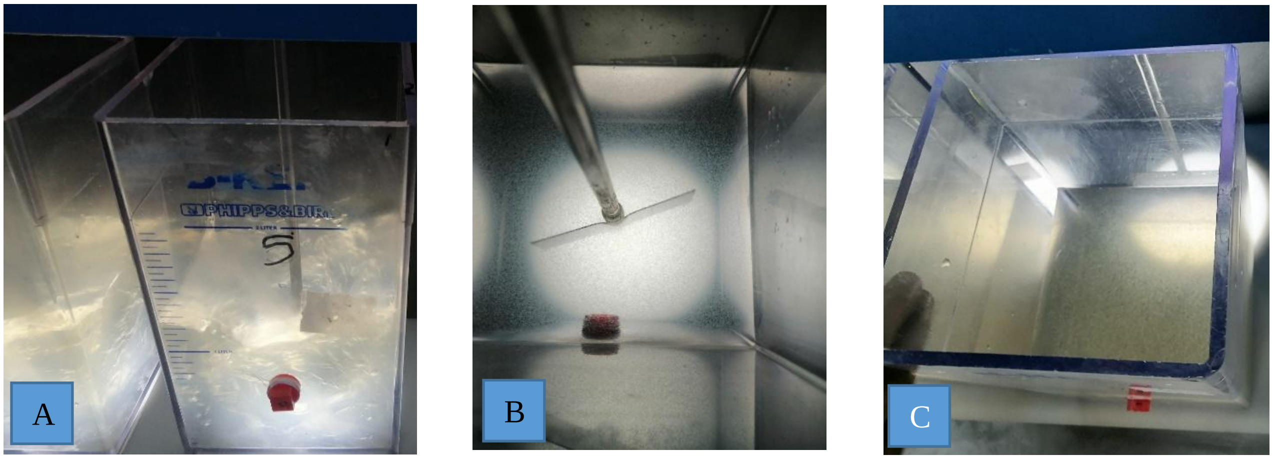

Figure 3. 9: Coagulation (Left), flocculation (Middle) and Sedimentation (Right)

A pipette was then used to extract 50 ml of the treated water from vessel C to determine the turbidity using a turbidity meter shown on Figure 3.7 above. The data collected from this investigation were used to generate a curve that depicts turbidity against coagulant dose, the curve will be outlined in Chapter 04, which presents results and discussion of this investigation.

3.10.2 **Experiment 02:** Determination of Optimal coagulation pH

Table 3. 5: Experimental information

Characteristics	Description
Coagulant	Polyelectrolyte (Zeta Floc) (6 mg/l)
Coagulant Aid	-
pH range	7.8-8.3
Initial Turbidity	62.4 NTU
Rapid Mixing Intensity	1 Min @ 100 rpm
Flocculating Mixing Intensity	20 Mins @ 30 rpm
Settling	20 Mins

Experimental Outline

This step of the study is aimed at determining the optimal dosing pH under which the coagulation process can partake. Here the pH of the raw water was altered by either adding acidity or alkalinity to the source water to simulate different varying pH scenarios that could possibly occur, this investigation was necessitated by the fact that the pH of the source water varies gradually from time to time due to either seasonal change or the type of effluent that trickles its way to the Vaal dam. The jar test was then performed using the optimal coagulant dose that was established in Experiment 01. The table below depicts the varying pH as well as the optimal coagulant dose-volume used.

Table 3. 6: Investigation of the optimal coagulation pH.

Vessel Number	**1**	**2**	**3**	**4**	**5**	**6**
Sample pH	7.8	7.9	8.0	8.1	8.2	8.3
Sample Volume (ml)	1000 ml for all					
Coagulant Aid(mg/l)	None					
Coagulant dose (mg/l)	6mg/l					
Coagulant Volume (ml)	60 ml					

Experimental Procedure

The pH of the samples was conditioned as depicted on table 3.6 above and the constant amount of 6mg/l of the coagulant was added across the six vessels under initial rapid mixing of 150 rpm for 1 minute. The speed of the impeller was reduced to 20 rpm to create floc formation conditions for 20 minutes. Lastly, the vessels were removed from the equipment and put on a steady stable table to allow the sedimentation process to unfold, this process was allowed to unfold for 20 minutes. A pipette was then used to extract 50 ml of the treated water to determine the turbidity using a turbidity meter. The data collected from this investigation was used to generate a curve that depicts pH against turbidity, the curve will be outlined and discussed in Chapter 04, which presents results and discussion.

3.10.3 **Experiment 03:** Re-determination of the optimal coagulant dose @ optimum pH

Table 3. 7: Experimental information

Characteristics	Description
Coagulant	Polyelectrolyte (Zeta Floc) (1-6 mg/l)
Coagulant Aid	-
pH	8.3
Initial Turbidity	62.4 NTU
Rapid Mixing Intensity	1 Min @ 100 rpm
Flocculating Mixing Intensity	20 Mins @ 30 rpm
Settling	20 Mins

Experimental outline

In this stage of the investigation, experiment 01 was re-done this time around with the water being treated under optimal pH conditions that were established in experiment 03 which was found to be 8.3. The main objective of this investigation is to re-establish the optimal dosing rate at this optimal pH. The parameters used in this experiment are outlined in the table below.

Table 3. 8: Re-Determination of optimal coagulant dose at optimal pH.

Vessel Number	**1**	**2**	**3**	**4**	**5**	**6**
Sample pH	8.3					
Sample Volume (ml)	1000ml for all					
Coagulant Aid(mg/l)	None					
Coagulant dose (mg/l)	1 mg/l	2mg/l	3mg/l	4mg/l	5mg/l	6mg/l
Coagulant Volume (ml)	10 ml	20 ml	30 ml	40 ml	50 ml	60 ml

The vessels were loaded with 1000 ml of sample water at optimal pH and the coagulant was added across the six vessels as per the Table 3.8 above, the initial rapid mixing of 150 rpm for 1 minute was run. The speed of the impeller was reduced to 20 rpm to create floc formation conditions for

20 minutes. Lastly, the vessels were removed from the equipment and put on a steady stable table to allow the sedimentation process to unfold, this process was allowed to unfold for 20 minutes. A pipette was then used to extract 50 ml of the treated water to determine the turbidity using a turbidity meter. The data collected from this investigation were used to generate a curve that depicts coagulant dose against turbidity, the curve will be outlined and discussed in Chapter 04, which presents results and discussion.

3.10.4 **Experiment 04:** Effect of initial mixing intensity @ optimal Coagulation dose and optimal pH

Table 3. 9: Experimental information

Characteristics	Description
Coagulant	Polyelectrolyte (Zeta Floc) (6 mg/l)
Coagulant Aid	-
pH	8.3
Initial Turbidity	62.4 NTU
Rapid Mixing Intensity range	1 Min @ (50-170) rpm
Flocculating Mixing Intensity	20 Mins @ 30 rpm
Settling	20 Mins

Experimental Outline

This section of the experiment was concerned with investigating the impact of the initial mixing intensity of the coagulant and the source water, this was motivated by the literature that outlined that the coagulation flocculation process is not only affected by chemical interaction between the chemicals and colloidal particles, but also by physical parameters such as the hydraulic conditions associated with the process. In this investigation, the optimal dosing parameters that were established in subsequent experiments were used, that is the optimal pH of 8.3 that was determined in experiment 2 and the optimal coagulant dose of 6 mg/l that was determined in experiment 3. For this Jar Test, the equipment was prepared and adjusted to varying stirrer rotation speeds for each vessel, as shown in Table 3.10.

Table 3. 10: Effect of initial mixing intensity

Vessel Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing Intensity (rpm)	50	80	100	130	150	170
Sample Volume (ml)	1000ml for all					
pH	8.3					
Coagulant Aid(mg/l)	None					
Coagulant dose (mg/l)	6 mg/l					
Coagulant Volume (ml)	60 ml					

Experimental procedure

The samples were run simultaneously at different stirrer speeds as indicated in table 3.10 above, this rapid mixing was timed to run for about 1 minute after dosing the coagulant for each sample. The speed was then reduced to 20 rpm for 20 minutes to create conditions for floc formation for all the vessels. Apart from varying the initial mixing intensity, other operational parameters were the same as the optimal coagulation conditions that were determined in subsequent experiments 2 and 3. Lastly, the vessels were removed from the equipment and put on a steady stable table to allow the sedimentation process to unfold, this process was allowed to unfold for 20 minutes. A pipette was then used to extract 50 ml of the treated water to determine the turbidity using a turbidity meter. The data collected from this investigation were used to generate a curve that depicts rotation speed against turbidity, the curve will be outlined and discussed in Chapter 04, which presents results and discussion.

3.10.5 **Experiment 05:** The Effect of flocculation mixing time @ optimal coagulant dose, pH, Rapid and rapid mixing.

