Determinants of Key Drivers for Potable Water Treatment Cost in uMngeni Basin

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DECLARATION

This thesis is submitted to the Durban University of Technology for the Degree of Master of Technology (Environmental Health). I declare that this work is my own and has not been submitted before for any degree or examination to any other University or Institution. Data and procedures presented here are the original work of the candidate unless indicated otherwise by a citation or acknowledgement.

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I hereby approve the final submission of the following dissertation.

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This______ day of __________, 2014, at Durban University of Technology

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ABSTRACT

The study entailed the determination of key water quality parameters significantly influencing treatment cost in uMngeni Basin. Chemical dosage was used as a substitute for treatment cost as the study indicated that cost, in its monetary value, is influenced by market forces, demand and supply, which are both not directly linked to water quality. Chemical dosage is however, determined by the quality of water and thus provides a clear illustration of the effect of pollution on treatment cost.

Three specific objectives were set in an effort to determine key water quality parameters influencing treatment costs in uMngeni Basin. The fourth objective was to develop a model for predicting chemical dosages. The first approach was analysis of temporal and spatial variability of water quality in relation to chemical dosage during production of potable water. The trends were explained in relation to river health status. For this purpose, time-series, box-plot, and the Seasonal-Kendal test were employed. The results showed that the quality of water significantly deteriorated from upstream to downstream in relation to algae, turbidity and *Escherichia coli (E. coli)*. High mean range of *E. coli* (126-1319 colony count/100mL) and turbidity (2.7-38.7 NTU) observed indicate that the quality of water along the basin is not fit for human consumption as these parameters exceeded the target range stipulated in South Africa's guidelines for domestic use. For water intended for drinking purpose, turbidity should be below 5 NTU, while zero *E. coli* count is expect in 100 mL.

Among the six sampling stations considered along the uMngeni Basin, three dam outflows (Midmar, Nagle and Inanda) showed an improved quality compared with their respective inflow stations. This was expected and could be attributed to the retention and dilution effects. These natural processes help by providing a self-purification process, which ultimately reduces the treatment cost.

While considering the importance of disseminating water quality information to the general public and non-technical stakeholders, the second objective of the study was to develop two water quality indices. These were; (1) Treatability Water Quality Index and (2) River Health Water Quality Index. The Treatability Water Quality Index was

developed based on the Canadian Council Minister of Environment Water Quality Index (CCME-WQI). The technique is used to determine fitness of water against a set of assigned water quality resource objectives (guidelines). The calculated Harmonised Water Quality Resource Objectives (HWQRO) were used to compare the qualities of the raw water being abstracted at Nagle and Inanda Dam for the purpose of treatment. The results showed that Nagle Dam, which supplies Durban Heights, is significantly affected by *E. coli* (42% non-compliance), turbidity (20% non-compliance) and nitrate (18% non-compliance) levels. Wiggins Water Treatment Plant which abstracts from Inanda Dam has a problem of high algae (mean 4499 cell/mL), conductivity (mean 26.21 mS/m) and alkalinity (mean 62.66 mg/L) levels.

The River Health Water Quality Index (RHWQI) was developed using the Weighted Geometric Mean (WQM) method. Eight parameters, namely, *E. coli,* dissolved oxygen, nitrate, ammonia, turbidity, alkalinity, electrical conductivity and pH were selected for indexing. Rating curves were drawn based on the target ranges as stipulated in South Africa's guidelines for freshwater ecosystems. Five classes were used to describe the overall river health status. The results showed that the water is still acceptable for survival of freshwater animals. A comparison of the RHWQI scores (out of 100) depicted that dam inflow station (MDI(61.6), NDI(74.6) and IDI(63.8)) showed a relatively deteriorated quality as compared with their outflows (MDO(77.8), NDO(74.4) and IDO(80)).

The third objective was to employ statistical analysis to determine key water quality parameters influencing chemical dosage at Durban Heights and Wiggins Water Treatment Plants. For each of the two treatment plants, treated water quality data-sets were analysed together with their respective raw water data-set. The rationale was to determine parameters showing concentration change due to treatment. The t-test was used to determine the significance of concentration change on each of the 23 parameters considered. Thereafter, the correlations between water quality parameters and the three chemicals used during treatment (polymer, chlorine and lime) were analysed. The results showed that the concentrations of physical parameters namely, algae, turbidity and total organic carbon at both treatment showed a significant statistical ($p<0.05$) reduction in concentration ($R/Ro<0.95$). This results implies that such parameters were key drivers for chemical dosage.

From the results of the first three objectives, it is recommended that implementing measures to control physical parameter pollution sources, specifically sewage discharges and rainfall run-off from agricultural lands along the uMngeni Basin should assist in reducing the chemical dosage and ultimately cost.

The fourth objective was to develop chemical dosage models for prediction purposes. This was achieved by employing a polynomial non-linear regression function on the XLStat 2014 program. The resultant models showed prediction power (R^2) ranging from 0.18 (18%) up to 0.75 (75%). However, the study recommends a comparative study of the developed models with other modelling techniques.

PREFACE

Aspects of the work covered in this dissertation will be published and presented elsewhere:

1. Journal Article; I Rangeti*, B Dzwairo, GJ Barratt, FAO Otieno. *Ecosystem – Specific Water Quality Indices*: A Review. Revised article submitted to the journal. African Journal of Aquatic Science.

2. Book Chapter: I Rangeti*, B Dzwairo, GJ Barratt, FAO Otieno. *Validity and Errors in Water Quality Data: A Review.* Proposal accepted and Full paper submitted to INTECH Publishers.

3. Conference Paper: I Rangeti*, B Dzwairo, GJ Barratt, FAO Otieno. *Determining water quality parameters which influence chemical dosage in uMngeni basin*. Proceedings of the WISA 2014. Nelspruit, South Africa, 26-29 May 2014

4. Journal paper; I Rangeti1*, B Dzwairo, GJ Barratt, FAO Otieno. *Spatial and temporal water quality trends along uMngeni Basin for river health and treatability*. To be submitted.

5. Conference Paper: I Rangeti*, B Dzwairo, GJ Barratt, FAO Otieno. *A River Health Water Quality Index for uMngeni Basin (South Africa).* Abstract submitted to the 15th WaterNet/WARFSA/GWP-SA, Lilongwe, Malawi, 29 - 31 October 2014

GLOSSARY

CCME-WQI	Canadian Council Minister of Environment - Water Quality Index
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
IDI	Inanda Dam Inflow
IDO	Inanda Dam Outflow
MDI	Midmar Dam Inflow
MDO	Midmar Dam Inflow
MUWMA	Mvoti to Umzinkulu Water Management Area
NDI	Nagle Dam Inflow
NDO	Nagle Dam Outflow
RHWQI	River Health Water Quality Index
SANS	South African National Standard
TWQI	Treatability Water Quality Index
UNNWWAP	United Nation World Water Assessment Programme
WQI	Water Quality Index
WHO	World Health Organisation

CHAPTER ONE: OVERVIEW

1.1. Introduction

This chapter provides the background to this research. It outlines the problem statement, objectives, scope and limitations of the study. Finally, the structure of the dissertation is outlined.

1.2. Background

The escalating cost of producing potable water has been an issue of major concern (Dzwairo, Otieno and Ochieng 2011). A series of survey by the Global Water Intelligence have reported that global water tariffs rose by an average of 8.5% between June 2009 and June 2010 and a further 6.8% between July 2010 and July 2011 (Global Water Intelligence 2010; Zetland 2011). While factors like treatment technology, labour, electricity and government standards contribute to treatment costs, the fast deterioration of the quality of fresh water resources has been cited as the major driver of treatment cost (Dearmont, McCarl and Tolman 1998; Pretty *et al.* 2002; Sauer and Kimber 2002; Dzwairo 2011). Water, which is of poor quality, is not readily available and it generally requires sophisticated technology to make it fit for domestic use (Dearmont, McCarl and Tolman 1998; Lange and Hassan 2006; Netshidaulu 2007; Dzwairo 2011). This creates water scarcity as treated water becomes unaffordable to the poor.

During the purification of drinking water, a number of chemicals (e.g. disinfectants, coagulants and oxidants) are deliberately added at various stages. The objective is to produce water that is biologically, chemically and aesthetically acceptable for drinking purposes. The cost of chemicals is a major component of the operating cost of a potable water treatment plant (Dennison and Lyne 1997; Gebremedhin 2009). Additionally, the types and quantities of chemicals vary depending on a range of factors, such as, the incoming raw water quality, treatment technology, compulsory standards and the intended use.

Each water quality parameter (e.g. turbidity, pH, microorganisms, algae, nitrates, calcium etc.,) has either a direct or an indirect effect on chemicals used during treatment. For example, a high alkalinity level can help reduce the lime dosage, which is generally applied to create high pH levels. High pH is favourable for the coagulation process. A coagulant is a chemical used to agglomerate suspended particles into flocs which can then be removed by filtration (Voortman and Reddy 1997). An elevated level of turbidity tends to increase the coagulant dosage. It is, however, important to note that parameters are interrelated and cannot be investigated in isolation. A comprehensive study should help quantify the effect of the different parameters being monitored in order to give an overview of the treatability of raw water.

Besides the direct and obvious economic implications of using poor quality water, its consumption exposes consumers to various water-related illnesses like typhoid and cholera. Water-borne diseases alone cause approximately 3.4 million deaths annually (WHO 2003a). The use of poor quality raw water during treatment to potable water increases the risk of compromising the quality of final drinking water (Tiba and Hodgson 2008). Access to safe drinking water positively impacts on livelihoods by reducing poverty, improving education and health, and ensuring environmental sustainability (COHRE *et al.,* 2007).

In context to this situation, in 2007 the United Nations announced that fresh water scarcity resulting from pollution activities, population growth and climate change, are the main potential challenges for the 21st century, disregarding war and diseases (UN 2007). These factors could explain the presence of an estimated 768 million people (11% of the world's population) still living without access to safe drinking water (UNICEF 2012). Apart from the economic implications, increased pollutant levels may cause irreversible effects on aquatic life.

