

CHAPTER 1: INTRODUCTION

1.1 Background

Drinking or potable water is one of the essential components of the human body. According to the World Health Organization (WHO, 1997), the provision of an adequate supply of safe water was one of eight components of primary health care identified by the International Conference held in 1978 in Alma-Ata, Kazakhstan. However, in most countries, the major risks associated with human health are linked to the consumption of polluted water. An estimated 80 percent of all diseases, and well above one third of deaths in developing countries, may be caused by the consumption of contaminated water. However, the provision of potable water is a monumental task. In South Africa, water use and consumption is regulated mainly by the Department of Water and Environmental Affairs (DWEA) and the Water Services Act of 1997. This Act states that potable water quality should comply with prescribed National Drinking Water Standards (SANS 241, 2006). An ideal situation exists when drinking water quality satisfies the SANS 241 (2006) Class I limit which is suitable for lifetime consumption. The most critical situation exists when a constituent does not comply with SANS 241 (2006) Class II limits, which is regarded as a failure, and may pose a health threat to consumers.

Problems associated with potable water contamination can emanate from various points within a water supply system. This implies changes from the point of withdrawal (source), to the Water Treatment Plant (WTP) and through the network. As part of the overall potable water contamination problem or quality deterioration, this research focused on drinking water quality deterioration between points where the clean water leaves the purification plant up to points of both consumer withdrawal and water sale. According to Zaslow and Herman (1996), people are increasingly concerned about the safety of the water that they drink. Drinking water may be contaminated at the original water source, during treatment, or during distribution to the consumers. Surface water (river or lake), can be exposed to acid rain, storm water runoff, pesticide runoff, and industrial waste.

This water is partially cleansed by exposure to sunlight, aeration, and microorganisms in the water. On the other hand, groundwater (private wells and some public water supplies) generally takes longer to become contaminated, but the natural cleansing process may take much longer (Zaslow and Herman, 1996).

Farooq et al. (2008) studied coli-forms and chlorine residual at a water network in Rawalpindi, Pakistan. The study was undertaken to examine the drinking water quality of Rawal Treatment Plant and its network. The aim of that study was to determine a potential relationship between the presence of microorganisms and chlorine residual in the network. Three forms of chlorine were measured at different stations. Data collected indicated that the pH ranged from 7.02 to 7.30; turbidity was from 0.34 to 2.79 NTU; conductivity ranged between 359 and 374 $\mu\text{S}/\text{cm}$; and Total Dissolved Solids (TDS) values were between 180 and 187 mg/ℓ . That study made the following conclusions:

- a)** Many of the stations' total coli-forms were less than 1.1 MPN/100 $\text{m}\ell$.
- b)** The results of tested samples for faecal coli-forms were positive for some stations.
- c)** Microbiological count was inversely proportional to residual chlorine. As the chlorine concentration increased, microbial counts decreased.

A recommendation, based on the results, was that regular monitoring of residual chlorine concentration and total coli-forms in the water distribution system should be carried out to ensure that sufficient chlorine residual is always present at the consumer end. Although this study managed to recommend that regular monitoring of residual chlorine was necessary, it did not relate residual chlorine deficiency with the overall quality of water and how it affected the consumers.

Zuthi et al. (2009) assessed the water quality supplied in the Chittagong City of Bangladesh. The study focused on the deterioration of water quality supplied to the residents of the city. The results revealed that the water quality was at risk of deteriorating during its flow through the distribution system, as regular monitoring of the network was not done according to a defined schedule. Furthermore, microbial water quality parameters examined at some selected locations suggested that the

presence of pathogenic organisms in the water exceeded the permissible limit. The water quality test results revealed that microbial water quality deteriorated during its flow from the treatment plant through the distribution system. Biochemical Oxygen Demand (BOD) values were also found to be high. Presence of faecal coli-forms, as well as total coli-forms, were noted at some locations in the distribution system. This study concluded that the authorities should implement a regular monitoring program to prevent possible contamination of water along its distribution by means of cross connections, cross contamination by leaking pipes or improper domestic storage. This study further emphasized the need for monitoring, yet failed to mention what can be done to improve the current system and rectify the associated problems.

1.2 Statement of the Problem

Magalies Water (MW) abstracts, purifies and sells water as a Water Service Provider. One of the water treatment plants operated by MW is the Klipdrift WTP. Although the Klipdrift WTP is generally 95-100 percent compliant with quality requirements, water quality deteriorates along the bulk distribution main from the plant to Modimolle area point of sale. This observation was made after tests were conducted by the Scientific Services Department of MW. Water is not treated further beyond this point, but is distributed to the consumers directly by the Water Service Authority. Water at the point of consumption was found to be 93 percent compliant (due to water quality deterioration in the distribution system) instead of 100 percent. This poses a problem for MW as a service provider, in terms of water safety. Modelling and simulating the network in its current state is therefore imperative in investigating the cause of this deterioration.

1.3 Justification of the Study

Drinking water quality can deteriorate significantly between points of treatment and the consumer; hence, water utilities may encounter some microbiological problems in their distribution systems. Furthermore, potable water systems may provide a habitat for microorganisms, which may be sustained through organic and inorganic nutrients present in the system.

Excessiveness in microbiological substances may lead to aesthetic deterioration of water quality, and can interfere with methods used to monitor parameters of health significance (Ndambuki, 2006). Potable water that does not meet the quality standards presents problems in various ways. These problems can vary from serious illnesses to staining clothing by hard water. Thus, compliance of potable water quality with global and local standards is important to ensure continued healthy consumption of water by both humans and animals.

1.4 Delineation

This research was confined within the boundaries of chemical, physical and microbiological parameters. The research did not consider other aspects such as pressures in the system, which might also contribute to the quality of the water. Furthermore, this study did not focus on raw water coming into the plant nor the impact of the pipe material in the network.

1.5 Research Objectives

1.5.1 Main Objective

The overall objective of this research was to investigate and model water quality characteristics within Modimolle network.

1.5.2 Specific Objectives

The specific objectives were to:

- a) Determine the quality of the clean water before it leaves the plant.
- b) Model the network using EPANET software.
- c) Simulate the water quality variation in the network in its current state.
- d) Design an optimal water quality model for the network.

1.6 Outline of the Dissertation

This dissertation has five chapters. Chapter 1: Introduction. Chapter 2: Literature Review; presents the development in water quality deterioration. Chapter 3: Research Methodology, apparatus and materials. Chapter 4: Presentation and Analysis of results and Chapter 5: Conclusions and recommendations.

CHAPTER 2: LITERATURE REVIEW

Most water utilities in South Africa have a challenge of managing pipelines that are constructed to transport drinking water to the end user or consumer in terms of maintaining water quality. Drinking water quality can deteriorate significantly between the treatment plant and the consumer's tap. Conventional ways of supplying water involve abstracting it from a source (river, lake or dam) and transporting it to a WTP, where water is purified to suite human consumption. Clean water is then stored in large reservoirs, ready for distribution to the consumer. Water will vary in quality from point of abstraction to the point of withdrawal for use, with raw water having the poorest quality in their entire distribution system.

The levels of contaminants in drinking water can be high enough to cause acute health effects. Examples of acute health effects are nausea, lung irritation, skin rash, vomiting, dizziness, and even death. Contaminants are more likely to cause chronic health effects, and these are effects that occur long after repeated exposure to small amounts of a chemical. Examples of chronic health effects include cancer, liver and kidney damage, disorders of the nervous system, damage to the immune system and birth defects. There is little evidence relating chronic health effects to specific drinking water contaminants (Zaslow and Herman, 1996).

2.1 Critical Water Quality Parameters

The critical water quality parameters are:

- a)** Physical parameters – Colour, Turbidity, pH and Conductivity.
- b)** Chemical parameters – Chlorine, Residual Chlorine, Iron, Manganese, Alkalinity, Hardness and Magnesium.
- c)** Microbiological parameters – E-coli, Heterotrophic Plate Count and Total coli forms.

According to SANS 241 (2006), water shall comply with requirements for class I for lifetime consumption in relation to the physical, organoleptic and chemical composition. Water shall comply with the upper limit of class II for consumption for a limited period. Water is deemed to fail compliance for physical and chemical

requirements of this standard when a confirmed sample exceeds the upper limit of class II, but only for items that pose a health threat. Failure on aesthetic determinants alone does not necessarily imply that the water is unsafe for drinking. Water that is not quality compliant causes not only health problems, but also other problems, such as corrosion of the transporting pipes, scale forming on metals and colouring of clothes. Each of these parameters affect quality of potable water in a different way. The degree to which this (scaling and corrosion) occurs is also a function of pH (a measure of the acidity or basicity of a solution); alkalinity and dissolved oxygen concentration. In areas with hard water, household pipes can become clogged with scale and cause incrustations on kitchen utensils, increasing soap consumption. Hard water is thus both a nuisance and an economic burden to the consumer. It has been suggested that a hardness level of 80 to 100 mg/ℓ (as CaCO₃) provides an acceptable balance between corrosion and incrustation (Health Canada, 1979).

Health Canada (1979) further states that chlorine gas, even at low concentrations, can irritate eyes, nasal passages and lungs; it can even kill in a few breaths. Nitrites produce a serious illness (brown blood disease) in fish, even though they do not exist for very long in the environment. Nitrites also react directly with hemoglobin in human blood to produce methemoglobin, which destroys the ability of blood cells to transport oxygen. This condition is especially serious in babies under three months of age, as it causes a condition known as methemoglobinemia or "blue baby" disease. Water with nitrite levels exceeding 1.0 mg/ℓ should not be given to babies. These are just a few problems associated with the issue of water quality deterioration. If these problems persist, lives could be lost, and the poorest of the poor could feel the pinch, economically, caused by the poor quality of water.

According to the South African Water Quality Guidelines (1996), domestic water users can experience a range of impacts because of changes in the quality of potable water. These impacts may be categorised as follows:

- a) **health impacts** (short term and long term).
- b) **aesthetic impacts**, including changes in water taste, odour or colour; staining of laundry or household fittings.

- c) **economic impacts**, which may include increased cost of treatment; increased cost of distribution due to scaling, corrosion or deposition of sediments in the water distribution system and scaling or corrosion of household pipes, fittings and appliances.

For this reason, the following elements/parameters were chosen, as they were believed to be the parameters that pose a threat to the system as far as health, aesthetic and economic impacts are concerned. Based on the South African Water Quality Guidelines (1996), the critical water quality parameters tested during this study are:

a. Physical Parameters

i. Turbidity - This is a measure of the light-scattering ability of water and is indicative of the concentration of suspended matter in water. The survival of microorganisms is often associated with turbidity; hence, low turbidity minimizes the potential for transmission of infectious diseases. The probability of the presence of carcinogenic asbestos fibres is also reduced under conditions of low turbidity. Turbidity also affects the aesthetic quality of water.

ii. Colour - In potable water, colour can be of natural origin or it may be an industrial result of effluents containing soluble coloured materials. Most natural causes of colour are associated with the presence of dissolved organic matter. There are no direct health consequences related to the presence of colour in drinking water, except when colourants are toxic. Aesthetic effects are mainly visual, but some colourants (iron or manganese) may stain or otherwise affect household appliances. Hence, it is required to remove colour in potable water.

iii. pH - If the pH level is less than 7 in potable water acidic conditions prevail, while at pH levels greater than 7, water becomes alkaline. The pH level of water does not have direct health consequences, except at extremes. The main significance of pH in domestic water supplies relates to its effects on water treatment. The selection of raw water as a drinking water source is never based solely on pH. The taste of potable water and its corrosivity are some of the

factors influenced by pH levels. At low pH levels, water may taste sour, while at high pH levels, water tastes bitter or soapy. Corrosion of the supply pipe material in the water supply system is a major source of metal contamination in drinking water.

iv. Conductivity - The TDS is a measure of the amount of various inorganic salts present in the water. TDS concentration is the direct measure of the electrical conductivity (EC) of water. EC is a measure of the ability of water to conduct an electrical current. Water with extremely low concentrations of TDS may be objectionable because of its flat, insipid taste, whereas high concentrations of salts impart an unpleasant taste to water and may also negatively affect the kidneys. Excessively high concentrations of TDS may adversely affect plumbing and appliances, and hence maintenance and replacement requirements.

b. Chemical Parameters

i. Residual Chlorine - Free chlorine at any given node in the system safeguards the quality of water in case of any intrusion of contamination into the system. According to SANS 241 (2006), residual chlorine requirements at any given point in the distribution system has to be kept to a minimum of 0.2 mg/ℓ. Should any hazardous contaminants enter the system; this free chlorine will be able to kill the harmful pathogens. If this concentration of residual chlorine is not upheld, safety of the water to the consumers cannot be guaranteed.

ii. Iron - Biologically iron is an important micro-nutrient required by all living organisms. However in high concentrations, iron becomes an aesthetic concern, since ferrous salts are unstable under the pH conditions prevailing in drinking water and precipitate as insoluble ferric hydroxide, which settles out as a rust-coloured silt. Excessive ingestion of iron may result in tissue damages as a consequence of iron accumulation. Effects of excessive iron in potable water are mostly aesthetic, such as the staining of surfaces of baths, hand basins and lavatory cisterns. Iron causes discolouration of water supplies when present at low concentrations. Iron that settles out in distribution systems gradually reduces

the flow rate of water. The only associated health consequences are those that could arise from the presence of microbial deposits on internal surfaces of plumbing.

iii. Manganese - At high concentrations, manganese has aesthetic, rather than toxic, effects. An unpleasant taste is imparted to beverages, with staining of plumbing fixtures and laundry often occurring. It has been suggested that the presence of manganese in drinking water may be inversely related to cardiovascular mortality. A link between manganese ingestion and Parkinson's Disease has been tentatively suggested, but not confirmed. Manganese also supports the growth of certain unwanted organisms in water distribution systems, giving rise to taste, odour and turbidity problems.

iv. Alkalinity - Alkalinity is a measure of the capacity of the water to resist a change in pH. The measurement of alkalinity and pH determines the corrosiveness of the water. Scaling in pipe material may form with excessive amount of alkalinity. Chemical corrosion may occur when the alkalinity is too low. Alkalinity is not detrimental to humans.

v. Hardness - Water hardness may be described as the soap-destroying power of water, caused by the presence of calcium and magnesium salts. Temporary hardness is attributable to the presence of bicarbonates of calcium and magnesium, and can be removed by boiling water. On the other hand permanent hardness is attributed to other salts, such as sulphate and chloride salts, which cannot be removed by boiling. Excessive hardness of water may give rise to scaling in plumbing and household heating appliances, and hence has adverse economic implications. It also results in an increase in soap required to produce good foam when bathing and in household cleaning. This may lead to scum formation through the formation of insoluble salts of long-chain fatty acids, the chief component of soaps. These scum are unaesthetic, leading in the long term to the marking of enamel surfaces of baths and hand-basins.

vi. Magnesium - Magnesium, together with calcium, is responsible for the hardness in water. Excess magnesium intake results in diarrhoea. Magnesium, together with calcium, is responsible for scaling problems caused by deposits of carbonates in appliances using heating elements and plumbing that transports hot water. It further inhibits the lathering of soap, which results in scum formation.

c. Microbiological organisms

i. E-coli (Faecal Coli-forms) - Faecal coli-forms, and more specifically *Escherichia coli* (E-coli), are the most commonly used bacterial indicators of faecal pollution. The presence of E-coli confirms the presence of faecal pollution in drinking water. Not all organisms are of human faecal nature, some organisms are definitely from warm-blooded animals. These organisms can be transmitted via the faecal/oral route by contaminated or poorly treated drinking water, and may cause diseases such as gastroenteritis, salmonellosis, dysentery, cholera and typhoid fever or even fatality. Higher concentrations of faecal coli-forms in water will indicate a higher risk of contracting waterborne diseases, even if small amounts of water are consumed.

ii. Heterotrophic bacterial count - They are used to indicate the general microbial quality of water, assess the efficiency of water treatment and disinfection processes, to test the integrity of the distribution systems for after-growth and to determine the quality of water used in industrial processes. Plate counts do not indicate possible faecal pollution, nor do they represent the total number of bacteria present in water; only those bacteria able to grow under favourable conditions of the test are counted. A high plate count in treated water is indicative of inadequate treatment of the water, post-treatment contamination or bacterial after-growth in the distribution system. Therefore, pathogenic microorganisms, bacteria, viruses or parasites could possibly be present in the water and pose a health risk when the water is used for domestic consumption.

iii. Total coli-forms - Total coli-forms bacteria are normally used to assess the hygienic quality of water, to evaluate the efficiency of water treatment and the

integrity of the distribution system. They should not be detected in clean water supplies. If detected, it suggests inadequate treatment, post-treatment contamination and/or after-growth. The total coli-forms group includes bacteria of faecal origin and indicates the possible presence of bacterial pathogens, especially when detected in conjunction with other faecal coli-forms. These organisms may cause diseases, such as gastroenteritis, salmonellosis, dysentery, cholera and typhoid fever or may even cause fatality.

2.2 Contaminants Origin in Potable Water

There are four groups of contaminants:

- a. Microbiological Pathogens:** These are serious health risks in water.
- b. Inorganics:** Toxic and metals in water.
- c. Organics:** Toxic metals in water.
- d. Radioactive elements:** Radon is from the decaying of uranium in rocks.

Figure 1 shows the process with which contaminants end up in the water supply system from the environment. Contaminants that are likely to arise from a planned activity need to be identified. It is not exhaustive with regard to activities or with regard to contaminants from the listed activities, i.e. for some activities there may be some additional contaminants not listed. Furthermore, some of the contaminants introduced by a certain activity may not arise from it at a very high level of concern. Estimation of contaminant load from non-point source activities is not as straightforward, because the contaminants and the levels that are released into the environment may not be well characterised.

Irrespective of the amount of contaminant released by an activity, it will not cause pollution of the source water unless there is some pathway by which the contaminants can reach the receiving water (see Figure 1). A degree of attenuation may occur as contaminants pass over land or through water. The extent of attenuation depends on the nature of the discharge and environmental conditions (Ministry for the Environment, 2010).

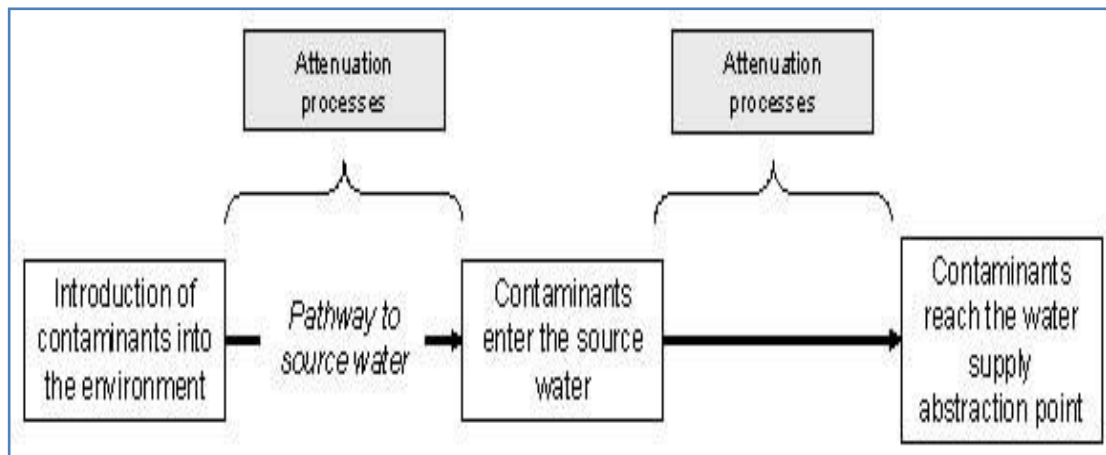


Figure 1: Introduction of contaminants into the environment (Ministry for the Environment, 2010)

2.3 Processes that may Attenuate Contaminants in the Source Water

According to the Ministry for the Environment (2010), even when contaminants have reached the source water, there are still processes acting to reduce their concentration and these include, inter alia:

- a. The initial dilution by the receiving water body.
- b. Sedimentation as particles settle to the bottom of the river.
- c. Adsorption.
- d. Inactivation - this applies to microorganisms and is the result of the exposure to sunlight and the dilution by tributaries.

Re-suspension of sediment may increase the concentrations of contaminants reaching the abstraction point. The Klipdrift WTP receives water from a source which is approximately 18 km away. Conveying water over such a long distance to the plant through a canal plays a significant role in adding pollutants and contaminants to this water.

2.4 Contamination of Water Source as a Result of Rainfall or Irrigation

DWEA (2009), states that water, either as rain or from irrigation, is usually the vehicle by which contaminants are moved along pathways to source waters. Some of

the consequences of rain can reduce contaminant concentrations through dilution, but overall rainfall needs to be viewed as a factor that will increase contaminant concentrations. The increase in concentration will occur for a limited period, but the water treatment plant must be able to produce safe drinking water during this time. The assessment of a new catchment activity needs to consider the ‘worst-case’ level of contamination by trying to evaluate how a rain event will affect pollution of the source water. Where the planning for an activity includes measures to mitigate the effect of rainfall, the risk created by the activity will be reduced.

2.5 Raw Water Source

Even though this study did not focus much on raw water, it was imperative to highlight the source of raw water coming into the plant. The Klipdrift WTP mainly draws water from the Leeukraal dam, which is situated in the Hammanskral region, Gauteng province. This dam is the main source of raw water to the plant. However, there are instances whereby the dam is unable to supply full demand to the plant, and in that case, the Roodeplaat dam, which is situated in the Wallmannsthal region, Gauteng province, supports the Leeukraal dam in terms of supply. A canal, which is 18 km long, carries water from the Roodeplaat dam to the plant. Water from the Leeukraal dam is pumped to the plant whereas water from the Roodeplaat dam flows by means of gravity.

2.6 Klipdrift Water Treatment Plant

Klipdrift WTP as shown in Figure 2, is situated close to the town of Hammanskral. Hammanskral is situated north of Pretoria along the N1 main road heading towards the Limpopo province. This plant supplies water to areas under the Gauteng and Limpopo provinces.



Figure 2: Klipdrift Water Treatment Plant

The pipeline that supplies water from the Klipdrift WTP to Modimolle is the longest bulk supply line within the MW system. Figure 3 shows the plant process train, as was observed on site, which is the conventional way of purifying water. pH correction of the raw water is not done at the plant. pH Adjustment is only applied to water coming from the Leeukral dam, which is a secondary raw water source. At the inlet, water is pre-chlorinated before it proceeds to the next process element. A coagulant, Polymer, is added to the water as it passes to the filtration process. It was noted that the plant has no flocculation process, as water flows straight into the next process phase after the dosing of a coagulant. The coagulant is not given sufficient contact time to mix with the water.

The water then flows into the Dissolved air flotation filters (DAFF), where it is forced from underneath the filter beds. At the same time, air is forced in to push the suspended solids to the surface of the filter beds. The solids then form scum, which float into the discharging channel. From the DAFF process, water is again dosed with chlorine as it goes into the clear-water storage, where sufficient contact time is allowed. The water is pumped from there by two pumps stations to Modimolle

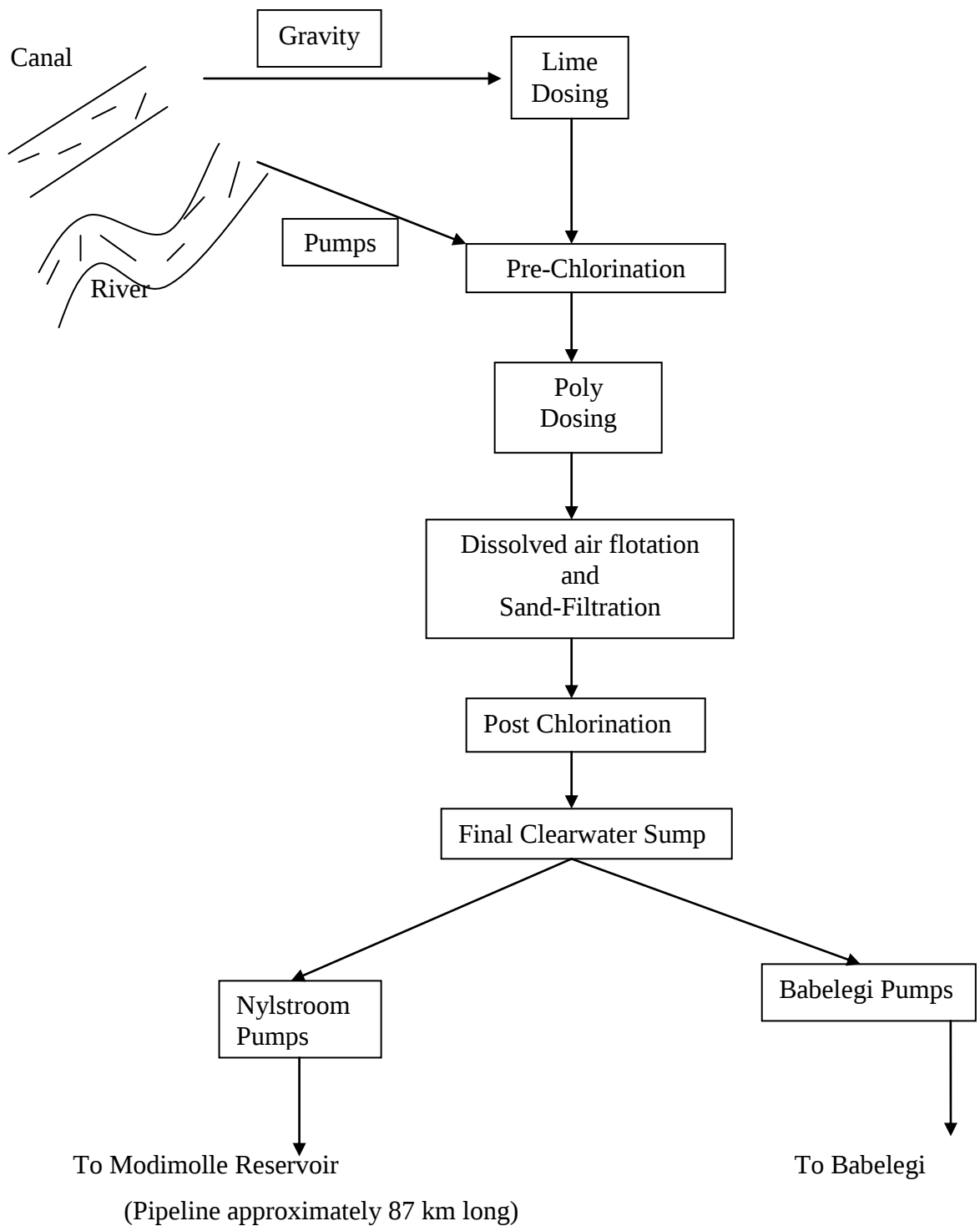


Figure 3: Klipdrift Water Treatment Plant Process Train

(Nylstroom pumps) and to Babelegi (Babelegi pumps). The Babelegi section of the system does not form part of this research.

The design capacity of this plant is 18 Mℓ/d but the plant runs up to 22 Mℓ/d. The fact that this plant is being operated beyond its design capacity suggests that the quality of water will be of sub-standard. The absence of a flocculation process means that the retention time is reduced, causing flocs not to form adequately. Since there are no sedimentation tanks, the filters have to primarily manage the removal of all solids, which puts strain on the filters. The plant's pumping system is very old. A refurbishment of the pumping system was recently undertaken but its inefficiency is still a problem. The MW company is planning to re-build the pumping system in the future but the plans are still in the pipeline.