Table 3. 11: Experimental information

Characteristics	Description
Coagulant	Polyelectrolyte (Zeta Floc) (6 mg/l)
Coagulant Aid	-
pH	8.3
Initial Turbidity	62.4 NTU
Rapid Mixing Intensity	1 Min @ 100 rpm
Flocculating Mixing Intensity	20 Min @ (5-35) rpm
Settling	20 Mins

Experimental Outline

In this experiment hydraulic conditions were further investigated, the optimal dosing conditions that were obtained in experiments 2,3, and 4 were used to investigate the impact of flocculation mixing intensity. The jar test was prepared for this set of experiment, whereby the only variable is mixing intensity and other operational parameters were kept constant. The table below depicts the parameters considered during this experiment:

Table 3. 12: The impact of flocculation agitation time

Vessel Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing intensity (rpm)	5	10	15	20	30	35
Sample Volume (ml)	1000ml for all					
pH	8.3					
Coagulant Aid(mg/l)	None					
Coagulant dose (mg/l)	6 mg/l					
Coagulant volume (ml)	60 ml					

Experimental Procedure

The jar test machine was run with the initial mixing intensity set to 150 rpm for 1 minute after the addition of a coagulant to all the vessels. Then after the flocculation, mixing time was lowered to different times as depicted in Table 3.12 above. Lastly the vessels were removed from the equipment and put on a steady stable table to allow the sedimentation process to unfold, this process was allowed to unfold for 20 minutes. A pipette was then used to extract 50 ml of the treated water to determine the turbidity using a turbidity meter. The data collected from this investigation was used to generate a curve that depicts mixing time against turbidity, the curve will be outlined and discussed in Chapter 04, which presents results and discussion.

3.11 Experiments and procedure for regime 02

3.11.1 Experiment 01: Determination of Optimal Coagulant dose

Table 3. 13: Experimental information

Characteristics	Description
Coagulant dosage range	Polyelectrolyte (Zeta Floc) (1-6 mg/l)
Coagulant Aid	lime(30mg/l)
Initial Turbidity	62.4 NTU
Rapid Mixing Intensity	1 Min @ 100 rpm
Flocculating Mixing Intensity	20 Min @ 30 rpm
Settling	20 Mins

Experimental Outline

In this investigation, the qualitative analysis was first conducted by first measuring the initial properties of the raw water as depicted in Table 3.2. During this investigation, the variable parameter is the coagulant dose, which was varied from 1 mg/l to 6 mg/l as shown in Figure 3.10 In this regime, lime was added at constant concentration of 30 mg/l to act as a coagulant aid.

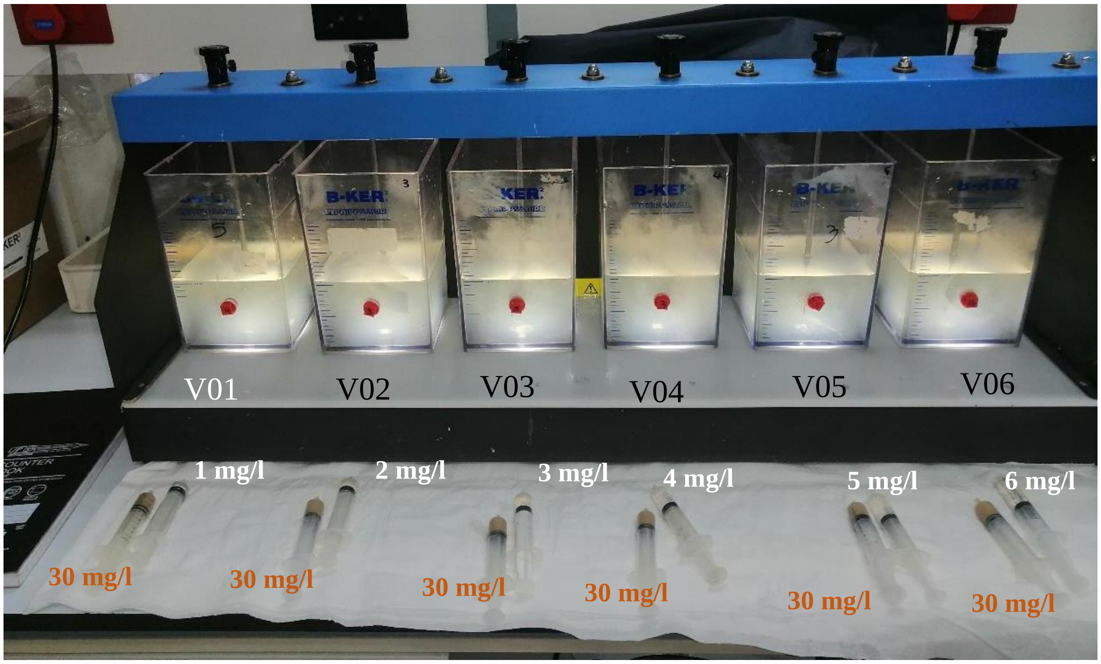

Figure 3. 10: Dosing of the coagulant (Polyelectrolytes) and the coagulant aid (lime) to the vessels.

With reference to Figure 3.10, the vessels were labelled accordingly from Vessel (V) 1 to 6. The volume of raw water used in the experiment is 1L (1000ml) on each vessel. In this experiment, the coagulant used is polyelectrolytes (Zeta Floc) and the coagulant aid used is lime. Coagulant dosage volume was varied while coagulant aid was kept constant across the vessels with an intent to determine the optimal dosage as depicted in Table 3.14.

Table 3. 14: Investigation of the optimal coagulant dose.

Vessel Number	**1**	**2**	**3**	**4**	**5**	**6**
Sample pH	8.06					
Sample Volume (ml)	1000ml for all					
Coagulant Aid(mg/l)	30 mg/l					
Coagulant Volume (ml)	30 ml					
Coagulant dose (mg/l)	1 mg/l	2mg/l	3ml/l	4mg/l	5mg/l	6mg/l
Coagulant Volume	10ml	20ml	30ml	40ml	50ml	60ml

Experimental Procedure

Firstly, the samples were lined up at the jar test apparatus with six vessels and stainless-steel stirrers submerged in each vessel for agitation purposes. The coagulant and coagulant aid were subsequently added in the order depicted in Table 3.14 above. Each jar was agitated at 150 rpm for 1 minute to induce rapid mixing, this was done to ensure unsure that the maximum dispersion of the coagulant is archived throughout each Jar. The stirrer was adjusted at 20 rpm for 20 minutes, to create a quiescent condition through which the flocculation process can occur. Lastly, the vessels were removed from the equipment and put on a steady stable table to allow the sedimentation process to unfold., this process was allowed to unfold for 20 minutes Figure 3.11 shows the coagulation, flocculation, and sedimentation processes.

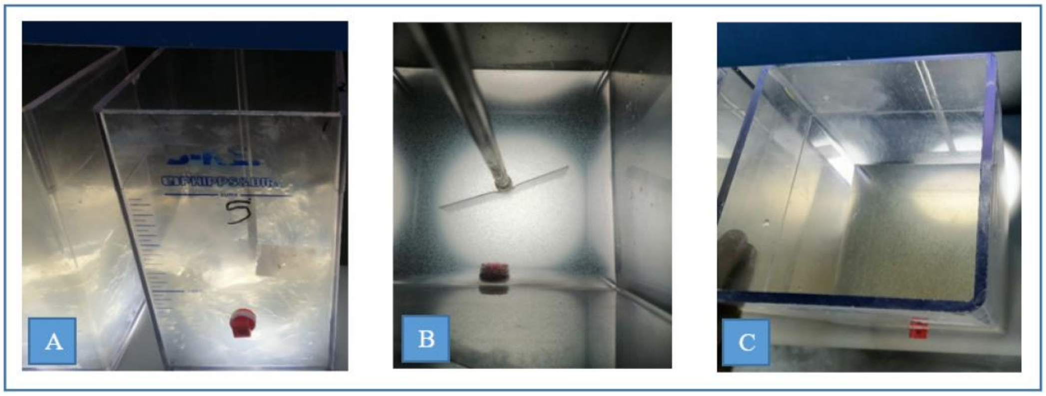

Figure 3. 11: Coagulation (Left), flocculation (Middle), and Sedimentation (Right)

A pipette was then used to extract 50 ml of the treated water from vessel C to determine the turbidity using a turbidity meter shown in Figure 3.7. The data collected from this investigation were used to generate a curve that depicts turbidity against coagulant dose, the curve will be outlined in Chapter 04, which presents results and discussion of this investigation.