In Africa, deterioration of water quality is attributed to both point and non-point pollution, poor management strategies and lack of political will to implement policies that aim to reduce polluting activities and water scarcity (Falkenmark 1989; Donkor 2003; Swatuk 2005; Adedeji and Ako 2009).

South Africa is no exception to both pollution and water scarcity (Huntley, Siegfried and Sunter 1982; Herold 2009; Muller *et al.* 2009). Estimates indicate that the country could experience severe water scarcity by 2030 (NBI 2012). South Africa is even listed among the 30 driest countries in the World, with only 8.6% of its rainfall being available as surface water (Cannata *et al.* 2010). This is one of the lowest conversion ratios in the world. Furthermore, the spatial distribution of the water resources is mismatched between demand and supply. Determination of key water quality parameters influencing chemical dosage during treatment could therefore assist water resource managers to formulate and implement methods of protecting raw water sources. This should maintain the water resources in a viable state instead of exploring new and pristine water resources which could get exhausted, considering the current rate of population growth (1.34% which is considered to be high compared to the global average for 1.1%) (Statistics South Africa, 2013)

South Africa's guidelines for water intended for domestic use are comparable with global guidelines (Department of Water Affairs and Forestry 1996a; Environmental Protection Agency 2009; WHO 2011). When the expected quality levels are not met, potable water users will either pay an additional cost for treatment or at least risk contracting waterborne disease that may result in loss of human life (Loucks and Van Beek 2005). In areas where the quality of water significantly deteriorates downstream (e.g. Vaal Basin in South Africa), accumulated cost due to diminishing quality is sometimes either offloaded to customers in the form of tariffs or that the water utility might be operating at a loss (Dzwairo, Otieno and Ochieng 2011). This situation also increases the risk of compromising the quality of final water which could result in loss of life (Tiba and Hodgson 2008).

In cases where tariffs incorporate associated cost due to diminishing water quality, poor families might fail to pay the resultant high tariffs. As a result, they resort to poor quality sources even though they live in a community serviced by a potable water supply. Thus, the water industry should seek to produce high quality water at a reasonable cost to ensure its availability to all (WHO 2007; Valentin, Denoeux and Fotoohi n.d.). Determination of key water quality parameters that drive treatment cost could help in strategising effective methods for protecting the water resource, choice of cost effective treatment processes as well as forecasting treatment budget.

It is concerning that quality variability was omitted in the Government Gazette No. 29697 of the 16th of March 2007 for the pricing of raw water in South Africa. The Department of Water Affairs (DWA) is currently (2013) pricing raw water at the same annually stipulated price regardless of its quality (Dzwairo, Otieno and Ochieng 2011; Elder IV *et al.* 2012). The price is set after consultation with interested stakeholders such as water utilities, local governments and industries. Treatment plants, despite receiving water of variable quality, should produce drinking water of a compulsory high quality standard as stipulated in the South African National Standard for drinking water (SAN 241:2011). This suggests that water treatment utilities downstream of catchments receiving poor quality water, might either be operating at a loss or offloading the associated treatment cost to the end user in tariffs.

In the Vaal Basin (South Africa) where the price of raw water contributes about 50% of the total production cost as reported by Wyk (2001), quality variability is a significant cost factor among water utilities abstracting upstream-downstream of each other within a basin (Dzwairo 2011). Such a scenario increases the risk of compromising quality of the final potable water, with potential adverse effects on human health, such as diarrhoea, typhoid and some cancers (Tiba and Hodgson 2008). Communities residing along the river bank, who depend primarily on the river, could also suffer increased disease outbreak as a result of using contaminated water. Research targeting the Upper and Middle Vaal Water Management Catchment Areas in South Africa concluded that incorporating water quality variability into the cost chain for water services had the impact of trading pollution among upstream-downstream users (Dzwairo 2011; Dzwairo, Otieno and Ochieng 2011).

The uMngeni[1] Basin (Figure 1-1) is no exception to water scarcity, pollution and the escalating potable water treatment cost. A report by the Department of Water Affairs

[1] In this study, the river studied was referred to as, “uMngeni”. It is however also spelt as Mgeni and Umgeni in some text.

states that the quality of water was fair upstream of uMngeni River, but generally deteriorated downstream (Department of Water Affairs and Forestry 2003). Direct discharge of sewage effluent into the river has been cited as the significant polluting activity in the Basin (Department of Water Affairs and Forestry 2003; Isikhungusethu Environmental Services 2011). A study by Dennison and Lyne (1997) on DV Harris Water Treatment plant in Pietermaritzburg recognises water quality variability as the major reason for the high treatment cost at that plant. Although the study was performed in uMngeni Basin, there is a need for review since water quality is not static as pollution sources always vary.

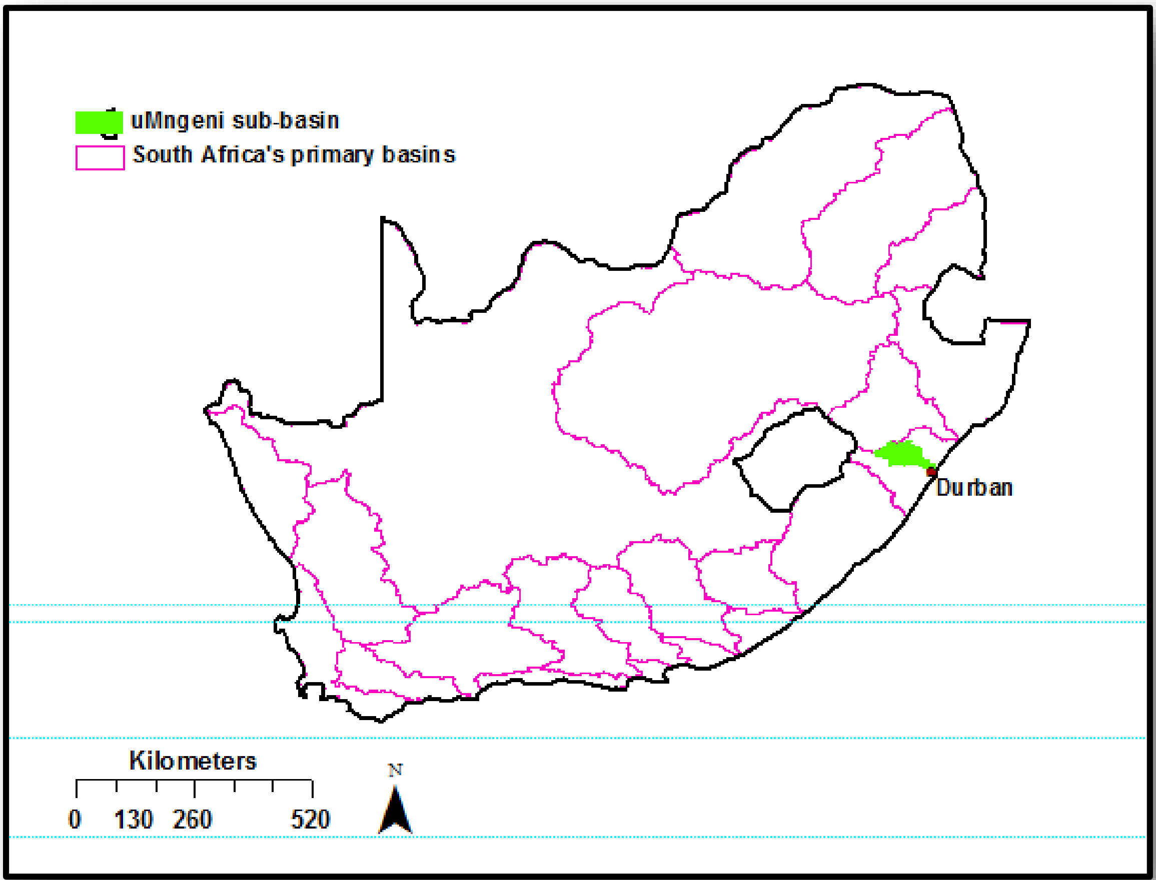


Figure 1-1: South Africa’s hydrological basins showing the position of uMngeni Basin

Graham (2004) conducted a study that was similar to the one by Dennison and Lyne (1997). The research focused on dams in uMngeni Basin to determine the impact of algae on treatment cost. It reported that increased algae was significantly affecting treatment cost. Following Graham's (2004) approach, this study statistically determined the significance of different water quality parameters monitored on treatment cost and further developed two water quality indices: (1) River Health Water Quality Index and (2) Treatability Water Quality Index. Non-linear regression models were also developed in an effort to predict chemical dosage at the two treatment plants Durban Heights and Wiggins. `

1.3. Problem Statement

In the uMngeni Basin, the deterioration of water quality has been reported and is attributed to informal settlements, agricultural run-offs and sewage effluent discharge (Graham 2004; Gebremedhin 2009). A recent study by Ganesh, Lin and Singh (2013) have reported that the quality of the lower sections of uMngeni River is severely contaminated by pathogenic bacteria like *Salmonella spp*, *Shigella spp*, *Vibrio cholerae* and viruses. These findings have resulted in uMngeni River being described as one of the 'dirtiest rivers in South Africa'' (Carnie 2013). This is of concern to the health of communities and directly implies an increase in treatment cost since the river system serves as an abstraction source for three treatment plants.

Personal communication by the treatment operational personnel at both Durban Heights and Wiggins Water Works showed that both plants have no rule or equation that predicts the dosage of polymer, chlorine and lime. Chemical dosage is currently determined by a laboratory technique known as the Jar Test. The test requires an operator to take raw water sample of the same quality and apply different quantities of the coagulant to each sample while maintaining pH. After a short period of time, each sample is analysed and the dosage that produces the optimal result is used as a set point to a Streaming Current Detector (SCD) or Ion Charger Analyser (ICA). To ensure good effluent quality, an operator adjusts the coagulant doses in accordance with the quality of raw water**.** Although the SCD have been serving for feedback control at these plants, concern has been raised for need to predictive tools to forecast budget (Valentin, Denoeux and Fotoohi n.d.). Under-dosing leads to a failure to meet the expected standard while excessive coagulant overdosing leads to increased treatment costs and public health concerns.