2.7 Pipeline from Klipdrift Water Treatment Plant to Modimolle

The Modimolle pipeline is approximately 87 km in length and consists of two different diameters, i.e. 450 mm and 300 mm, both being steel pipes. The 450 mm diameter is approximately 62 km in length and the remaining 300 mm diameter is approximately 25 km in length. According to Maul et al. (1991), a potable water network has two phases of water; phase one being the water and phase two being the solids present on the pipe wall and the suspended particles entrained in the flowing water. The biomass (colonized suspended material by microorganisms) is attached to the pipe wall, thereby forming a bio-film. These microorganisms form an ecosystem, which is stable and difficult to remove, and constitute the primary cause of degradation of the microbiological quality of the water.

According to Maul et al. (1991), the maintenance of chlorine residual in a network is often implemented as a means of limiting the proliferation of the heterotrophic bacterial flora and to minimize the risk of accidental post-contamination of the water.

2.8 Waterborne Diseases Due to Contamination in the Distribution System

It is common knowledge that consuming contaminated water may have serious health impacts on human life. According to Water treatment and purification (1998), when faecal bacteria are present in the aquatic environment, it indicates that human and/or animal faeces or urine contaminates the water that contains pathogenic

microorganisms. However, a specific kind of faecal bacteria needs to be detected in the water in order for this conclusion to be true as not all faecal coli-forms are found from contamination of faeces. It can then be deduced that pathogenic bacteria or viruses are present in the surface or fresh water and that this results from faecal contamination. Lack of information on the deterioration of water quality within a distribution system due to contaminant intrusion exposes consumers to contaminants. The emphasis is now being shifted towards water quality properties, as water distribution systems are required to comply with standards that were non-existent at the time of the design. Water supply industries are being directed to shift their focus from water line delivering capacities to water quality when a water network system is being evaluated (Ndambuki, 2006).

Microorganisms may introduce some deadly diseases if ingested by humans or animals. Typical diseases linked with these microorganisms include fever, intestinal disease, typhoid fever and hepatitis. According to Rangwala (1969), harmful bacteria cause waterborne diseases. He asserts that waterborne diseases are predominant in developing countries, with an estimated five million babies dying annually from waterborne diseases in such countries. Furthermore, one in six of the world's population suffers every year from waterborne diseases.

According to WHO (1997), apart from people dying of waterborne outbreaks, there exist other detrimental issues. One of the problems associated with this is the direct economic impact on countries and continents affected by these outbreaks, as shown in Figure 4. Surveys conducted by WHO indicate that about eighty six percent of rural populations in developing countries are without reasonable access to safe water.

According to Rangwala (1969), patients suffering from such diseases spread harmful organisms through their intestinal discharges. Many of the microorganisms pathogenic to animals and humans are carried in waters derived from surface sources.

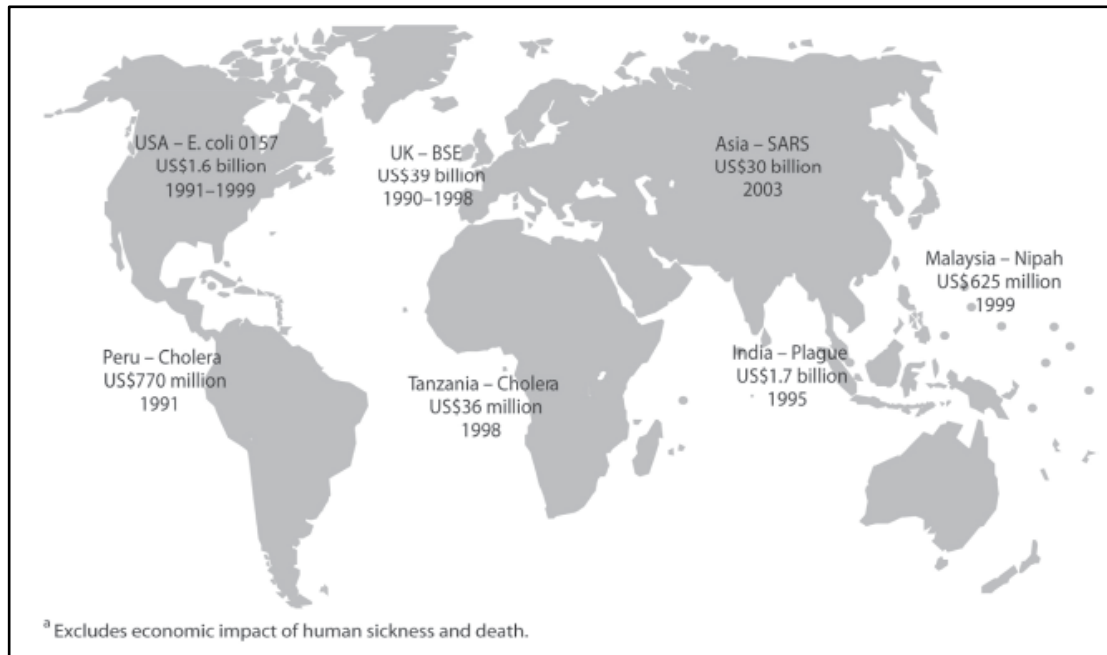


Figure 4: Direct economic impact of selected infectious disease outbreaks (WHO, 1997)

Faecal coli-forms have been shown to represent 93 – 99 percent of coli-forms bacteria in faeces from humans and animals. *Escherichia coli*, (E-Coli) which are indicator organisms, may comprise up to 97 percent of coli-forms bacteria in human faeces. Crittenden (2005) states that it is impossible to eliminate diseases that are caused by faecal bacteria since they can also spread through the contamination of food, activities at day-care centres, and other endeavours of asymptotic carriers. Eliminating them from water will only reduce the waterborne outbreaks.

2.9 Microbiology of Networks for Drinking-Water Supplies

According to Maul et al. (1991), the problems associated with microbiology in the water arise as a result of the increase in the density of organisms present over time as water travels long distances to the consumer. Current treatment processes are not intended to produce water that is sterile, but simply render it pleasant to drink and safe for human health.

Consumption of contaminated water is a major source of Cholera, which is a leading water related disease in Sub-Saharan Africa. The Limpopo province, where

Table 1: Cholera Outbreaks Across South Africa (Benson, 2009)

Province	Cases	Deaths	CFR	Occurrence
Mpumalanga	4165	30	0.72%	21/11/08 to 31/01/ 09
Limpopo	3680	20	0.54%	15/11/08 to 31/01/09
Gauteng	234	3	1.28%	19/11/08 to 31/01/09
Western Cape	9	0	0.00%	19/11/08 to 23/01/09
North West	7	0	0.00%	15/11/08 to 24/01/09
Kwa-Zulu Natal	2	1	50.00%	19/11/08 and 04/01/09
Eastern Cape	1	0	0.00%	11/12/08
Free State	1	0	0.00%	18/12/08
Northern Cape	1	0	0.00%	12/12/08
Total	8100	51	0.63%	

*CFR: Percentage deaths in relation to a number of cases.

Modimolle is situated, had the largest number of outbreaks of this disease, with 793 reported cases of infections. Table 1 shows cases reported and related deaths for the period of November 2008 to January 2009.

These are alarming statistics. Other challenges identified included problems with the chlorination of water, hence the challenge of potable water quality deterioration. In a One of the recommendations stated that short-term measures to address the need for safe water be implemented.

2.10 Water Quality Deterioration in Reservoirs

A study was conducted by the Water Research Commission (2001) on ‘Water quality Deterioration in Potable Water Reservoirs Relative to Chlorine Decay’. Although that study recognized the need for monitoring of quality through the entire distribution system, it only focused on reservoirs as a point of quality deterioration out of the entire system. It also did not consider other water quality parameters, as only residual chlorine was researched. The objectives of that study were to:

- a)** Characterize the flow patterns in reservoirs in terms of residence time distribution (RTD).
- b)** Relate chlorine losses of the water age (based on RTD-values and kinetic models).
- c)** Account for chlorine losses due to the wall and the bottom effects.
- d)** Account for atmospheric losses.
- e)** Relate the bacteriological quality of the water to the levels of chlorine in the reservoirs.
- f)** Compare the bacteriostatic effect of monochloramine and free residual chlorine in reservoirs.

That particular study concluded that reservoirs should be designed to ensure that the internal arrangements are optimal to prevent short-circuiting, as well as the formation of stagnant water pockets. Chlorine loss, or chlorine decay, was found to be influenced by a variety of factors. It also found that relatively deep penetration of water into the concrete structure occurred. A state of equilibrium was therefore only reached after a long period. Empirically it was found that the concrete accelerates the loss of chlorine and that aged concrete had a lesser influence on the chlorine decay than freshly made concrete. There was very little correlation found between the bacterium and chlorine levels inside reservoirs. Furthermore, it was found that some organisms do survive the disinfection process and the surviving bacteria served as inoculums for biofilms and after-growth in the distribution system. That study recommended the following:

- a)** Development of a more accurate chlorine decay test method.
- b)** Operational conditions for a distribution system must be optimised.

- c) Treatment processes must be optimised to prevent or minimise after-growth within the distribution system.
- d) Differences and similarities should be investigated in the operation of small and large distribution systems for optimum water distribution and quality.
- e) Finally, but importantly, differences and similarities in the water quality parameters of small rural water storage tanks and large reservoirs should also be investigated.

Although that particular study managed to identify problems associated with water quality deterioration in reservoirs, it certainly did not consider other components of the system, such as the pipelines, which are essentially the major part of any network.

2.11 Water Quality Deterioration in Distribution or Storage Due to Biofilm Formation

Biofilm is a term used to describe a layer of microorganisms which forms in a pipeline. This layer is formed when microorganisms present in water attach themselves to the internal walls of the pipeline. The formation of this layer occurs when favourable conditions prevail within a pipeline. The layers formed are often evenly distributed throughout the pipe and patchy looking.

Momba et al. (2000) studied the composition of the biofilm formation, factors that govern their formation and their effect on the deterioration of drinking water quality. The study further discussed the enumeration of bacteria in biofilms. It concluded that formation of biofilms associated with events of re-growth or after-growth in water systems is the main reason for the deterioration of bacteriological quality. Factors affecting biofilm formation are efficiency of the disinfectant being used and the ability to retain residual chlorine concentrations in the drinking water pipeline. Pipe material and water temperature were also among the influencing factors. The study by Momba et al. (2000) also concluded that, although the detection of faecal coliforms bacteria is a main concern in potable water, it is also crucial to control the

general bacterial population. This is because many heterotrophic bacteria present in the biofilms have been relegated to secondary opportunistic pathogens in humans. It was also found that, apart from the heterotrophic organisms, a number of other pathogenic and toxigenic microbiological agents were present in the biofilm. Diseases associated with these pathogens range from viral and bacteriological gastro-enteric diseases to infections, such as Hepatitis A and giardiasis.

Momba et al. (2000) further suggest that, for the control of biofilm formation in pipelines, the use of less reactive monochloramines (that are more persistent) be implemented. Furthermore, the use of hydrogen peroxide, which maintains a longer disinfectant residual throughout the distribution system, should be considered. These two disinfectants apparently penetrate the biofilm more effectively, resulting in better control of biofilm formation than the more reactive disinfectants, such as free chlorine. Although the study gave some recommendations for controlling biofilm formation by using less reactive monochloramines or hydrogen peroxide, the recommendations fell short in combating biofilm that had already formed.

2.12 Drinking Water Quality Framework for South Africa

Manus and Hodgson (2006) suggested that current investigations on potable water quality show an unacceptably high incidence of poor drinking water quality in non-metropolitan municipalities in South Africa. They attribute this to the following reasons:

- a) A lack of understanding by Water Service Authorities (WSAs) regarding the requirements for effective drinking water quality management.
- b) Inadequate management, including monitoring of drinking water services.
- c) Inadequate asset management.
- d) Inadequate WSAs institutional capacity, i.e. staffing, funding, expertise and education.
- e) Lack of intervention to address poor drinking water quality when detected.

Based on the recognition of these challenges, the Department of Water Affairs then developed a drinking water quality framework for South Africa. Although the

ultimate goal of formulating a frame work for drinking water in South Africa was achieved, the impact of water quality deterioration along the distribution system was completely ignored. Manus and Hodgson (2006) did not consider the deterioration of quality in the distribution system as the cause of water quality problems; instead, they cited the role of the WSAs and the non-adherence to regulations as possible causes.

2.13 The Effects of Supplied Potable Water Quality on Human Health in Urban Development

According to Manus and Hodgson (2006), water-related hazards will not be totally eliminated even when communities in low socio-economic environments are supplied with treated piped water. Factors such as contamination of water in the pipes due to low pressure and breakdowns in the network system can give rise to infections, such as diarrhoea. The study further revealed that diarrheal infections were the main contributors to infant mortality. Although the study focused on aspects of contamination of water in the pipeline due to low pressure, the pipe material and length of haulage were not mentioned, which could influence these results.

2.14 Water Quality Deterioration Due to Surge Events

According to WHO (2004), a surge in pressure and flow can occur when pumps are switched off or when valves and hydrants are operated. Any change in flow can result in a surge event. However, common causes include the operation of pumps, valves and hydrants. This can result in a deterioration of water quality, as the surge can disturb deposits in the pipe or on the pipe wall. These operations may also cause low pressures that could allow ingress of contaminants. The risk of significant surge, and hence water quality problems, is greater in long un-branched pipes than in branched pipes, because branched pipes reduce the surge.

Excessive water pressure can influence water quality by requiring more frequent main and service repairs. A plausible conclusion drawn from the above is that the longer the length of pipes in a water distribution system, the greater the risk of water quality deterioration due to the possibility of a surge occurrence.

Table 2 shows the impact of water age in the network. According to a Environmental Protection Agency (2002), water age is a major factor contributing to water quality deterioration within a distribution system. Water age is primarily controlled by system design and system demands. Thus, water age can vary significantly within a given system. Increased temperatures typically associated with increased water age can cause reactions to occur faster and hence cause water quality deterioration to occur quicker.

Table 2: Summary of water quality problems associated with water age (Source: Environmental Protection Agency, 2002)

Chemical issues	Biological issues	Physical issues
*Disinfection by-product Formation	*Disinfection by-product Biodegradation	Temperature increases
Disinfectant decay	*Nitrification	Sediment Deposition
*Corrosion control effectiveness	*Microbial re-growth / recovery / shielding	Colour
Taste and odour	Taste and odour	

*** Denotes water quality problem with direct potential public health impact.**

For poorly buffered waters, increased water age can no longer comply with water quality parameter requirements. Potential health issues associated with Nitrification and Microbiological Re-growth may arise. Tools for evaluating water age include hydraulic models, tracer studies and monitoring programs. From the Environmental Protection Agency (EPA) study, a conclusion was made that the longer the pipe lengths, the greater the water age and hence the possibility of water quality deterioration. All the studies mentioned in this chapter have so far focused on a portion of the distribution system, and none of them have investigated the deterioration of water quality from the source to the consumer. This research aimed to address this gap by focusing on the deterioration of water quality from source to tap, with the main focus on the bulk main pipes.

2.15 Residual Chlorine Decay in Potable Water

Nagatani et al. (2006) simulated residual chlorine decay in water distribution system of Osaka Water in Japan. The simulation of free chlorine decay was done using EPANET software using data collected in field sampling. That study sought to investigate first-order bulk decay coefficients and its relations with water temperature through bottle tests. That study found that relationship between wall reaction coefficients and water temperature, prediction method for wall reaction coefficients and C-factors with pipe age and pipe lining material obtained from GIS database could be predicted. Furthermore, the study concluded that, to contribute to implementation of strict chlorine concentration control, free chlorine concentration simulation in distribution network for the entire city area would have been established in near future.

This study recommended that, in order for a complete simulation to be undertaken, field study to obtain wall reaction decay coefficient (k_w) for pipes are required. Wall reaction decay coefficient (k_w) for aged pipes, relationship between wall reaction decay coefficient (k_w) and water temperature and C-factors for aged pipes considering lining materials are also required for a proper simulation. Though this study makes good recommendations, lengths of the pipe were not mentioned as a requirement. The pipe elevations, node demand and pipe length will be explored in this study to comprehend chlorine decay in the network.

Robescue et al. (2008) modelled chlorine decay in drinking water mains. That study presented a theoretical model based on dispersion equation, which was validated with experimental measurements in drinking water mains that supply Ramnicu-Valcea town, Romania. That study concluded that a Mathematical model presented could be used to well predict chlorine concentration in water mains. Furthermore, data introduced in the program could be easily modified taking into account a given situation and the results were immediately obtained and thus, identifying points where additional chlorination is needed

Though this study achieved its objective of formulating a theoretical equation that would help identify the areas of concern in terms of chlorine decay, the study focused only on the chlorine in the network. The tracking of chlorine decay was lacking in that study.

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

Water quality for consumption remains a challenge in developing countries, such as South Africa. This challenge will remain unresolved for as long as attention is not given to the problem. The Department of Water Affairs is constantly monitoring the quality of water being supplied to the consumers by WSAs, but this monitoring is not sufficient, as appropriate action is not always taken. This research aimed to investigate and model water quality characteristics within Modimolle network, from a treatment plant to the furthest point of the pipeline. Stemming from this overall objective, specific objectives were set as objective (a), determining the quality of the clean water before it leaves the plant. This objective would help understand the quality of water produced by the plant and released into the system. Objective (b), modelling the network using EPANET software. This objective would give a scenario of the network and its supply. Objective (c), simulating the water quality variation in the network in its current state. This objective would help in understanding the current quality patterns within the network and show where quality deterioration occurs. Then lastly, objective (d), designing an optimal water quality model for the network. This last objective would then recommend remedial action in terms of chemical dosing.

The methodology adopted attempted to address the set objectives, which would lead to the attainment of the main objective. In addressing objective (a), which was to determine the quality of the clean water before it leaves the plant, a sampling point was chosen at the exit of the plant, where water had already been chlorinated. This point was situated at the exit of the chlorination basin, just before clean water is released into the clear water tank.

Clean water samples were taken throughout the 2010 season and the first month of the 2011 season, i.e. from February 2010 to January 2011. Samples were taken at intervals of one sample per month. In order to ensure consistent monitoring of distributed water quality, sampling and testing of clean water was done at least three

times in 24 hours. Only one of these results was used in this research for ease of discussion. Sample collections covered both the rain and dry seasons for the year 2010. Appendix A shows the rain pattern in the Gauteng province, (DWEA, 2009).

In order to meet objective (b), that is the modelling of the network using EPANET software, a lay-out plan of the network of the Modimolle area was acquired from the Modimolle municipality. Upon acquisition, the lay-out plan was sub-divided into sections, so that sampling could take place per section. Samples were then taken at these sections and tested. Using the results of the tested samples, the network was then modelled. Sections found to have very poor water quality results were then monitored throughout the season (total samples equalling ten). The sampling throughout the system was done on the same days. The reason for this was to be able to determine the direct relationship between water that leaves the plant, as well as water that reaches the consumer. To achieve objective (c), the results obtained in objective (b) were used as input data for the modelling the network. Results from objective (c) were then used to design an optimal water quality model for the studied network, and hence achieve objective (d).

3.1 Apparatus and Instrumentation

3.1.1 Apparatus Used and their Respective Functions

This study required specific apparatus to enable the tests to be performed in the laboratory of the Scientific Services Department, MW. The laboratory is situated in the Vaalkop area, some 65 km away from Rustenburg. Most of the apparatus was readily available in the laboratory, and a small fee was negotiated to use this apparatus with the laboratory. The following apparatus was used; among others:

- a)** Sterilised sampling bottles (250 ml) - Used for taking samples and storing them in transit.
- b)** Water Bath - For boiling water.
- c)** Liqui TOC II - Determination of dissolved carbon.
- d)** Quanti discs - Used for determination of Total Plate counts.
- e)** Quanti tray sealer and UV lamp - Used to seal quanti trays.

- f)** Quanti disc reader - Used to read quanti tray discs.
- g)** pH and Conductivity meter - For the readings of pH and Conductivity.
- h)** Oven - Used for drying samples.
- i)** Monochloramine - For detection of monochlorine.
- j)** Mercury analyser - For analysis of mercury.
- k)** Incubator - Used for incubation of quanti trays.
- l)** Cooler box - Used for keeping samples in transit cold.

Appendix B shows the photos of some of the above mentioned apparatus used in the laboratory of MW Scientific Services in Vaalkop. In addition to the laboratory apparatus, Personal Protective Equipment (PPE), was used.

3.1.2 Calibration of Apparatus

Apparatus used for testing the samples required calibration in order to record accurate results. Calibration of apparatus was done by specialist companies, who issued certificates of calibrations. Most of the apparatus used in a laboratory have expiry dates, which were checked before use.

3.2 Sampling

3.2.1 Sampling at the Klipdrift Water Treatment Plant

According to the Quality of Domestic Water Supplies (2000), a procedural guide for sampling must be followed in order to ensure proper sampling of domestic water. Sampling was necessary since testing could not be done on site. The Quality of Domestic Water Supplies guideline gives an indication of where water should be sampled for purposes relating to water quality analysis. The purpose of the guideline is to provide correct procedure that must be followed to collect a representative water quality sample from a water supply intended for domestic use. In order to ensure that sampling was done properly and samples were preserved, this guide was used. Figure 5 shows areas (marked in black dots) where sampling can be done from source to point of use along the water distribution system. Sampling points were established according to this guideline for the purpose of this study. Samples were

collected from various points through the entire system. Samples were collected and transported by the MW pipeline inspection team.

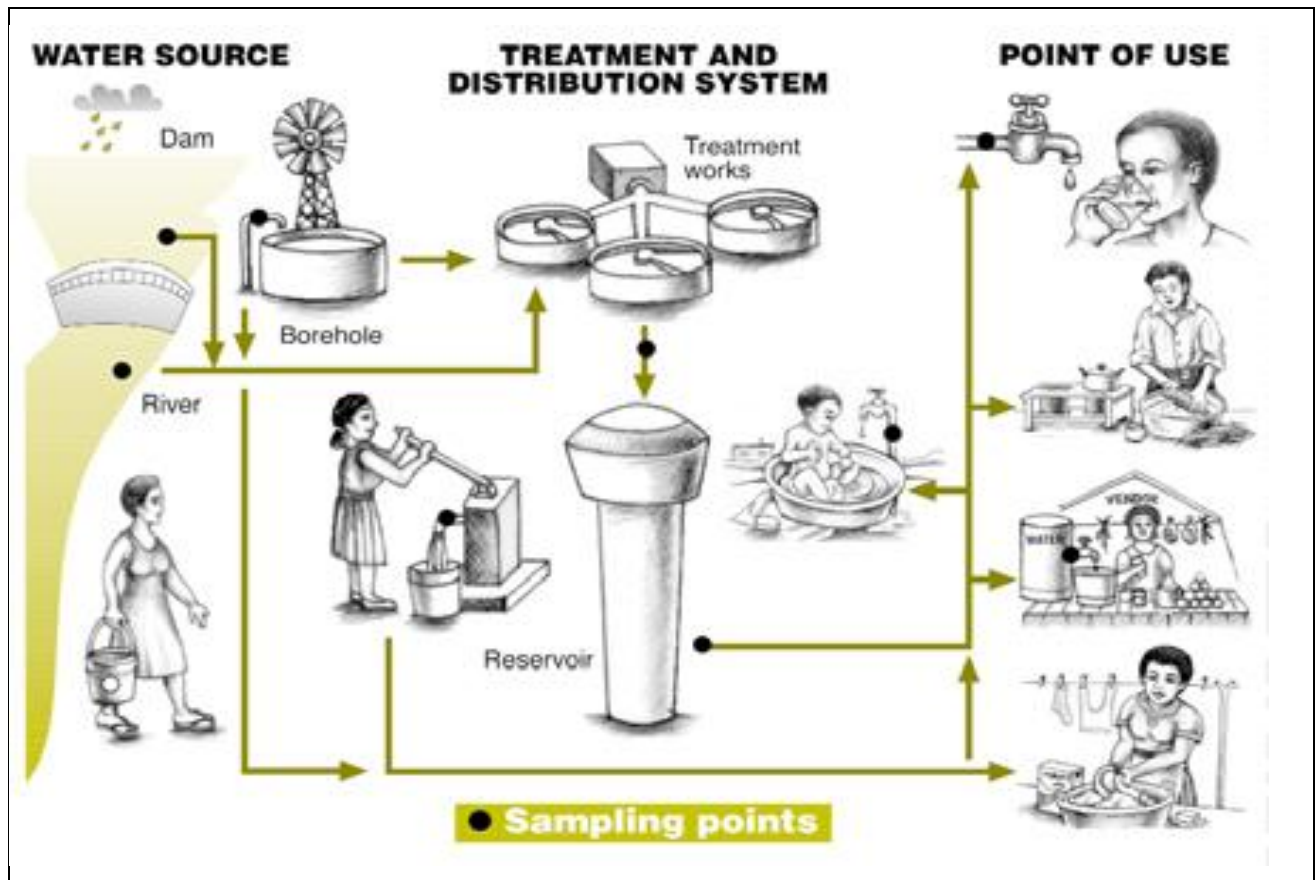


Figure 5: Water supply system with points where water samples should be collected to assess domestic water quality (Quality of Domestic Water Supply, 2000).

In order to achieve objective (a), samples were collected from the outlet point on the clear water storage, just before the water is distributed along the line to Modimolle. Raw water quality parameters are monitored by MW on a monthly basis.

Figure 6 shows the clear water tank from the Klipdrift WTP. Water flowing into this tank is clean as it has already been treated and chlorinated. In order to ensure consistent monitoring of distributed water quality, sampling and testing of clean water is done frequently (at least once a day) at the plant. Only one of these results was used for the purpose of this study for ease of discussion.

3.2.2 Sampling along the Main Pipeline to Modimolle

The length of the main pipeline from the Klipdrift plant to Modimolle selling point (Modimolle Reservoir) is approximately 87 km. Four different sampling points were established along this pipeline. The first sampling point was established at the plant, immediately after the clear water storage tank. This point is used by MW for their regular quality monitoring at the plant before the water is pumped out. The second point is called Carousel/Sondela supply off-take. This point was established for the purposes of the study. Thirdly, the Bela-Bela off-take point and lastly, the Modimolle Reservoir sampling point, which is at the end of the bulk supply line. The distances between these points are:

- a) Klipdrift plant (at the plant) to Carousel/Sondela is approximately 25 km
- b) Carousel/Sondela to Bela-Bela is approximately 29 km
- c) Lastly, Bela-Bela to Modimolle Reservoir is 43 km

Samples (250 ml bottles used per sample) were collected from four points along the line and at two points in the extension 11 Modimolle residential area. The extension 11 area is supplied directly from MW. The water from the Klipdrift WTP is separated at a set of reservoirs in Modimolle, where water from the Modimolle scheme is also pumped. One reservoir supplies extension 11 directly, whereas the rest of the supply is mixed with water from the Donkerpoort scheme (see Figure 7). Samples were collected on a monthly basis in order to get a true reflection of water quality variation.

Since the main line is a high pressured line, extreme caution was exercised in creating the sampling points. From the main line, long nozzles were drilled in and equipped with ball valves to allow for opening and closing of the water for sampling. In order to ensure that these sampling points were secured required strategically creating them in the existing chambers along the pipe route. These chambers are equipped with lockable lids and keys which are kept by the MW officials.



Figure 6: Top of clear water storage

3.2.3 Water Sampling within the Study Area

The sampling crew also proceeded to take samples in the Modimolle community. Permission was requested and granted by Modimolle officials. Water supplied by the Klipdrift plant goes directly into the ground reservoir. Water is then pumped into the elevated reservoir, which feeds the extension 11 community. Figure 7 shows the bulk supply of water for the Modimolle municipality. The system can basically be divided into two; firstly, the supply from the Klipdrift plant up to Bosveldig and extension 11; secondly the supply from the Donkerpoort scheme up to Part 5 and 6.