3.11.2 **Experiment 02:** Determination of Optimal coagulation pH

Table 3. 15: Experimental information

Characteristics	Description
Coagulant	Polyelectrolyte (Zeta Floc) (6 mg/l)
Coagulant Aid	lime (30mg/l)
pH range	7.8-8.3
Initial Turbidity	62.4 NTU
Rapid Mixing Intensity	1 Min @ 100 rpm
Flocculating Mixing Intensity	20 Min @ 30 rpm
Settling	20 Mins

Experimental Outline

This step of the study is aimed at determining the optimal dosing pH under which the coagulation process can partake. Here the pH of the raw water was altered by either adding acidity or alkalinity to the source water to simulate different varying pH scenarios, this investigation was necessitated by the fact that the pH of the source water varies gradually from time to time due to either seasonal change or the type of effluent that trickles its way to the Vaal dam. The jar test was then performed using the optimal coagulant dose that was established in Experiment 01. The table below depicts the varying pH as well as the optimal coagulant dose-volume used.

Table 3. 16: Investigation of the optimal coagulation pH.

Vessel Number	**1**	**2**	**3**	**4**	**5**	**6**
Sample pH	7.8	7.9	8.0	8.1	8.2	8.3
Sample Volume (ml)	1000ml for all					
Coagulant Aid(mg/l)	30 mg/l					
Coagulant Volume (ml)	30 ml					
Coagulant dose (mg/l)	6 mg/l					
Coagulant dose (mg/l)	60 ml					

Experimental Procedure

The pH of the samples was conditioned and the constant amount of 6mg/l of the coagulant and 30 mg/l were respectively added across the six vessels under initial rapid mixing of 150 rpm for 1 minute. The speed of the impeller was reduced to 20 rpm to create floc formation conditions for 20 minutes. Lastly, the vessels were removed from the equipment and put on a steady stable table to allow the sedimentation process to unfold, this process was allowed to unfold for 20 minutes. A pipette was then used to extract 50 ml of the treated water to determine the turbidity using a turbidity meter. The data collected from this investigation were used to generate a curve that depicts pH against turbidity, the curve will be outlined and discussed in Chapter 04, which presents results and discussion.

3.11.3 **Experiment 03:** Re-determination of the optimal coagulant dose @ optimum pH

Table 3. 17: Experimental information

Characteristics	Description
Coagulant dosage range	Polyelectrolyte (Zeta Floc) (1-6 mg/l)
Coagulant Aid	-
pH	8.3
Initial Turbidity	62.4 NTU
Rapid Mixing Intensity	1 Min @ 100 rpm
Flocculating Mixing Intensity	20 Min @ 30 rpm
Settling	20 Mins

Experimental outline

In this stage of the investigation, experiment 01 was re-done this time around with the water being treated under optimal pH conditions that were established in experiment 03 which was found to be 8.3. The main objective of this investigation is to establish the optimal dosing rate at this optimal pH. The parameters used in this experiment are outlined in the table below.

Table 3. 18: Re-Determination of optimal coagulant dose at optimal pH.

Number	**1**	**2**	**3**	**4**	**5**	**6**
Sample pH	8.3					
Sample Volume (ml)	1000 ml for all					
Coagulant Aid(mg/l)	30 mg/l					
Coagulant Aid Volume (ml)	30 ml					
Coagulant dose (mg/l)	1 mg/l	2 mg/l	3 mg/l	4 mg/l	5 mg/l	6 mg/l
Coagulant Volume (ml)	10 ml	20 ml	30 ml	40 ml	50 ml	60 ml

The vessels were loaded with 1000 ml of sample water at optimal pH, the polyelectrolytes and the lime were added across the six vessels as per the table above, the initial rapid mixing of 150 rpm for 1 minute was run. The speed of the impeller was reduced to 20 rpm in order to create floc formation conditions for 20 minutes. Lastly, the vessels were removed from the equipment and put on a steady stable table in order to allow the sedimentation process to unfold, this process was allowed to unfold for 20 minutes. A pipette was then used to extract 50 ml of the treated water in order to determine the turbidity using a turbidity meter. The data collected from this investigation were used to generate a curve that depicts coagulant dose against turbidity, the curve will be outlined and discussed in Chapter 04, which presents results and discussion.

3.11.4 **Experiment 04:** Effect of initial mixing intensity @ optimal Coagulation dose and optimal pH

Table 3. 19: Experimental information

Characteristics	**Description**
Coagulant	Polyelectrolyte (Zeta Floc) (6 mg/l)
Coagulant Aid	lime (30 mg/l)
pH	8.3
Initial Turbidity	62.4 NTU
Rapid Mixing Intensity range	1 Min @ (50-170) rpm
Flocculating Mixing Intensity	20 Mins @ 30 rpm
Settling	20 Mins

Experimental Outline

This section of the experiment was concerned with investigating the impact of the initial mixing intensity of the coagulant and the source water, this was motivated by the literature that outlined that the coagulation flocculation process is not only affected by chemical interaction between the chemicals and colloidal particles, but also by physical parameters such as the hydraulic conditions associated with the process. In this investigation, the optimal dosing parameters that were established in subsequent experiments were used, that is the optimal pH of 8.3 that was determined in experiment 2 and the optimal coagulant dose of 6 mg/l that was determined in experiment 3. For this Jar Test, the equipment was prepared and adjusted to varying stirrer rotation speeds for each beaker, as shown in the table below.

Table 3. 20: Effect of initial mixing intensity

Vessel Number	1	2	3	4	5	6
Mixing Intensity (rpm)	50	80	100	130	150	170
Sample Volume (ml)	1000 ml for all					
pH	8.3					
Coagulant Aid(mg/l)	30 mg/l					
Coagulant Volume	30 ml					
Coagulant dose (mg/l)	6 mg/l					
Coagulant Volume (ml)	60 ml					

Experimental procedure

The samples were run simultaneously at different stirrer speeds as indicated in Table 3.20 above, this rapid mixing was timed to run for about 1 minute after dosing both the coagulant and the coagulant aid for each sample. The speed was then reduced to 20 rpm for 20 minutes to create conditions for floc formation for all the vessels. Apart from varying the initial mixing intensity, other operational parameters were the same as the optimal coagulation conditions that were determined in subsequent experiments 2 and 3. Lastly, the vessels were removed from the equipment and put on a steady stable table in order to allow the sedimentation process to unfold, this process was allowed to unfold for 20 minutes.

3.11.5 **Experiment 05:** The Effect of flocculation mixing intensity @ optimal coagulant dose, pH, Rapid and rapid mixing.

Table 3. 21: Experimental information

Characteristics	Description
Coagulant	Polyelectrolyte (Zeta Floc) (6 mg/l)
Coagulant Aid	lime (30 mg/l)
pH	8.3
Initial Turbidity	62.4 NTU
Rapid Mixing Intensity range	1 Mins @ 100 rpm
Flocculating Mixing Intensity	20 Mins @ (5-35) rpm
Settling	40 Mins

Experimental Outline

In this experiment hydraulic conditions were further investigated, the optimal dosing conditions that were obtained in experiments 2,3, and 4 were used to investigate the impact of flocculation mixing time. The jar test was prepared for this set of experiments, whereby the only variable is mixing time and other operational parameters were kept constant. The table below depicts the parameters considered during this experiment:

Table 3. 22: The impact of flocculation agitation time

Vessel Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing intensity (rpm)	5	10	15	20	30	35
Sample Volume (ml)	1000 ml for all					
pH	8.3					
Coagulant Aid(mg/l)	30 mg/l					
Coagulant dose (mg/l)	6 mg/l					
Coagulant Volume	60 ml					

Experimental Procedure

The jar test machine was run with the initial mixing intensity set to 150 rpm for 1 minute after the addition of a coagulant and the coagulant aid to all the vessels. Then after the flocculation, mixing time was lowered to different times as depicted in Table 3.22 above. Lastly, the vessels were removed from the equipment and put on a steady stable table in order to allow the sedimentation process to unfold, this process was allowed to unfold for 20 minutes. A pipette was then used to extract 50 ml of the treated water in order to determine the turbidity using a turbidity meter. The data collected from this investigation were used to generate a curve that depicts mixing time against turbidity, the curve will be outlined and discussed in Chapter 04, which presents results and discussion.

Chapter 4 : Results and Discussion

4.1 Introduction

This chapter presents and analyses the experimental data gathered from the series of experiments that were performed throughout this study. The data were thoroughly analysed and interpreted using a variety of scientific methods, and the results generated from the study were thoroughly discussed.

4.2 Characterization of source water

The table below depicts the initial properties of the sample water that were measured before coagulation, flocculation, and sedimentation processes of the study. It was important to record the initial physiochemical properties of the water to be able to compare them with the residual properties of the treated water. The sample were collected during the winter period. During summer it has been reported that the turbidity can be above 70 NTU on average, due to the large number of suspended solids that are deposited in the Vaal dam by streams that feeds the Vaal dam. The parameter of concern is Turbidity, which is a greater indicator of the removal of suspended solids in raw water. Coagulants have been found to have an optimal pH through which they become effective in clarification of turbidity. pH of the raw water was also monitored throughout this work; other physicochemical properties of water were monitored as depicted by the table below.