While it is understandable that the main agenda of a water quality monitoring program is to generate information for decision-making, it is of concern that the program has been described as suffering the "data-rich, but information-poor syndrome". This is due to the accumulation of large volumes of data which has been under-utilised for decision-making (Ward, Loftis and McBride 1986; Maasdam 2000). Umgeni Water is not an exception with huge volumes of water quality monitoring data accumulating daily. For instant, the current Water Quality Index at Umgeni Water has been considered too general for determining fitness for potable treatment since it also contains parameters deemed irrelevant for showing the overall treatability status. This may lead to an incorrect evaluation of the overview status of water quality which could result in the use of polluted water. It is however, a prerogative right for every environmentalist to assist in updating tools for monitoring for the purpose of protecting the aquatic ecosystems and potable water abstraction source. Analysis of the accumulated monitoring data should assist in developing a better Water Quality Index for decision making.

Early water quality studies have been basically econometric, reflecting the effect of diminishing quality due to pollution using the price of the chemical (Dearmont, McCarl and Tolman 1998; Graham 2004; Gebremedhin 2009). While considering that the price of chemicals is directly influenced by market forces, a low demand and high supply might fail to reflect the effect of diminishing raw water quality as it usually results in low chemical cost. Such a scenario makes it cheap to produce potable water using raw water of poor quality, thus making it difficult to sensitise the polluter on the essence of maintaining raw resources in a good state. However, chemical dosage is determined by the quality of raw water and would thus provide a better reflection of the effect of pollution.

1.4.Justification

Umgeni Water is the largest water treatment utility in KwaZulu Natal and draws its raw water from dams within uMngeni Basin. Determining key water quality parameters influencing chemical dosage during treatment could help water resources managers focus on the protection of raw water quality instead of exploring new pristine water resources which could get exhausted, given the current rising rate of population growth. With regard to the study area, uMngeni Basin, the findings could help sensitise Mvoti to Umzinkulu Water Management Area, on the importance of maintaining a water source that meets minimum guidelines in order to reduce the treatment cost.

Since water quality is not static, a review of spatial and temporal water quality trends should assist in determining the pollution pattern and the long-term viability of the basin as a provider of raw water for potable water production. The temporal trends could help determine the time of year when a given parameter could significantly impact treatment. Such knowledge should assist in budgeting chemical dosage for a treatment plant.

The dissemination of water quality information especially to the general public and policy makers has been a major challenge due to the bulk nature of monitoring data. A water quality index (WQI) is a tool that summarises and presents large amounts of technical data as a single value to enhance communication. A single value is more understandable by concerned stakeholders especially policy makers and the public who always expects an understandable means of assessing and comprehending the status of the water resource (Wepener *et al.* 1992; Cude 2001; Nasirian 2007). The two WQIs; (1) for determining the treatability of raw water and (2) for assessing the overall river health water quality of uMngeni River, could serve the purpose as effective tools for disseminating information. A raw water treatability WQI would assist in giving an overview of the level of treatment expected for a given quality of water. A river health WQI on the other hand, would assist in assessing the overall pollution pattern of a catchment.

The models to be produced should assist in minimising under or over budgeting of chemicals, both of which are detrimental to the cost efficiency running of a potable water treatment plant. This could assist in budget forecasting thus ensuring the long-term provision of higher quality potable water at an affordable price.

A holistic approach should help ensure the sustainable availability of potable water at a reasonable cost, as well as protection of aquatic ecosystems. A management tool such as a WQI could assist in classifying abstraction points in a catchment area. The index together with the models could help justify the necessity of pricing raw water according to quality variability by the Department of Water Affairs. For potable water end-users, the benefit is health intrinsic as it insures the supply of high quality at an equitable tariff structure. Finally, it could be extended to other potable water providers.

1.5.Main Objective:

The general objective of this study is to determine water quality parameters significantly influencing chemical dosage when producing potable water production using raw water abstracted in uMngeni Basin.

1.5.1.Specific objectives:

The following specific objectives were identified for the purpose of this study:

1. To evaluate the spatial and temporal water quality trend along uMngeni River in relation to river health status and potable treatment cost.
2. To produce two water quality indices: (1) for describing the general river health status and (2) determining the treatability of raw water being abstracted in uMngeni Basin.
3. To statistically determine water quality parameters whose concentrations showed significant change due to treatment and to correlate them with polymer, chlorine and lime dosage at Durban Heights and Wiggins treatment plants.
4. To develop models for predicting polymer, chlorine and lime dosage at Durban Heights and Wiggins Water Treatment Plants.

1.6.Scope and Limitation of the Study

- The study focused primarily on uMngeni River and dams along its course. Nevertheless, the catchment also drains other rivers with dams where water is also being abstracted. The river uMngeni provides 90.5% of the total raw water used by Umgeni Water to produced potable water as depicted in Table 1-1. The study assumed that such a proportion would give a justifiable reflection of the whole catchment area.

- The study was limited to Durban Heights (largest plant) which produces a proportion of 42% and Wiggins (second largest) which produces 21.4% of the total production as shown in Table 1-1. Based on the fact that these two plants contribute a total of 63.4% among the twelve treatment plant utilities, the study considered them as a reasonable representation of the overall treatment operations in the basin.

- The study only considered water quality parameters as significant variables in determining treatment costing thus factoring out other elements such as electricity and wages, which could also affect potable water treatment cost.

Table 1-1: Proportion of the potable water volumes produced by Umgeni Water's treatment plants

Adopted and modified: Source: (Umgeni Water 2014)

Water Treatment Plants	**Dam supplying raw water**	**Primary River system**	**Volume produced Ml/d**	**% of total potable water**
Durban Heights	Nagle	uMngeni	523	42
Wiggins	Inanda	uMngeni	267	21.4
Midmar	Midmar	uMngeni	246	19.7
DV Harris	Midmar	uMngeni	92	7.4
Hazelmere	Hazelmere		46	3.7
Amanzimtoti	Nungwane	South Coast	20	1.6
Mvoti	Mvoti River	Mvoti	20	1.6
Mzinto	EJ Smith and Umzimo Dam	South Coast	12	1.0
Mtwalume	Mtwalume River	South Coast	9.6	0.8
Ixopo	Ixolo Dam	Mkomazi	2.5	0.2
Maphephethwa	Nagle	uMngeni	2.6	0.2
Ilembe Rural Schemes		Mooi	6	0.5

1.7.Structure of the Thesis

Chapter One: Introduction

This chapter provides an introduction of the study. The problem statement, objectives, scope and limitations of the study are discussed.

Chapter Two: Literature Review

The chapter reviews the relevant literature in relation to the main objectives; water pollution, water quality trend analysis, potable water treatment, water quality indices and chemical dosage models. It starts with an overview of water quality situation around the world, South Africa and in uMngeni Basin. The chapter proceeds to discuss the effect of different water quality parameters on chemical processes during treatment and on river and human health. Different methods of developing water quality index and models are discussed.

Chapter Three: Study Area

This chapter covers the study area. It describes the physical setting of the uMngeni Basin along with aspects of water quality and pollution. The chapter further discusses the positioning of the abstraction points and the operations of Umgeni Water.

Chapter Four: Material and Methods

A narrative description of the methods used to research the thesis topic is outlined in this chapter. The sections describes methods for analysing water quality trends, developing water quality indices and models.

Chapter Five: Results and Discussions

The findings based entirely on the four specific objectives of the study are presented and discussed in detail against the contents of the literature reviewed.

Chapter Six: Conclusion and Recommendations

This chapter concludes the study and further give recommendations for future research work.

1.8.Summary

The objective of the chapter was to give a background of the study. The problem statement is outlined in relation to the South African situation and the study area, uMngeni Basin. The chapter describes how the variability of water quality significantly affects treatment cost. The need to shift from the “data-rich, information-poor syndrome’’ syndrome is discussed. To counter act the “data-rich, information-poor syndrome”, two water resource management tools, water quality indices and models are to be developed for Umgeni Water. The indices are anticipated to improve the dissemination of water quality information to non-technical stakeholders including the general public. Chemical dosage models are to serve the purpose of predicting chemical dosage. In conclusion, the four objectives are collectively anticipated to justify the need of pricing raw water according to quality variability.

CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

This chapter reviews the relevant literature within the specific objectives aspects; water pollution, water quality trend analysis, Water Quality Index (WQI) and modelling. It starts with a description of the water quality problems in South Africa and focusses attention on uMngeni Basin. Emphasis is on how the variability in concentration of different water quality parameters influence chemical dosage and the overall river health status. The major characteristics in historical data-sets which needs attention during the analysis are also discussed. The chapter also described the different methodologies of developing WQIs. Finally, the different methods for determining chemical dosage are described.

2.2. South Africa's Water Quality Situation

CSIR (2010) highlighted that the quality of water in the country's main catchment areas, the upper and middle reaches of the Vaal, uMngeni, Crocodile River (West) and the upper and lower reaches of the Olifants River have been gradually deteriorating at a rate that now poses a serious health risk to humans and livestock. In the Vaal Basin, Dzwairo (2011) noted that the quality of water deteriorated downstream and cited mine effluent as the main polluting activity.

Along uMngeni River, the quality of water is generally fair upstream, but gradually deteriorates downstream (Department of Water Affairs and Forestry 2003; Alexander and Smith 2005). Sewage effluent has been cited as the main source of river pollution (*Fresh Water Resources: State* 1999; Graham 2004; Alexander and Smith 2005; CSIR 2010). At Howick Sewage Treatment Plant, operations are always close to full capacity (CSIR 2010). The utility have been reportedly discharging raw sewage into uMngeni River particularly during the rainy season to relieve overloading (CSIR 2010). This also applies to Darvill Waste-water Treatment Plant in Pietermaritzburg where sewage effluent is creating problems in the uMsunduze River (CSIR 2010). Unskilled operators, outdated and inadequate sewage treatment infrastructure have been aggravating the pollution situation in the uMngeni Basin (Snyman, Van Niekerk and Rajasakran 2006; Rietveld, Haarhof and Jagals 2009).