Water, as supplied by the MW's Klipdrift plant, gets mixed with water from the Donkerpoort scheme after the 2.9 Mℓ reservoir (A). Hence, the reason to sample at extension 11 which is supplied by the Klipdrift water system. Extension 11 is the only section supplied directly, without water mixing, with water from the Klipdrift plant. Two points furthest away from the elevated tank were then identified and used as sampling points within the community.

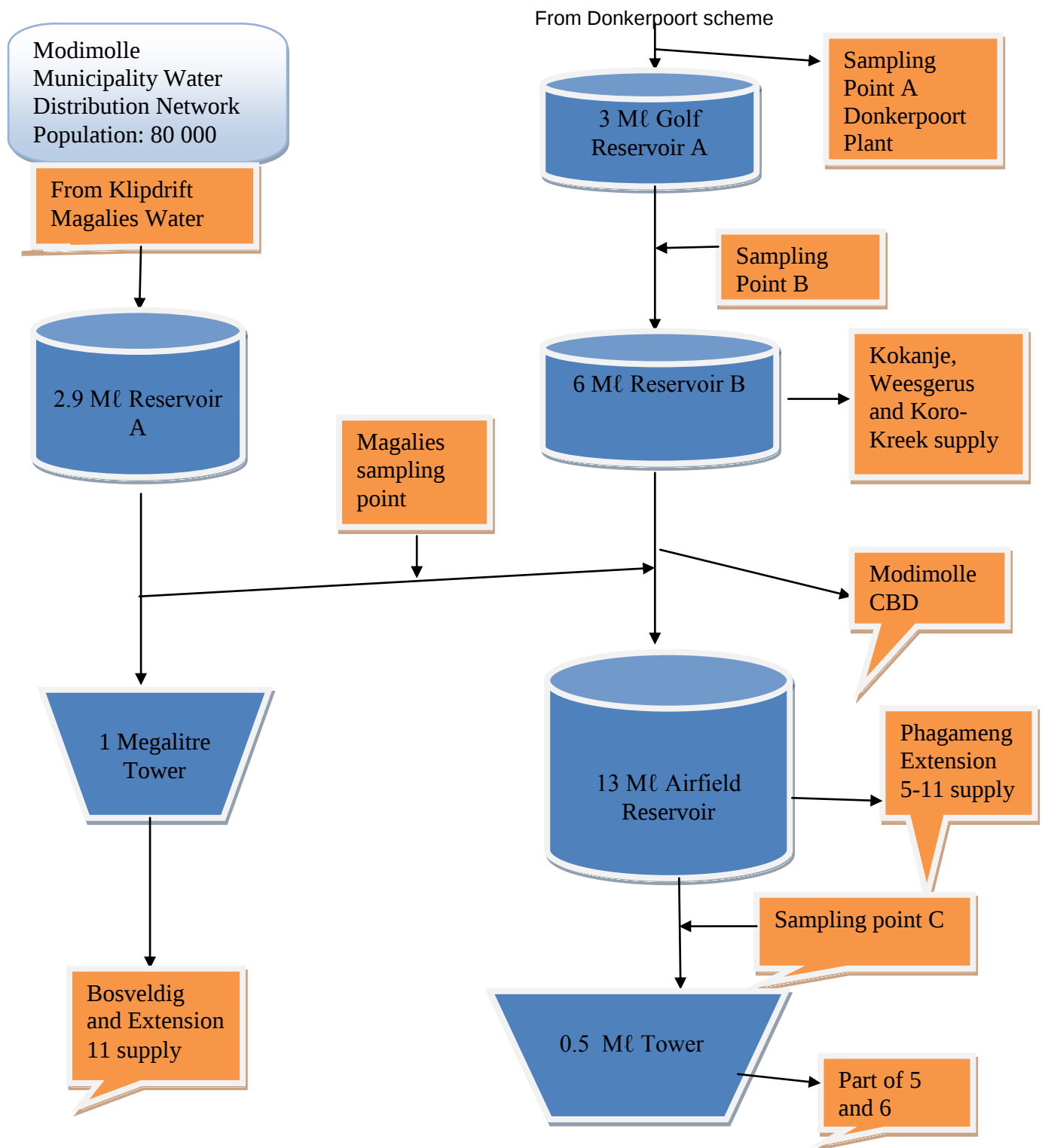


Figure 7: Modimolle Bulk Water Supply System
(Source: Modimolle Local Municipality).

These points were chosen in order to monitor a worst case scenario in terms of change of water quality from the elevated reservoir to the furthest point. Since these points were in the community area, owners of respective stands had to give permission for the withdrawal of water from their taps.

Ultimately, all the collected samples were transported to the laboratory of MW in Vaalkop. Vaalkop is the main Water Treatment Works, owned and operated by MW. It is equipped with a laboratory for testing the water quality of all MW operated plants. This laboratory is some 60 km from the furthest sampling point. Cooler boxes were used to store samples in transit and also to ensure that the quality of sampled water remained undisturbed for the duration of the trip.

Sampling bottles were marked to indicate the sampling points. This information was needed to interpret water quality at a site, especially if the water quality results obtained from the laboratory indicate a sudden change.

3.3 Data Testing

SANS 241 (2006), shows the guidelines for required limit of the different water parameters allowed in drinking water (See Appendix C). Parameters tested in this study were based on these guidelines. According to Quality of Domestic Water Supplies: Analysis Guideline (2005), there are basically four methods of manual laboratory testing for water parameters and they include:

- a)** Gravimetric methods - analysis by mass.
- b)** Volumetric methods - analysis by volume.
- c)** Colorimetric methods - analysis by colour.
- d)** Instrumentation methods - analysis by instrumentation.

The instrumentation method is a modern, sophisticated way of performing the analysis and was used in this research. Samples were tested immediately upon arrival at the Vaalkop laboratory.

3.3.1 Initial Testing

Initial sampling and testing were done for purposes of confirming the problem of water quality deterioration. The water is assumed to be 93 percent compliant by the time it reaches a point of sale. As mentioned in chapter 1, the water travels a long distance from the plant to the last bulk point, which is the Modimolle Reservoir. Water leaving the Klipdrift plant, was determined as 97 percent compliant with the SANS 241 standards, as regulated by the Department of Water Affairs. For the first few months, i.e. February, March and April of the year 2010, sampling along the bulk main was done to validate these values and to ascertain if there was any water quality deterioration along the pipeline to Modimolle.

3.3.2 Safety in Data Testing

MW is a government entity, which complies with the requirements of the Department of Water Affairs. Standard safety precautions, such as wearing of protective glasses, clothing, gloves, and shoes were observed in the laboratory. In addition, the analyst (laboratory technician) was aware of special hazards and risks associated with specific chemicals and observed the prescribed safety precautions. Furthermore, procedures for safe disposal of waste generated during the analysis, such as waste toxic chemicals were observed. Testing of samples was carried by the MW laboratory scientists throughout the entire study.

3.4 Modelling Using EPANET

EPANET is a computer program that performs extended period simulations of hydraulic and water quality behaviour within pressurised pipe networks. The software was downloaded for free from the internet. A self tutorial was undertaken for a period of two months before applying it to this research. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of chemical species throughout the network during a simulation period (comprising multiple time steps). In addition to chemical species, water age and source tracing can also be modelled.

For the purpose of this study, only water chemical simulations were performed, in particular residual chlorine. The reason for modelling residual chlorine is because most of the other parameters which were found to be within limits. The other parameters can also be easily managed. However, free chlorine shortage, especially at the consumer point, poses a great risk if no chlorine is available to combat harmful contaminants entering the system.

The Department of Water Affairs stipulates a minimum of 0.2 mg/ℓ free chlorine to be available at any given node in a system. The standard modelling duration in EPANET is 24 hours. There is no specific guideline for modelling, but the period for the modelling must be compatible with the water quality objective for each parameter being modelled. For the purpose of this study, the system was modelled for 24 hours. The modelling was done for another 48 and 72 hours to monitor the effects of time on residual chlorine. Only the 24 hours results are reported for ease of discussion.

After sampling and testing of the potable water from the Klipdrift plant to the consumer point, the system was then modelled. The parameter that was modelled was the residual chlorine. Before data could be entered into the software, pipes were schematically drawn to represent the scenario on the ground. The input data required to run the model was:

- a) Elevations at nodes
- b) Demand at nodes
- c) Initial quality (chlorine in this case)
- d) Pipe diameter, material and lengths
- e) Pipe roughness factor (Hazen Williams Coefficient)

EPANET allows one to compare results of a simulation against measured field data. Data calibration was achieved by time series plots for selected nodes in the network. Using EPANET required a lot of data, such as:

- a) Lay-out plan of the water distribution system to be modelled - pipe size, material and lengths. This lay-out plan was acquired from the Modimolle

municipality. The lay-out was very old, faded and did not have any contours on it.

- b) Demand information - This information was extracted from the MW Infrastructure Management Query System (IMQS).
- c) Contours for elevations - These were sourced from a company called Centre for Geographical Analysis.

The network was modelled first, and then the bulk line. The reason for this was to establish the required residual chlorine within the network, then assess what the Klipdrift plant, through the bulk line, was capable of doing. Because the drawing was obtained from the Modimolle municipality was badly faded, it could not be loaded onto EPANET. The water lay-out was redrawn by hand over the faded water pipelines. This lay-out was superimposed on to the contours acquired from Centre for Geographical Analysis (CGA), in order to get the elevations necessary for the modelling. An MW Geographic Information System (GIS) officer assisted with this exercise. In modelling the network, the lengths of the pipes were confirmed using Google Earth. In modelling the bulk line, IMQS was used to verify the pipe route, sizes, material and lengths. Both the networks were modelled in their current state. A new design was then modelled with figures that would yield the desired water quality at the consumer point.

3.4.1 Modelling assumptions

As discussed in sub-section 3.4, EPANET software was used to model the network as objective (c) of this study necessitated. Modelling this network required that some assumptions be made in order to rationalize the modelling exercise. The following assumptions were made:

- ❖ C-Factor for the Hazen Williams was taken as 120, as the C-factor for new pipes is given as 140 for Asbestos pipes. Appendix E shows a table with all the C-factors. Most of the pipe material was installed over 40 years ago below ground, hence, the assumption of 120 for older pipes instead of 140 for new pipes. This assumption could not be based on any scientific existence.

- ❖ For demand estimation, the Human settlement and planning design guideline (2009) was used to derive the demand, as no information was available from the Modimolle municipality. A high income residential group was assumed since extension eleven is a upper market area. For high income residential group, the guideline indicates water consumption as 1000 litres per dwelling unit per day. A number of units, fed by a particular node, were then counted and multiplied by 1000 litres to give the demand required at that node.

3.4.2 Mathematical equations

In order to calculate the major (head) losses, in metres, EPANET uses the following formula: (1) $h_L = Aq^B$ where h_L denotes head loss, A denotes coefficient, q is flow rate and B denotes flow exponent. The minor losses were calculated using (2) $h_L = K(v^2/2g)$ where K is the minor loss coefficient, v denotes velocity of flow and g is the gravitational acceleration. The calculation of chlorine decay was based mainly on pipe wall reaction. The formula (3) $R = K_b C^n$ was used for the determination of pipe wall reaction. R is the rate of reaction, K_b denotes bulk reaction rate coefficient, C is the reactant concentration and n is the reaction order. These formulas are built into the EPANET software and calculation are based on the input data. The input data on the software is huge. Typical input data is shown on Appendix G.

3.5 Sample Preservation

Sample handling, and subsequent preservation, is an important aspect of water quality testing that is often neglected. In order to ensure that the chemical characteristics of the water do not change, samples must be preserved to keep the quality of the water as stable as possible until the analysis can be done. The following preservation techniques were used:

- a) To minimise water quality changes between sampling and analysis, samples were kept as cold as possible, without being frozen. This was achieved by placing samples in a cooler box with ice cubes in it.
- b) Ice was mixed with water in order to avoid freezing of the samples, breakage of glass containers and changes in the pH level.

Preservation is normally recommended when samples cannot reach the laboratory within 24 hours of sampling. However, preservation was done to ensure that the samples maintain their original characteristics. The methodology formulated at the beginning of the study was followed as planned. Two alterations to the methodology were made. Firstly, a lay-out plan with contours (elevations) could not be sourced from the Modimolle municipality, hence they were sourced from Cape Town. Secondly, samples were taken during each month of 2010 (with the exception of only two months as mentioned previously), resulting in a total of ten samples, as opposed to the six samples that were initially planned.

CHAPTER 4: PRESENTATION AND DISCUSSION OF RESULTS

4.1 Introduction

As mentioned in chapter 3, the overall objective of this research was to investigate and model water quality characteristics within Modimolle network. The parameters used in modelling the system were physical (turbidity; colour; pH and conductivity), chemical (residual chlorine; iron; manganese; alkalinity; hardness; magnesium) and microbiological organisms (E-coli; heterotrophic plate count; total coli-forms). According to South African Water Quality Guidelines (1996), domestic water users can experience a range of impacts as a result of changes in the quality of potable water. These impacts can range from health hazards to economic impacts.

4.2 Raw Water Quality Results

Table 3 shows monthly data of monitored parameters from the raw water source. The results are for the period from January to December 2010. Only the quality of the main raw water source (Leeukral dam) was measured. Even though the Roodeplaat dam, which is situated in the Wallmannsthal region in Gauteng, occasionally supplies water to the plant, it serves only as a back-up when the main source requires maintenance or is too low.

The raw water turbidity values ranged from 2 NTU to 81 NTU (see Table 3). These results show that the plant will have to operate efficiently for it to be able to reduce these turbidity values to below 1 NTU. The colour of the raw water is constantly above the SANS limit of 20 mg/ℓ. Although colour will have to be removed from the water, it does not pose any health risk to human consumption, but makes the water aesthetically unpleasant, depending on the chemical responsible. None of the pH levels were greater than 9.5 units. In terms of SANS 241 (2006), pH level of potable or drinking water may range from 5.0 to 9.5, hence the reason for not doing pH correction at Klipdrift plant. pH levels were, however, monitored throughout the distribution system to detect if any changes occurred, whereby adjustments could be made accordingly, as pH influences taste, corrosivity and solubility of water.

Table 3: Raw water quality test results - Year 2010

Raw Water Quality												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Turbidity (NTU)	9	13	11	81	51	33	7	3	2	7	10	68
Colour (mg/ℓ)	46	42	47	74	74	40	30	29	28	42	38	147
pH (pH units)	8.99	8.12	8.22	8.24	7.94	8.19	7.81	8.21	8.26	8.3	8.29	8.36
Conductivity (mS/m)	45.8	48.7	47.7	46.2	44.7	46.8	48.7	54.6	56.9	59.7	65.1	73.1
Iron (µg/ℓ)	0.097	0.039	0.054	0.281	0.099	0.073	2.774	1.599	0.147	0.045	0.065	0.202
Manganese (µg/ℓ)	0.01	0.012	0.01	0.015	0.016	0.01	0.172	0.054	0.038	0.013	0.01	0.011
Alkalinity (mg/l CaCO ₃)	159	157.1	153.1	144.2	144.1	170.2	154.9	216.7	203.8	199.1	180.6	145
Hardness (mg/l CaCO ₃)	157.9	111.4	140.8	125.6	145.9	164.8	199	236.7	360.7	194.5	198.5	135.5
Magnesium (mg/ℓ)	19.5	15	17.7	15	17.9	21.1	25.3	28.6	37.6	37.6	29.3	18
E-coli (per 100 ml)	461	248	328	1046	231	210	131	517	258	249	1414	2419
Coli-forms (per 100 ml)	2419	2419	2419	2419	2419	1553	921	2419	2419	2419	2419	2419

According to SANS 241 (2006), conductivity values for class I water should not exceed 150 mS/m. All the values of the raw water were less than 150 mS/m for the sampling period. The results show that conductivity has no significant threat, but was monitored throughout the study as the quality of raw water changes continuously.

Iron and manganese should not exceed 0.2 and 0.1 mg/ℓ respectively for class I water. Although there is no scientific proof to substantiate this, the iron content increased during the dry period, i.e. April, July and August, whereby iron content rose above 0.2 mg/ℓ. Manganese values were constantly below 0.1 mg/ℓ, with the exception of July. According to South African Water Quality Guidelines (1996), manganese has no significant aesthetical or health impacts; therefore no real threat can be expected from high levels of manganese.

The measurement of alkalinity and pH determines the corrosiveness of water. For class I water, alkalinity and hardness should not exceed 250 mg/ℓ. Values observed were constantly far below these values, with an exception of September. MW has since come to the conclusion that alkalinity and hardness will not pose any threat to

potable water, and has subsequently discontinued the monitoring of these parameters in its potable water. They are, however still monitored in raw water so that any drastic change can indicate that clean water needs to be checked for any variations. Magnesium concentrations need not exceed 70 mg/ℓ in drinking water. Magnesium raw water concentrations have remained very low over the past years. Similarly, magnesium content is not monitored for the same reason.

Higher concentrations of faecal coli-forms (E-coli as indicator organism) in water indicate a higher risk of contracting waterborne disease, even if small amounts of water are consumed. Total coli-forms suggest inadequate treatment, post-treatment contamination and/or after-growth. The total coli-forms group includes bacteria of faecal origin and indicates the possible presence of bacterial pathogens, especially when detected in conjunction with other faecal. According to SANS 241 (2006), the tolerance on these indicator organisms is zero for class I water. Proper and thorough disinfection will have to be carried out at the plant to remove these, since large quantities were found to exist in the raw water (see Table 3). Graphic depiction of the results in Table 3 are shown in Figures 8 to 18 for a better understanding of the fluctuation of the raw water parameters throughout the season.

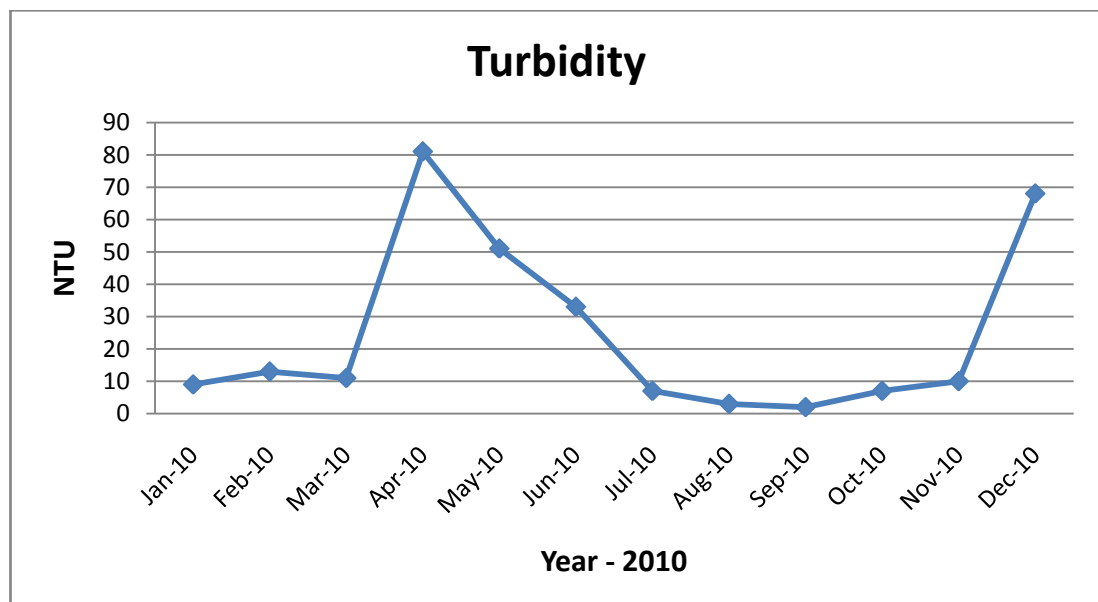


Figure 8: Turbidity fluctuation in the raw water

Figure 8 shows that turbidity is on the decline during dry months (April to September) of the season and rises during the wet season (October to March). One particular reason for the rise in turbidity during the rainy season is the erosion of soil by storm water resulting from a rainstorm. Clean water must have a maximum turbidity of 1 NTU for the water to be fit for life-time consumption (class I water). Turbidity between 1 and 5 NTU is stipulated for class II water, meaning that this water may be consumed for a limited time period. Therefore, the plant operations cost may be higher in the wet months due to an added cost of more flocculants. Maintenance costs may also be higher, as the plant will be operated at a higher rate than when the turbidity is lower.

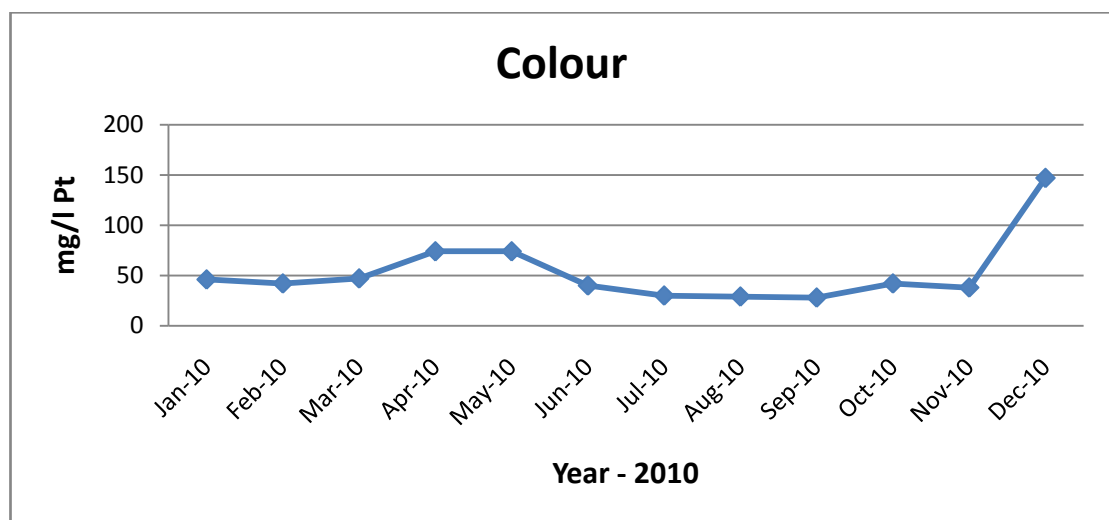


Figure 9: Colour fluctuation in the raw water

In potable water, colour can be of natural origin or it may be as an industrial result of effluents containing soluble coloured materials. Most natural causes of colour are associated with the presence of dissolved organic matter. Hence, the requirement to remove colour in potable water. Figure 9 shows the variation of colour in raw water throughout the season. The graph shows that colour remains fairly constant between a maximum of 80 mg/l and minimum of 20 mg/l for the major part of the year. However, between November and December, it shows an increase. It is not clear what caused the spike in colour, but it is interesting to observe that the spike in colour happened exactly at the same time when there was a spike in turbidity (compare Figure 8).

The potential toxicity of metal ions and chemicals, which can be protonated (example ammonia), is influenced by pH. Changes in pH level affect the degree of dissociation of weak acids and bases. This effect is of special importance as the toxicity of many compounds is affected by their degree of dissociation. Corrosion in the water supply system is a major source of metal contamination in drinking water. Metals that have the potential for causing such contamination are lead, copper and zinc.

Lead is subject to corrosion at a pH level higher than 12. Corrosion of cadmium is only significant at levels below 6. Other metals which are frequently used in household plumbing, and that may be affected by pH, are copper and zinc. The selection of raw water as a drinking water source is never based solely on pH levels. The taste of potable water and its corrosivity are some of the factors influenced by pH. The quality of the raw water source remains consistent, i.e. pH levels are above the value of seven throughout the year as illustrated in Figure 10. In the rainy season (September to February), the pH level is more stable. Dry months (March to August)

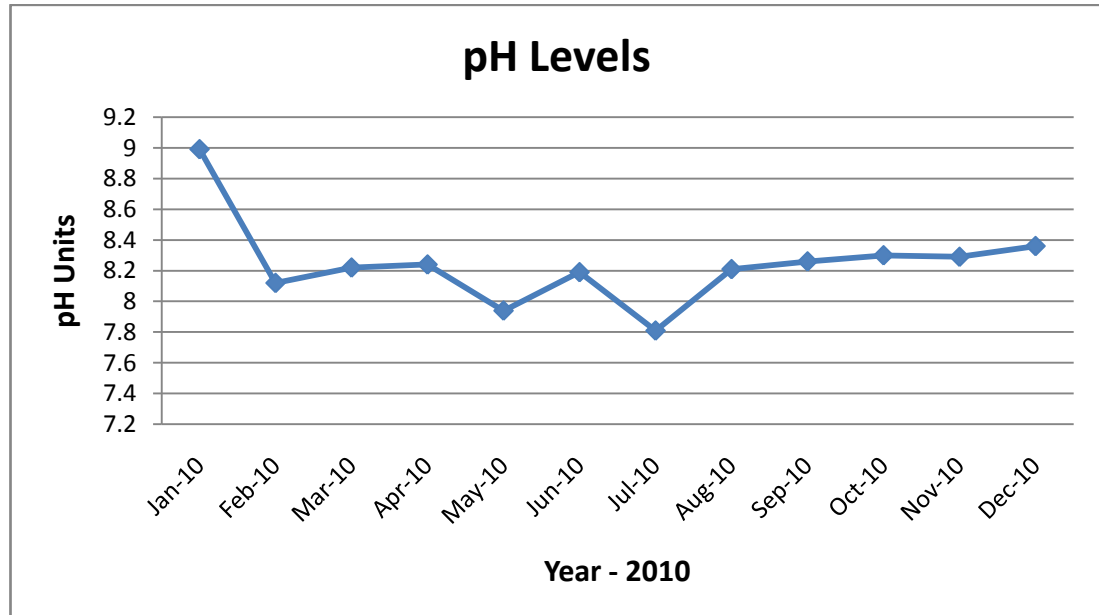


Figure 10: pH level fluctuation in the raw water

have more fluctuation with pH declining from about 9 units in January to about 7.7 units in July. This implies that minimal pH correction is required in this water, since potable water can have pH levels from 6 to 8.5 for class I water.