Table 4. 1: The initial physiochemical properties of the raw water.

Chemical and Physical Properties	Measured initial Value
pH	8.06
Temperature	20 ° C
Turbidity	62.4 NTU
TSS (mg/l)	9
TDS (mg/l)	283
CaCO3 (mg/l)	79
NO3 - (mg/l)	29
SO4 2- (mg/l)	98

4.3 Optimal dose and dosing conditions of coagulant

In this section of the study, six sets of experiments were carried out with the intent to determine the optimal dosage as well as the conditions under which a coagulant can be dosed optimally. In order to achieve this, the first step was to determine the optimal dose of the coagulant agent. This was followed by the determination of optimal pH with respect to the optimal dosing rate that was determined in the first step. After determining the optimal pH, the optimal coagulation was re-determined, this time around at optimal pH conditions. Since one of the objectives of the study is to optimize the water treatment process, further investigations were conducted to establish the effect of rapid mixing intensity, flocculation mixing intensity, and flocculation time.

Raw water treatment regimes.

For the purpose of this study, two treatment regimens were considered as shown below:

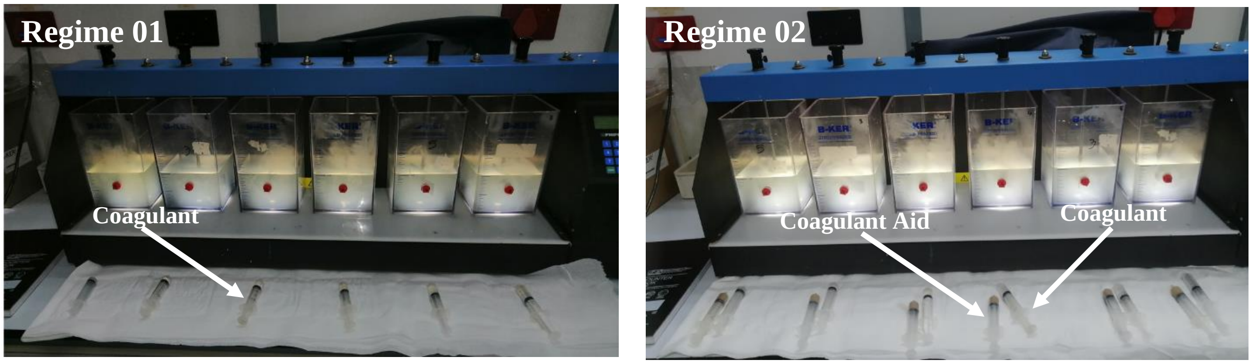

Figure 4. 1: Determination of optimal coagulant dose using Regime 01 and 02.

In this investigation, two water treatment regimens were identified and defined. Regime 01 involved the treatment of water using polyelectrolytes as a primary coagulant, while Regime 02 involved the usage of polyelectrolytes as a primary coagulant and lime as a coagulant aid as seen in Figure 4.1 above.

4.4 Experiment 01: Optimal Dose of poly electrolyte coagulant.

4.4.1 Results Outline

The main objective of this experiment is the reduction of turbidity, which is promoted by the agglomeration of suspended particles that results in larger particles forming flocs that can undergo the process of sedimentation. Table 4.2 depicts the results that were generated in both regimes 01 and 2.

Table 4. 2: Optimal Dose of poly electrolyte coagulant.

Regime 01						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Coagulant dose (mg/l)	1	2	3	4	5	6
Coagulant aid (mg/l)	None	None	None	None	None	None
Raw Water Turbidity (NTU)	6.4	62.4	62.4	62.4	62.4	62.4
Residual Turbidity (NTU)	51.3	25.4	15.2	11.2	8.3	6.3
Regime 02						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Coagulant dose (mg/l)	1	2	3	4	5	6
Coagulant aid (mg/l)	30	30	30	30	30	30
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Residual Turbidity (NTU)	43	18.2	12.3	9.23	6.23	3.17

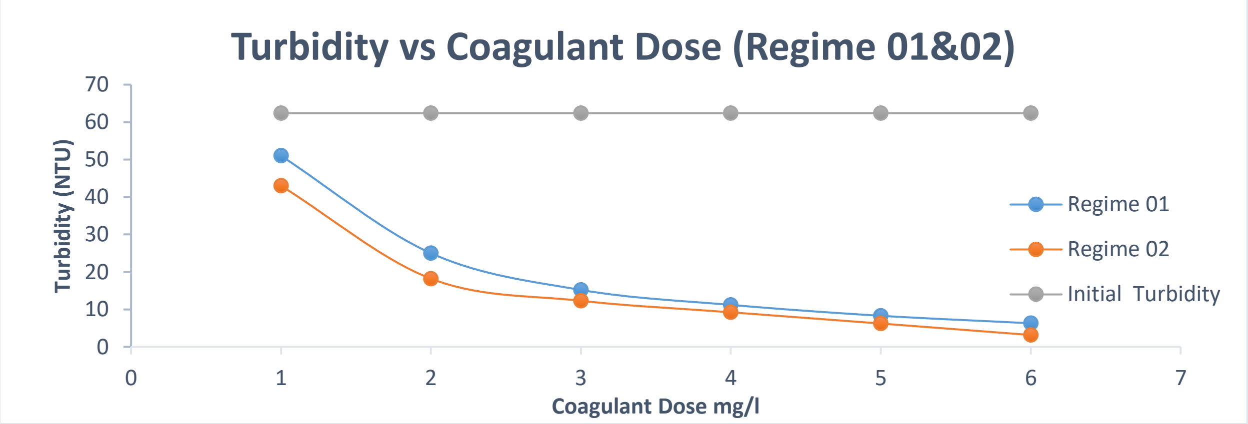

Figure 4. 2: The graphical representation of coagulant dose vs Turbidity of Regime 01&02

4.4.2 Effect of coagulant dosage

In this context, the optimal coagulant dose is a point whereby the dosage yields the lowest possible turbidity. According to Figure 4.2 we can see the impact of coagulant in both regimes from the initial dosage of 1 mg/l; at this dosage the turbidity of regime 01 and 02 is 51.3 NTU and 43 NTU respectively; at this dosage the sizes of flocs formed were hardly noticeable due to a high turbidity.

Regime 01 achieved the lowest turbidity of 6.3 NTU at a coagulant dosage of 6 mg/l while regime 02 achieved the turbidity of 3.17 NTU at a coagulant dosage of 30mg/l. The effect of the addition of milk of lime as a coagulant aid promotes better flocculation conditions. This is so because lime has a tendency to increase the alkalinity of the raw water which turns to create better coagulation conditions.

As alkalinity increased, the ions which are electrically charged particles in the raw water also increased. As a result, there is an attraction between positively charged particles and colloidal particles. These particles eventually agglomerate together and form much larger particles that are referred to as flocs, which are much heavier particles that settle much quicker and better than colloidal particles. The impact of lime addition as a coagulant aid has resulted in a 49% decrease in turbidity in regime 02 relative to regime 01 for the same amount of coagulant dose of 6 mg/l. This is in line with findings in literature (Azil *et al.*, 2021).

4.5 Experiment 02: Optimal pH

4.5.1 Results Outline

The work done by Cao *et al.*, 2010 revealed that pH values do affect the surface charges, and it also has a great impact on micro-flocculation. The same authors further mentioned that in recent times, many researchers focused on coagulation effects and coagulants, while fewer investigated the formation of flocs under different coagulation pH. This implies that controlling the level of pH could in some way or another improve the process of coagulation.

The objective of this experiment was to determine the optimal pH with respect to the above determined optimal coagulation dose. Physicochemical properties of water from the Vaal Dam changes from time to time, these changes are influenced by seasonal variations and the kind of pollutants that are introduced to the Vaal dam, by the rivers that feed it; acid mine drainage, industrial effluent and sewage that have trickled their way to the Vaal dam, all these factors have collectively proved to be the contributors of variation in the physicochemical properties of Vaal dam water.

Given that pH has proven to be one of the factors that greatly affect coagulation and flocculation processes, it was found necessary to investigate the optimal pH through which the coagulation and flocculation process can take place, hence this experimental work was necessitated. Table 4.3 depicts the results that were obtained from the experimental work that was performed in this study, furthermore the curves were generated for analysis purposes, and they are depicted on Figure 4.3.

Table 4. 3: The effect of pH.