Agricultural run-off of fertilisers and dung from dairies and piggeries are also causing pollution along uMngeni River (Isikhungusethu Environmental Services 2011). As a result, a report by Isikhungusethu Environmental Services (2011) for the uMgungundlovu District Municipality claimed that phosphorous loads along uMngeni had increased by 85% at Midmar Dam, 132% at Albert Falls and 668% at Nagle Dam in the recent decades. These dams are all in the same river system and run into each other, which may exacerbate the increased levels of pollution from one dam to the next.

Isikhungusethu Environmental Services (2011) further projected that Midmar and Albert Falls dams would soon be classified as eutrophic, while Nagle Dam could reach hypertrophic levels by 2019. Such reports are of concern when considering that pollution tends to increase treatment costs. Determination of key parameters in a watershed should help continuously assess the long-term sustainability of the basin (Khan and Simpson 2002).

2.3. Effect of Diminishing Raw Water Quality on Treatment Cost

During the production of potable water, numerous chemicals are added to make water safe for drinking purposes. The cost of chemical dosage is significant and directly reflects the economic impact of a deterioration of raw water quality. A study by Dearmont, McCarl and Tolman (1998) reported that a 1% increase in turbidity caused a one-fourth of a percent increase in chemical cost. Following other studies, Dearmont, McCarl and Tolman (1998) used turbidity as a primary indicator of water quality and modelled how its change influenced coagulation (Forster, Chris and Douglas 1987; Moore and M. 1987; Holmes 1988). That study produced an econometric model that predicts treatment cost as a function of raw water quality variability.

In Zimbabwe, deterioration of water quality in Lake Chivero, which supplies Morton Jeffrey Water Works in Harare and produces potable water for 2.5 million customers, caused a significant increase in chemical usage during a period of 5 years (Maya 1996). Maya (1996) reported that the amount of aluminium sulphate, a chemical used for coagulation at Morton Jeffrey doubled from 35-40 gm $^{-3}$ in 1991 to 75-80 gm $^{-3}$ in 1992, and then 100 gm $^{-3}$ by 1995. The study concluded that improving pollution prevention methods should ultimately reduce treatment cost.

In Kampala, Uganda, the treatment cost increased four-fold in 13 years, as noted in a study by Oyoo (n.d) to determine the impacts of the deterioration in the quality of water in Lake Victoria. The study indicated that an increase in treatment cost from 1992 to 2005 was as a result of a rise in aluminium sulphate dosage (Oyoo n.d). This increase in aluminium sulphate, a coagulant that was being used, was attributed to the gradual deterioration in raw water quality.

Similar studies have been conducted in the study area of KwaZulu-Natal, South Africa. At DV Harris Water Treatment Plant in Pietermaritzburg, Dennison and Lyne (1997) identified the variability of water quality as the main driver of high water treatment cost at that plant. High electricity consumption resulting from frequent backwashing of filters clogged by algae was cited as a significant driver of treatment cost (Dennison and Lyne 1997). The study also reported low turbidity level as significantly exacerbating treatment cost. The rise in treatment cost was a result of bentonite, an inorganic mineral composition which is normally added to enhance the formation of flocs.

Graham (2004) conducted a similar study to establish the relationship between raw water quality parameters, in particular the types and abundance of algal species, and treatment cost at four treatment plants; Hazelmere, Durban Heights, DV Harris, and Wiggins. The study utilised monthly water quality monitoring data ranging from 1990 to 1996 and concluded that algae was the main driver causing the escalating of treatment cost. Although Graham (2004) study was significant since it produced a model for prediction of algae bloom, the fact that water quality is not static stimulates the need for the continual determination of key water quality determinants that influence cost with time.

2.4. Water Quality Trends Analysis

The principal research question in any water monitoring program is to determine whether the quality of water has changed over time (Darken 1999). Where such change is noted, the next step would be to statistically test its significance. Chandler and Scott (2011) defined trend analysis as the use of an empirical approach to quantify and explain changes arising in a system over a period of time. This assists in determining the pollution pattern and provides a scientific basis for making decisions (Mozejko 2012).

For a catchment serving as an abstraction source for a potable water treatment plant, trends assist in assessing its long term viability as a raw water source. A comparison of the change in water quality variability in relation to chemical dosage should assist determine parameters that exhibit the greatest effect during treatment.

Antonopoulos, Papamichail and Mitsiou (2001) outlined that trend analysis has gained considerable attention over the years mainly due to two reasons. The first reason is to determine whether water quality has changed and further establish the cause for such a change. The second reason is the presence of a substantial quantity of data that is suitable for an analysis (Antonopoulos, Papamichail and Mitsiou 2001). The success of a trend analysis according to Reckhow, Kepford and Hicks (1993) depends on the main principles listed below:

- acquisition of water quality data from a properly designed monitoring program,
- application of appropriate statistical methods for trend detection, and
- a clear understanding of relevant water quality parameter correlations.

A wide range of methods has been formulated to analyse trends in water quality data-sets. These range from simple descriptive methods such as, time-series plots, box-plots to new machine learning techniques such as Artificial Neural Network (ANN) (Helsel and Hirsch 1992; Recknagel *et al.* 2002). Although observational methods, such as the time-series, may show the presence of a trend in a data-set, there is still a need for applying some statistical test to determine its significance (Helsel and

Hirsch 1992; Mozejko 2012). The success of this analysis primarily depends on selection of an appropriate method that accommodates the common characteristics in secondary data-sets.

The different statistical methods for testing water quality trend can be categorised as either parametric or non-parametric (Hirsch, Alexander and Smith 1991; Fu and Wang 2012). A parametric method assumes normality in the data-set while non-parametric methods assumes robustness (Helsel and Hirsch 1992; NWQMS 2000). While parametric methods have been widely cited as more effective in detecting monotonic trend, studies have widely recommended non-parametric techniques, which generally over-ride the effects of outliers, missing values and censored values (Hirsch, Slack and Smith 1982a; Helsel and Hirsch 1992). The Seasonal-Kendal test is an example of a non-parametric test method.

However, when using secondary data in developing water quality management tools such as water quality indices and models, there is a need to consider common characteristics in data-sets. A review of these common characteristics should assist in effective trend analysis and the formulation of more appropriate decision-making tools such as water quality indices and models.

2.5. Secondary Data Characteristics and Treatment Methods

While a water quality monitoring program aims to generate reliable data to assist in decision making, it should be highlighted that errors tends to arise at various stages of the process. If these errors are not identified and treated appropriately, and are incorporated into decision making tools like a water quality index (WQI), the resultant effect could be detrimental. For example, a potable WQI which does not incorporate *Escherichia. coli (E. coli)* may classify water as clean while it is actually contaminated with pathogenic bacteria that can cause human fatality.

Before subjecting data to in-depth statistical analysis, a visual scan of the data-set can assist in assessing its integrity. This can assist to distinguish values that are distinct and which might require attention during the analysis and modelling stages. However, because some of the underlying anomalies cannot be determined by such a general virtual scan, one might have to also consider using statistical methods. The common characteristics in water quality data-sets, outliers, missing values and censored-values are reviewed in the below section.

2.5.1 Outliers (extreme observation)

Outliers are observations that appear to differ in their characteristics from the bulk of the data to which they are assigned (Díaz Muñiz *et al.* 2012). They usually arise from an imprecise measurement tool, sample contamination, incorrect laboratory analysis technique, mistakes during data transfer, incorrect statistical distribution assumption or a novel phenomenon (Iglewicz and Hoaglin 1993). Incorporating outliers into a management tool, for instance in a water quality model might result in a faulty tool that can ultimately lead to decisions that are costly to the environment (Chiang, Pell and Seasholtz 2003).

If an outlier is ascertained to be erroneous, based on judgmental or scientific grounds, it can be discarded (Snyman, Van Niekerk and Rajasakran 2006). This option is usually used when the data assumes normal distribution and under the assumption that if the outlier is removed, the data-set becomes normal (Helsel and Hirsch 1992). Rousseeuw and Leroy (1987) however, regarded this practice as the least reliable and instead, recommended the use of robust statistical approaches like the Seasonal-Kendal test which accommodates extreme values.

Both observational (graphical) and statistical techniques have been applied to identify outliers in different studies. Among the common observational methods are the box-plots, time series, histogram, ranked data plots and normal probability plots (Silva-Ramírez *et al.* 2011). These methods basically detect an outlier value by quantifying how far it lies from the other values. This could be the difference between the outlier and the mean of all points, between the outlier and the next closest value or between the outlier and the mean of the remaining values (Stoimenova *et al*. 2006).

The box-plots and time-series are the common simple observational methods for identifying outliers (Silva-Ramírez *et al.* 2011). A box-plot method according to Environmental Protection Agency (2006) identifies outliers as:

- data points between 1.5 and 3 times the Inter Quantile Range (IQR) above the 75th percentile or between 1.5 and 3 times the IQR below the 25th percentile, and
- data points that exceed 3 times the IQR above the 75th percentile or exceed 3 times the IQR below the 25th percentile.

The limitation of a box plot is that it is basically a descriptive method that does not allow for hypothesis testing and thus cannot determine the significance of an outlier (Köster and Hutchinson 2008). Furthermore, because observational methods may sometimes fail to identify subtle outliers, the next step could be to apply statistical techniques.

Statistical modelling techniques like linear regression (Autio, Juhola and Laurikkala 2007), multivariate analysis (Rousseeuw and Leroy 1987; Barnett and Lewis 1995) and time-series analysis (Autio, Juhola and Laurikkala 2007) have been used to detect outliers in studies. The strength of multivariate methods is on their ability to incorporate the correlation or covariance between variables thus making them more correct as compared to univariate methods.

For data intended for trend analysis, studies have recommended the application of nonparametric techniques such as the Seasonal-Kendal test where transformation techniques does not yield symmetric data (USEPA and Department of Ecology 2011). Should a parametric test be preferred on a data-set that includes outliers, practitioners may evaluate the influence of outliers by performing the test twice, once using the full data-set (including the outliers) and again on the reduced data-set (excluding the outliers). If the conclusions are essentially the same, then the suspect datum may be retained, failing which a nonparametric test is recommended.

In addition to statistical analysis methods, Rousseeuw and Leroy (1987) further recommended the use of a model in to identify outliers. Since the model are derived using the catchment's natural background data, they allow one determine a deviation from the usual pattern. A significant deviation from the known natural pattern can be regarded as an outlier.