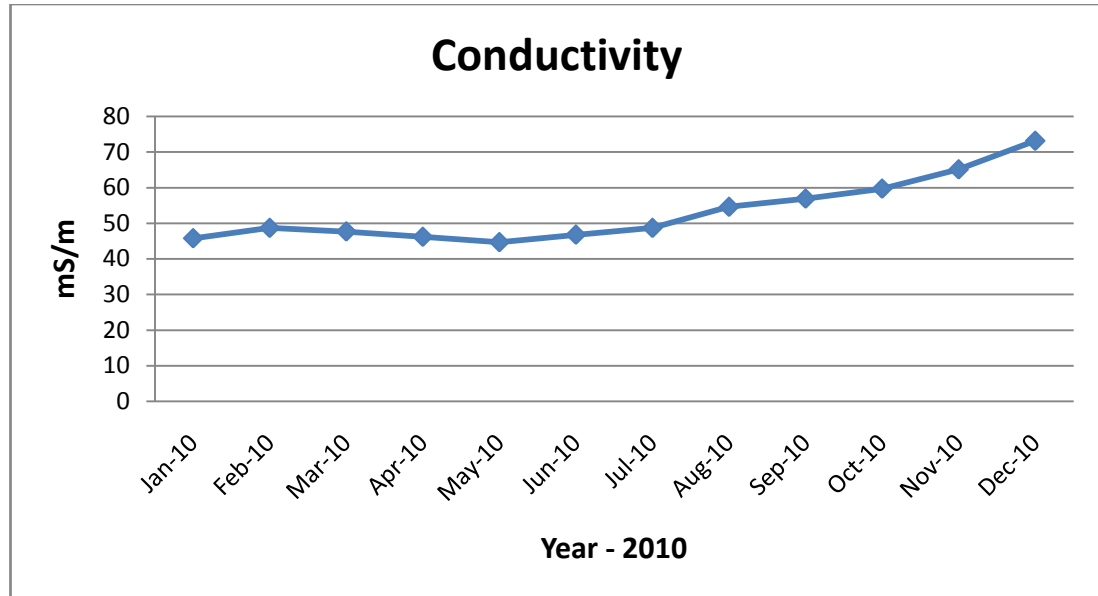


Figure 11: Fluctuation of raw water conductivity

Conductivity is given by the direct proportion of the TDS, in other words, the more the dissolved solids, the higher the value of conductivity. According to Stream Team (2004), addition of fresh water (rain) lowers conductivity, as rainwater has a low conductivity and eventually dilutes mineral concentrations. Conductivity is affected by temperature (the warmer the water, the higher the conductivity and vice versa). Soil and rocks release dissolved solids into the waters that flow through or over them. Therefore, the geology of a certain area determines conductivity. In this instance, it is possible that conductivity rises due to an increase of temperature from August onward, which is the beginning of the summer months. Conductivity rises shows a rising pattern from January to December, as shown in Figure 11. It is unclear if this rise continues in the next season, or what the trend was in the previous season. The rise gets much steeper in the rainy season as opposed to a more flat slope in the dry season. Conductivity is, in this instance, not a threat, as it remains within the limits of class I for treated water.

Biologically, iron is an important micronutrient required by all living organisms. However, in high concentrations, iron becomes an aesthetic concern since ferrous salts are unstable under pH conditions prevailing in drinking water and precipitates as insoluble ferric hydroxide, which settles out as a rust-coloured silt. Excessive ingestion of iron may result in tissue damages as a consequence of iron accumulation. Excessive iron carried from raw water into treated water will have effects which are mostly aesthetic, such as staining of surfaces of baths, hand basins and lavatory cisterns.

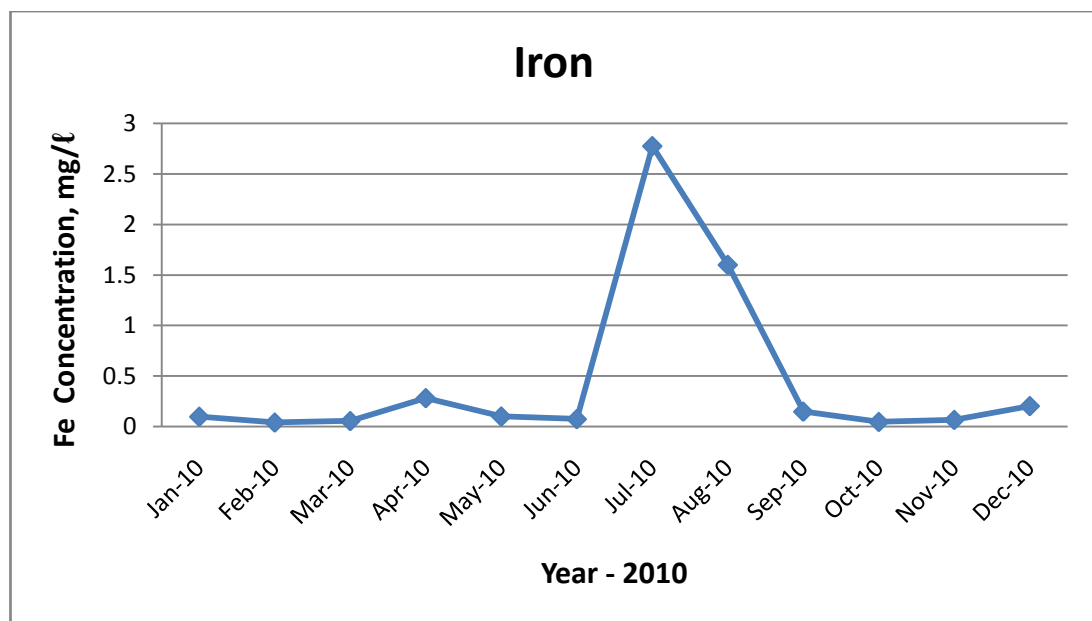


Figure 12: Iron fluctuation in raw water

Iron causes discolouration of water supplies when present at low concentrations. Iron that settles out in distribution systems gradually reduces the flow rate of water. The only associated health effects are those that could arise from the presence of microbial deposits on internal surfaces of plumbing.

Figure 12 shows that iron is not really a concern, as it is very low in the raw water throughout the season. Iron levels are generally close to zero. It is interesting to note that a spike in iron content exists between the months of June and August, which are winter months. Though the spike could not be attributed to any event at the time but

Iron and manganese are some of the most abundant naturally occurring elements found within the underlying soil. The sources in groundwater originate from weathering of iron bearing minerals and rocks, with some contributions from manmade influences and sources including industrial effluents, acid-mine drainage, sanitary wastewaters. Since South Africa has a huge problem with the acid-mine drainage, it would therefore make sense to attribute the iron (and Manganese) spikes to such. According to SANS 241 (2006), for class I water, iron has to be lower than 0.2 mg/ℓ.

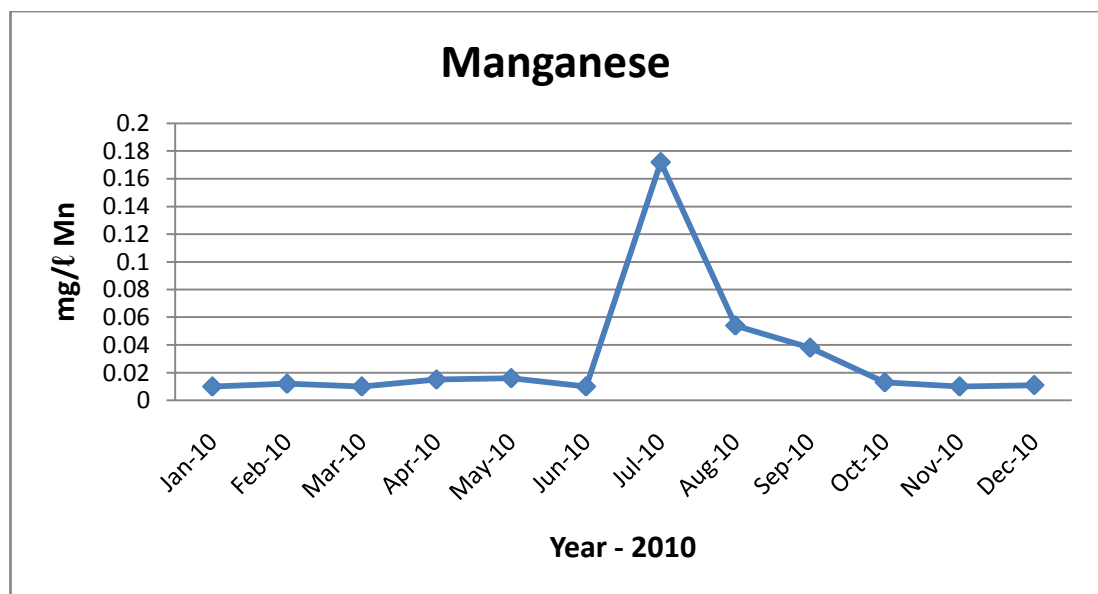


Figure 13: Fluctuation in manganese content in raw water

The graph shows that the manganese content is very low in the raw water throughout the season. Similar to the iron content, the levels are generally close to zero. Manganese levels spiked at almost the same time, and for the same duration, as that of the iron content. This suggests a close relationship between iron and manganese. Manganese is, however, not a threat, as it remains within the limits (0.1 mg/ℓ) of class I water for drinking purposes.

The maximum allowable content of alkalinity content in class I potable water is 250 mg/ℓ. As can be seen in Figure 14, observed raw water content of alkalinity is mostly below 175 mg/ℓ, which is half of the maximum allowable content. It is for this

reason that alkalinity is deemed to pose no threat in the water due to its low concentrations.

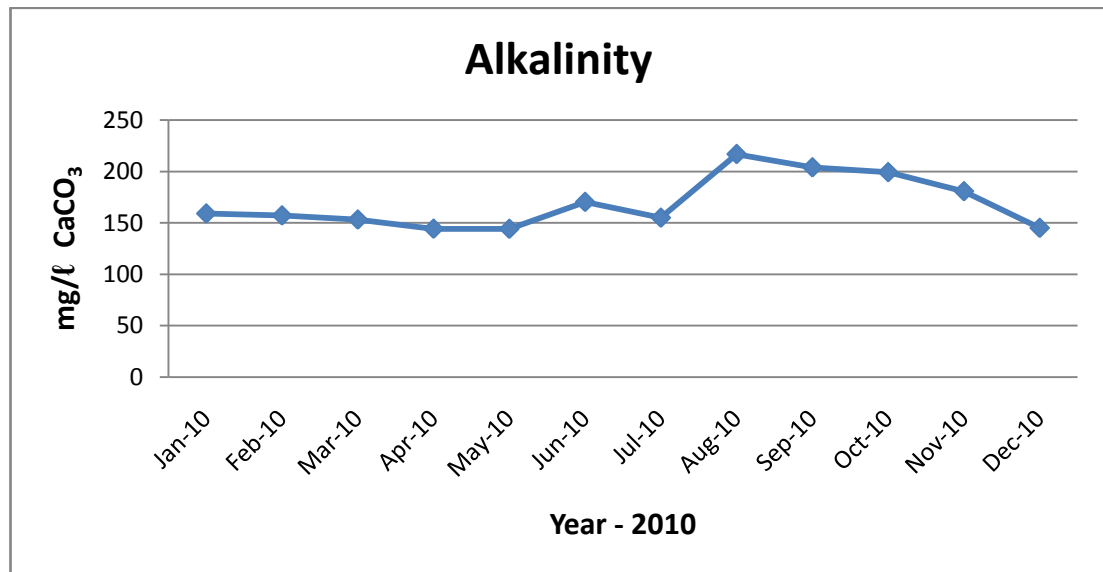


Figure 14: Fluctuation in alkalinity of the raw water

Figure 15 shows that the hardness of the raw water rises in the dry months (March to August) of the season and decreases over the rainy season (September to February). The reason for the decrease may be that the raw water source is diluted with storm water occurring from a rainstorm. Hardness remains below 250 mg/l for the better part of the season.

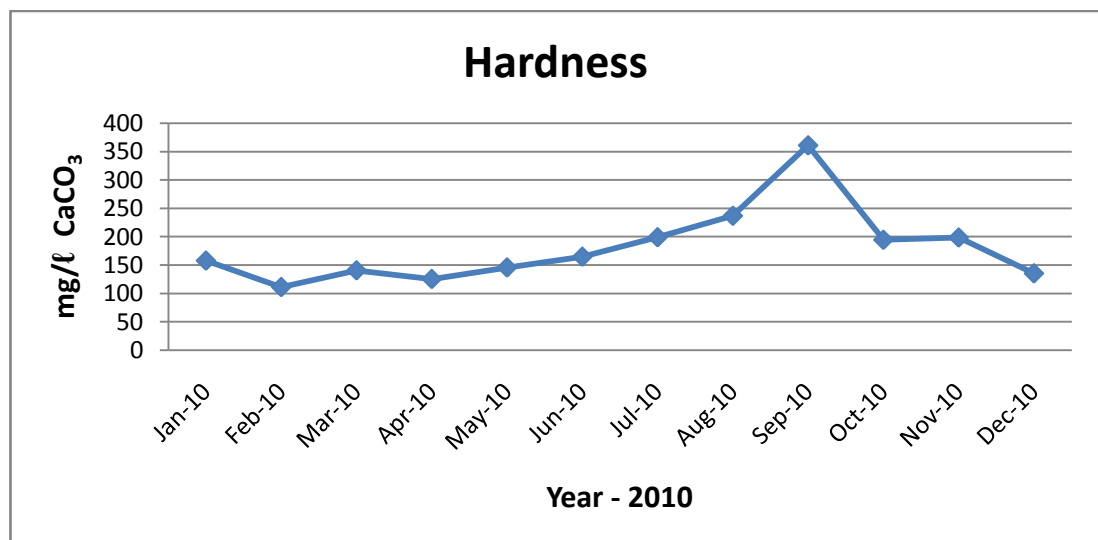


Figure 15: Fluctuation of hardness in raw water

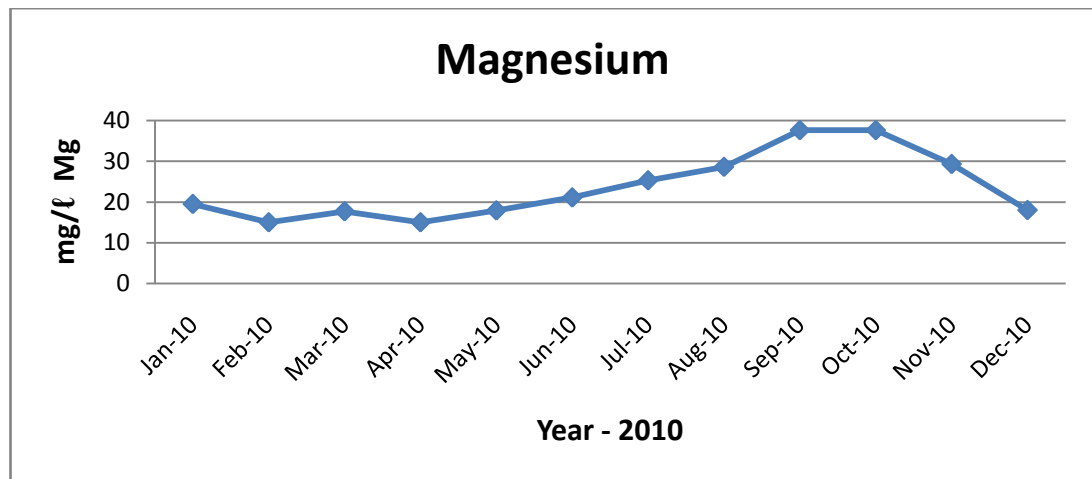


Figure 16: Magnesium fluctuation in the raw water

The Magnesium trend is similar to that of hardness, as illustrated by Figure 16. Again, in the dry season, Magnesium is on the rise and declines in the rainy season (September to February). For class I water, maximum Magnesium levels of 70 mg/l can be tolerated. In this case, the levels of Magnesium hardly reaches 40 mg/l in the raw water, hence, Magnesium requires no attention.

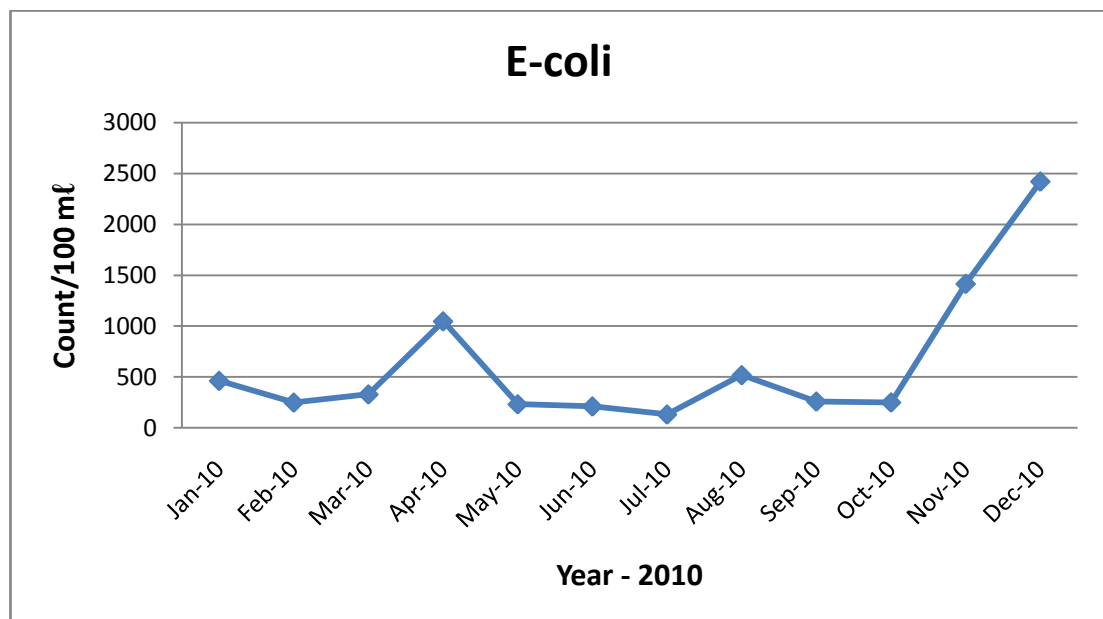


Figure 17: Fluctuation in E-coli levels in the raw water source

Figure 17 shows the levels of E-coli in raw water. During the dry season (March to August), it is fairly low and spikes in the rainy season (September to February). The main reason for this spike could be that, whenever sewer blockages occur, sewage flows through storm water drains into a fresh water source. E-coli content is unwanted in clean water for class 1 water and very little tolerance (1 count/100 mL) is allowed for class II water. This implies that a fresh water source is often polluted by faecal matter which requires the plant to operate adequately to remove these unwanted substances.

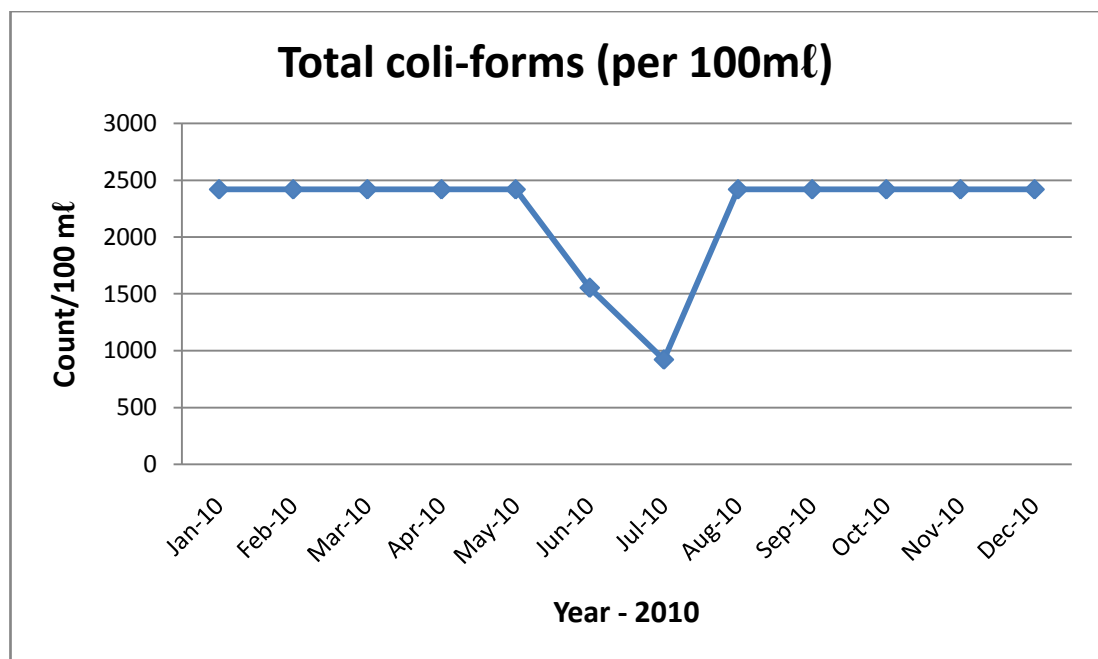


Figure 18: Fluctuation in total coli-forms content of the raw water

The total coli-forms of sampled raw water remain fairly high and constant for the better part of the year (at approximately 2500 count per 100 mL, see Figure 18). It dropped sharply between the months of May and August and stabilized again afterwards. Total coli-forms exceeding 10 counts per 100 mL in clean water would call for alert action, as coli-forms need to be treated and removed from clean water. There is no clear reasons as to why there was a decrease in total coli-forms content, but noteworthy is the fact that the drop occurred during the dry season. This

suggests the possibility of less contaminated storm water being received by the raw water body.

4.3 Potable Water Quality Tests Results

In addressing the first objective of the study, sampling was done at the plant and labelled sampling point number 1. The sampling points were numbered 1 to 6, from the plant to the furthest point in the monitored section of the Modimolle network. The numbers 1 to 6 represent the Klipdrift plant, the Sondela off-take, the Bela-Bela off-take, Modimolle Reservoir, 21 Olienhoud Street in extension 11 and 106 Kerk Street in extension 11 respectively. Sondela off-take and the Bela-Bela off-take were sampling points installed for the purpose of this research. The results of February 2010 were not complete, and this is the reason why they were not included in the analyses. They were merely used as a preliminary set of results to investigate the problem of water deterioration in the bulk line up to the consumer point.

The results of the modelled network are discussed in this section, while the detailed results are attached in Appendix F. The results are of samples taken from the plant, along the bulk line and into the Modimolle network. The Modimolle network is supplied by water from the Klipdrift plant, as well as from other sources, such as boreholes and their own (Modimolle's) three Mega-litre plant. According to the water supply lay-out (as built information), the section from which the network was monitored for the purposes of this study (extension 11) is supplied directly by water from the Klipdrift plant, and not by any other source. This fact was verified on site. According to SANS 241 (2006), drinking water has to be of a certain standard to be classified as class I or class II. This standard specifies the quality of acceptable drinking water, defined in terms of microbiological, physical, and chemical parameters at the point of delivery.

In terms of SANS 241 (2006), class I water should have a turbidity value of less than 1 NTU. Figure 19 illustrates the variation in turbidity over a period of ten months. Representative data obtained from the MW laboratory are shown in Appendix D. At the Klipdrift plant (sampling point 1), it is expected that the turbidity will be zero.

The fact that water leaving the plant already shows some turbidity readings confirm that the plant is not operating efficiently in reducing turbidity to set limits as shown in Appendix C.

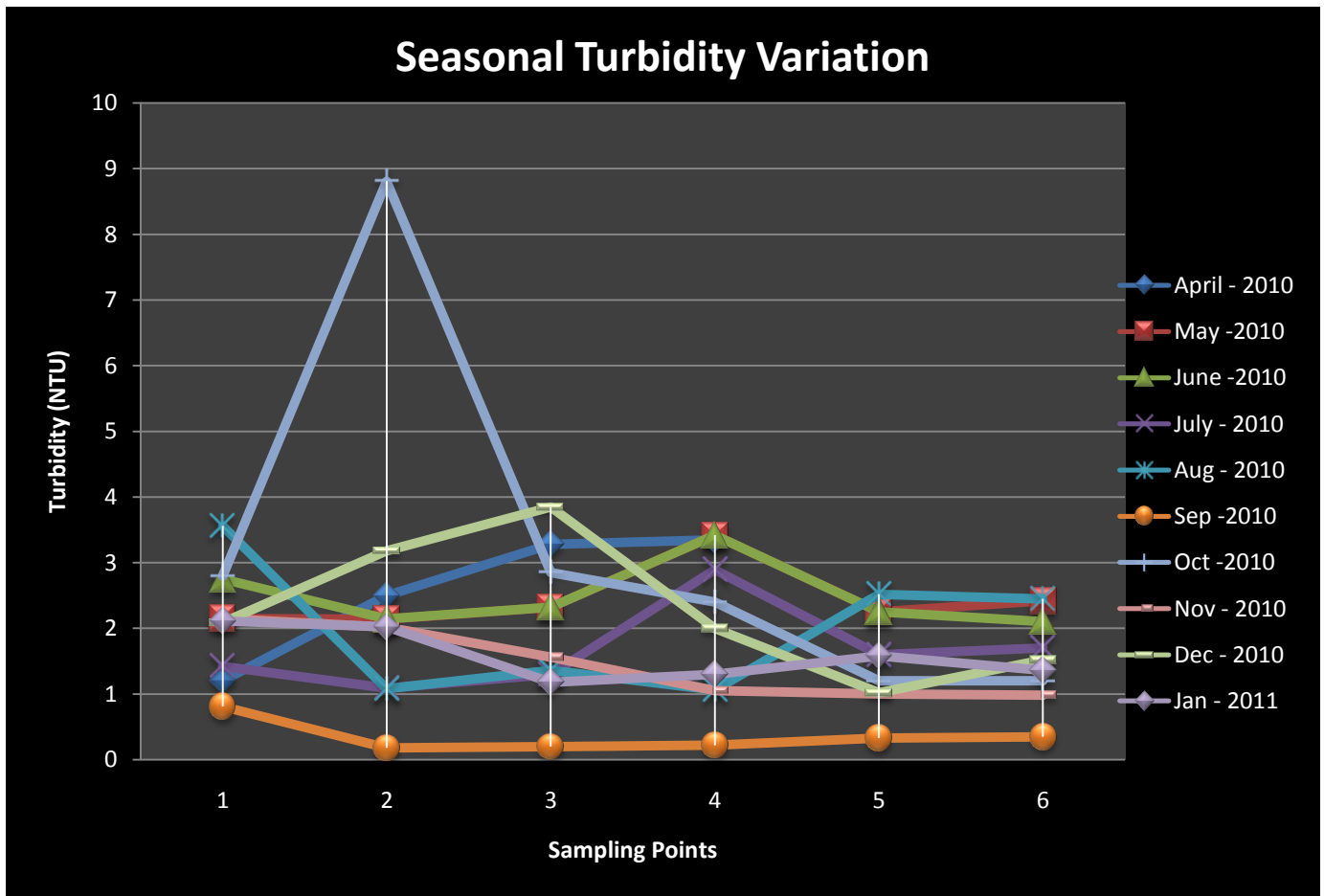


Figure 19: Variation of turbidity

At the Modimolle Reservoir (sampling point 6), turbidity was recorded to be low in September (a value of 0.35). During the September month, the plant managed to produce water of lowest turbidity (below 1 NTU), this seems to be the reason for lowest turbidity values in the network. For the rest of the studies duration, turbidity levels were well above 1 NTU. This means that water is consumed as class II water for most of the year. It is uncertain for how long this has been the case due to a lack of data. According to SANS 241 (2006), class II water can be consumed for only a limited period of time. This period depends on the parameters concerned, for example, total chromium may be consumed for a maximum of three months, whereas

total trihalomethanes may be consumed for a period of up to ten years. SANS 241 (2006), class II specifies water quality range that poses an increasing risk to consumers dependant on the concentration of the determinant within the specified range.

From the results depicted in Figure 19, it is clear that there is a deterioration of water quality throughout the system. There are clear rises on the graph, particularly points 2 to 3; 3 to 4 and 4 to 5. These spikes clearly indicate that water is contaminated between those sections. The contamination could be a result of sub-surface water ingress into the potable water line, given the age (more than 40 years) of the pipeline. Between points 5 and 6, turbidity is ranging between 1 and 3 NTU at the consumption point. This clearly indicates that consumers are exposed to the danger of consuming polluted water. It further indicates that a problem exists within the water distribution system that supplies the Modimolle community.