Regime 01						
Number	**1**	**2**	**3**	**4**	**5**	**6**
pH	7.8	7.9	8.0	8.1	8.2	8.3
Coagulant aid (mg/l)	6					
Coagulant aid (mg/l)	None	None	None	None	None	None
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Residual Turbidity (NTU)	54.8	52.1	25.2	15.5	10.8	5.2
Regime 02						
Number	**1**	**2**	**3**	**4**	**5**	**6**
pH	7.8	7.9	8.0	8.1	8.2	8.3
Coagulant aid (mg/l)	6					
Coagulant aid (mg/l)	30	30	30	30	30	30
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Residual Turbidity (NTU)	44.4	20.3	11.4	6.1	4.4	1.02

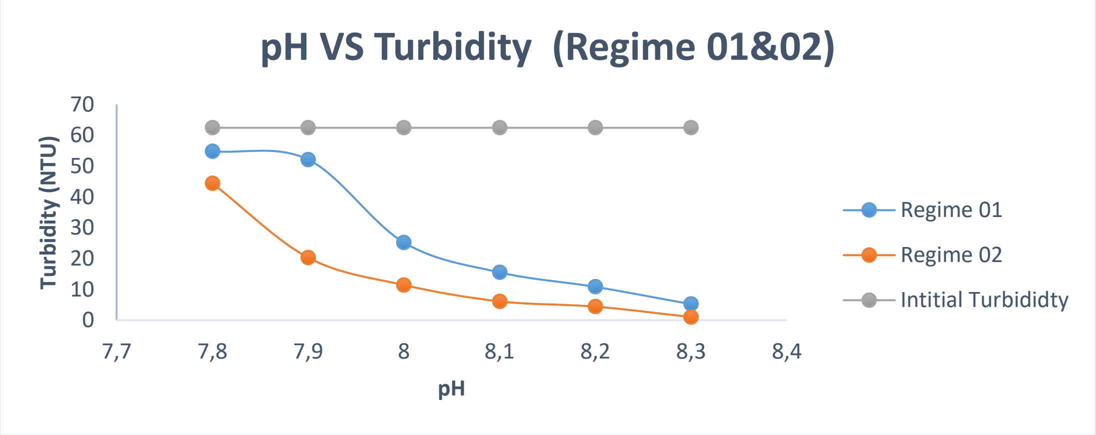

Figure 4. 3: The effect of pH on turbidity.

4.5.2 The effect of pH

From Figure 4.3 above, the turbidity falls drastically with the increase in pH, for regime 01 it was established that the optimal pH is 8.3 which yields the turbidity of 5.2 NTU, while regime 02 archived the turbidity of 1.02 NTU at the same pH of 8.3. AS much as both regimes have their optimal pH of 8.3, the turbidity of regime 02 is way lower than that of regime 01, this is so because of the alkalinity effect that is introduced by the milk of lime which is acting as a coagulant aid in regime 02. Both curves in Figure 4.3 display a falling gradient on average, which is linked to the abrupt drop in turbidity, this implies that alkaline conditions do foster effective coagulation and flocculation conditions. The coagulant aid influenced an 80% reduction in turbidity of regime 02 in relation to regime 01.

4.6 Experiment 03: Redetermination of optimal Coagulant dose at Optimal pH.

4.6.1 Results outline

Following the optimal conditions that were established in experiment 2, whereby an optimal coagulation pH was found to be 8.3, the main objective of this experiment is the redetermination of optimal coagulation dose at optimal pH. The table below depicts the results that were generated in both regimes 01 and 2 of this investigation.

Table 4. 4: Optimal coagulant dose at optimal pH.

Regime 01						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Coagulant dose (mg/l)	1	2	3	4	5	6
pH	8.3					
Coagulant aid (mg/l)	None	None	None	None	None	None
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	45.3	20.3	10.2	7.4	5.1	4.3
Regime 02						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Coagulant dose (mg/l)	1	2	3	4	5	6
pH	8.3					
Coagulant aid (mg/l)	30	30	30	30	30	30
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	38	15.5	8.34	5.4	3.4	3.9

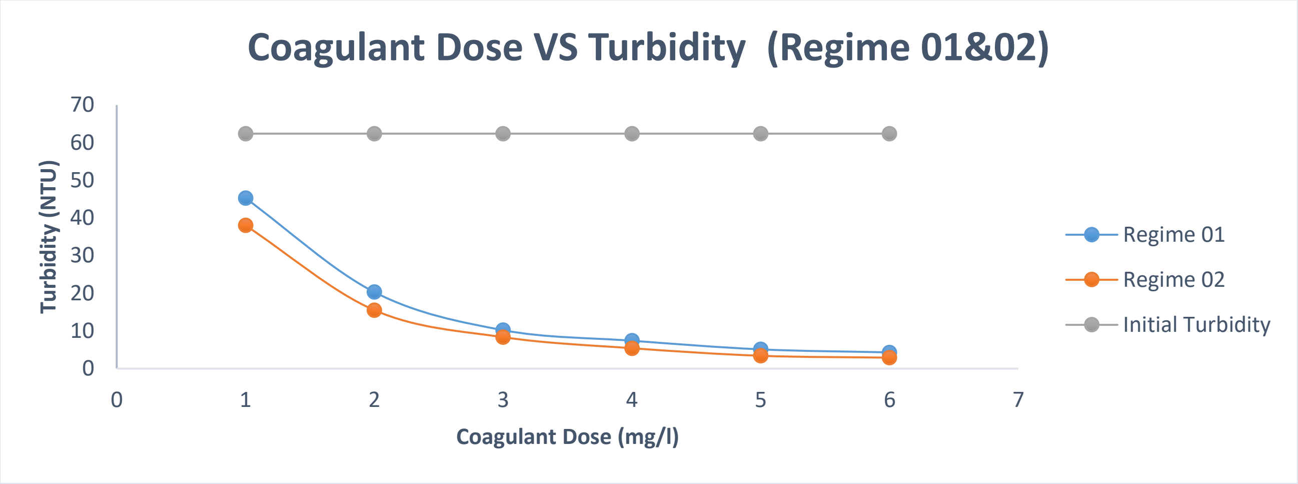

Figure 4. 4: The graphical representation of coagulant dose vs Turbidity of Regime 01&02

4.6.2 Effect of coagulation dosage

Given that, the optimal coagulant dose is the dosage that yields the lowest possible turbidity. According to Figure 4.5 regime 01 achieved the lowest turbidity of 4.3 NTU at a coagulant dosage of 6 mg/l while regime 02 achieved the turbidity of 3.9 NTU at a coagulant dosage of 6mg/l and the optimal pH. The addition of milk of lime as a coagulant aid does promote much better flocculation conditions, this is so because lime increases the alkalinity of the raw water.

As alkalinity increases the ions, electrically charged particles in the raw water also increase; as a result, the attraction between positively charged particles and colloidal particles occurs. The particles formed eventually agglomerate together and form much larger particles that are referred to as flocs, which are much heavier particles that settle much quicker. The impact of lime addition as a coagulant aid has resulted in about 33% decrease in turbidity in regime 02 relative to regime 01 for the same amount of coagulant dose of 6 mg/l, the impact of the coagulant aid can be seen in this experiment.

4.7 Experiment 04: Effect of initial mixing intensity

4.7.1 Results Outline

From the result that was obtained in experiment 03, the coagulant dosage that yielded the lowest possible turbidity was found to be 6 mg/l for both regimes. The main objective of this experiment is to establish the optimal initial mixing intensity. The table below depicts the results that were generated in both regimes 01 and 2 of the experiment.

Table 4. 5: The effect of initial mixing intensity on pH.

Regime 01						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing Intensity (rpm)	30	50	100	150	170	190
Coagulant (mg/l)	6mg/l					
Coagulant aid (mg/l)	None	None	None	None	None	None
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	57.7	30.2	4.3	20.8	30.3	35.4
Regime 02						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing Intensity (rpm)	30	50	100	150	170	190
Coagulant dose (mg/l)	6mg/l					
Coagulant aid (mg/l)	30	30	30	30	30	30
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	48	15.5	3.0	37.4	45.4	60.9

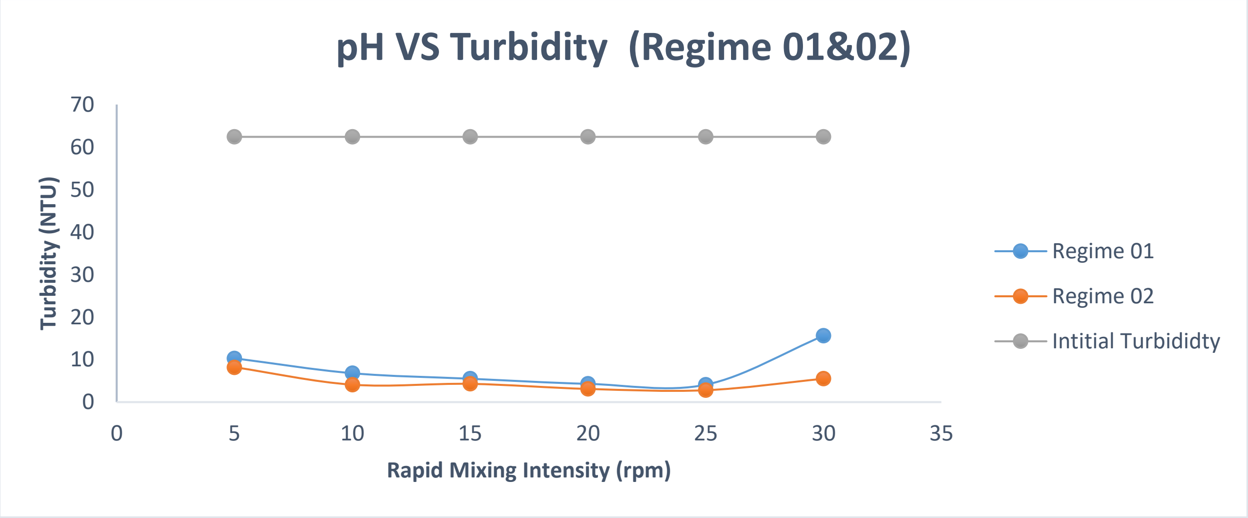

Figure 4. 5: The effect of initial mixing intensity on pH.