2.5.2 Missing value

While most statistical methods presumes a complete data-set for analysis, missing values are frequently encountered problems in water quality studies (Noor and Zainudin 2008; Ssali and Marwala n.d). Missing values complicate data analysis, cause loss of statistical efficiency and reduces statistical estimation power (Noor and Zainudin 2008; Ssali and Marwala n.d). Gaps in water quality data-sets may arise due to several reasons, among which are imperfect data entry, equipment error, loss of sample before analysis and incorrect measurements (Calcagno *et al.* 2010).

The best way to treat missing values is to repeat the experiment and generate a complete data-set. This option is, however, not feasible with a retrospective study. Where it is not possible to re-sample, one can use either a model or the non-model approach to estimate missing values (Lakshminarayan, Harp and Samad 1999).

Ssali and Marwala (n.d) suggested the use of mean of all reported values to estimate missing values. Its major advantage is that it produce a complete data-set, which in turn allows for the use of standard analysis techniques. However, as the proportion of missing data increases, deletion tends to introduce biasness and inaccuracies in subsequent analyses.

Fogarty (2006), recommended a model-based substitution method as more flexible and less ad hoc than non-model techniques. A simple modelling technique is to regress the previous observations into an equation which estimates missing values (Ssali and Marwala n.d). Unlike the arithmetic mean and median replacement methods, regression imputation techniques estimates missing values of a given variable using data of other parameters. This tends to reduce the variance problem, which is common with the arithmetic mean imputation and median replacement methods (Nieh 2011)

Güler *et al.* (2002) suggested the estimation of missing values by using the known relationship between two parameters. For instance, missing conductivity values can be calculated from the total dissolved solids value (TDS) by a simple linear regression as shown in Steel, Clarke and Whitfield (1996).

2.5.3 Censored values

Censored values are results below detection limit (BDL) or above the detection limit (ADL) (Lin and Niu 1998; Darken 1999). These usually arise when a laboratory procedure fails to detect the concentration of a parameter being monitored because it is either too small or too large for the detection range of the instrument or methodology.

While there is generally no universally accepted method of treating censored values, deletion has been regarded as the worst form of treatment (Helsel 2006). Lopaka and Helsel (2005) and Nishanth *et al.* (2012) explained that discarding censored values tend to produce a strong upward bias in all subsequent measurements, in this instance, means and medians. Some studies considered censored data as missing values and thus substituted them with zero or the mean of reported values (Data Analysis and Interpretation 2000).

The relatively easy and most common method of handling censored values is to replace them with a real number value so that they conform to the rest of data. The United State Environmental Agency suggested substitution if censored data is less than 15% of the total data-set (Kalderstam *et al.* 2013). Dzwairo (2011) multiplied BDL of less than 1.1 by the factor 0.75 to give 0.825. Hewett and Ganser (2007) recommended substituting with $\frac{1}{2}$BDL or $\frac{1}{\sqrt{2}}$BDL if the sample size is less than 20 and contains less than 45% of its data as censored values. Kang (2013) however, criticised substitution and illustrated how the practice could produce poor estimates of correlation coefficients and regression slopes.

For data assuming normality and containing censored results, the Maximum Likelihood Estimation method (MLE) is used (Sanford, Pierson and Crovelli 1993; Antweiler and Taylor 2008). The MLE approach generates an equation that calculates the mean and standard deviation from values assumed to represent both the detect and non-detect results (Helsel 1990). This technique has been recommended as effective when the sample size is large and shows a definable distribution (Helsel and Cohn 1988; Hewett and Ganser 2007). However, it is ineffective for a small data-set and has fewer than 50 BDLs (Helsel 1990).

When data assumes an independent distribution and contains censored values, non-parametric methods like the Kaplan-Meir method, can be considered for analysis (Lopaka and Helsel 2005). The Kaplan-Meir method creates an estimate of the population mean and standard deviation, which is adjusted for data censoring, based on the fitted distribution model. Just like any non-parametric techniques for analysing censored data, the Kaplan-Meier is only applicable to right-censored results (i.e. greater than) (Fu and Wang 2012). To use the method on left-censored values, the results must be converted to right-censored by flipping them over to the largest observed value (Hewett and Ganser 2007; Antweiler and Taylor 2008; Fu and Wang 2012). Antweiler and Taylor (2008) however found the Kaplan-Meier method to be effective when summarising a data-set containing up to 70% of censored results.

2.6. Methods for Developing Water Quality Indices

Early water quality classification has basically been descriptive, with turbidity, presence or absence of certain macro and micro-organisms etc., having been unit to described the quality of water (Couillard and Lefebvre 1985). Such an approach produced huge complex numerical reports that made it difficult for politicians, decision-makers and the general public to understand since they lacked expertise as well as time to follow up (Hallock 2002; Parmar and Parmar 2010). Nasirian (2007) highlighted that this was of concern as the approach could not convey the necessary information to the general public who have a right to know about the status of their environment. There was, thus a need, for a tool that translates bulk water quality monitoring data to information that can be understood by the community and policy-makers (Horton 1965;

Cude 2001; Hallock 2002). Furthermore, interpretation of a large number of water quality data is required to enhance effective water pollution control and water resources management.

A Water Quality Index (WQI) has emerged as a tool that can translate huge data sets to a single value (Horton 1965; Walsh and Wheeler 2012). It has been widely recognised as a mathematical instrument that incorporates data of multiple water quality parameters and gives an overall single value that rates the general health status of a water system (Couillard and Lefebvre 1985; Stambuk-Gijanovic 1999; Cude 2001; Wepener *et al.* 2006). A single value is more understandable and helps keep the public, who are the custodian of the resource, updated. By keeping the public updated, it makes them more participatory in policy formulation and decision making regarding the protection of the water resource. Couillard and Lefebvre (1985) and Wepener *et al.* (2006) have described a WQI as a bridge between water quality monitoring and reporting.

2.6.1. Steps for developing a Water Quality Index

WQIs are basically developed using four steps namely; parameter selection, data transformation, assigning of weight factors and aggregation of the overall Water Quality Index (Couillard and Lefebvre 1985; Wepener *et al.* 2006; Boyacioglu 2007; Dzwairo 2011).

1. ***Parameter selection***

Whereas hundreds of parameters may be monitored by an agent, only a few need to be considered when developing a specific index. This stage can be regarded as the most tricky because the exclusion of relevant parameters may lead to the loss of important information. Incorporating many parameters tends to produce an unwieldy index that may not give a better description of the fitness of water for its intended use. In cases where an important parameter, e.g. *E. coli,* is excluded in an index for determining the fitness of water for drinking purposes, the resulting tool would be faulty. This could ultimately lead to human health consequences. Thus, the choice of parameters to include in an index continues to present a major challenge.

Horton (1965) used a committee to debate whether or not to include a parameter. Brown *et al.* (1970) administered questionnaires to experts in order to capture their opinion on the best parameters for consideration in the WQI. Both approaches were criticised as researchers argued that "experts" judgements were biased towards their backgrounds, making it almost impossible to construct an agreeable water quality index (Lohani and Todino 1984).

Principal Component Analysis (PCA) has been suggested as a better approach of selecting parameters to include in an index (Pesce and Wunderlin 2000; Wepener *et al.* 2006). The approach reduces huge water quality monitoring data sets without loss of information, and can explain the variance among a large set of correlated variables using Principal Components (Pesce and Wunderlin 2000; Wepener *et al.* 2006).

Wepener *et al.* (2006) and House and Ellis (1980) however, suggested that three criteria should be fulfilled for a parameter to be considered significant for inclusion in an index. In specific, (a) data for that parameter must be readily available, (b) it should be an important indicator of water quality change or pollution and (c) there should be maximum water quality criteria set for the variable selected.

2. Data transformation

Water quality parameters are generally measured in varying ranges and expressed as different units. The purpose of variable transformation is thus to eliminate units and produce a dimensionless scale with two end-points (Couillard and Lefebvre 1985). The highest normalised value shows acceptable quality while the lowest depicts unacceptable with regard to the intended use (Richardson 1997). Numerous ranges have been suggested, some of which are 10 to 100, 0 to 25, 0 to 14, 0 to 5 and 0 to 1 (Wepener *et al.* 2006). Dzwairo (2011) used the range 1 to 5 as suggested by House and Ellis (1980), who argued that water always has some economic value (e.g. transport,) even if it is polluted, and thus should always have a value greater than zero. Some studies have purposely avoided zero in order to counter act the eclipsing (underestimation) problem in indexing (Wepener *et al.* 2006).

Although several variable transforming methods have been suggested, the Rating Curve (RC) method has been widely regarded as the most efficient technique (Walski and Parker 1974; Smith 1990; Wepener *et al.* 1992). This approach uses a graph or mathematical function to transform the measure value to an approximate ‘score’, value (Couillard and Lefebvre 1985). Other transformation methods such as rating tables, non-parametric multivariate ranking procedures as well as multiple regression analysis have also been developed to transform data (Wepener *et al.* 2006).

3. Assigning Weight Factors

The third step is to assign a Weight Factor (WF) to each parameter considered in accordance to its importance as an indicator for an intended purpose (Pesce and Wunderlin 2000; Jonnalagaddai and Mhere 2001; Dzwairo *et al.* 2012). Dzwairo *et al.* (2012) described a WF as a barometer to signal the level of harmful exposure to elucidate negative effects.

To rate a given parameter, one must have some background knowledge about that parameter (i.e. toxicity, permissible levels etc.). Parameters that have higher permissible limits are generally less harmful. Weightage is thus inversely related to its permissible limits (Kumar and Dua 2009). For example, in developing an index for determining suitability of water for drinking, faecal coliforms are assigned a higher WF than dissolved oxygen (DO). This is due to detrimental effects brought by the consumption of water containing faecal coliform. In most cases, WFs are averaged so that their sum is usually one (Couillard and Lefebvre 1985).