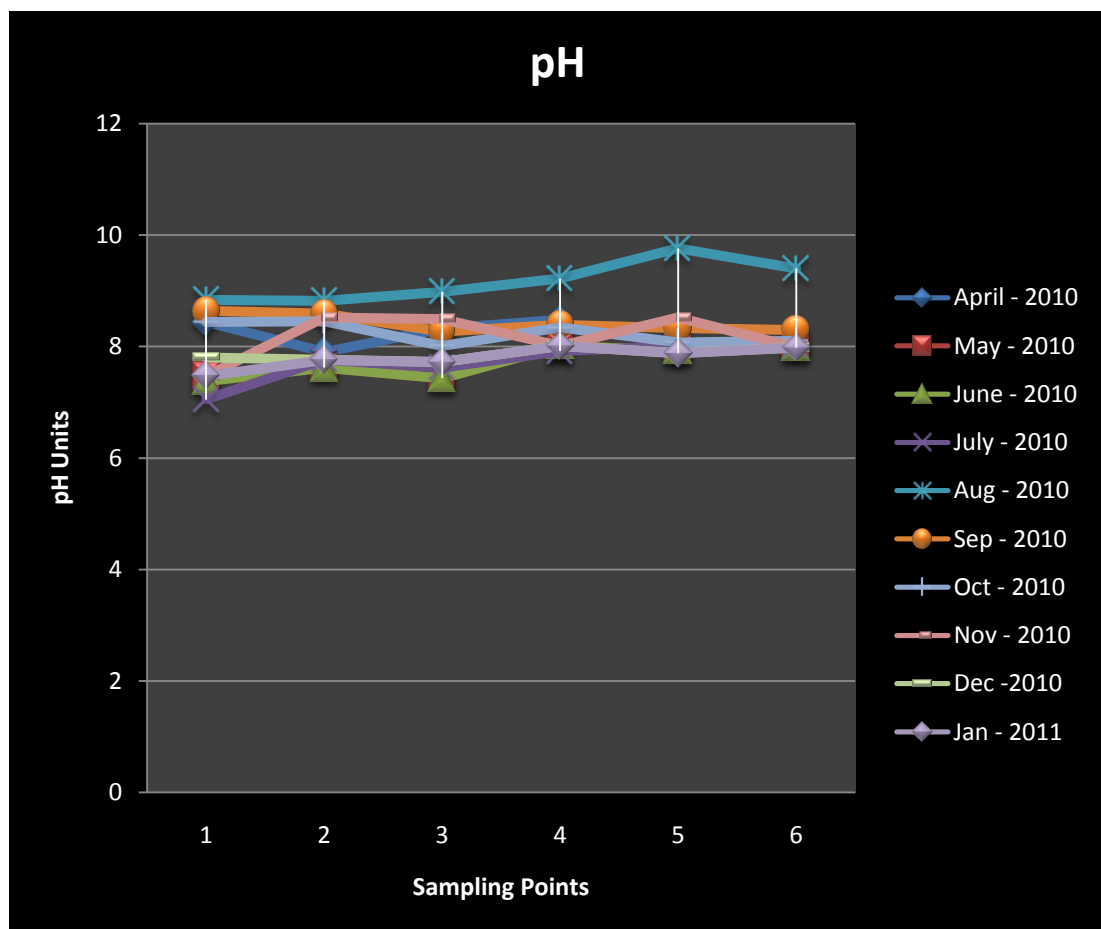


Figure 20: Variation of pH

Figure 20 shows pH variations for the year 2010. In August, pH levels rose to more than 9 units between points 4 and 6. This rise occurred beyond the reservoir in Modimolle. According to American Ground Water Trust (2003), ground water passing through carbonate-rich rocks (e.g. limestone and marbles) usually has pH levels values far greater than 7, as the acidic water is “neutralized.” Ground water might have entered the system either due to a leaking joint, or after a burst pipe was repaired, with the possibility of the line not being rinsed properly. However, this spike does not indicate a health hazard, as there are no proven incidents of poor health resulting from consumption of water with high pH levels. Taste of water, its corrosivity and solubility are all influenced by pH levels, therefore, the increase in pH levels will be aesthetically displeasing.

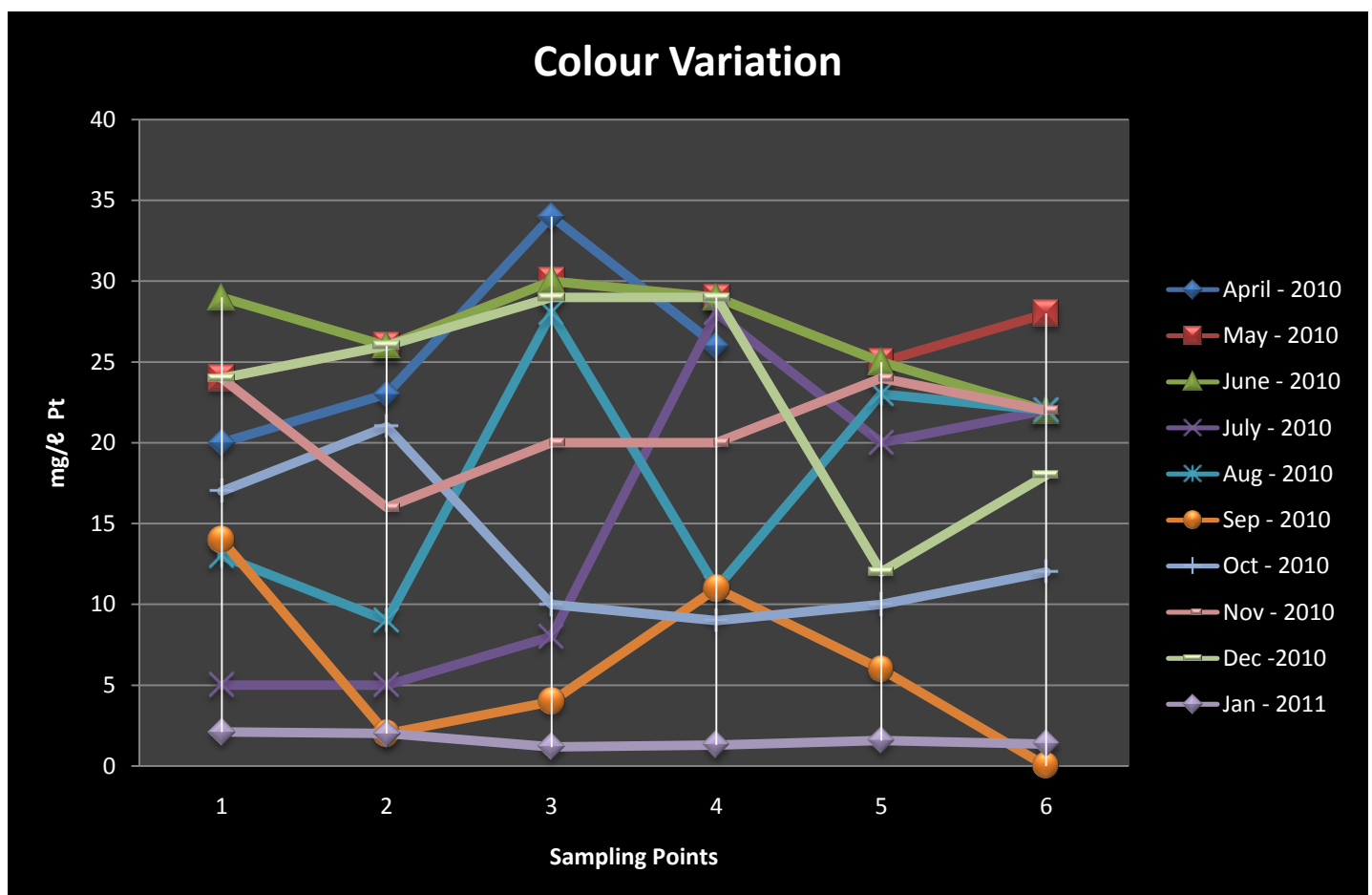


Figure 21: Colour variation

Although the presence of colour in water does not necessarily indicate that the water is not potable, the observed amount of colour in the clean water was high throughout the system, this implies that water is aesthetically unpleasing. (see Figure 21). Some of the major contributors of colour in raw water is the dye, due to human activity, as well as algae present in the fresh water source. It was mentioned that the plant is currently over stressed, therefore it is unable to operate efficiently. It is possible that the plant is not coping with colour removal since the process train is inadequate, i.e. lack of proper flocculation/coagulation process.

Figure 22 shows conductivity variation in the system. Conductivity remains low in the water, largely below 60 mS/m. Problems associated with conductivity (health risks), affect pipe material and taste, especially when conductivity starts to shoot above 70 mS/m. High levels of TDS, in terms of conductivity, are unwanted in water. Very low levels of TDS values are also a cause for concern. Appropriate steps to either increase or decrease these levels should be taken. Therefore, conductivity is perceived as a not as a threat at this stage. Conductivity was, however, monitored in the raw water. Any significant change, being either a sharp decline or increase, would have to be noted with appropriate steps being taken to balance it.

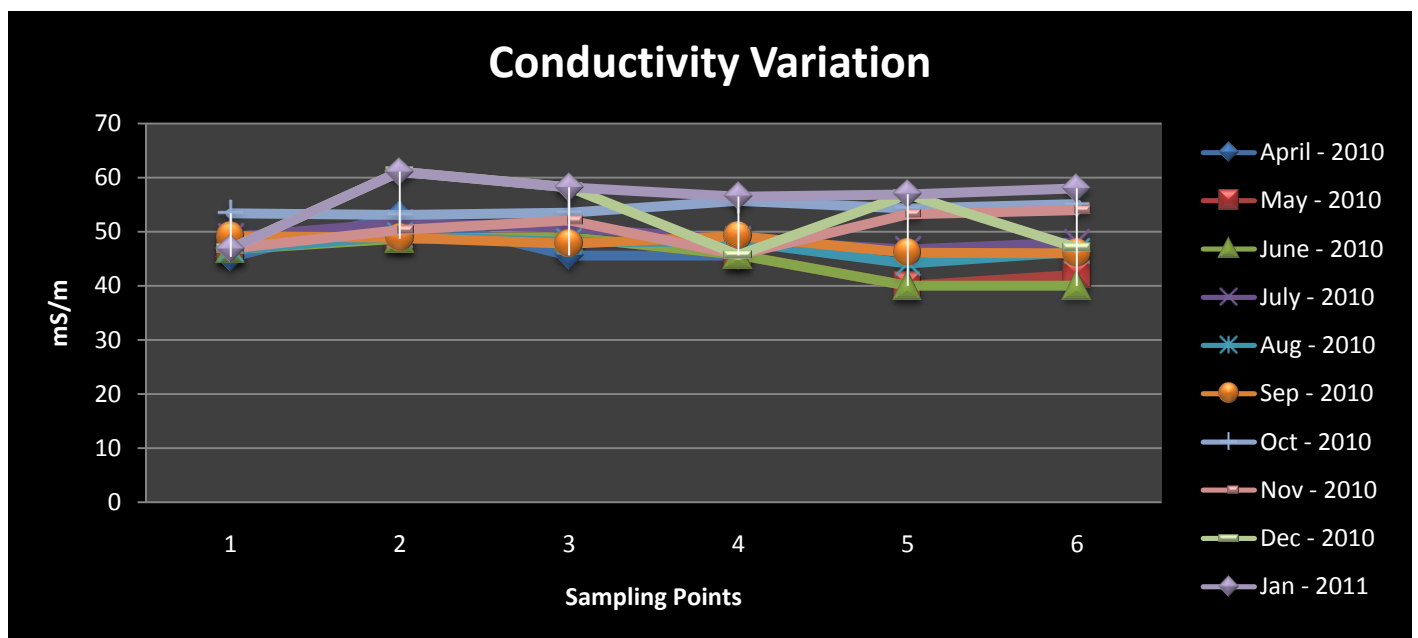


Figure 22: Conductivity variation

The main purpose of residual chlorine is to kill the harmful pathogens that enter the system. It is essentially disinfection of water that safeguards potable water from any harmful pathogens. When water is disinfected at the plant, there has to be an additional amount of chlorine added that goes with the water to the consumer point. This residual chlorine, if in right concentration, will attack any harmful pathogens it comes into contact with. If however, there is little or no residual chlorine in the system, contamination in the system cannot be fought off and this will lead to consumption of contaminated water. If this happens, fatality could result.

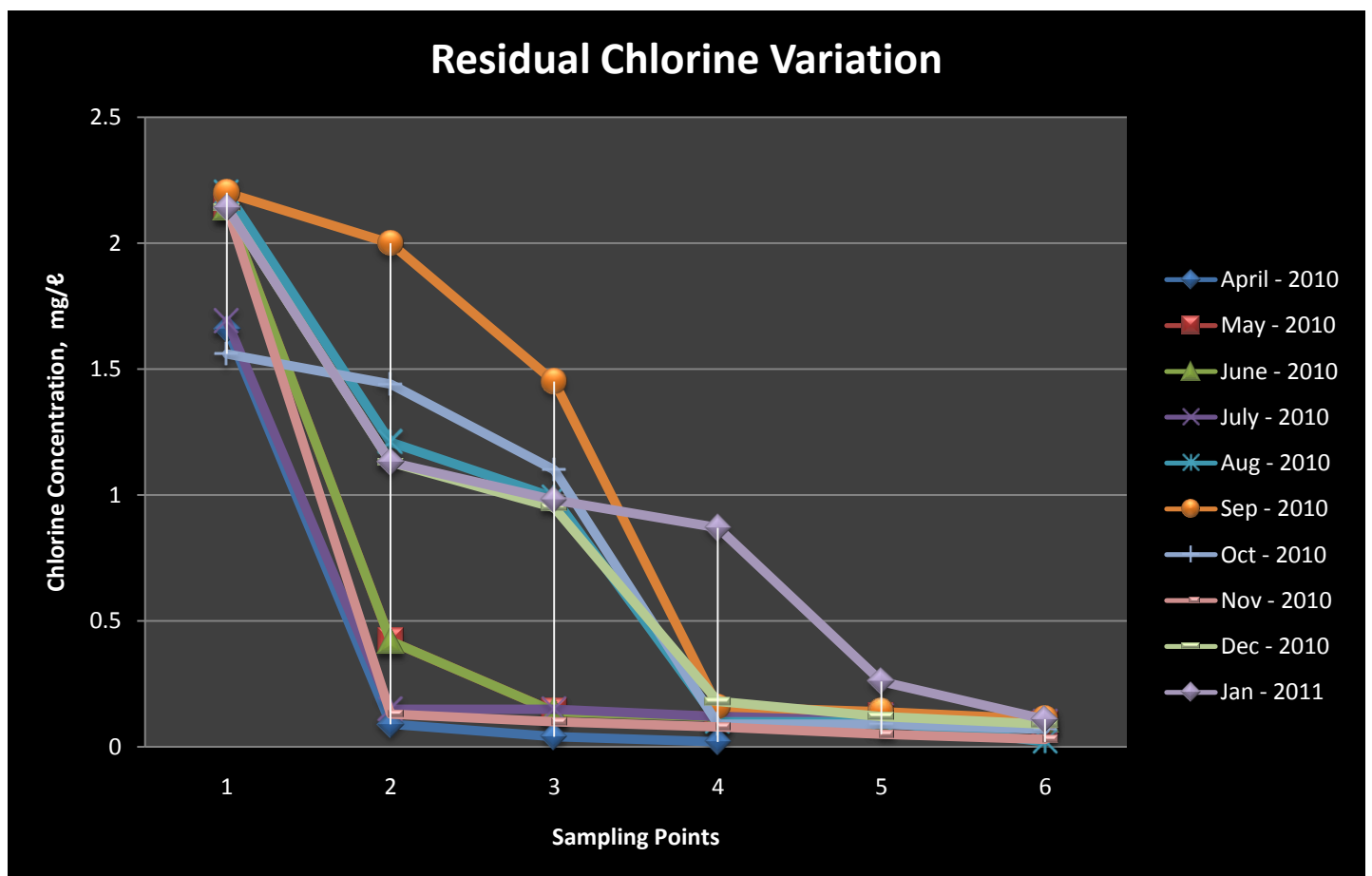


Figure 23: Residual chlorine variation

As shown in Figure 23, the plant generally produces water with a residual chlorine value of between 2 and 2.5 mg/l. It is assumed that when water reaches the consumer, a minimum of 0.2 mg/l of residual chlorine will be left at any node in the system. Between points 4 and 6, residual chlorine drops to below 0.2 mg/l. This is

an indication that residual chlorine is completely exhausted along the system. It signifies danger in that consumers may be consuming contaminated water. Should any contamination occur within this distribution system, people might consume this contaminated water and get sick or even die.

Interesting to note, is the fact that, most of the dry season months (April, May and June and July), have the most chlorine decay, as indicated by the steep decline on the graph. The reason for this could be that, during the dry season, ground water is not recharged by infiltrating run-off, there by diluting ground water, as there is no rain. The inverse, lesser chlorine decay during wet season, is also observed for the same reason.

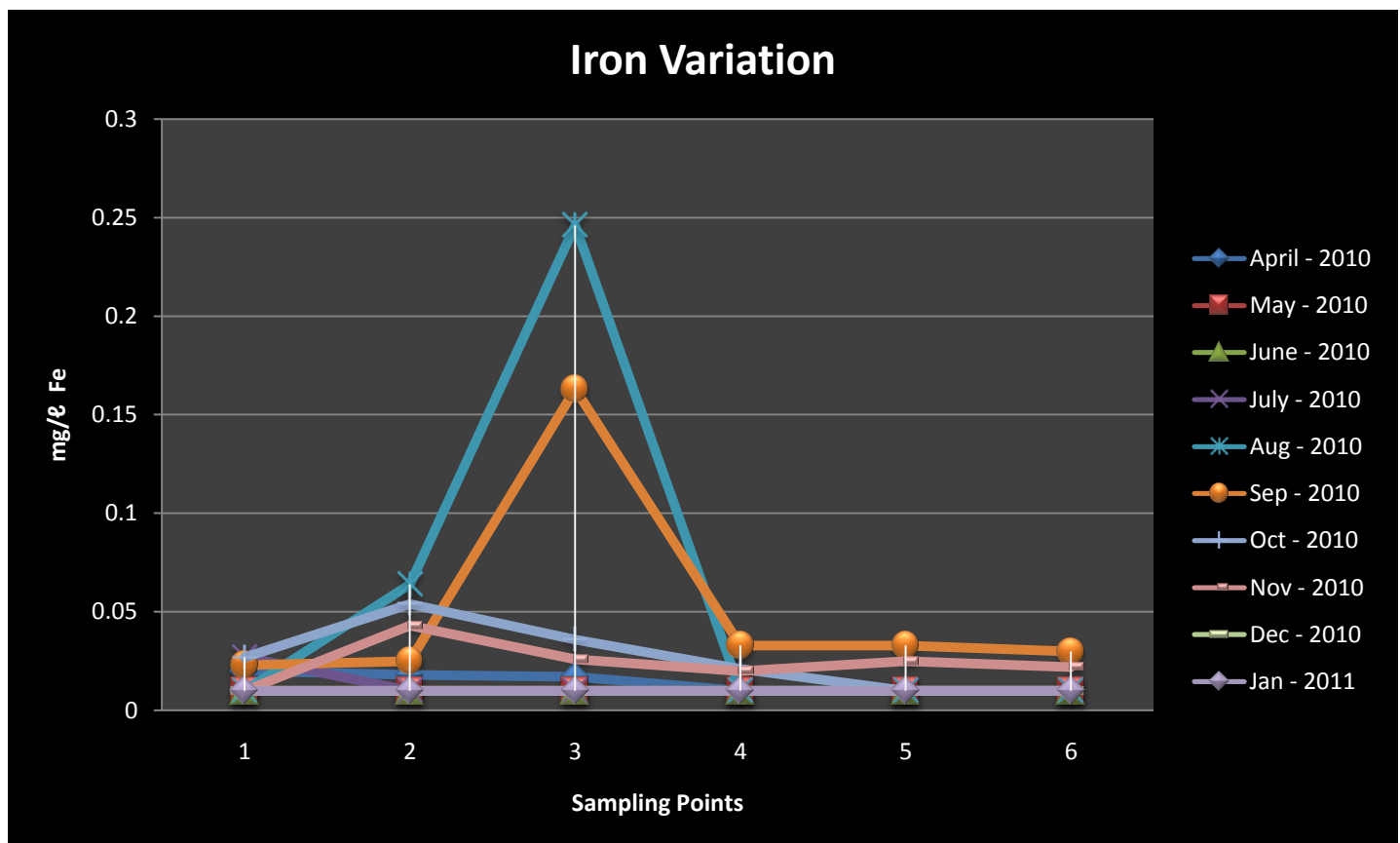


Figure 24: Iron variation

Figure 24 shows the levels of iron throughout the season. Iron content must remain below 0.2 mg/l for purified class I water. The results indicate that the iron content is

satisfactory, except between points 2 and 4 (August and September). Iron content generally remains below the stipulated maximum throughout the season, thus it does not pose any threat to the system. This means that even where iron content increased, it was not significant. Therefore, iron content does not seem to render water unsafe for consumption, nor does it have any aesthetic impacts. However it will have to be monitored closely, especially in the months where rises occurred. According to South African Water Quality Guidelines (1996), excessive concentrations of iron may result in haemochromatosis, wherein tissue damage may occur as a consequence of iron accumulation.

There are visible spikes of iron on the graph, these may be attributable to the fact that rainfall run-off seeping through soil can cause iron to dissolve and leach into groundwater, it is therefore probable that ground water may have entered the pipeline between these points.

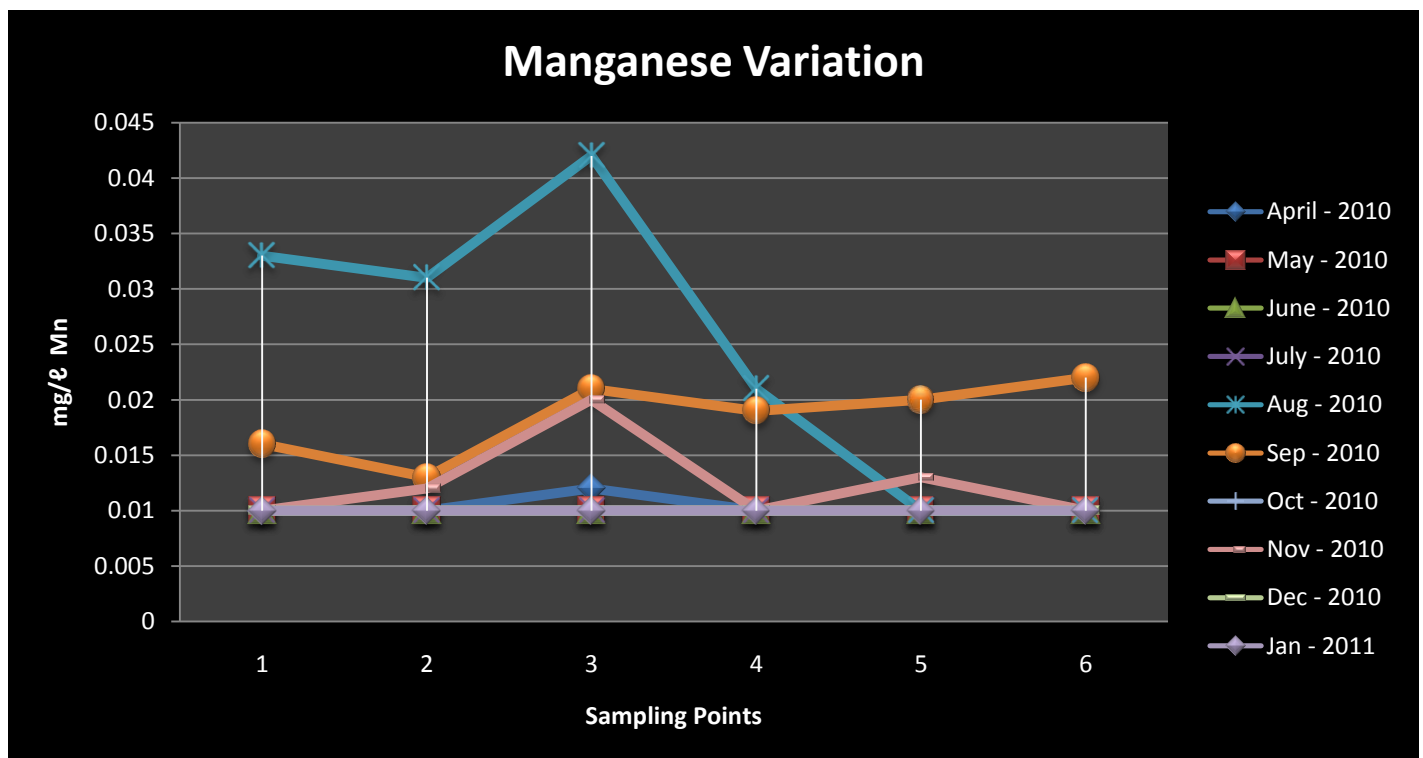


Figure 25: Manganese variation

Figure 25 shows the levels of manganese throughout the season. The content of manganese must remain below 0.1 mg/l for clean water of class I. Even though some spikes exist, it is still very low. Manganese content generally remains below the stipulated maximum throughout the season. This implies that manganese does not pose any threat to the consumers.

4.4 Modelling Results from EPANET Software



Figure 26: Modimolle Area in relation to SA (Source: SA Places)

Figure 26 shows the Modimolle area (circled in thick black and labelled Modimolle) in the Limpopo province in relation to South Africa. Figure 27, extracted from Google earth, shows a zoomed section of Modimolle, indicating the exact location of the study area (extension 11). Attempts were made to source a plan lay-out (showing water lay-out) from the Modimolle municipality, but the officials were unable to

produce a proper plan. The plan acquired was only suitable to capture the sizes and lengths of pipe in the EPANET software.

Having modelled the system with a residual chlorine value (0.18 mg/l as the highest obtained in the season at the reservoir) over 24 hours, the results shown in Table 4 were obtained. At the Modimolle Reservoir, the highest chlorine residual recorded after sampling throughout the season was 0.18 mg/l in the month of December 2010. This value (0.18 mg/l) was then used as the initial residual chlorine at the reservoir when modelling the system. Choosing this value assumed that, at best, the system can only produce 0.18 mg/l of residual chlorine from the Klipdrift plant up to the Modimolle Reservoir.



Figure 27: Extension 11 distribution lay-out (Source: Google Earth)

The corresponding values of residual chlorine at the furthest point of consumption was recorded as 0.11 mg/ℓ (see Table 4) after sampling and testing throughout the season. Because these values (0.18 and 0.11 mg/ℓ at the reservoir and furthest point respectively) were fixed, different values for wall reactions were tried and finally, a wall reaction value of -0.069 (at Hazen Williams C-factor of 120) yielded the required value of residual chlorine at the consumption point. Pipe wall reaction is the rate of water quality reactions occurring at or near the pipe.

Table 4: Summary of chlorine concentration at different times

Levels of Chlorine at Modimolle Reservoir (mg/ℓ)	Readings at furthest point at given time (mg/ℓ)		
	08h00	16h00	24h00
0.18	0.11	0.10	0.11
0.20	0.12	0.11	0.12
0.25	0.16	0.14	0.16
0.30	0.18	0.16	0.19
0.31	0.21	0.18	0.20
0.34	0.23	0.20	0.22

In addressing objectives (b), and (c), the bulk line (see Figure 28) from the Klipdrift WTP, as well as the network (see Figure 27) were modelled separately and optimised to ensure a good water quality model for the network. Figure 28 shows a drawing extracted from MW's Infrastructure Management Query System (IMQS). All the data (elevations, pipe material, diameters and lengths and pump curves) was inserted into EPANET software and verified using IMQS.