4.7.2 The effect of mixing intensity

Mixing intensity is one of the most important parameters during the coagulation-flocculation process of water treatment. The most optimal mixing intensity conditions are the ones that yield the lowest possible residual turbidity. Even though researchers have been doing a lot of work on the coagulation-flocculation process, according to the work of Kan *et a*l., 2002, little is still understood about the role of rapid mixing in water treatment, Kan *et a*l., 2002 further stated that rapid mixing has a great impact on charge destabilization and sweep coagulation.

This experimental work was greatly influenced by the observation of Kan *et a*l., 2002. This experimental work demonstrated that the mixing intensity constitutes a great factor in determining the overall effectiveness of the coagulation-flocculation process. It further demonstrated that the formation of bigger coagulation particles is not only limited to the chemical interactions between particles, but it has a lot to do with the hydraulic condition within the coagulation basin.

In figure 4.5 it was deduced that turbidity does decrease with the increase in mixing intensity up to 100 rpm, this is so because of the electric neutralization due to hydrolysis of the coagulant coupled with the compression on the electric double layer which subsequently results in the formation of the molecular complexes that contribute to the formation of flocs. The optimal turbidity of 4.3 NTU and 3.0 NTU for both regimes 01 and 02 were deduced at 100 rpm. Notably, as you increase the mixing intensity for the range 100-180 rpm, there is a sudden increase in turbidity, this is so because the high mixing intensity turns to break flocks that were formed. The findings from this study supports the work that was done by Huang, 2002, in his work he established that rapid-mixing does indeed affect the effectiveness of the coagulation-flocculation process, which was found to be the case in this study. This investigation demonstrated that the studies on rapid mixing can either be approached in two ways, microscopically or macroscopically, the choice between the two will be governed by whether we focus on physical or chemical parameters.

4.8 Experiment 05: Effect of the flocculation mixing intensity

4.8.1 Results Outline

Following from the optimal conditions that were obtained on experiments 3&4, whereby an optimal coagulation dosage was found to be 6 mg/l and a flash mixing of 100 rpm for both regimes, the main objective of this experiment is to establish the optimal flocculation intensity. The table below depicts the results that were generated in both regimes 01 and 2 of the experiment.

Table 4. 6: Effect of the flocculation mixing intensity.

Regime 01						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing Intensity (rpm)	5	10	15	20	30	35
Coagulant (mg/l)	6 mg/l					
Coagulant aid (mg/l)	None	None	None	None	None	None
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	10.3	6.8	5.5	4.3	4.1	15.6
Regime 02						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing Intensity (rpm)	5	10	15	20	25	30
Coagulant dose (mg/l)	6mg/l					
Coagulant aid (mg/l)	30	30	30	30	30	30
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	8.2	4.1	4.3	3.1	2.8	5.5

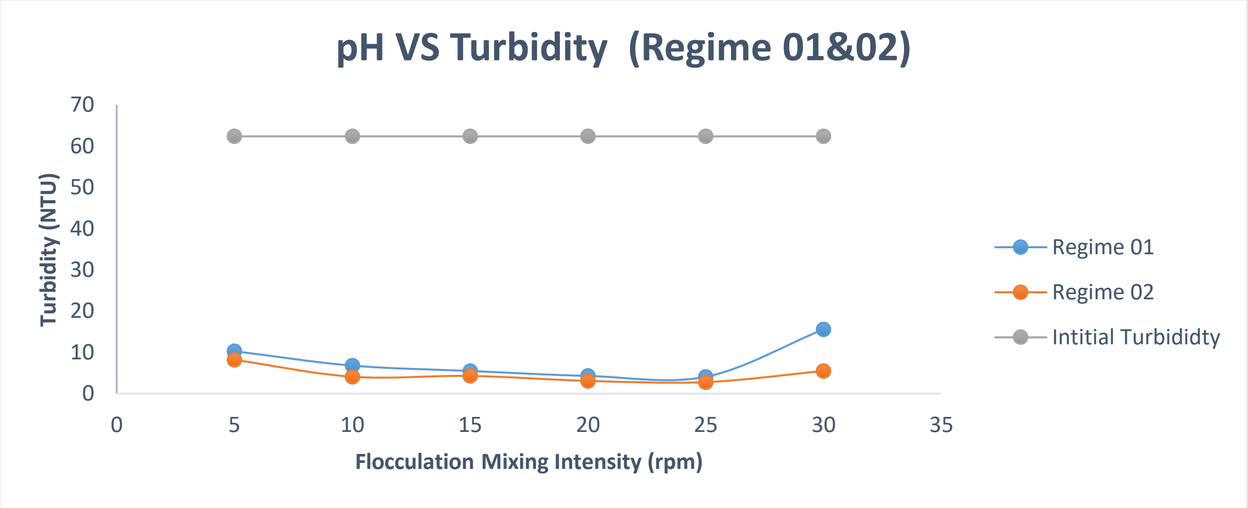

Figure 4. 6: The effect of flocculation mixing.

4.8.2 The effect of flocculation mixing

The primary principle of the flocculation process is to establish the environment for floc formation, but the nature of this process is not only influenced by the type of coagulation agent or coagulant aid used; the work conducted by Oruc & Sabah, 2006 on the effect of mixing conditions on flocculation revealed that hydraulic condition does have a greater influence on the formation of larger agglomerates that can be settled with ease. Figure 4.6 demonstrates the variation of turbidity with varying flocculation mixing in each sample. It was established that low mixing speeds ranging from 5-15 rpm turned to yield slightly higher turbidity than those in this observation is attributed to the fact that the mixing energy on this range doesn't promote enough collision between particles, as much as you do not want vigorous collision between particles, the energy steel need to be enough to promote the formation of solid-polymer agglomerates that grows. The optimal turbidity is obtained for both regimes 1 and 2 obtained are found to be 4.1 NTU and 2.8 NTU for regimes 01 and regime 2 respectively; this was archived at the range 20-25 rpm. The range 25-30 rpm displayed a sharp increase in turbidity, this is so because high-shear mixing has reached a point whereby flocs are being broken, which turns out to increase turbidity. These results were also found to be in alignment with the work of (Oruc & Sabah, 2006). The key experimental results summary for both regimes obtained in this work are depicted in Figure 4.7.

Chapter 4 Summary

The final water quality results obtained from regime 01 & 02 proved to be better than that obtained from the currently used Activated silica – Lime regime; the poly-lime regime proved to yield the best results whereby a turbidity of 2.8 NTU was archived ; which is significantly lower than the 6.3 NTU that is achieved using the current regime, the summarized physicochemical properties and overall experimental results are depicted on Table 4.7 and Figure 4.7 respectively. The current regime uses high lime, this results in a sudden increase in pH as depicted on the table below; the pH of 8.9 is above the standardized pH for drinking water in South Africa which is defined to be within the range 7.8 to 8.4 as per SANS 241. This means an additional downstream process needs to be employed to lower the pH to acceptable levels as per quality requirements. Currently the reduction in pH is achieved through the carbonation of water using carbon dioxide, this happens in a continuously stirred open flume which manages to reduce the pH to a range 7.8 to 8.4; however, this happens at a significant cost; hence the need for an alternative process.

Table 4. 7: The comparison between the final physicochemical properties of regime 01& 02 with the currently used Lime- Activated Silica regime.