4. Aggregation

Aggregation has been defined by Tasić and Feruh (2012) as the process of adding transformed variables to come up with a single number that represents an approximate overall value of individual components. Several formulae have been suggested and used (Couillard and Lefebvre 1985; Wepener *et al.* 2006). However, aggregation functions can be generally categorised as additive, multiplicative, minimum and maximum operator forms (Ott 1978) In most cases, the choice of an aggregation method is influenced by their main limitations namely; ambiguity, eclipsing and rigidity (Ball and Chruch 1980; Couillard and Lefebvre 1985; Wepener *et al.* 2006). A most appropriate aggregation function would be one that is either free from or minimises ambiguity, eclipsing and rigidity problems.

Ambiguity (over-estimation) is when the value of an index exceeds a limit value when none of the individual quality scores do (Couillard and Lefebvre 1985; Wepener *et al.* 2006). This inconvenience can be avoided by standardising the index, which is done by dividing by the number of parameters. Eclipsing (under-estimation) is when an overall index score is acceptable but one or more of the variables exceed acceptable limits (Couillard and Lefebvre 1985; Wepener *et al.* 2006). Rigidity exists when additional variables are included in the index to address specific water quality concerns (Couillard and Lefebvre 1985). The following sections describes the common aggregation methods.

❖ *Weighted Arithmetic Mean*

The Weighted Arithmetic Mean method has been widely used in many studies (Brown *et al.* 1970; Landwehr and Deininger 1976; Couillard and Lefebvre 1985; Dinius 1987; Jonnalagaddai and Mhere 2001).

In order to calculate the overall index with this method, water quality components are multiplied by a Weight Factor and then aggregated using Equation 2-1. The weighted arithmetic mean method, has, however, been criticised because of the eclipsing problem (Couillard and Lefebvre 1985; Hallock 2002; Liou, Lien and Wang 2004). Thus, one should take this limitation into consideration when adopting the method or when interpreting the results (Parmar and Parmar 2010).

Equation 2-1

$$WQI = \sum_{i=1}^{n} Sli * Wi$$

Where *WQI* = Water Quality Index

Sli= Sub-Index

n = number of sub-indices

Wi= Weight Factor given to a parameter

- *Weighted Geometric Mean*

Since McClleland (1974) and Walski and Parker (1974) were concerned with the arithmetic mean method's lack of sensitivity (eclipsing), they proposed the weighted geometric mean, Equation 2-2, as a better alternative. Walski and Parker (1974) and Joung *et al.* (1979) described the weighted geometric mean as a less biased aggregation method. This method has also became known as NSF-WQI after being recommended and adopted by the National Sanitation Foundation of United States of America. It was developed to provide a standardised method for comparing water quality of various bodies of water.

Equation 2-2

$$WQI = \prod_{i=1}^{n} Sli^{wi}$$

Where *WQI* = Water Quality Index

Sli = Sub-index i

n = number of sub-indices

Wi = Weight Factor given to a parameter

However, some caution needs to be exercised as the method can exhibit eclipsing at low weights and when increasing the scale indices. The method also tends to lose its sensitivity as the number of variables increase (Walski and Parker 1974; Ball and

Chruch 1980; Dinius 1987; Swamee and Tyagi 2000; Chua *et al.* 2012). Thus, one needs to consider ways of counteracting these problems when adopting this method. For example, avoiding zero as a minimum normalised value (Q-value) counteracts the eclipsing problem. The use of few parameters also tends to retain the index sensitivity.

- *Minimum Operator*

Studies have highlighted the minimum operator, Equation 2-3, to be a better method since it avoids eclipsing and does not exhibit ambiguity (Smith 1990; Pesce and Wunderlin 2000; Flores 2002; Prakirake, Chaiprasert and Tripetchkul 2009). The index uses the lowest sub-index rating to calculate the final index score. This concept is similar to the limiting nutrient idea, where the poorest quality parameter can define the state of the water system (Couillard and Lefebvre 1985).

Equation 2-3

$$I = \min(\, q_1 * q_{2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots o} q_n \,)$$

When using the minimum operator index, the parameter that has the strongest influence on a system such as the biotic components of a river ecosystem should be selected. According to Nagels *et al*. (2001), the minimum operator method is particularly important for certain designated uses, like primary contact recreation. The main advantage of this method is that there is no restriction on the number of determinants employed. It also allow the introduction of new determinants without affecting index computation. Furthermore, the method is not ambiguous.

However, the usefulness of this aggregation is questionable because of lack of information it conveys. Wepener *et al.* (2006) advocated its use in combination with another aggregation method. Swamee and Tyagi (2000) however, described the minimum operator as totally insensitive to changes in the other variables, and concluded that it is not useful for monitoring purposes or for comparing two water bodies.

❖ *Solway Modified Un-weighted Sum*

The Solway Modified Un-weighted Sum method, Equation 2-4, have been described as a sensitive aggregation method with less bias to changes in water quality variables throughout their range (Richardson 1997).

Equation 2-4

$$I = \frac{1}{100}\left(\frac{1}{n}\sum_{i=1}^{n} q_2\right)$$

Wepener *et al.* (2006) recommended this method when less is known about the importance of one given parameter as compared to others. Furthermore, it can be applied when it is not possible to compare factors, which have a direct and interactive effect on each other, e.g. pH and heavy metals.

❖ *Canadian Council Minister of Environment Water Quality Index (CCME-WQI)*

The Canadian Council Minister of Environment Water Quality Index (CCME-WQI) was founded in 1995 based on a water quality index developed by British Columbia University (Fataei *et al.* 2013). This model compares water quality observations to benchmark values of different parameters instead of normalising the observed values by the use of rating curves. The benchmark values may be derived from national or local water quality guidelines or site-specific background information. Concentrations exceeding an upper screening benchmark indicate that the parameter in question is clearly of concern, and that remedial actions are likely to be needed. The CCME-WQI has been used to characterise the quality of water for several intended uses including agriculture, the protection of aquatic life and treated drinking water (Khan, Husain and Lumb 2003; Lumb, Halliwell and Sharma 2006).

One of the main limitations that have hampered the development of a universal water quality index for determining the treatability of water sources has been on the choice of parameter. In most cases, parameters of concern at one location may not be of concern elsewhere and therefore are rarely monitored. However, if a consistent set of parameters are routinely monitored, then an alternative index might be required that can incorporate all parameters at a given location. The CCME-WQI counters such limitation and provides a flexible template that is adaptable to any site. Practitioners are free to select appropriate parameters and guidelines for their purposes. This assists in accommodating the site specific and treatment considerations associated for water intended for a specific use such as drinking (UNEP and GEMS 2007).

The CCME-WQI (Equation 2-5) contains three components, F_1 (Equation 2-6), F_2 (Equation 2-7) and F_3 (Equation 2-8) as shown in this section.

Equation 2-5

$$WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2} + F_3^2}{1.732}\right)$$

Where WQI = Water Quality Index

F_1 = ***Scope:*** The percentage of parameters that exceed the guideline (Equation 2-6).

Equation 2-6

$$F_1 = \left[\frac{Number\ of\ \ Failed\ Parameters}{Total\ number\ of\ parameters}\right] * 100$$

F_2 = ***Frequency:*** the percentage of individual tests for each parameter that exceeds the guideline (Equation 2-7). “Failed parameters” are parameters that exceeded the guidelines.

Equation 2-7

$$F_2 = \left[\frac{Number\ of\ FailedTests}{Total\ number\ of\ test}\right] * 100$$

F_3 = ***Amplitude****:* the extent (excursion) to which the failed test exceeds the guideline (Equation 2-8).

Equation 2-8

$$F_3=[\frac{nse}{0.01+0.01}]$$

Calculating F_3 involves two steps that calculate excursion and normalised sum of excursion.

I. Qualitative Ranking

The description of the different water quality index scores is generally subjective since indices are normally site specific. The Department of Irrigation and Drainage (2009) summarised the various water quality range that has been used to describe water quality indices in Table 2-1. The higher value indicated that the water still supports the aquatic organisms while a smaller score values indicates high pollution level. A narrative description is used to describe the status of each range.

Table 2-1: A summary of water quality scores range and its respective description Source: (Department of Irrigation and Drainage 2009)

Class	USA	Class	Oregon	Class	British Columbia	Class	UWQI	Class	Korea
Excellent	91-100	Excellent	90-100	Excellent	0 - 3	Excellent	95-100	Very low	91-100
Good	71-90	Good	85-89	Good	4 - 17	Good	75-94	Low	71-90
Medium	51-70	Fair	80-84	Fair	18 - 43	Fair	50-74	Medium	51-70
Fair	26-50	Poor	60-79	Borderline	44 - 59	Marginal	25-49	High	26-50
Poor	0-25	Very poor	10 - 59	Poor	60 - 100	Poor	0-24	Very high	0-25

2.7. Chemical Processes during Potable Water Production

The principal objective of treating water is to produce water that is fit for domestic use in a reliable manner and at a reasonable cost (Schutte 2007). To achieve this goal, treatment plants basically employ some physical (filtration, sedimentation etc.) and chemical (disinfection, oxidation, coagulation, pH adjuster etc.) methods at different stages of treatment. Except for a few cases, each treatment stage removes many pollutants (Schutte 2007). For example, the disinfection process destroys a range of pathogens including viruses and bacteria as well as oxidise odour and colour causing pollutants such as iron (Fe^{2+}) and hydrogen sulphate (H_2S) (Parsons and Jefferson 2006; GE Power and Water 2012).

The use of different chemicals has been widely practised and generally accepted by different communities; even though there are some converse public health debates about their long term use. These chemicals are applied to reduce or eliminate the incidence of water-borne diseases, for other public health measures and to improve the aesthetic quality of drinking water (John and Trollip 2009). Chemical dosage depends primarily on the quality of raw water abstracted (Dzwairo 2011). In a normal conventional treatment process, coagulants, disinfectants, oxidants and pH adjusters are used at various stages of the overall treatment process (Dearmont, McCarl and Tolman 1998). Inappropriate dosage could result in the production of water with undesirable qualities. In a normal convectional treatment plant, the major four chemical dosage stages are pre-chlorination, pH adjustment, coagulation/ flocculation as well as post-chlorination. The role of the common chemicals used in a normal convectional treatment plant are briefly explained hereunder.