Objective (d) was achieved by designing the system to yield the required 0.2 mg/ℓ at any given node as per the Department of Water Affairs standard guidelines. In carrying out the design, the established wall reaction was fixed (when modelling using EPANET) and different values of chlorine dosage, as used at the reservoir, was used. In other words, the reservoir was treated as a dosing point and doses were varied, with the system being modelled each time the dose was changed. This was an iterative process and was repeated until the results showed that at any given point, a

residual chlorine value of 0.2 mg/ℓ was achieved. It was found that, after several iterations, residual chlorine concentration had to be increased to 0.34 mg/ℓ at the reservoir in order to yield 0.2 mg/ℓ at any given node in the network (see Table 4). Currently, Modimolle Reservoir yields 0.18 mg/ℓ of residual chlorine at most, and this means that residual chlorine will have to be increased from the current maximum of 0.18 to 0.34 mg/ℓ. Although this might be expensive, it is a small price to pay to ensure protection of consumers' health.

4.4.1 Bulk Distribution Modelling Results

After modelling the Modimolle network, it became evident that a severe deterioration of water quality throughout the system had resulted due to the residual value being less than 0.18 mg/ℓ. This value (0.18 mg/ℓ), at the Modimolle Reservoir was obtained by using residual chlorine concentration of 2.2 mg/ℓ at the plant (see Figure 23). The next step was to model the bulk line in order to investigate where along the pipeline the water quality was being compromised. Thus, the residual chlorine from the plant to the reservoir of Modimolle was modelled to determine where the losses occurred.

At the Klipdrift plant, the highest value (2.2 mg/ℓ) of residual chlorine was recorded in the month of August 2010, as shown on the representative data (see Appendix D). This value was then inserted into the program as the initial residual chlorine value at the plant.

In sub-section 4.4.2, it was concluded that a minimum of 0.34 mg/ℓ of residual chlorine is required at the reservoir in order to achieve the required 0.2 mg/ℓ residual chlorine at any node in the network. Thus, the bulk line was modelled with the objective of achieving this value (0.34 mg/ℓ) at the reservoir.

The plant never produced more than 2.2 mg/ℓ and the highest residual chlorine was 0.18 mg/ℓ at the reservoir. In order to obtain 0.18 mg/ℓ residual chlorine at the reservoir, the value of 2.2 mg/ℓ was used. After several iterations, the wall reaction coefficient was determined to be -0.6. It was established that most chlorine decay

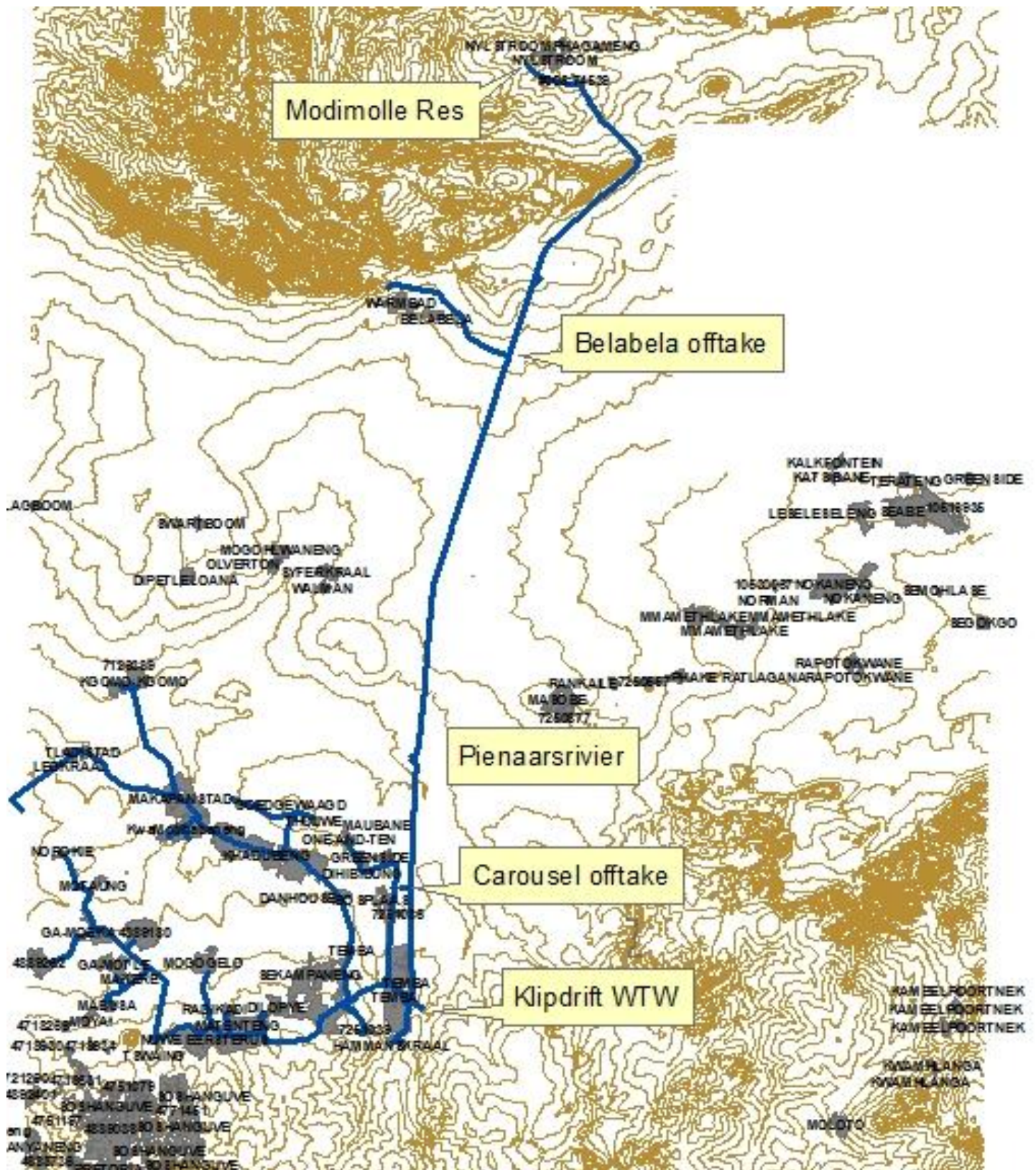


Figure 28: Bulk line from Klipdrift plant to Modimolle Reservoir

occurs between sampling points 2 (Carousel off-take) and 3 (Bela-Bela), where residual chlorine drops from 1.85 mg/ℓ to 0.41 mg/ℓ. Various values of residual chlorine were inserted at the plant, and the results are summarized in Table 5. Full results extracted from EPANET software are attached Appendix F.

The system was again modelled for 24 hours. Using these values and doing a few iterations resulted in the wall reaction coefficient of -0.6. The next step was to establish how much residual chlorine is necessary at the plant to yield 0.34 mg/ℓ at the reservoir. Table 5 indicates, that in order to have residual chlorine of 0.34 mg/ℓ at the reservoir, the required residual chlorine at the treatment plant should be a minimum of 4.0 mg/ℓ.

Table 5: Summary of residual chlorine concentration at different times at Modimolle Reservoir

Residual Chlorine at Klipdrift plant (mg/ℓ) Chlorine at Modimolle Reservoir (mg/ℓ)	Readings at Modimolle Reservoir (mg/ℓ)		
	08h00	16h00	24h00
2.20	0.00	0.20	0.20
3.00	0.00	0.27	0.27
4.00	0.00	0.34	0.34

In summary of this chapter, it was highlighted that most chlorine decay takes place in the bulk main, between points 2 (Carousel off-take) and 3 (Bela-Bela off-take). The wall reactions of the bulk main and Modimolle network pipes were very different, being -0.6 and -0.069 respectively. The larger wall reaction factor suggests that most chlorine decay is occurring in the bulk main. Modimolle Reservoir currently receives water with 0.18 mg/ℓ residual chlorine value, and the furthest consumer point has a 0.11 mg/ℓ residual chlorine value. The Klipdrift plant needs to increase its chlorine dosage from 2.2 mg/ℓ to 4 mg/ℓ, in order to satisfy the requirements of residual chlorine at the reservoir and subsequently at the consumption point furthest. This is almost double the current chlorine dosage at the plant, and will prove costly.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research provided a detailed analysis of potable water quality deterioration of one of the water networks of the MW Board, from the Klipdrift WTP to the Modimolle network. The study also highlighted sections within the system where major water quality deterioration occurs. In this study, it was found that water quality deteriorates drastically throughout the system. The modelling and simulation of the system revealed that drinking water at the furthest consumption point had both high turbidity and low residual chlorine content, which poses a serious health risk to the consumers.

Following these findings, options for an optimum water quality model were explored based on the requirements of SANS 241 (2006). In addressing the objectives of this research study, the conclusions drawn in relation to the findings include:

- a) Results revealed that out of the eleven parameters monitored, six parameters were found to be within the drinking water standards, therefore posing no threat to the treatability of raw water. Those parameters were:
 - I. pH level from the raw water source were constantly between 1.0 and 9.0 units. This finding confirmed that there was no need for pH correction at the Klipdrift plant, as is currently the case. In terms of conductivity, all the values in the raw water were less than 150 mS/m for the duration of the 2010 season.
 - II. Manganese values were constantly below 0.1 mg/l, with the exception of July. Manganese content can be induced by many things, e.g. industrial usage, oxidation process, etc. Any of these occurrences could have happened.

- III. Values for alkalinity, hardness and magnesium were generally below the limit (250 mg/l for Alkalinity and Hardness and 70 mg/l for Magnesium) in the drinking water.

Emanating from the above, a conclusion was drawn that these parameters did not have any impact on the treatability of water at the Klipdrift WTP.

- b)** The plant's operational capacity exceeded the design capacity by 22.2 percent on average. The design capacity of the plant is 18 Ml/d but the plant is currently operated at 22 Ml/d. This may be a possible reason why the water quality output from the plant is below standard. The plant only managed to produce water with a turbidity value of less than 1 NTU in the month of September 2010. This means that, for eleven months during the study, the plant produced sub-standard (turbidity exceeding 1 NTU) water quality. Apart from these factors, there was still the issue of dilapidating infrastructure. All these facts point to the conclusion that the plant is not operating efficiently, and is unable to serve its intended purpose.
- c)** The bulk line to Modimolle Reservoir is approximately 87 km long, and consists of two different diameters, i.e. 450 mm and 300 mm, both steel pipes. The results obtained show that a wall reaction factor of about -0.6 is currently present in the pipes. With this coefficient, most chlorine decay occurs between sampling points 2 (Carousel off-take) and 3 (Bela-Bela), whereby residual chlorine drops from 1.85 mg/l to 0.41 mg/l. In terms of turbidity, there were clear spikes, particularly between points 2 and 3 and 3 and 4. Colour kept fluctuating throughout the system. Iron content was satisfactory, except between points 2 and 4 in the months of August to November. These facts indicate that the length of pipe, with the given wall reaction, contribute largely to the chlorine decay and subsequently water quality deterioration of water. The fact that there was a turbidity spike in the month of October 2010 is not sufficient to suggest that storm water ingress is present in this pipeline. The spike could have been a result of a burst pipe. The possibility of storm water ingress or any other contaminants along the

line, is not ruled out, but might be minimal. Therefore, it can be concluded that most water quality deterioration occurs along the bulk main line.

- d) From the Klipdrift WTP, water is pumped to the Modimolle Reservoir, whereby storage takes place prior to distribution. Although no tests were conducted with regard to storage time and quality impacts, the results obtained show that turbidity levels drop beyond the storage point, suggesting that settlement has occurred. Beyond point 4, there is no observed rise in turbidity, instead, a decline is observed. It may therefore be concluded that storage tanks play an important role in improving the quality of water being distributed to the consumers.
- e) In terms of turbidity, there were no visible spikes between points 4 and 6. This fact suggests that there is no ingress of contaminated substances in the network. Residual chlorine had further deteriorated from the reservoir (point 4) to the furthest point (point 6). This implies that chlorine decay occur due to the ageing of the infrastructure (biofilm formation), as was mentioned in sub-section 4.4.1 (pipes are over 40 years old). Having established a residual chlorine value of 0.18 mg/ℓ at the reservoir, a maximum of 0.11 mg/ℓ of residual chlorine was obtained at the furthest point. It was found that the wall reaction of pipes in the network, which is predominantly Asbestos pipes, have a wall reaction factor of -0.069. With that wall reaction factor, it was found that the furthest point enjoys a minimum of 0.2 mg/ℓ residual chlorine when the reservoir releases water with a residual chlorine value of 0.34 mg/ℓ. This indicates that the Klipdrift plant does not cater for the furthest consumer point, which is located in Modimolle area. Hence consumers within this network are faced with the risk of potential waterborne diseases and fatalities.

5.2 Recommendation

Based on the analysis of results carried out in this study, the following recommendations are made:

- i. The Klipdrift WTP needs upgrading in terms of capacity. The upgrade will have to revisit the current process train in relation to the original process, whereby some process elements were omitted due to design errors.
- ii. In order to produce quality portable water, the Klipdrift WTP must be refurbished to improve its treatment efficiency.
- iii. A section of the bulk main, between the Carousel (sampling point 2) and Bela-Bela (sampling point 3), needs to be monitored separately so as to assess the underlying causes of deterioration of water quality, since major water quality deterioration was observed there.
- iv. In order to ensure adequate residual chlorine, more chlorine will have to be added at the plant. This may prove to be costly in terms of additional chlorine, however, it is a small price to pay for improved protection of consumers' health.
- v. In order to ensure the optimal performance of the entire system, further studies will have to be undertaken with a view to optimise every process of the treatment plant.

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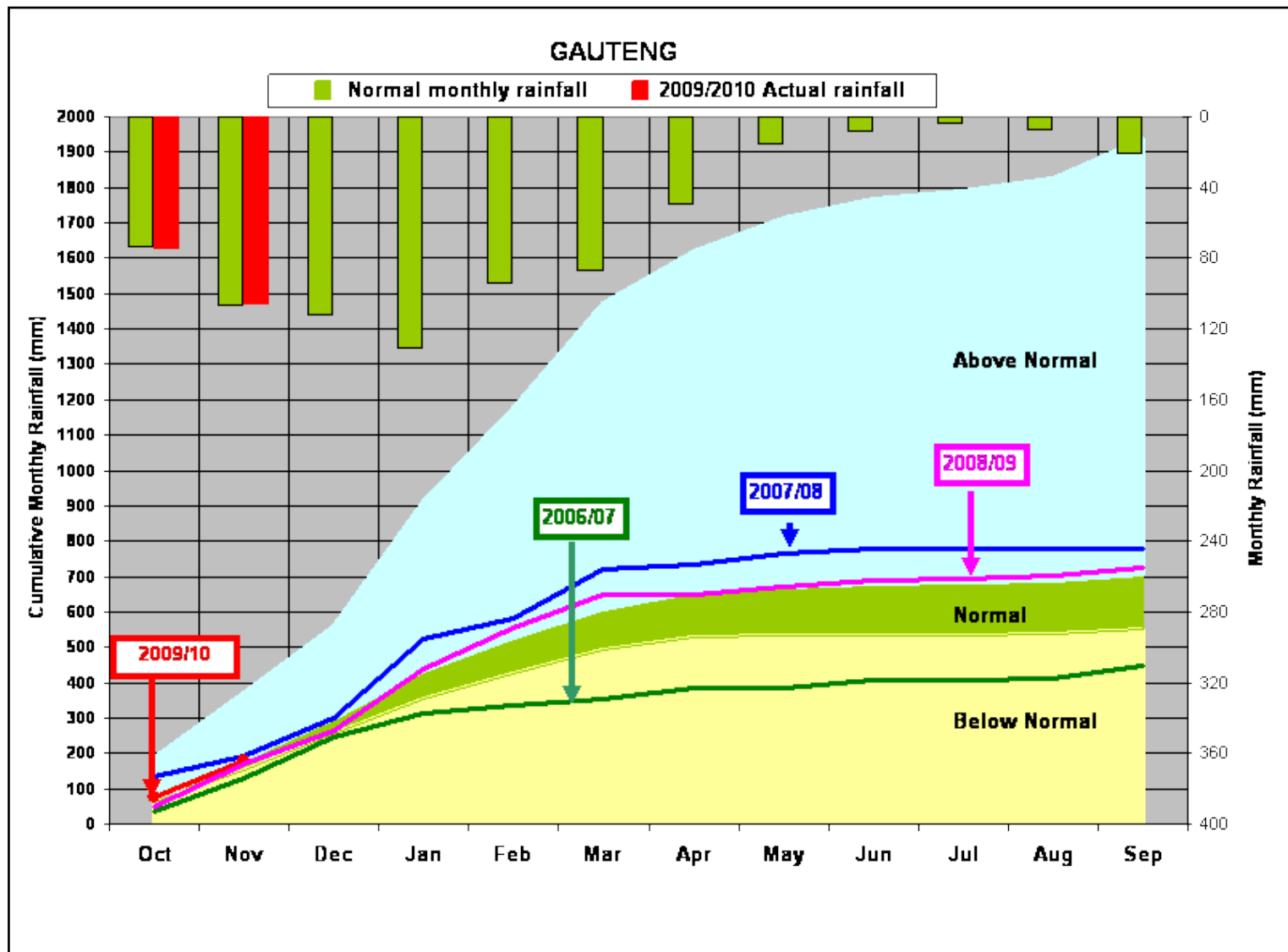
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APPENDIX A - Rainfall pattern Gauteng (Department of Water Affairs)



APPENDIX B - Laboratory photos



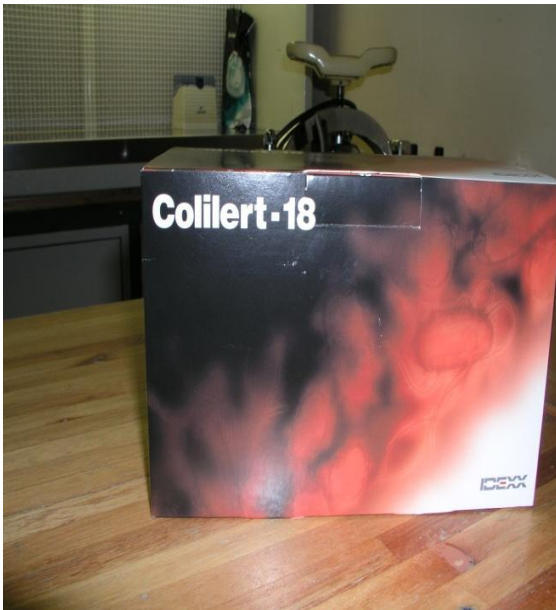
Quanti sealer



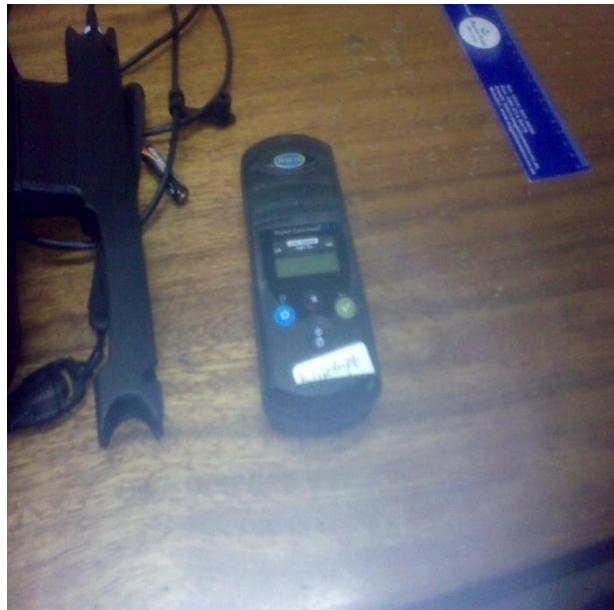
Mercury analyser



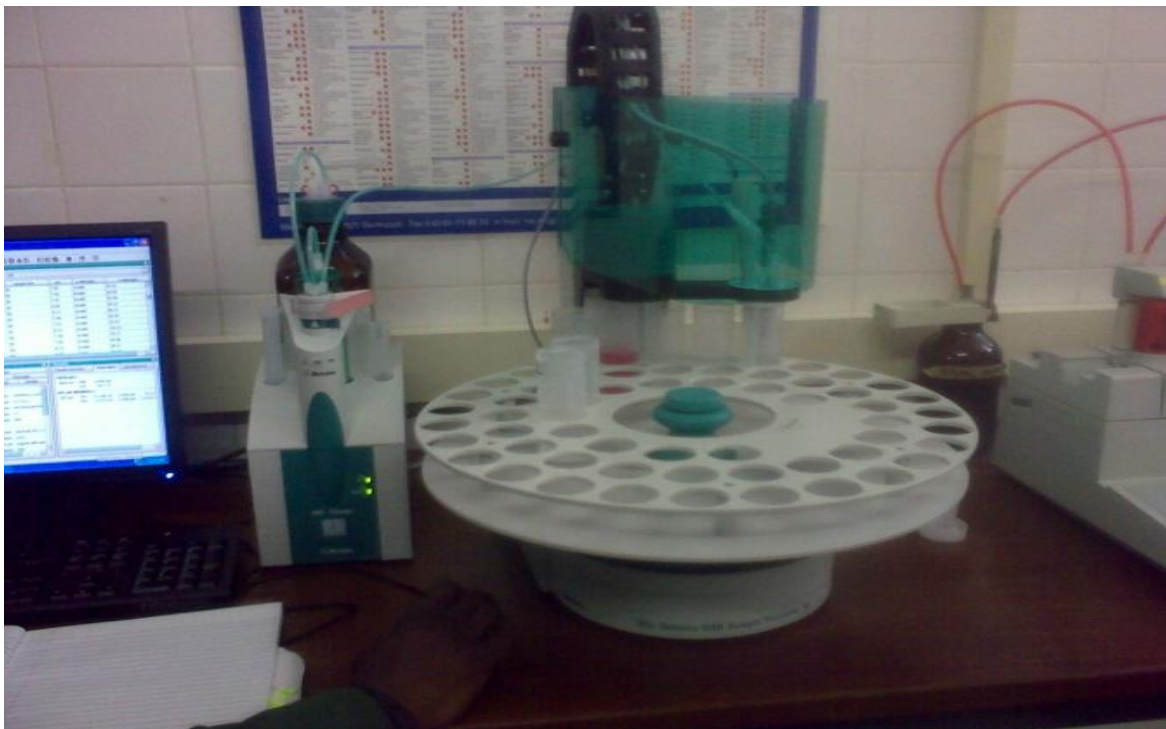
Water bath



Quanti disc



Monochloramine



Quanti disc reader



Incubator



Liqui TOC II



Sterilized sampling bottles



pH and Conductivity metre

APPENDIX C - Physical, organoleptic and chemical requirements

SANS 241: 2006

Edition 6.1

Table 2 — Physical, organoleptic and chemical requirements

1	2	3	4	5
Determinand	Unit	Class I (recommended operational limit)	Class II (max. allowable for limited duration)	Class II water consumption period, (a) max.
Physical and organoleptic — requirements				
Colour (aesthetic)	mg/l pt	< 20	300 – 500	No limit(b)
Conductivity at 25 °C (aesthetic)	mS/m	< 150	10 – 50	7 years
Dissolved solids (aesthetic)	mg/l	< 1 000	10 – 50	7 years
Odour (aesthetic)	Ton	< 5,0	5 – 10	No limit(b)
pH value at 25 °C (aesthetic/ operational)	pH Units	5,0 - 9,5	100 – 500	No limit(c)
Taste (aesthetic)	FTN	< 5,0	500 – 1 000	No limit
Turbidity (aesthetic/operational/ indirect health)	NTU	< 1,0	1 000 – 2 000	No limit(d)
Chemical requirements — macro determinand				
Ammonia as N (operational)	mg/l	< 1,0	1,0 – 2,0	No limit(d)
Calcium as Ca (aesthetic/operational)	mg/l	< 150	150 – 300	7 years
Chloride as Cl ⁻ (aesthetic)	mg/l	< 200	200 – 600	7 years
Fluoride as F ⁻ (health)	mg/l	< 1,0	1,0 – 1,5	1 year
Magnesium as Mg (aesthetic/ health)	mg/l	< 70	70 – 100	7 years
(Nitrate and nitrite) as N	mg/l	< 10	10 – 20	7 years
Potassium as K	mg/l	< 50	50 – 100	7 years
Sodium as Na	mg/l	< 200	200 – 400	7 years
Sulfate as SO ₄ - (health)	mg/l	< 400	400 – 600	7 years
Zinc as Zn (aesthetic/health)	mg/l	< 5,0	5,0 – 10	1 year

Table 2 (concluded)

1	2	3	4	5
Determinand	Unit	Class I (recommended operational limit)	Class II (max. allowable for limited duration)	Class II water consumption period, (a) max.
Chemical requirements — micro-determinand				
Aluminium as Al (health)	µg/L	< 300	300 – 500	1 year
Antimony as Sb (health)	µg/L	< 10	10 – 50	1 year
Arsenic as As (health)	µg/L	< 10	10 – 50	1 year
Cadmium as Cd (health)	µg/L	< 5,0	5,0 – 10	6 months
Total Chromium as Cr (health)	µg/L	< 100	100 – 500	3 months
Cobalt as Co (health)	µg/L	< 500	500 – 1 000	1 year
Copper as Cu (health)	µg/L	< 1000	1 000 – 2 000	1 year
Cyanide (recoverable) as CN–	µg/L	< 50	50 – 70	1 week
Iron as Fe	µg/L	< 200	200 – 2 000	7 years (b)
Lead as Pb (health)	µg/L	< 20	20 – 50	3 months
Manganese as Mn (aesthetic)	µg/L	< 100	100 – 1 000	7 years
Mercury as Hg (health)	µg/L	< 1,0	1,0 – 5,0	3 months
Nickel as Ni (health)	µg/L	< 150	150 – 350	1 year
Selenium as Se (health)	µg/L	< 20	20 – 50	1 year
Vanadium as V (health)	µg/L	< 200	200 – 500	1 year
Chemical requirements — organic determinand				
Dissolved organic carbon as C (aesthetic/health)	µg/L	< 10	10 – 20	3 months (e)
Total trihalomethanes (health)	µg/L	< 200	200 – 300	10 years (f)
Phenols (aesthetic/health)	µg/L	< 10	10 – 70	No limit (b)
a The limits for the consumption of class II water are based on the consumption of 2 L of water per day by a person of mass 70 kg over a period of 70 years. Columns 4 and 5 shall be applied together. b The limits given are based on aesthetic aspects. c No primary health effect – low pH values can result in structural problems in the distribution system. d These values can indicate process efficiency and risks associated with pathogens. e When dissolved organic carbon is deemed of natural origin, the consumption period can be extended. f This is a suggested value because trihalomethanes have not been proven to have any effect on human health.				