Chemical and Physical Properties	Measured initial Values	Regime 01	Regime 01	Current Regime
pH	8,06	8.1	8.3	8.9
Temperature (° C)	20	20	20	20
Turbidity (NTU)	**62.4**	**4.1**	**2.8**	**6.3**
TSS (mg/l)	9	1.2	1.9	3.2
TDS (mg/l)	283	1,2	0.9	2.3
CaCO3 (mg/l)	79	25	17	18
NO3 - (mg/l)	29	23	12	14
SO4 2- (mg/l)	98	0.5	0.2	0.5

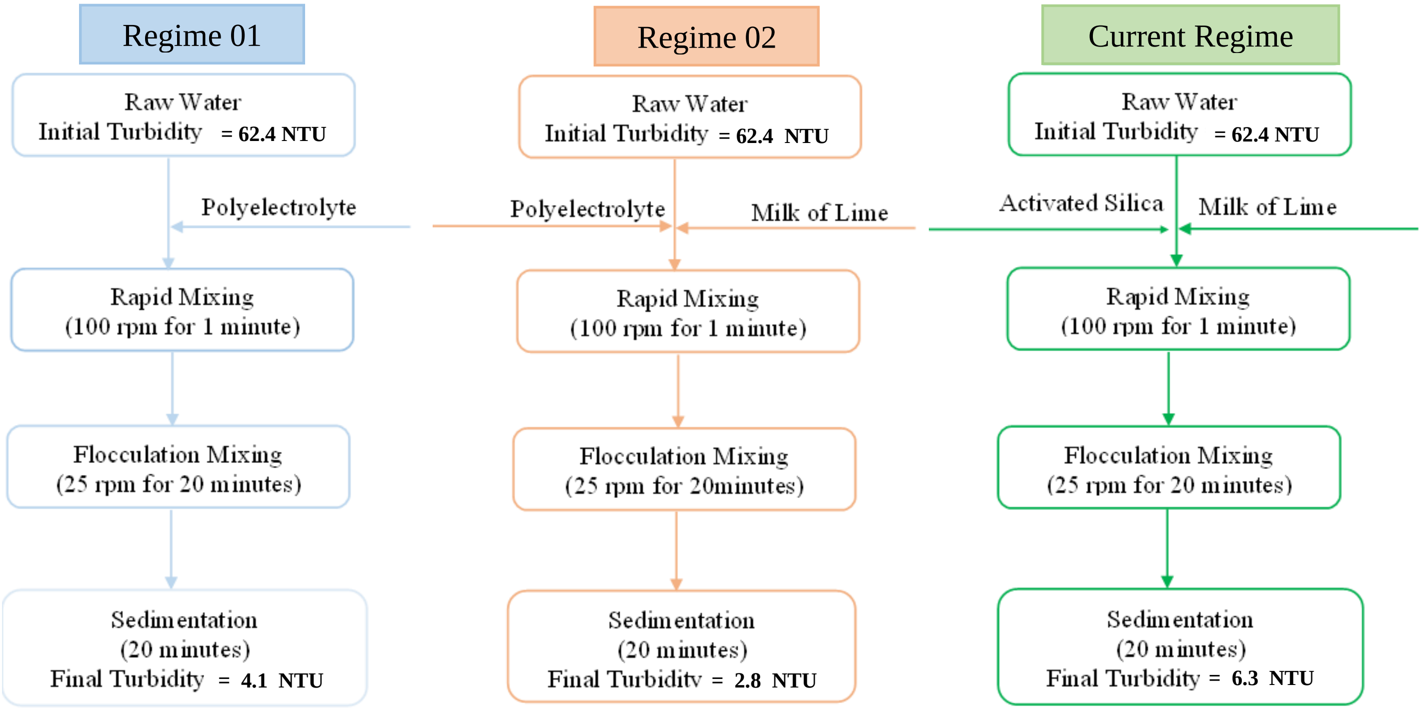

Figure 4. 7: Experimental results summary for regime 01,02 and the current regime.

Chapter 5 : Conclusion and Recommendations

5.1 Conclusions

In this study a series of Jar experiments were conducted with an intent to determine the optimal coagulation and flocculation parameters for the treatment of the raw water abstracted from the Vaal Dam, two defined regimes were investigated; regime 01 comprised of polyelectrolytes (Zeta-Floc) as a coagulant and regime 02 comprised of polyelectrolytes (Zeta- Floc) as a primary coagulant and lime as a coagulant aid. It was established that using polyelectrolyte and low lime regime yielded better coagulation results than using polyelectrolyte alone. Regime 02 displayed excellent colloidal particle removal efficiencies compared to Regime 01, this is so because the addition of low lime slightly increases the pH of the raw water, which favours coagulation-flocculation conditions.

Under optimal pH conditions with the optimal coagulant dosage of 6 mg/l, Regime 01 achieved turbidity of 4.1 NTU, while Regime 02 achieved the turbidity of 2.8 NTU at the same coagulant dosage of 6mg/l and optimum hydraulic conditions. These were achieved under the rapid mixing of 100 rpm and the flocculation intensity of 30 rpm for both regimes. The usage of polyelectrolyte and lime promoted the formation of large-sized and clear flocs that are easy to settle at the end of slow mixing. The comparison between the final physicochemical properties of regime 01& 02 with the currently used Lime- Activated Silica regime showed that regime 02 has a better removal efficiency than the current regime. The different in turbidity between regime 02 and the current regime is attributed the fact that the Zeta-Floc polymer has a lager molecular weight, which makes it to have a stronger affinity to suspended particles; this results in the agglomeration of suspended particles to form lager flocs that easily settles during sedimentation, due to the fact that settling velocity is directly proportional to the mass of the particle.

This work further revealed that the optimization of the conventional water treatment process is not only influenced by the chemical interaction between the coagulant and suspended particles, but it is also greatly influenced by the hydraulic conditions associated with the treatment process which are the initial rapid mixing as well as the flocculation mixing intensity.

5.2 Recommendations

It should be noted that this study serves as a significant work in the optimization of the coagulation and flocculation processes. From this study, it was established that regime 02 achieved a better removal efficiency than regime 01 and the current one. It is therefore recommended that the usage of low lime and polyelectrolyte is considered in raw water treatment as it is linked to a couple of cost saving benefits compared to the current process.

Regime 02 comes with reduced chemical and operational costs; it uses low chemical dosages that result in manageable sludge, while the currently used high lime regime is associated with a lot of coagulant and coagulant aid dosage that result high volumes of sludge being generated, which turns to increase further sludge treatment cost, storage and disposal challenges. It is also recommended that further work is done on investigating the settling kinetics of the flocs in the sedimentation basins, the settling kinetics studies can assist with the modelling of sedimentation basins, which is a very important aspect of water engineering. Finally, more robust investigation on a scaled-up plant is highly recommended, as this could be used to investigate the performance of this coagulation regime on a larger scale and most importantly a much more practical economic evaluating can be conducted.

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Appendices

Appendix A: Lab Apparatus used in the Study

A1: The Jar test experimental apparatus.

Figure A1. 1: The Jar Test apparatus used for coagulation and flocculation processes.

A2: Turbidimeter

Figure A1. 2: The turbidity meter used to measure initial and residual turbidity.

A3: Magnetic Agitator

Figure A1. 3 : Magnetic agitator used for feed preparation.

A3: Scale

Figure A1. 4 : The Scale used for feed preparation.