2.7.1. Pre-chlorination

The addition of chlorine at the head-works in a normal conventional treatment plant is mainly for the purpose of reducing odour, colour and taste problems. These pollutants makes water aesthetically unacceptable. By oxidising organic matter, the stage also reduces the biological oxygen demand and also aids the coagulation and settling stages.

Since chlorine is a strong oxidising agent, it quickly reacts with inorganic and organic compounds such as H_2S, Fe^{2+}, Mn^{2+}, NH_3, phenols, amino acids, proteins, and carbohydrates when dissolved in water (Parsons and Jefferson 2006; GE Power and Water 2012). These compounds normally cause taste and odour problems in drinking water. In oxidised form, these compound are normally insoluble and can then be clumped into flocs by the effect of a coagulant. The flocs are then removed by filtration and sedimentation. This oxidation process is not directly related to disinfection, but, significantly increase treatment cost. Determination of the chlorine breakpoint assist a treatment plant calculate the amount of chlorine serving the oxidation and residual effect (Taylor *et al.* 2001).

2.7.2. Oxidant

In most cases, metals and inorganic compounds present in a reduced state such as a Fe^{2+} and H_2S are the main cause of odour and colour problems in water. Since these pollutants are found in a dissolved state, their removal present a challenge. An oxidant such as potassium permanganate, chlorine and ozone works by oxidising these compounds to an insoluble oxide form (Yiasoumi, Evans and Rogers 2005). Iron for example is normally precipitated as ferric hydroxide ($Fe(OH)_2$), while manganese is precipitated as manganese oxide (MnO_2). The oxidised precipitate can then be agglomerated by the effect of a coagulant and finally removed by either sedimentation or filtration (Walmsely 2000). When the quality of water is relatively high, chlorine can also serve as an oxidant. However, for effect costing prediction, there is need for a treatment plant to determine the amount of chlorine serving the purpose oxidation purpose. Calculating the chlorine break point should assist in quantifying the amount of chlorine dosage serving the oxidation purpose.

Overdose of an oxidant also tends to create colour problems in the final water. Potassium permanganate for example may cause a pink colour, which makes water aesthetically unacceptable (WHO 2006b). If used in water containing toxin producing algae species, an oxidant can cause lyses of the cell membrane. This could lead to the release of toxins depending on the species of the algae, which can result in nerve, hepato or neuro health complications (Department of Water Affairs and Forestry 1996a; WHO 2006b). At Durban Heights and Wiggins, potassium permanganate is used only when high levels of manganese pollutant is noted.

2.7.3. pH adjuster

The level of pH in raw water is a major factor influencing the effectiveness of chemical treatment processes. It is used to create an environment for optimum coagulation. Lime (calcium carbonate, calcite, $CaCO_3$), quick lime (calcium oxide, CaO), and dolomite ($CaMg(CO_3)_2$) are normally used for this purpose. Low pH level is also known to be corrosive while high pH levels cause scale formation in the treatment and distribution system. Corrosion tends to cause leaks while scale-formation reduces the size of distribution pipes thus increasing pumping energy (Schutte 2007). These factors have substantial cost implications. Stabilisation of pH at neutral or slightly higher levels is thus expected to reduce the corrosion and scaling effect in distribution pipes and fixtures (Schutte 2007). The wide use of lime at most treatment plants including Durban Heights and Wiggins centres on its low price and availability.

2.7.4. Coagulation

While large particles can be easily removed by either allowing them to settle down due to weight (sedimentation) or by filtering them, the major challenge during treatment is on dissolved and suspended particles in water. These tend to create a cloudy appearance, which makes water aesthetically unacceptable (Department of Water Affairs and Forestry 1996a). Suspended organic particles can also be used as food by bacteria and thus causing re-contamination of water in the distribution system (Department of Water Affairs and Forestry 1996a; Payment, Waite and Dufour 2003). It is thus important to significantly reduce turbidity level before disinfection.

Colloidal particles in raw water typically have a net negative surface charge. A coagulant works by posing some degree of stability by means of neutralising the particulate charge. For example, if aluminium sulphate (alum) is dissolved in water, it forms aluminium ions (Al^{3+}), which neutralise the negative charges carried by the colloidal particles (Schutte 2007). When water is slowly stirred, the aluminium hydroxide flocs enmesh the small colloidal particles (Eikebrokk, Juhna and Østerhus 2006). The flocs readily settle and can be easily removed in a sedimentation tank (Schutte 2007). The success of the process depends on the treatment technology, raw water quality and purpose of the final water product. Turbidity, organic matter, pH, temperature among others affects the coagulation process (Pernitsky and Eng 2003).

The Jar test is widely used to determine the optimum coagulant dosage (Black *et al.* 1957; Schutte 2007).

The choice of a coagulant depends on the intended use of water and the treatment technology available. For example, inorganic coagulants tend to perform relatively better in high organic humic content water (Van Duuren 1998). Positively charged organic polyelectrolytes are however effective on many types of raw water (Freese, Hodgson and Nozaic 2004). Many countries generally use metal salts (e.g. aluminium or iron sulphates) and synthetic organic polyelectrolytes as coagulant.

Current studies have also determined the suitability of natural plants such as *Moringa* as coagulants (Ndabigengesere and Subba Narasiah 1998; Diaz *et al.* 1999). Even though *Moringa* eliminates the health concern associated with aluminium residues, studies have shown that the final water contains elevated level of organic residues (Ndabigengesere and Subba Narasiah 1998). Besides making the water aesthetically unacceptable, elevated organic residues levels also increase the chances of bacteria regrowth further causing recontamination of the treated water. High organic content also increases the chance of organic chlorinated formation, which are of health concern and have been linked to cancerous disease prevalence.

Although aluminium sulphate has been widely used as a coagulant in many treatment plants, it is slowly being replaced by polyelectrolytes due to a number of reasons. The first reason is that aluminium sulphate is only effective over a limited pH range of 6.5-7.5 (Ebeling *et al.* 2003). This means lime should be added when the pH of raw water if below 6.5. However, polyelectrolyte coagulants are effective over a wide range of pH and thus reducing the cost of adjusting pH as the case with aluminium sulphate. The second reason is that aluminium residual in treated water has been implicated to the pathogenesis of Alzheimer, a brain degenerative disease (Driscoll and Letterman 1995; Campell 2006; Gidde and Bhalero 2011). Even though some current studies have disputed such association, many countries have already took preventive measure by setting tolerable limits of aluminium residuals in drinking water. South Africa’s standards for example stipulates that drinking water should contain only contain aluminium residual of less than 300ug/L (South African Bureau of Standards 2011).

At Durban Heights and Wiggins Water treatment Plants, polyelectrolyte is used as a coagulant for a number of reasons (Freese, Hodgson and Nozaic 2004). These are man-made organic compounds made up of a long chain of smaller molecules, which just like metal coagulants work by charge neutralisation (Bolto and Gregory 2007). The first reason for its adoption is its effectiveness over a wide range of pH. By so doing, the cost associated with pH adjuster meant to optimise coagulation is ultimately reduced (Nozaic, Freese and Thompson 2001). As a result, Durban Heights recorded a significant reduction in chemical cost expenditure in the first five years of its use (Nozaic, Freese and Thompson 2001; Magadza 2003).

The second reason is that polymer has low water retention capacity (Nozaic, Freese and Thompson 2001). With this ability, flocs can dry up quickly thus reducing disposal costs. Thirdly, the reduction of aluminium content in potable water has been a result of mixed public health reaction towards its association to the prevalence of Alzheimer disease (Driscoll and Letterman 1995; Campell 2006; Gidde and Bhalero 2011). Even though studies have been conclusive with regard to the link between Alzheimer and alumininum, minimum limits of aluminium levels in drinking water are maintained as a precautionary measure. With such advantages, polyelectrolyte coagulants have lately gained popularity as a better alternative (Nozaic, Freese and Thompson 2001).

2.7.5. Post-chlorination

The primary purpose for post-chlorination is to inactivate microbial pathogens and prevent the spread of waterborne diseases (Parsons and Jefferson 2006; WHO 2006b; Schutte 2007; South African Bureau of Standards 2011). Disinfection of water entails the addition of the required amount of a chemical agent (disinfectant) to the water and allowing contact for a pre-determined period of time (under specified conditions of pH and temperature) (Payment, Waite and Dufour 2003). The type and concentration of pathogens in water determines dosage (Eikebrokk, Juhna and Østerhus 2006). Failure to effectively destroy harmful pathogens could cost human lives and thus, the process should never be compromised at any cost.

In South Africa, chlorine and its derivatives (i.e. chlorinates, chlorine dioxides etc.) are widely used for disinfectant during treatment. The wide use of chlorine is attributed to four main reasons. The first reason is its ability to destroy a wide range of pathogens namely bacteria (with exception of some spore forming protozoa such as cryptosporidium), algae and fungi (Payment 1999; Payment, Waite and Dufour 2003; WHO 2006b; NHMRC n.d). This is achieved by damaging the microorganism's cell membrane thus making it permeable. The absorption of the chlorine disrupts respiration and DNA activities which are the two crucial activities for cell growth (Forster and Murray 2001).

The second reason is the relatively low price of chlorine (Mancini, Roccaro and Vagliasindi 2004). A chemical that produces high quality water at a reasonable price would be more economical for operating a treatment plant where raw inputs significantly vary with time. The third reason is its oxidation ability. This helps reduce taste, odour and colour producing compounds which generally makes drinking water aesthetically unacceptable.

The last reason is the residual ability of chlorine and its derivatives. Excess (residual) chlorine tends to disrupts the growth of slime bacteria, algae and moulds and thus provides a partial safeguard against low level contamination of treated water on its way to the final consumer (Department of Water Affairs and Forestry 1996b; Laurent and Prevost 2005).

Even though chlorine is so widely used, it is now being slowly replaced by ozone in developed countries like the United State of America. This has been due to a number of reasons chief among them being the health concern of its by-products. Studies have linked disinfection by-products (DBP) such as trihalomethane (THM) to cancerous disease, birth defects and miscarriage. However, recent studies have been disputing such facts (Nozaic 2004; Abdullah *et al.* 2009; Legay *et al.* 2010).