APPENDIX D: Representative data of laboratory test results

February 2010

Sampling Points			Selected Analysed Parameters												
			Physical			Chemical						Microbiological			
			Turbidity	Colour	pH	Conductivity	Res.Chlorine	Iron	Manganese	Alkalinity	Hardness	Magnesium	E-Coli	Total Coli.	Heterotrophic Counts
Sampling Point 1			1.09	11	8.09	45.5	1.55	0.042	0.014	142.7	103.2	14.41	0	2	391
Sampling Point 2			3.62	27	8.12	52.5	0.06						200	200	391
Sampling Point 3			2.18	19			0.03								
Sampling Point 4			1.79	19			0.02								
Quality Criteria	Recommended Operational Limits (Class 1 of SANS specification)	max.	1	20	9.5	150	Alert level: <0.2	0.2	0.1	250	250	70	0	Alert level: >10	Alert level: >5000
	Maximum allowable for limited duration (Class 2 of SANS specification)	max.	5	50	10	370		2	1	300	300	100	1		

May 2010

Sampling Points			Selected Analysed Parameters												
			Physical			Chemical						Microbiological			
			Turbidity	Colour	pH	Conductivity	Res.Chlorine	Iron	Manganese	Alkalinity	Hardness	Magnesium	E-Coli	Total Coli.	Heterotrophic Counts
Sampling Point 1			2.15	24	7.47	46.9	2.14	0.01	0.01	None	None	None	0	0	391
Sampling Point 2			2.14	26	7.62	48.7	0.42	0.01	0.01	None	None	None	0	0	281
Sampling Point 3			2.32	30	7.43	49	0.14	0.01	0.01	None	None	None	0	0	58
Sampling Point 4			3.42	29	8.01	45.7	0.12	0.01	0.01	None	None	None	0	0	391
Sampling Point 5			2.25	25	7.93	40	0.12	0.01	0.01	None	None	None	0	0	None
Sampling Point 6			2.42	28	7.98	42	0.09	0.01	0.01	None	None	None	0	0	None
Quality Criteria	Recommended Operational Limits (Class 1 of SANS)	max.	1	20	9.5	150	Alert level: <0.2	0.2	0.1	250	250	70	0	Alert level: >10	Alert level: >5000
	Maximum allowable for limited duration (Class 2 of SANS specification)	max.	5	50	10	370		2	1	300	300	100	1		

August 2010

Sampling Points			Selected Analysed Parameters												
			Physical			Chemical						Microbiological			
			Turbidity	Colour	pH	Conductivity	Res.Chlorine	Iron	Manganese	Alkalinity	Hardness	Magnesium	E-Coli	Total Coli.	Heterotrophic Counts
Sampling Point 1			3.56	13	8.84	46.7	2.2	0.01	0.033	None	None	None	0	0	4
Sampling Point 2			1.08	9	8.82	49.2	1.21	0.064	0.031	None	None	None	0	0	0
Sampling Point 3			1.36	28	8.98	48.1	0.99	0.246	0.042	None	None	None	0	0	212
Sampling Point 4			1.06	11	9.22	48.2	0.1	0.01	0.021	None	None	None	0	0	322
Sampling Point 5			2.52	23	23	44.1	0.1	0.01	0.01	None	None	None	0	0	391
Sampling Point 6			2.45	22	10	46.3	0.02	0.01	0.01	None	None	None	0	0	None
Quality Criteria	Recommended Operational Limits (Class 1 of SANS)	max.	1	20	9.5	150	Alert level: <0.2	0.2	0.1	250	250	70	0	Alert level: >10	Alert level: >5000
	Maximum allowable for limited duration (Class 2 of SANS specification)	max.	5	50	10	370		2	1	300	300	100	1		

November 2010

Sampling Points			Selected Analysed Parameters												
			Physical			Chemical						Microbiological			
			Turbidity	Colour	pH	Conductivity	Res.Chlorine	Iron	Manganese	Alkalinity	Hardness	Magnesium	E-Coli	Total Coli.	Heterotrophic Counts
Sampling Point 1			2.15	24	7.47	46.9	2.14	0.01	0.01	None	None	None	0	0	391
Sampling Point 2			2.02	16	8.52	50.3	0.13	0.043	0.012	None	None	None	0	0	391
Sampling Point 3			1.56	20	8.49	52.1	0.1	0.026	0.02	None	None	None	0	0	65
Sampling Point 4			1.05	20	8.01	45.7	0.08	0.02	0.01	None	None	None	0	0	391
Sampling Point 5			1	24	8.52	53.2	0.05	0.025	0.013	None	None	None	0	0	391
Sampling Point 6			0.98	22	7.98	54	0.03	0.022	0.01	None	None	None	0	0	212
Quality Criteria	Recommended Operational Limits (Class 1 of SANS)	max.	1	20	9.5	150	Alert level: <0.2	0.2	0.1	250	250	70	0	Alert level: >10	Alert level: >5000
	Maximum allowable for limited duration (Class 2 of SANS specification)	max.	5	50	10	370		2	1	300	300	100	1		

December 2010

Sampling Points			Selected Analysed Parameters												
			Physical			Chemical							Microbiological		
			Turbidity	Colour	pH	Conductivity	Res.Chlorine	Iron	Manganese	Alkalinity	Hardness	Magnesium	E-Coli	Total Coli.	Heterotrophic Counts
Sampling Point 1			2.09	24	7.8	46.9	2.14	0.01	0.01	None	None	None	0	0	391
Sampling Point 2			3.18	26	7.76	61.1	1.13	0.01	0.01	None	None	None	0	0	281
Sampling Point 3			3.85	29	7.72	58.2	0.95	0.01	0.01	None	None	None	0	0	212
Sampling Point 4			2	29	8.01	45.7	0.18	0.01	0.01	None	None	None	0	0	391
Sampling Point 5			1.02	12	7.88	56.9	0.12	0.01	0.01	None	None	None	0	0	161
Sampling Point 6			1.52	18	7.98	47	0.09	0.01	0.01	None	None	None	0	0	None
Quality Criteria			Recommended Operational Limits (Class 1 of SANS)	max.	1	20	9.5	150	Alert level: <0.2	0.2	0.1	250	250	70	0
			Maximum allowable for limited duration (Class 2 of SANS specification)	max.	5	50	10	370		2	1	300	300	100	1

January 2011

Sampling Points			Selected Analysed Parameters																		
			Physical			Chemical							Microbiological								
			Turbidity	Colour	pH	Conductivity	Res.Chlorine	Iron	Manganese	Alkalinity	Hardness	Magnesium	E-Coli	Total Coli.	Heterotrophic Counts						
Sampling Point 1			2.11	24	7.47	46.9	2.14	0.01	0.01	None	None	None	0	0	None						
Sampling Point 2			2.02	18	7.76	61.1	1.13	0.01	0.01	None	None	None	0	0	86						
Sampling Point 3			1.18	11	7.72	58.2	0.98	0.01	0.01	None	None	None	0	0	0						
Sampling Point 4			1.3	6	8.01	56.5	0.17	0.01	0.01	None	None	None	0	0	391						
Sampling Point 5			1.58	1.58	7.88	56.9	0.09	0.01	0.01	None	None	None	0	0	161						
Sampling Point 6			1.36	1.48	7.98	58	0.04	0.01	0.01	None	None	None	0	0	None						
Quality Criteria			Recommended Operational Limits (Class 1 of SANS)	max.	1	20	9.5	150	Alert level: <0.2			0.2	0.1	250	250	70	0	Alert level: >10		Alert level: >5000	
			Maximum allowable for limited duration (Class 2 of SANS specification)	max.	5	50	10	370				2	1	300	300	100	1				

APPENDIX E - Hazen Williams factors used in pipes

Hazen Williams factors used in pipes (source: The Engineering Toolbox)

Material	Hazen-Williams Coefficient - C -
ABS - Acrylonite Butadiene Styrene	130
Aluminum	130 - 150
Asbestos Cement	140
Asphalt Lining	130 - 140
Brass	130 - 140
Brick sewer	90 - 100
Cast-Iron - new unlined (CIP)	130
Cast-Iron 10 years old	107 - 113
Cast-Iron 20 years old	89 - 100
Cast-Iron 30 years old	75 - 90
Cast-Iron 40 years old	64-83
Cast-Iron, asphalt coated	100
Cast-Iron, cement lined	140

Cast-Iron, bituminous lined	140
Cast-Iron, sea-coated	120
Cast-Iron, wrought plain	100
Cement lining	130 - 140
Concrete	100 - 140
Concrete lined, steel forms	140
Concrete lined, wooden forms	120
Concrete, old	100 - 110
Copper	130 - 140
Corrugated Metal	60
Ductile Iron Pipe (DIP)	140
Ductile Iron, cement lined	120
Fiber	140
Fiber Glass Pipe - FRP	150
Galvanized iron	120
Glass	130

Lead	130 - 140
Metal Pipes - Very to extremely smooth	130 - 140
Plastic	130 - 150
Polyethylene, PE, PEH	140
Polyvinyl chloride, PVC, CPVC	150
Smooth Pipes	140
Steel new unlined	140 - 150
Steel, corrugated	60
Steel, welded and seamless	100
Steel, interior riveted, no projecting rivets	110
Steel, projecting girth and horizontal rivets	100
Steel, vitrified, spiral-riveted	90 - 110
Steel, welded and seamless	100
Tin	130
Vitrified Clay	110
Wrought iron, plain	100

Wooden or Masonry Pipe - Smooth	120
Wood Stave	110 - 120

APPENDIX F: Modelling results

Modimolle Network Table - Nodes at 8:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/ℓ
Junc 2	0.00	1234.01	14.81	0.18
Junc 3	0.00	1234.01	15.81	0.18
Junc 4	0.01	1234.00	17.30	0.18
Junc 5	0.05	1233.99	16.89	0.18
Junc 6	0.05	1233.99	16.29	0.18
Junc 7	0.16	1233.98	28.18	0.17
Junc 8	0.01	1233.98	30.88	0.17
Junc 9	0.03	1233.98	51.68	0.11
Junc 10	0.03	1233.98	53.48	0.10
Junc 11	0.01	1233.98	57.08	0.11
Junc 12	0.01	1233.98	54.08	0.11
Junc 13	0.02	1233.98	53.18	0.12
Junc 14	0.04	1233.98	57.78	0.11
Junc 15	0.06	1233.98	57.28	0.12
Junc 16	0.01	1233.98	51.68	0.13
Junc 17	0.00	1233.98	48.78	0.14
Junc 18	0.01	1233.98	49.98	0.14
Junc 19	0.01	1233.98	44.78	0.16
Junc 20	0.03	1233.98	27.28	0.17
Junc 21	0.02	1233.99	22.39	0.17

Junc 22	0.02	1233.98	48.08	0.13
Junc 23	0.02	1233.98	30.78	0.17
Junc 24	0.00	1233.98	31.78	0.16
Junc 25	0.02	1233.98	34.78	0.15
Junc 26	0.00	1233.98	37.58	0.15
Junc 27	0.02	1233.98	37.28	0.16
Junc 28	0.01	1233.98	38.28	0.15
Junc 29	0.03	1233.98	38.58	0.15
Junc 30	0.03	1233.98	39.88	0.14
Junc 31	0.00	1233.98	44.48	0.15
Junc 32	0.01	1233.98	42.68	0.15
Junc 33	0.05	1233.98	48.38	0.14
Junc 34	0.02	1233.98	45.68	0.14
Junc 35	0.01	1233.98	47.98	0.14
Junc 36	0.10	1233.98	44.88	0.16
Junc 37	0.01	1233.98	27.98	0.16
Junc 38	0.05	1233.98	50.18	0.14
Junc 39	0.00	1233.98	45.68	0.15
Junc 40	0.03	1233.98	52.28	0.13
Junc 41	0.00	1233.98	42.78	0.15
Junc 42	0.00	1233.98	41.08	0.15
Junc 43	0.01	1233.98	38.58	0.15
Junc 44	0.00	1233.98	37.98	0.15
Junc 45	0.04	1233.98	37.28	0.15

Junc 46	0.09	1233.98	32.78	0.16
Junc 47	0.06	1233.98	35.58	0.16
Junc 48	0.01	1233.98	26.28	0.16
Junc 49	0.01	1233.98	22.98	0.16
Junc 50	0.03	1233.98	22.78	0.16
Junc 51	0.03	1233.98	24.98	0.16
Junc 52	0.02	1233.98	50.38	0.14
Junc 53	0.07	1233.98	51.78	0.13
Junc 54	0.00	1233.98	49.88	0.14
Junc 55	0.02	1233.98	43.78	0.15
Junc 56	0.05	1233.98	47.58	0.14
Junc 57	0.01	1233.98	47.88	0.14
Junc 58	0.05	1233.98	37.48	0.16
Junc 59	0.02	1233.98	52.38	0.12
Resvr 1	-1.51	1230.00	0.00	0.18

Modimolle Network Table - Nodes at 24:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1232.06	12.86	0.18
Junc 3	0.05	1231.69	13.49	0.18
Junc 4	0.10	1231.27	14.57	0.18
Junc 5	0.50	1230.07	12.97	0.18
Junc 6	0.50	1230.00	12.30	0.18
Junc 7	1.73	1229.45	23.65	0.17
Junc 8	0.10	1229.30	26.20	0.17
Junc 9	0.35	1228.90	46.60	0.11
Junc 10	0.35	1228.89	48.39	0.09
Junc 11	0.10	1228.90	52.00	0.11
Junc 12	0.15	1228.91	49.01	0.12
Junc 13	0.20	1228.95	48.15	0.12
Junc 14	0.40	1228.95	52.75	0.10
Junc 15	0.69	1229.00	52.30	0.12
Junc 16	0.15	1229.13	46.83	0.15
Junc 17	0.05	1229.17	43.97	0.15
Junc 18	0.15	1229.44	45.44	0.15
Junc 19	0.15	1229.45	40.25	0.15
Junc 20	0.30	1229.65	22.95	0.17
Junc 21	0.20	1229.80	18.20	0.17
Junc 22	0.25	1229.17	43.27	0.14

Junc 23	0.20	1229.55	26.35	0.17
Junc 24	0.00	1229.51	27.31	0.17
Junc 25	0.25	1229.43	30.23	0.15
Junc 26	0.00	1229.45	33.05	0.15
Junc 27	0.20	1229.49	32.79	0.16
Junc 28	0.10	1229.46	33.76	0.15
Junc 29	0.35	1229.28	33.88	0.15
Junc 30	0.35	1229.28	35.18	0.15
Junc 31	0.00	1229.38	39.88	0.15
Junc 32	0.10	1229.32	38.02	0.15
Junc 33	0.50	1229.26	43.66	0.15
Junc 34	0.25	1229.20	40.90	0.14
Junc 35	0.15	1229.17	43.17	0.14
Junc 36	1.09	1229.22	40.12	0.16
Junc 37	0.15	1229.59	23.59	0.17
Junc 38	0.50	1229.02	45.22	0.14
Junc 39	0.05	1229.02	40.72	0.14
Junc 40	0.30	1229.00	47.30	0.13
Junc 41	0.05	1229.03	37.83	0.14
Junc 42	0.00	1229.03	36.13	0.14
Junc 43	0.15	1229.03	33.63	0.15
Junc 44	0.00	1229.04	33.04	0.16
Junc 45	0.45	1229.05	32.35	0.16
Junc 46	0.99	1229.13	27.93	0.16

Junc 47	0.64	1229.07	30.67	0.17
Junc 48	0.15	1229.16	21.46	0.16
Junc 49	0.10	1229.17	18.17	0.16
Junc 50	0.30	1229.17	17.97	0.16
Junc 51	0.30	1229.22	20.22	0.16
Junc 52	0.20	1228.91	45.31	0.13
Junc 53	0.79	1228.91	46.71	0.12
Junc 54	0.00	1229.01	44.91	0.13
Junc 55	0.20	1228.97	38.77	0.14
Junc 56	0.59	1228.98	42.58	0.14
Junc 57	0.10	1229.01	42.91	0.14
Junc 58	0.50	1229.05	32.55	0.16
Junc 59	0.20	1229.07	47.47	0.13
Resvr 1	-16.63	1230.00	0.00	0.18

Modimolle Network Table - Nodes at 8:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1234.01	14.81	0.20
Junc 3	0.00	1234.01	15.81	0.20
Junc 4	0.01	1234.00	17.30	0.20
Junc 5	0.05	1233.99	16.89	0.20
Junc 6	0.05	1233.99	16.29	0.20
Junc 7	0.16	1233.98	28.18	0.18
Junc 8	0.01	1233.98	30.88	0.18
Junc 9	0.03	1233.98	51.68	0.13
Junc 10	0.03	1233.98	53.48	0.11
Junc 11	0.01	1233.98	57.08	0.12
Junc 12	0.01	1233.98	54.08	0.14
Junc 13	0.02	1233.98	53.18	0.15
Junc 14	0.04	1233.98	57.78	0.13
Junc 15	0.06	1233.98	57.28	0.13
Junc 16	0.01	1233.98	51.68	0.15
Junc 17	0.00	1233.98	48.78	0.16
Junc 18	0.01	1233.98	49.98	0.16
Junc 19	0.01	1233.98	44.78	0.18
Junc 20	0.03	1233.98	27.28	0.18
Junc 21	0.02	1233.99	22.39	0.19
Junc 22	0.02	1233.98	48.08	0.16

Junc 23	0.02	1233.98	30.78	0.18
Junc 24	0.00	1233.98	31.78	0.18
Junc 25	0.02	1233.98	34.78	0.17
Junc 26	0.00	1233.98	37.58	0.17
Junc 27	0.02	1233.98	37.28	0.18
Junc 28	0.01	1233.98	38.28	0.18
Junc 29	0.03	1233.98	38.58	0.17
Junc 30	0.03	1233.98	39.88	0.16
Junc 31	0.00	1233.98	44.48	0.17
Junc 32	0.01	1233.98	42.68	0.16
Junc 33	0.05	1233.98	48.38	0.16
Junc 34	0.02	1233.98	45.68	0.16
Junc 35	0.01	1233.98	47.98	0.16
Junc 36	0.10	1233.98	44.88	0.18
Junc 37	0.01	1233.98	27.98	0.18
Junc 38	0.05	1233.98	50.18	0.15
Junc 39	0.00	1233.98	45.68	0.16
Junc 40	0.03	1233.98	52.28	0.15
Junc 41	0.00	1233.98	42.78	0.16
Junc 42	0.00	1233.98	41.08	0.16
Junc 43	0.01	1233.98	38.58	0.17
Junc 44	0.00	1233.98	37.98	0.17
Junc 45	0.04	1233.98	37.28	0.17
Junc 46	0.09	1233.98	32.78	0.18

Junc 47	0.06	1233.98	35.58	0.18
Junc 48	0.01	1233.98	26.28	0.18
Junc 49	0.01	1233.98	22.98	0.18
Junc 50	0.03	1233.98	22.78	0.18
Junc 51	0.03	1233.98	24.98	0.18
Junc 52	0.02	1233.98	50.38	0.15
Junc 53	0.07	1233.98	51.78	0.14
Junc 54	0.00	1233.98	49.88	0.15
Junc 55	0.02	1233.98	43.78	0.16
Junc 56	0.05	1233.98	47.58	0.15
Junc 57	0.01	1233.98	47.88	0.15
Junc 58	0.05	1233.98	37.48	0.18
Junc 59	0.02	1233.98	52.38	0.14
Resvr 1	-1.51	1230.00	0.00	0.20

Modimolle Network Table - Nodes at 24:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1232.06	12.86	0.20
Junc 3	0.05	1231.69	13.49	0.20
Junc 4	0.10	1231.27	14.57	0.20
Junc 5	0.50	1230.07	12.97	0.20
Junc 6	0.50	1230.00	12.30	0.20
Junc 7	1.73	1229.45	23.65	0.19
Junc 8	0.10	1229.30	26.20	0.19
Junc 9	0.35	1228.90	46.60	0.12
Junc 10	0.35	1228.89	48.39	0.11
Junc 11	0.10	1228.90	52.00	0.12
Junc 12	0.15	1228.91	49.01	0.12
Junc 13	0.20	1228.95	48.15	0.12
Junc 14	0.40	1228.95	52.75	0.12
Junc 15	0.69	1229.00	52.30	0.13
Junc 16	0.15	1229.13	46.83	0.16
Junc 17	0.05	1229.17	43.97	0.16
Junc 18	0.15	1229.44	45.44	0.17
Junc 19	0.15	1229.45	40.25	0.17
Junc 20	0.30	1229.65	22.95	0.19
Junc 21	0.20	1229.80	18.20	0.19
Junc 22	0.25	1229.17	43.27	0.15

Junc 23	0.20	1229.55	26.35	0.19
Junc 24	0.00	1229.51	27.31	0.19
Junc 25	0.25	1229.43	30.23	0.17
Junc 26	0.00	1229.45	33.05	0.16
Junc 27	0.20	1229.49	32.79	0.19
Junc 28	0.10	1229.46	33.76	0.16
Junc 29	0.35	1229.28	33.88	0.16
Junc 30	0.35	1229.28	35.18	0.15
Junc 31	0.00	1229.38	39.88	0.16
Junc 32	0.10	1229.32	38.02	0.16
Junc 33	0.50	1229.26	43.66	0.16
Junc 34	0.25	1229.20	40.90	0.16
Junc 35	0.15	1229.17	43.17	0.16
Junc 36	1.09	1229.22	40.12	0.17
Junc 37	0.15	1229.59	23.59	0.19
Junc 38	0.50	1229.02	45.22	0.16
Junc 39	0.05	1229.02	40.72	0.16
Junc 40	0.30	1229.00	47.30	0.13
Junc 41	0.05	1229.03	37.83	0.16
Junc 42	0.00	1229.03	36.13	0.16
Junc 43	0.15	1229.03	33.63	0.16
Junc 44	0.00	1229.04	33.04	0.17
Junc 45	0.45	1229.05	32.35	0.17
Junc 46	0.99	1229.13	27.93	0.18

Junc 47	0.64	1229.07	30.67	0.19
Junc 48	0.15	1229.16	21.46	0.17
Junc 49	0.10	1229.17	18.17	0.17
Junc 50	0.30	1229.17	17.97	0.18
Junc 51	0.30	1229.22	20.22	0.18
Junc 52	0.20	1228.91	45.31	0.15
Junc 53	0.79	1228.91	46.71	0.13
Junc 54	0.00	1229.01	44.91	0.15
Junc 55	0.20	1228.97	38.77	0.16
Junc 56	0.59	1228.98	42.58	0.15
Junc 57	0.10	1229.01	42.91	0.16
Junc 58	0.50	1229.05	32.55	0.17
Junc 59	0.20	1229.07	47.47	0.16
Resvr 1	-16.63	1230.00	0.00	0.20

Modimolle Network Table - Nodes at 8:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1234.01	14.81	0.25
Junc 3	0.00	1234.01	15.81	0.25
Junc 4	0.01	1234.00	17.30	0.25
Junc 5	0.05	1233.99	16.89	0.25
Junc 6	0.05	1233.99	16.29	0.24
Junc 7	0.16	1233.98	28.18	0.23
Junc 8	0.01	1233.98	30.88	0.23
Junc 9	0.03	1233.98	51.68	0.16
Junc 10	0.03	1233.98	53.48	0.13
Junc 11	0.01	1233.98	57.08	0.16
Junc 12	0.01	1233.98	54.08	0.17
Junc 13	0.02	1233.98	53.18	0.18
Junc 14	0.04	1233.98	57.78	0.17
Junc 15	0.06	1233.98	57.28	0.17
Junc 16	0.01	1233.98	51.68	0.20
Junc 17	0.00	1233.98	48.78	0.21
Junc 18	0.01	1233.98	49.98	0.22
Junc 19	0.01	1233.98	44.78	0.22
Junc 20	0.03	1233.98	27.28	0.24
Junc 21	0.02	1233.99	22.39	0.24
Junc 22	0.02	1233.98	48.08	0.20

Junc 23	0.02	1233.98	30.78	0.24
Junc 24	0.00	1233.98	31.78	0.23
Junc 25	0.02	1233.98	34.78	0.22
Junc 26	0.00	1233.98	37.58	0.21
Junc 27	0.02	1233.98	37.28	0.23
Junc 28	0.01	1233.98	38.28	0.21
Junc 29	0.03	1233.98	38.58	0.20
Junc 30	0.03	1233.98	39.88	0.20
Junc 31	0.00	1233.98	44.48	0.22
Junc 32	0.01	1233.98	42.68	0.22
Junc 33	0.05	1233.98	48.38	0.21
Junc 34	0.02	1233.98	45.68	0.21
Junc 35	0.01	1233.98	47.98	0.20
Junc 36	0.10	1233.98	44.88	0.22
Junc 37	0.01	1233.98	27.98	0.23
Junc 38	0.05	1233.98	50.18	0.19
Junc 39	0.00	1233.98	45.68	0.21
Junc 40	0.03	1233.98	52.28	0.19
Junc 41	0.00	1233.98	42.78	0.21
Junc 42	0.00	1233.98	41.08	0.21
Junc 43	0.01	1233.98	38.58	0.21
Junc 44	0.00	1233.98	37.98	0.21
Junc 45	0.04	1233.98	37.28	0.22
Junc 46	0.09	1233.98	32.78	0.23

Junc 47	0.06	1233.98	35.58	0.23
Junc 48	0.01	1233.98	26.28	0.22
Junc 49	0.01	1233.98	22.98	0.22
Junc 50	0.03	1233.98	22.78	0.22
Junc 51	0.03	1233.98	24.98	0.23
Junc 52	0.02	1233.98	50.38	0.19
Junc 53	0.07	1233.98	51.78	0.19
Junc 54	0.00	1233.98	49.88	0.20
Junc 55	0.02	1233.98	43.78	0.20
Junc 56	0.05	1233.98	47.58	0.20
Junc 57	0.01	1233.98	47.88	0.20
Junc 58	0.05	1233.98	37.48	0.22
Junc 59	0.02	1233.98	52.38	0.20
Resvr 1	-1.51	1230.00	0.00	0.25

Modimolle Network Table - Nodes at 24:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1232.06	12.86	0.25
Junc 3	0.05	1231.69	13.49	0.25
Junc 4	0.10	1231.27	14.57	0.25
Junc 5	0.50	1230.07	12.97	0.25
Junc 6	0.50	1230.00	12.30	0.24
Junc 7	1.73	1229.45	23.65	0.23
Junc 8	0.10	1229.30	26.20	0.23
Junc 9	0.35	1228.90	46.60	0.16
Junc 10	0.35	1228.89	48.39	0.13
Junc 11	0.10	1228.90	52.00	0.16
Junc 12	0.15	1228.91	49.01	0.17
Junc 13	0.20	1228.95	48.15	0.18
Junc 14	0.40	1228.95	52.75	0.16
Junc 15	0.69	1229.00	52.30	0.18
Junc 16	0.15	1229.13	46.83	0.19
Junc 17	0.05	1229.17	43.97	0.20
Junc 18	0.15	1229.44	45.44	0.21
Junc 19	0.15	1229.45	40.25	0.21
Junc 20	0.30	1229.65	22.95	0.23
Junc 21	0.20	1229.80	18.20	0.24
Junc 22	0.25	1229.17	43.27	0.19

Junc 23	0.20	1229.55	26.35	0.23
Junc 24	0.00	1229.51	27.31	0.23
Junc 25	0.25	1229.43	30.23	0.22
Junc 26	0.00	1229.45	33.05	0.21
Junc 27	0.20	1229.49	32.79	0.23
Junc 28	0.10	1229.46	33.76	0.21
Junc 29	0.35	1229.28	33.88	0.20
Junc 30	0.35	1229.28	35.18	0.20
Junc 31	0.00	1229.38	39.88	0.21
Junc 32	0.10	1229.32	38.02	0.21
Junc 33	0.50	1229.26	43.66	0.21
Junc 34	0.25	1229.20	40.90	0.21
Junc 35	0.15	1229.17	43.17	0.20
Junc 36	1.09	1229.22	40.12	0.22
Junc 37	0.15	1229.59	23.59	0.23
Junc 38	0.50	1229.02	45.22	0.19
Junc 39	0.05	1229.02	40.72	0.20
Junc 40	0.30	1229.00	47.30	0.19
Junc 41	0.05	1229.03	37.83	0.20
Junc 42	0.00	1229.03	36.13	0.20
Junc 43	0.15	1229.03	33.63	0.20
Junc 44	0.00	1229.04	33.04	0.22
Junc 45	0.45	1229.05	32.35	0.22
Junc 46	0.99	1229.13	27.93	0.22