A4: pH Meter

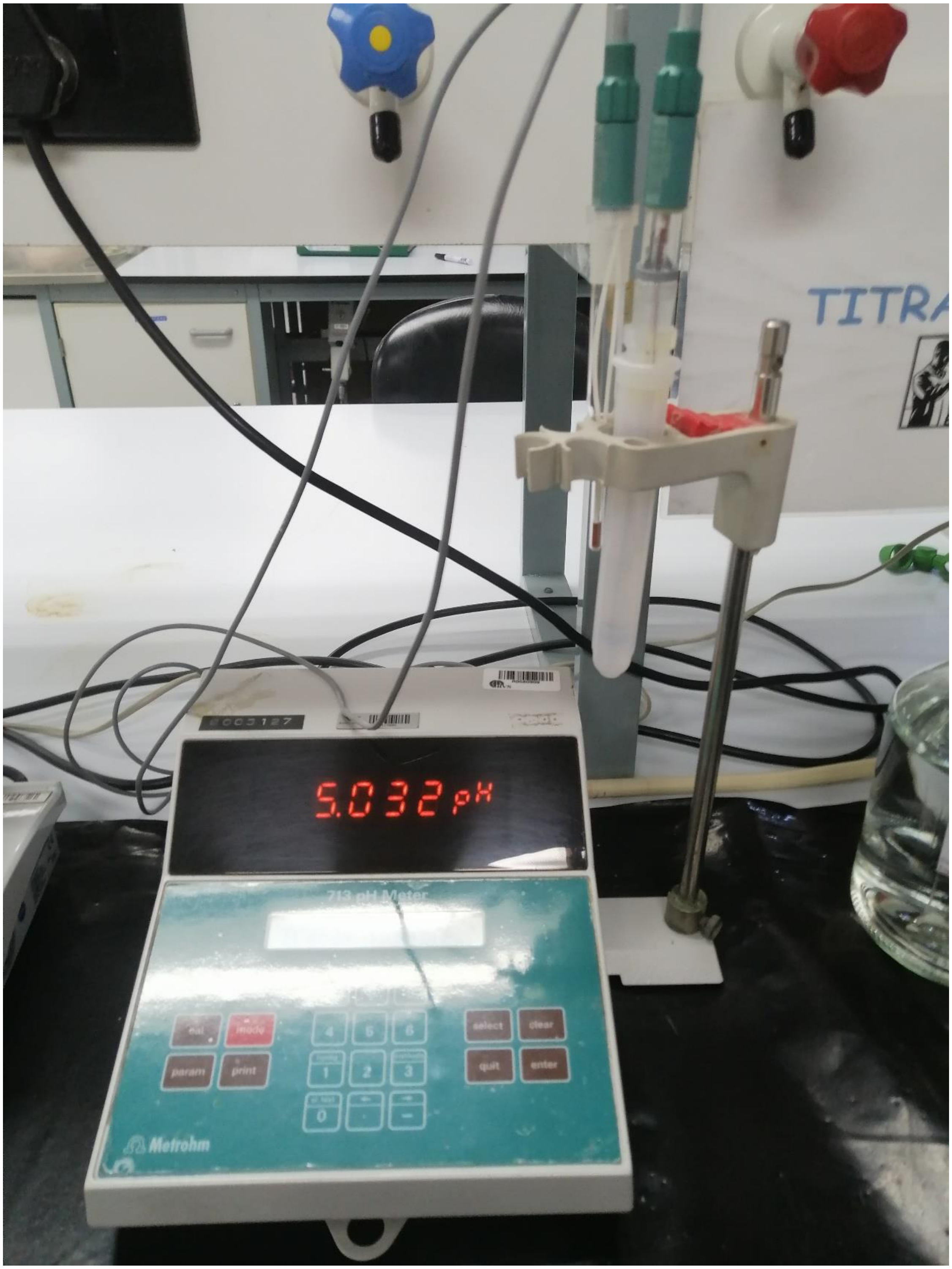

Figure A1. 5 : pH meter used for sample pH measurement.

A5: Multi-parameter photometer

Figure A1. 6 : The photometer used to measure initial and final water quality.

Appendix B: Experimental Results with measured residual turbidity.

Experiment 01: Optimal Dose of poly electrolyte coagulant.

Table B 1. 1: Optimal Dose of poly electrolyte coagulant.

Regime 01						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Coagulant dose (mg/l)	1	2	3	4	5	6
Coagulant aid (mg/l)	None	None	None	None	None	None
Raw Water Turbidity (NTU)	6.4	62.4	62.4	62.4	62.4	62.4
Residual Turbidity (NTU)	51.3	25.4	15.2	11.2	8.3	6.3
Regime 02						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Coagulant dose (mg/l)	1	2	3	4	5	6
Coagulant aid (mg/l)	30	30	30	30	30	30
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Residual Turbidity (NTU)	43	18.2	12.3	9.2	6.2	3.1

Experiment 02: Optimal pH

Table B 1. 2: Optimal pH

Regime 01						
Number	**1**	**2**	**3**	**4**	**5**	**6**
pH	7.8	7.9	8.0	8.1	8.2	8.3
Coagulant aid (mg/l)	6					
Coagulant aid (mg/l)	None	None	None	None	None	None
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Residual Turbidity (NTU)	54.8	52.1	25.2	15.5	10.8	5.2
Regime 02						
Number	**1**	**2**	**3**	**4**	**5**	**6**
pH	7.8	7.9	8.0	8.1	8.2	8.3
Coagulant aid (mg/l)	6					
Coagulant aid (mg/l)	30	30	30	30	30	30
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Residual Turbidity (NTU)	44.4	20.3	11.4	6.1	4.4	1.02

Experiment 03: Redetermination of optimal Coagulant dose at Optimal pH.

Table B 1. 3: Redetermination of optimal Coagulant dose at Optimal pH.

Regime 01						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Coagulant dose (mg/l)	1	2	3	4	5	6
pH	8.3					
Coagulant aid (mg/l)	None	None	None	None	None	None
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	45.3	20.3	10.2	7.4	5.1	4.3
Regime 02						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Coagulant dose (mg/l)	1	2	3	4	5	6
pH	8.3					
Coagulant aid (mg/l)	30	30	30	30	30	30
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	38	15.5	8.34	5.4	3,4	3.9

Experiment 04: Effect of initial mixing intensity

Table B 1. 4: Effect of initial mixing intensity.

Regime 01						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing Intensity (rpm)	30	50	100	150	170	190
Coagulant (mg/l)	6mg/l					
Coagulant aid (mg/l)	None	None	None	None	None	None
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	57.7	30.2	4.3	20.8	30.3	35.4
Regime 02						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing Intensity (rpm)	30	50	100	150	170	190
Coagulant dose (mg/l)	6mg/l					
Coagulant aid (mg/l)	30	30	30	30	30	30
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	48	15.5	3.0	37.4	45.4	60.9

Experiment 05: Effect of the flocculation mixing intensity

Table B 1. 5: Effect of the flocculation mixing intensity

Regime 01						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing Intensity (rpm)	5	10	15	20	30	35
Coagulant (mg/l)	6 mg/l					
Coagulant aid (mg/l)	None	None	None	None	None	None
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	10.3	6.8	5.5	4.3	4.1	15.6
Regime 02						
Number	**1**	**2**	**3**	**4**	**5**	**6**
Mixing Intensity (rpm)	5	10	15	20	25	30
Coagulant dose (mg/l)	6mg/l					
Coagulant aid (mg/l)	30	30	30	30	30	30
Raw Water Turbidity (NTU)	62.4	62.4	62.4	62.4	62.4	62.4
Turbidity (NTU)	8.2	4.1	4.3	3.1	2.8	5.5

Appendix C: Final physicochemical properties.

Table C 1. 1: Final physicochemical properties for regime 01&02 on Experiment 01

Chemical and Physical Properties	Measured initial Values	Regime 01 Final Values	Regime 01 Final Values
pH	8.06	8.1	8.3
Temperature (° C)	20	20	20
Turbidity (NTU)	62.4	6.3	3.17
TSS (mg/l)	9	7.3	5.1
TDS (mg/l)	283	120	80
CaCO3 (mg/l)	79	57	42
NO3 - (mg/l)	29	18	12
SO4 2- (mg/l)	98	53	37

Table C 1. 2: Final physicochemical properties for regime 01&02 on Experiment 03

Chemical and Physical Properties	Measured initial Values	Regime 01 Final Values	Regime 01 Final Values
pH	8.06	8.1	8.3
Temperature (° C)	20	20	20
Turbidity (NTU)	62.4	4.3	3.9
TSS (mg/l)	9	5.1	4.8
TDS (mg/l)	283	84	60
CaCO3 (mg/l)	79	36	31
NO3 - (mg/l)	29	12	8
SO4 2- (mg/l)	98	44	25

Table C 1. 3: Final physicochemical properties for regime 01&02 on Experiment 04

Chemical and Physical Properties	Measured initial Values	Regime 01 Final Values	Regime 01 Final Values
pH	8.06	8.1	8.3
Temperature (° C)	20	20	20
Turbidity (NTU)	62.4	4.3	3.0
TSS (mg/l)	9	2.1	1.4
TDS (mg/l)	283	34	20
CaCO3 (mg/l)	79	27	16
NO3 - (mg/l)	29	4	5
SO4 2- (mg/l)	98	13	7

Table C 1. 4: Final physicochemical properties for regime 01&02 on Experiment 05

Chemical and Physical Properties	Measured initial Values	Regime 01 Final Values	Regime 01 Final Values
pH	8.06	8.1	8.3
Temperature (° C)	20	20	20
Turbidity (NTU)	62.4	4.1	2.8
TSS (mg/l)	9	1.2	0.9
TDS (mg/l)	283	25	17
CaCO3 (mg/l)	79	23	12
NO3 - (mg/l)	29	0.5	0.2
SO4 2- (mg/l)	98	5	1

Table C 1. 5: Statistical analysis on water quality parameters.

Parameter	**Regime 01**		**Regime 02**	
	Range	**Mean**	**Range**	**Mean**
Turbidity (NTU)	6.3-4.1	5.2	3.2- 2.8	2,9
TSS (mg/l)	7.3-1.2	4.5	5.1- 0.9	3
TDS (mg/l)	120-25	72.5	80- 17	48.5
CaCO3 (mg/l)	57-23	40	42- 12	27
NO3 - (mg/l)	18-0.5	9.3	12- 0.2	6
SO4 2- (mg/l)	53- 5	29	37-1	19

Appendix D: Plagiarism Report

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