Junc 47	0.64	1229.07	30.67	0.23
Junc 48	0.15	1229.16	21.46	0.22
Junc 49	0.10	1229.17	18.17	0.22
Junc 50	0.30	1229.17	17.97	0.23
Junc 51	0.30	1229.22	20.22	0.23
Junc 52	0.20	1228.91	45.31	0.20
Junc 53	0.79	1228.91	46.71	0.18
Junc 54	0.00	1229.01	44.91	0.19
Junc 55	0.20	1228.97	38.77	0.20
Junc 56	0.59	1228.98	42.58	0.19
Junc 57	0.10	1229.01	42.91	0.20
Junc 58	0.50	1229.05	32.55	0.22
Junc 59	0.20	1229.07	47.47	0.19
Resvr 1	-16.63	1230.00	0.00	0.25

Modimolle Network Table - Nodes at 8:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1234.01	14.81	0.30
Junc 3	0.00	1234.01	15.81	0.30
Junc 4	0.01	1234.00	17.30	0.30
Junc 5	0.05	1233.99	16.89	0.29
Junc 6	0.05	1233.99	16.29	0.29
Junc 7	0.16	1233.98	28.18	0.28
Junc 8	0.01	1233.98	30.88	0.28
Junc 9	0.03	1233.98	51.68	0.20
Junc 10	0.03	1233.98	53.48	0.17
Junc 11	0.01	1233.98	57.08	0.18
Junc 12	0.01	1233.98	54.08	0.20
Junc 13	0.02	1233.98	53.18	0.21
Junc 14	0.04	1233.98	57.78	0.20
Junc 15	0.06	1233.98	57.28	0.21
Junc 16	0.01	1233.98	51.68	0.24
Junc 17	0.00	1233.98	48.78	0.25
Junc 18	0.01	1233.98	49.98	0.25
Junc 19	0.01	1233.98	44.78	0.26
Junc 20	0.03	1233.98	27.28	0.28
Junc 21	0.02	1233.99	22.39	0.29
Junc 22	0.02	1233.98	48.08	0.23

Junc 23	0.02	1233.98	30.78	0.28
Junc 24	0.00	1233.98	31.78	0.28
Junc 25	0.02	1233.98	34.78	0.26
Junc 26	0.00	1233.98	37.58	0.25
Junc 27	0.02	1233.98	37.28	0.27
Junc 28	0.01	1233.98	38.28	0.25
Junc 29	0.03	1233.98	38.58	0.25
Junc 30	0.03	1233.98	39.88	0.25
Junc 31	0.00	1233.98	44.48	0.26
Junc 32	0.01	1233.98	42.68	0.26
Junc 33	0.05	1233.98	48.38	0.25
Junc 34	0.02	1233.98	45.68	0.25
Junc 35	0.01	1233.98	47.98	0.24
Junc 36	0.10	1233.98	44.88	0.26
Junc 37	0.01	1233.98	27.98	0.28
Junc 38	0.05	1233.98	50.18	0.24
Junc 39	0.00	1233.98	45.68	0.26
Junc 40	0.03	1233.98	52.28	0.22
Junc 41	0.00	1233.98	42.78	0.26
Junc 42	0.00	1233.98	41.08	0.26
Junc 43	0.01	1233.98	38.58	0.26
Junc 44	0.00	1233.98	37.98	0.26
Junc 45	0.04	1233.98	37.28	0.27
Junc 46	0.09	1233.98	32.78	0.27

Junc 47	0.06	1233.98	35.58	0.28
Junc 48	0.01	1233.98	26.28	0.27
Junc 49	0.01	1233.98	22.98	0.27
Junc 50	0.03	1233.98	22.78	0.27
Junc 51	0.03	1233.98	24.98	0.28
Junc 52	0.02	1233.98	50.38	0.24
Junc 53	0.07	1233.98	51.78	0.22
Junc 54	0.00	1233.98	49.88	0.24
Junc 55	0.02	1233.98	43.78	0.25
Junc 56	0.05	1233.98	47.58	0.24
Junc 57	0.01	1233.98	47.88	0.25
Junc 58	0.05	1233.98	37.48	0.27
Junc 59	0.02	1233.98	52.38	0.23
Resvr 1	-1.51	1230.00	0.00	0.30

Modimolle Network Table - Nodes at 24:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1232.06	12.86	0.30
Junc 3	0.05	1231.69	13.49	0.30
Junc 4	0.10	1231.27	14.57	0.30
Junc 5	0.50	1230.07	12.97	0.29
Junc 6	0.50	1230.00	12.30	0.29
Junc 7	1.73	1229.45	23.65	0.28
Junc 8	0.10	1229.30	26.20	0.28
Junc 9	0.35	1228.90	46.60	0.19
Junc 10	0.35	1228.89	48.39	0.17
Junc 11	0.10	1228.90	52.00	0.19
Junc 12	0.15	1228.91	49.01	0.19
Junc 13	0.20	1228.95	48.15	0.22
Junc 14	0.40	1228.95	52.75	0.19
Junc 15	0.69	1229.00	52.30	0.21
Junc 16	0.15	1229.13	46.83	0.24
Junc 17	0.05	1229.17	43.97	0.25
Junc 18	0.15	1229.44	45.44	0.26
Junc 19	0.15	1229.45	40.25	0.27
Junc 20	0.30	1229.65	22.95	0.28
Junc 21	0.20	1229.80	18.20	0.29
Junc 22	0.25	1229.17	43.27	0.24

Junc 23	0.20	1229.55	26.35	0.28
Junc 24	0.00	1229.51	27.31	0.28
Junc 25	0.25	1229.43	30.23	0.26
Junc 26	0.00	1229.45	33.05	0.26
Junc 27	0.20	1229.49	32.79	0.27
Junc 28	0.10	1229.46	33.76	0.26
Junc 29	0.35	1229.28	33.88	0.25
Junc 30	0.35	1229.28	35.18	0.24
Junc 31	0.00	1229.38	39.88	0.27
Junc 32	0.10	1229.32	38.02	0.27
Junc 33	0.50	1229.26	43.66	0.25
Junc 34	0.25	1229.20	40.90	0.25
Junc 35	0.15	1229.17	43.17	0.24
Junc 36	1.09	1229.22	40.12	0.26
Junc 37	0.15	1229.59	23.59	0.28
Junc 38	0.50	1229.02	45.22	0.24
Junc 39	0.05	1229.02	40.72	0.25
Junc 40	0.30	1229.00	47.30	0.23
Junc 41	0.05	1229.03	37.83	0.26
Junc 42	0.00	1229.03	36.13	0.26
Junc 43	0.15	1229.03	33.63	0.26
Junc 44	0.00	1229.04	33.04	0.26
Junc 45	0.45	1229.05	32.35	0.26
Junc 46	0.99	1229.13	27.93	0.27

Junc 47	0.64	1229.07	30.67	0.28
Junc 48	0.15	1229.16	21.46	0.26
Junc 49	0.10	1229.17	18.17	0.26
Junc 50	0.30	1229.17	17.97	0.26
Junc 51	0.30	1229.22	20.22	0.28
Junc 52	0.20	1228.91	45.31	0.23
Junc 53	0.79	1228.91	46.71	0.22
Junc 54	0.00	1229.01	44.91	0.24
Junc 55	0.20	1228.97	38.77	0.24
Junc 56	0.59	1228.98	42.58	0.24
Junc 57	0.10	1229.01	42.91	0.25
Junc 58	0.50	1229.05	32.55	0.26
Junc 59	0.20	1229.07	47.47	0.23
Resvr 1	-16.63	1230.00	0.00	0.30

Modimolle Network Table - Nodes at 8:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1234.01	14.81	0.31
Junc 3	0.00	1234.01	15.81	0.31
Junc 4	0.01	1234.00	17.30	0.31
Junc 5	0.05	1233.99	16.89	0.30
Junc 6	0.05	1233.99	16.29	0.30
Junc 7	0.16	1233.98	28.18	0.29
Junc 8	0.01	1233.98	30.88	0.29
Junc 9	0.03	1233.98	51.68	0.21
Junc 10	0.03	1233.98	53.48	0.18
Junc 11	0.01	1233.98	57.08	0.21
Junc 12	0.01	1233.98	54.08	0.22
Junc 13	0.02	1233.98	53.18	0.22
Junc 14	0.04	1233.98	57.78	0.21
Junc 15	0.06	1233.98	57.28	0.22
Junc 16	0.01	1233.98	51.68	0.26
Junc 17	0.00	1233.98	48.78	0.26
Junc 18	0.01	1233.98	49.98	0.27
Junc 19	0.01	1233.98	44.78	0.27
Junc 20	0.03	1233.98	27.28	0.29
Junc 21	0.02	1233.99	22.39	0.30
Junc 22	0.02	1233.98	48.08	0.24

Junc 23	0.02	1233.98	30.78	0.29
Junc 24	0.00	1233.98	31.78	0.29
Junc 25	0.02	1233.98	34.78	0.27
Junc 26	0.00	1233.98	37.58	0.27
Junc 27	0.02	1233.98	37.28	0.29
Junc 28	0.01	1233.98	38.28	0.27
Junc 29	0.03	1233.98	38.58	0.26
Junc 30	0.03	1233.98	39.88	0.25
Junc 31	0.00	1233.98	44.48	0.27
Junc 32	0.01	1233.98	42.68	0.27
Junc 33	0.05	1233.98	48.38	0.26
Junc 34	0.02	1233.98	45.68	0.26
Junc 35	0.01	1233.98	47.98	0.25
Junc 36	0.10	1233.98	44.88	0.27
Junc 37	0.01	1233.98	27.98	0.29
Junc 38	0.05	1233.98	50.18	0.24
Junc 39	0.00	1233.98	45.68	0.27
Junc 40	0.03	1233.98	52.28	0.23
Junc 41	0.00	1233.98	42.78	0.27
Junc 42	0.00	1233.98	41.08	0.27
Junc 43	0.01	1233.98	38.58	0.27
Junc 44	0.00	1233.98	37.98	0.27
Junc 45	0.04	1233.98	37.28	0.27
Junc 46	0.09	1233.98	32.78	0.28

Junc 47	0.06	1233.98	35.58	0.29
Junc 48	0.01	1233.98	26.28	0.27
Junc 49	0.01	1233.98	22.98	0.27
Junc 50	0.03	1233.98	22.78	0.28
Junc 51	0.03	1233.98	24.98	0.29
Junc 52	0.02	1233.98	50.38	0.25
Junc 53	0.07	1233.98	51.78	0.22
Junc 54	0.00	1233.98	49.88	0.24
Junc 55	0.02	1233.98	43.78	0.26
Junc 56	0.05	1233.98	47.58	0.24
Junc 57	0.01	1233.98	47.88	0.26
Junc 58	0.05	1233.98	37.48	0.28
Junc 59	0.02	1233.98	52.38	0.24
Resvr 1	-1.51	1230.00	0.00	0.31

Modimolle Network Table - Nodes at 24:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1232.06	12.86	0.31
Junc 3	0.05	1231.69	13.49	0.31
Junc 4	0.10	1231.27	14.57	0.31
Junc 5	0.50	1230.07	12.97	0.30
Junc 6	0.50	1230.00	12.30	0.30
Junc 7	1.73	1229.45	23.65	0.29
Junc 8	0.10	1229.30	26.20	0.29
Junc 9	0.35	1228.90	46.60	0.21
Junc 10	0.35	1228.89	48.39	0.18
Junc 11	0.10	1228.90	52.00	0.20
Junc 12	0.15	1228.91	49.01	0.22
Junc 13	0.20	1228.95	48.15	0.22
Junc 14	0.40	1228.95	52.75	0.21
Junc 15	0.69	1229.00	52.30	0.23
Junc 16	0.15	1229.13	46.83	0.25
Junc 17	0.05	1229.17	43.97	0.26
Junc 18	0.15	1229.44	45.44	0.26
Junc 19	0.15	1229.45	40.25	0.28
Junc 20	0.30	1229.65	22.95	0.29
Junc 21	0.20	1229.80	18.20	0.30
Junc 22	0.25	1229.17	43.27	0.25

Junc 23	0.20	1229.55	26.35	0.29
Junc 24	0.00	1229.51	27.31	0.29
Junc 25	0.25	1229.43	30.23	0.27
Junc 26	0.00	1229.45	33.05	0.27
Junc 27	0.20	1229.49	32.79	0.29
Junc 28	0.10	1229.46	33.76	0.27
Junc 29	0.35	1229.28	33.88	0.26
Junc 30	0.35	1229.28	35.18	0.25
Junc 31	0.00	1229.38	39.88	0.28
Junc 32	0.10	1229.32	38.02	0.27
Junc 33	0.50	1229.26	43.66	0.26
Junc 34	0.25	1229.20	40.90	0.26
Junc 35	0.15	1229.17	43.17	0.25
Junc 36	1.09	1229.22	40.12	0.27
Junc 37	0.15	1229.59	23.59	0.29
Junc 38	0.50	1229.02	45.22	0.25
Junc 39	0.05	1229.02	40.72	0.26
Junc 40	0.30	1229.00	47.30	0.24
Junc 41	0.05	1229.03	37.83	0.26
Junc 42	0.00	1229.03	36.13	0.26
Junc 43	0.15	1229.03	33.63	0.26
Junc 44	0.00	1229.04	33.04	0.27
Junc 45	0.45	1229.05	32.35	0.27
Junc 46	0.99	1229.13	27.93	0.28

Junc 47	0.64	1229.07	30.67	0.29
Junc 48	0.15	1229.16	21.46	0.27
Junc 49	0.10	1229.17	18.17	0.27
Junc 50	0.30	1229.17	17.97	0.27
Junc 51	0.30	1229.22	20.22	0.29
Junc 52	0.20	1228.91	45.31	0.24
Junc 53	0.79	1228.91	46.71	0.23
Junc 54	0.00	1229.01	44.91	0.24
Junc 55	0.20	1228.97	38.77	0.25
Junc 56	0.59	1228.98	42.58	0.25
Junc 57	0.10	1229.01	42.91	0.25
Junc 58	0.50	1229.05	32.55	0.27
Junc 59	0.20	1229.07	47.47	0.25
Resvr 1	-16.63	1230.00	0.00	0.31

Modimolle Network Table - Nodes at 8:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1234.01	14.81	0.34
Junc 3	0.00	1234.01	15.81	0.34
Junc 4	0.01	1234.00	17.30	0.34
Junc 5	0.05	1233.99	16.89	0.33
Junc 6	0.05	1233.99	16.29	0.33
Junc 7	0.16	1233.98	28.18	0.32
Junc 8	0.01	1233.98	30.88	0.32
Junc 9	0.03	1233.98	51.68	0.23
Junc 10	0.03	1233.98	53.48	0.20
Junc 11	0.01	1233.98	57.08	0.23
Junc 12	0.01	1233.98	54.08	0.24
Junc 13	0.02	1233.98	53.18	0.25
Junc 14	0.04	1233.98	57.78	0.23
Junc 15	0.06	1233.98	57.28	0.25
Junc 16	0.01	1233.98	51.68	0.28
Junc 17	0.00	1233.98	48.78	0.29
Junc 18	0.01	1233.98	49.98	0.30
Junc 19	0.01	1233.98	44.78	0.30
Junc 20	0.03	1233.98	27.28	0.32
Junc 21	0.02	1233.99	22.39	0.33
Junc 22	0.02	1233.98	48.08	0.27

Junc 23	0.02	1233.98	30.78	0.32
Junc 24	0.00	1233.98	31.78	0.32
Junc 25	0.02	1233.98	34.78	0.29
Junc 26	0.00	1233.98	37.58	0.29
Junc 27	0.02	1233.98	37.28	0.32
Junc 28	0.01	1233.98	38.28	0.30
Junc 29	0.03	1233.98	38.58	0.29
Junc 30	0.03	1233.98	39.88	0.28
Junc 31	0.00	1233.98	44.48	0.30
Junc 32	0.01	1233.98	42.68	0.30
Junc 33	0.05	1233.98	48.38	0.29
Junc 34	0.02	1233.98	45.68	0.28
Junc 35	0.01	1233.98	47.98	0.28
Junc 36	0.10	1233.98	44.88	0.30
Junc 37	0.01	1233.98	27.98	0.32
Junc 38	0.05	1233.98	50.18	0.26
Junc 39	0.00	1233.98	45.68	0.29
Junc 40	0.03	1233.98	52.28	0.26
Junc 41	0.00	1233.98	42.78	0.29
Junc 42	0.00	1233.98	41.08	0.30
Junc 43	0.01	1233.98	38.58	0.30
Junc 44	0.00	1233.98	37.98	0.30
Junc 45	0.04	1233.98	37.28	0.30
Junc 46	0.09	1233.98	32.78	0.31

Junc 47	0.06	1233.98	35.58	0.32
Junc 48	0.01	1233.98	26.28	0.31
Junc 49	0.01	1233.98	22.98	0.31
Junc 50	0.03	1233.98	22.78	0.31
Junc 51	0.03	1233.98	24.98	0.32
Junc 52	0.02	1233.98	50.38	0.27
Junc 53	0.07	1233.98	51.78	0.26
Junc 54	0.00	1233.98	49.88	0.27
Junc 55	0.02	1233.98	43.78	0.29
Junc 56	0.05	1233.98	47.58	0.28
Junc 57	0.01	1233.98	47.88	0.28
Junc 58	0.05	1233.98	37.48	0.30
Junc 59	0.02	1233.98	52.38	0.27
Resvr 1	-1.51	1230.00	0.00	0.34

Modimolle Network Table - Nodes at 24:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.00	1232.06	12.86	0.34
Junc 3	0.05	1231.69	13.49	0.34
Junc 4	0.10	1231.27	14.57	0.34
Junc 5	0.50	1230.07	12.97	0.33
Junc 6	0.50	1230.00	12.30	0.33
Junc 7	1.73	1229.45	23.65	0.32
Junc 8	0.10	1229.30	26.20	0.32
Junc 9	0.35	1228.90	46.60	0.22
Junc 10	0.35	1228.89	48.39	0.19
Junc 11	0.10	1228.90	52.00	0.22
Junc 12	0.15	1228.91	49.01	0.24
Junc 13	0.20	1228.95	48.15	0.24
Junc 14	0.40	1228.95	52.75	0.22
Junc 15	0.69	1229.00	52.30	0.25
Junc 16	0.15	1229.13	46.83	0.28
Junc 17	0.05	1229.17	43.97	0.29
Junc 18	0.15	1229.44	45.44	0.30
Junc 19	0.15	1229.45	40.25	0.30
Junc 20	0.30	1229.65	22.95	0.32
Junc 21	0.20	1229.80	18.20	0.33
Junc 22	0.25	1229.17	43.27	0.27

Junc 23	0.20	1229.55	26.35	0.31
Junc 24	0.00	1229.51	27.31	0.31
Junc 25	0.25	1229.43	30.23	0.30
Junc 26	0.00	1229.45	33.05	0.29
Junc 27	0.20	1229.49	32.79	0.31
Junc 28	0.10	1229.46	33.76	0.29
Junc 29	0.35	1229.28	33.88	0.28
Junc 30	0.35	1229.28	35.18	0.29
Junc 31	0.00	1229.38	39.88	0.29
Junc 32	0.10	1229.32	38.02	0.29
Junc 33	0.50	1229.26	43.66	0.29
Junc 34	0.25	1229.20	40.90	0.28
Junc 35	0.15	1229.17	43.17	0.28
Junc 36	1.09	1229.22	40.12	0.30
Junc 37	0.15	1229.59	23.59	0.32
Junc 38	0.50	1229.02	45.22	0.26
Junc 39	0.05	1229.02	40.72	0.29
Junc 40	0.30	1229.00	47.30	0.26
Junc 41	0.05	1229.03	37.83	0.29
Junc 42	0.00	1229.03	36.13	0.29
Junc 43	0.15	1229.03	33.63	0.29
Junc 44	0.00	1229.04	33.04	0.30
Junc 45	0.45	1229.05	32.35	0.30
Junc 46	0.99	1229.13	27.93	0.31

Junc 47	0.64	1229.07	30.67	0.32
Junc 48	0.15	1229.16	21.46	0.30
Junc 49	0.10	1229.17	18.17	0.30
Junc 50	0.30	1229.17	17.97	0.30
Junc 51	0.30	1229.22	20.22	0.32
Junc 52	0.20	1228.91	45.31	0.27
Junc 53	0.79	1228.91	46.71	0.25
Junc 54	0.00	1229.01	44.91	0.28
Junc 55	0.20	1228.97	38.77	0.28
Junc 56	0.59	1228.98	42.58	0.27
Junc 57	0.10	1229.01	42.91	0.29
Junc 58	0.50	1229.05	32.55	0.31
Junc 59	0.20	1229.07	47.47	0.27
Resvr 1	-16.63	1230.00	0.00	0.34

Bulk Network Table - Nodes at 8:00 Hrs

	Elevation	Initial Quality	Demand	Chlorine
Node ID	m	mg/ℓ	LPS	mg/ℓ
Junc 2	1102	0	0.50	2.20
Junc 3	1063	0	11.57	1.81
Junc 4	1090	0	3.50	0.80
Junc 5	1125	0	17.36	0.55
Junc 6	1181	0	2.50	0.43
Junc 7	1188.3	0	2.50	0.00
Junc 8	1210.9	0	2.50	0.00
Junc 9	1141	0	2.50	0.00
Junc 10	1163	0	0.00	0.00
Junc 11	1174	0	15.00	0.00
Resvr 1	1088	2.2	-397.18	2.20
Tank 12	1230	0	339.24	0.00

Bulk Network Table - Nodes at 24:00 Hrs

	Elevation	Initial Quality	Demand	Chlorine
Node ID	m	mg/ℓ	LPS	mg/ℓ
Junc 2	1102	0	5.50	2.20
Junc 3	1063	0	127.31	1.77
Junc 4	1090	0	38.50	0.70
Junc 5	1125	0	190.97	0.46
Junc 6	1181	0	27.50	0.32
Junc 7	1188.3	0	27.50	0.21
Junc 8	1210.9	0	27.50	0.20
Junc 9	1141	0	27.50	0.16
Junc 10	1163	0	0.00	0.13
Junc 11	1174	0	165.00	0.11
Resvr 1	1088	2.2	-585.34	2.20
Tank 12	1230	0	-51.94	0.20

Bulk Network Table - Nodes at 8:00 Hrs

	Demand	Head	Pressure	Chlorine
Node ID	LPS	m	m	mg/l
Junc 2	0.50	3394.42	2292.42	3.00
Junc 3	11.57	3221.91	2158.91	2.47
Junc 4	3.50	2656.59	1566.59	1.09
Junc 5	17.36	2421.91	1296.91	0.75
Junc 6	2.50	2059.62	878.62	0.58
Junc 7	2.50	1705.73	517.43	0.00
Junc 8	2.50	1660.65	449.75	0.00
Junc 9	2.50	1519.73	378.73	0.00
Junc 10	0.00	1391.62	228.62	0.00
Junc 11	15.00	1289.13	115.13	0.00
Resvr 1	-397.18	1088.00	0.00	3.00
Tank 12	339.24	1230.00	0.00	0.00

Bulk Network Table - Nodes at 24:00 Hrs

	Elevation	Initial Quality	Demand	Chlorine
Node ID	m	mg/ℓ	LPS	mg/ℓ
Junc 2	1102	0	5.50	3.00
Junc 3	1063	0	127.31	2.42
Junc 4	1090	0	38.50	0.95
Junc 5	1125	0	190.97	0.62
Junc 6	1181	0	27.50	0.44
Junc 7	1188.3	0	27.50	0.30
Junc 8	1210.9	0	27.50	0.28
Junc 9	1141	0	27.50	0.23
Junc 10	1163	0	0.00	0.18
Junc 11	1174	0	165.00	0.15
Resvr 1	1088	3.0	-585.34	3.00
Tank 12	1230	0	-51.94	0.27

Bulk Network Table - Nodes at 8:00 Hrs

	Elevation	Initial Quality	Demand	Chlorine
Node ID	m	mg/ℓ	LPS	mg/ℓ
Junc 2	1102	0	0.50	4.00
Junc 3	1063	0	11.57	3.30
Junc 4	1090	0	3.50	1.45
Junc 5	1125	0	17.36	0.99
Junc 6	1181	0	2.50	0.78
Junc 7	1188.3	0	2.50	0.00
Junc 8	1210.9	0	2.50	0.00
Junc 9	1141	0	2.50	0.00
Junc 10	1163	0	0.00	0.00
Junc 11	1174	0	15.00	0.00
Resvr 1	1088	4	-397.18	4.00
Tank 12	1230	0	339.24	0.00

Bulk Network Table - Nodes at 24:00 Hrs

	Elevation	Initial Quality	Demand	Chlorine
Node ID	m	mg/ℓ	LPS	mg/ℓ
Junc 2	1102	0	5.50	4.00
Junc 3	1063	0	127.31	3.22
Junc 4	1090	0	38.50	1.27
Junc 5	1125	0	190.97	0.83
Junc 6	1181	0	27.50	0.58
Junc 7	1188.3	0	27.50	0.39
Junc 8	1210.9	0	27.50	0.37
Junc 9	1141	0	27.50	0.30
Junc 10	1163	0	0.00	0.24
Junc 11	1174	0	165.00	0.21
Resvr 1	1088	4	-585.34	4.00
Tank 12	1230	0	-51.94	0.37

APPENDIX G: Input data

Network Table - Nodes

	Elevation	Base Demand	Initial Quality
Node ID	m	LPS	mg/L
Junc 2	1219.2	0	0
Junc 3	1218.2	0.009	0
Junc 4	1216.7	0.018	0
Junc 5	1217.1	0.09	0
Junc 6	1217.7	0.09	0
Junc 7	1205.8	0.315	0
Junc 8	1203.1	0.018	0
Junc 9	1182.3	0.063	0
Junc 10	1180.5	0.063	0
Junc 11	1176.9	0.018	0
Junc 12	1179.9	0.027	0
Junc 13	1180.8	0.036	0
Junc 14	1176.2	0.072	0
Junc 15	1176.7	0.126	0
Junc 16	1182.3	0.027	0

Junc 17	1185.2	0.009	0
Junc 18	1184	0.027	0
Junc 19	1189.2	0.027	0
Junc 20	1206.7	0.054	0
Junc 21	1211.6	0.036	0
Junc 22	1185.9	0.045	0
Junc 23	1203.2	0.036	0
Junc 24	1202.2	0	0
Junc 25	1199.2	0.045	0
Junc 26	1196.4	0	0
Junc 27	1196.7	0.036	0
Junc 28	1195.7	0.018	0
Junc 29	1195.4	0.063	0
Junc 30	1194.1	0.063	0
Junc 31	1189.5	0	0
Junc 32	1191.3	0.018	0
Junc 33	1185.6	0.09	0
Junc 34	1188.3	0.045	0
Junc 35	1186	0.027	0
Junc 36	1189.1	0.198	0

Junc 37	1206	0.027	0
Junc 38	1183.8	0.09	0
Junc 39	1188.3	0.009	0
Junc 40	1181.7	0.054	0
Junc 41	1191.2	0.009	0
Junc 42	1192.9	0	0
Junc 43	1195.4	0.027	0
Junc 44	1196	0	0
Junc 45	1196.7	0.081	0
Junc 46	1201.2	0.18	0
Junc 47	1198.4	0.117	0
Junc 48	1207.7	0.027	0
Junc 49	1211	0.018	0
Junc 50	1211.2	0.054	0
Junc 51	1209	0.054	0
Junc 52	1183.6	0.036	0
Junc 53	1182.2	0.144	0
Junc 54	1184.1	0	0
Junc 55	1190.2	0.036	0
Junc 56	1186.4	0.108	0

Junc 57	1186.1	0.018	0
Junc 58	1196.5	0.09	0
Junc 59	1181.6	0.036	0
Resvr 1	1230	#N/A	0.34