The ineffectiveness of chlorine on spore forming bacteria such as clostridium and cryptosporidium is of great concern. A cryptosporidiosis outbreak in 1993 in

Milwaukee, Wisconsin (USA), resulted in more than 400,000 persons being infected and the death of at least 50 people (Morris *et al.* 1996).

With consideration of the potential effects of DBPs, the Department of Water have set limits in drinking water (Department of Water Affairs and Forestry 1996a). For Class I limits (suitable for lifetime consumption), THMs must be less than 200µg/L while for Class II, the tolerable concentration maybe between 200 – 300ug/L for a period of 10 years (South Africa Bureau of Standards 2006). It however makes sense not to compromise disinfection in an attempt to control DBPs.

2.8. Effects of Major Water Quality Parameters on Chemical Dosage, Human and Aquatic Organisms

While a monitoring agent may sample several water quality parameters, only a few which directly reflect the fitness of such water for an intended use need to be considered in describing the overall status of a catchment. Incorporating all parameters in a water quality management tool such as a WQI could result in a tool that is complex and which might not clearly reflect the fitness of such water for the intended use. However, the major challenge is on the selection of parameters that would reflect a clear overview of the overall water quality. For example, in a river ecosystem WQI, parameters considered should be of importance with regard to the survival of aquatic animals and plants.

On the other hand, when developing a water quality index for determining the treatability of raw water, one should have knowledge about the effect of different parameters on the chemical process. This will assist in choosing parameters that give a clearer overview of the fitness of such water for a specific use. This next section reviews how the variability of the selected parameters influence chemical processes, specifically disinfection, coagulation and pH adjuster. The sections also discusses the effect of selected parameters on human health and aquatic ecosystems. Knowledge gained should assist in choosing parameters for inclusion in the two indices. Furthermore, it will assist in assigning Weight Factors (WFs) for the two different indices, i.e. river and raw water treatability WQI to be produced.

2.8.1 Temperature

- ***Effect of temperature on fresh water ecosystem***

Temperature has long been recognised as an important environmental factor in both terrestrial and aquatic ecosystems. It plays a pivotal role over biological activities, such as growth and reproduction (Sweeney and Vannote 1981). Change of the surrounding environment temperature over a long period of time tends to affect the evolutionary, physiological and behavioural responses of individual organisms. This ultimately result in a shift of the river ecosystem status (Arnell 1999; Bates *et al.* 2008).

Different species of fish have different temperature tolerant limits (Davis and McCuen 2005). Temperature fluctuations beyond threshold levels can have a dramatic effect on endocrine processes; (NRC 1980; Palani, Liong and Tkalich 2008), hatching success (Yip and Konasewich 1972; Scheibe and Konasewich 1981), feeding, respiration, enzymatic kinetics and growth (Sweeney and Vannote 1981; McLaren and Kim 1995). Death of aquatic animals can result from exposure to either extremely high or low water temperatures. With such concerns, many studies have considered temperature as a significant parameter in developing a water quality index that describes the river health status (Townsend, Hildrew and Francis 1983; Clements *et al.* 2000; Walsh *et al.* 2001).

- ***Effect of temperature on human health***

Although water temperature may not directly bear any effect on human health, its effect on other parameters is of great concern. An increased temperature in poorly disinfected water tends to promote re-growth of bacteria, which ultimately re-contaminates water (Payment, Waite and Dufour 2003; WHO 2003b). A rise in temperature also increases the solubility of many compounds. In soluble form, some of these compounds tends to be detrimental to human health (Eikebrokk, Juhna and Østerhus 2006).

- ***Effect of temperature on disinfection***

Ideally, a rise in temperature increases the rate of disinfection up-to a known optimum level in the absence of other factors. Above that level, the disinfectant starts to fall apart as a result of chemical valorisation, hence reducing the rate of disinfection. As a result, studies have also attributed the high chlorine dosage in summer as meant to compensate chlorine loss due to sun radiation (Veenstra and Schnoor 1980).

Butterfield and Wattie (1946) while studying *E. coli* noted a five-fold increase in the bactericidal effectiveness of chlorine between 2°C to 5°C and 20°C to 25°C. Ames and Whitney-Smith (1944) working on a U.S. Army research observed a nine-fold increase in the disinfection effectiveness between 8°C and 40°C. Chambers (1976) highlighted that temperature hardly alters the effectiveness of chlorine at pH range of 7.0 to 8.5. However, at higher pH values, a four to eight-fold increase in chlorine effectiveness was observed over the temperature range 4°C to 22°.

- ***Effect of temperature on coagulation***

Temperature impacts coagulation by affecting the viscosity of the water. It affects the rate of solubility of the metal hydroxide precipitate (Eikebrokk, Juhna and Østerhus 2006). The hydrolysed insoluble metal forms can be agglomerated by a coagulant to form flocs. In general, the higher the temperature**,** the faster is the coagulation reaction. Low temperature on the other hand retards the kinetics hydrolysis of particle and further increase the viscosity during coagulation. The result is a reduction of the strength and size of flocs (Gleick 2010). Also, a decrease in temperature tends to increase the viscosity of water such that the rate of sedimentation decreases (Camp, Root and Bhoota 1940).

In a treatment plant with a fixed flow rate and basin capacity, low temperatures in winter tends to result in a reduction of turbidity removal efficiency by the coagulation and sedimentation process as compared in summer. Even though, little can be done operationally to remedy temperature variation, a treatment plant should have strategies to take into account the effect of low temperature during the winter months.

A study by Al-Layla, Middlebrooks and Porcella (1974) also noted that temperature is inversely proportional to the amount of alum used. The study reported that algae removal is improved by 24% at a temperature of 10°C, and by 40% at 20°C and by 63% at 35°C when using alum used as a coagulant. Hurst *et al.* (2004) observed that for the same coagulant dose, cold temperature conditions (viz., 5 ^{0}C) produced smaller flocs than at warmer temperature conditions (viz., 20^{0} C).

2.8.2. Turbidity

- ***Effect of turbidity on fresh water ecosystems***

In a physical sense, turbidity is a reduction in the clarity of water due to the presence of suspended or colloidal particles (Department of Water Affairs and Forestry 1996b; WHO 2006b). Higher turbidity in a river ecosystem causes the reduction in light penetration and ultimately photosynthesis (Telesnicki and Goldberg 1995). Since photosynthesis is the primary energy producing process in an aquatic ecosystem, such a reduction will have far-reaching consequences especially to high trophic level aquatic animals.

Furthermore, it is known that fish gills are delicate and easily damaged by abrasive silt particles (Bates *et al.* 2008). Fish generally have a mechanism of opening and closing their gills to filter out silt. However, when in excess, silt causes irritation, which in turn stimulate the production of mucus to protect the gill surface (Bates *et al.* 2008). Excess mucus tends to impede the circulation of water over the gills and interfere with fish respiration.

- ***Effect of turbidity on human health***

Even though, the consumption of turbid water might necessarily have no direct human health effects, its association with microbial organisms is of public health concern (Health Canada 2003). By controlling turbidity, one would also be eliminating other pollutant substances (Environmental Protection Agency 1999). Due to the detrimental effects of high turbidity water, the South Africa’s potable water standards (SANS 241:11) recommends that turbidity in drinking water should be reduced to less than 1 NTU (South African Bureau of Standards 2011). For aesthetic purposes, the South Africa’s standards stipulate that a maximum load of 5 NTU is acceptable.

- ***Effect of turbidity on coagulation***

Studies conducted at different treatment plants have noted that increased turbidity levels tend to significantly increase the treatment cost (Dearmont, McCarl and Tolman

1998; Graham 2004; Gebremedhin 2009). Dennison and Lyne (1997) however reported that 'clean water', low turbid, was causing an increased treatment cost at DV Harris treatment plant in Pietermaritzburg. The study noted that the relatively low turbid water resulted in the formation of poor flocs, which are rather expensive to remove and dispose. To enhance flocs formation, bentonite was used. It can be either natural clay or a composition of inorganic minerals, which works by absorbing a wide variety of contaminants and encapsulating them to form flocs (Chatterjee, Chatterjee and Woo 2009). Bentonite is normally added prior to coagulant dosage so that it adds weight to the floc and also acts as a seed for promoting floc formation (Leopold and Freese 2009).

- ***Effect of turbidity on chlorination***

LeChevallier, Evans and Seidler (1981) studied the efficiency of chlorination on the destruction of coliforms in unfiltered surface water supplies and found a negative correlation with turbidity ($r = -0.777$; $P < 0.01$). The study showed that coliforms concentration was reduced by 20% when turbidity was reduced from 13 NTU to 1.5 NTU. A model developed in that study predicted that an increase of turbidity from 1.0 to 10.0 NTU caused an eight-fold decrease in the disinfection efficiency at a fixed chlorine dose.

Oston, Williams and Bothwell (1981) study at Ottawa plant showed that pre-chlorination dosage requirements were strongly correlated to the increase in turbidity level. In Oregon, chlorine demand had a positive correlation with both turbidity and total organic carbon levels (LeChevallier, Evans and Seidler 1981). That study produced a model that suggested a 180% increase in chlorine demand for a turbidity increase from 1.0 to 5.0 NTU.

2.8.3. pH

- ***Effect of pH on fresh water ecosystem***

There is no definitive pH range within which all freshwater aquatic life is unharmed and outside which adverse impacts occur. The acceptable range of pH to aquatic life, particularly fish, depends on numerous other factors, which includes the species type and dissolved ion content. Caspers (1981) however identified 5-9 as the pH range that does not have a direct lethal effect to most fresh water animals especially fish. Outside this range, fish tend to suffer adverse physiological effects, which increases severity as the degree of deviation increases until lethal levels are reached (USEPA 1976). With such concerns, many studies have considered pH a significant parameter in developing a water quality index that describes the river health status (Townsend, Hildrew and Francis 1983; Clements *et al.* 2000).

❖ ***Effect of pH on human health***

The South Africa National Standards (SANS 241:2011) and the guidelines for domestic use categorised pH as a ‘Level 1’ parameter (Department of Water Affairs and Forestry 1996a). This class includes parameters that have to be continuously assessed when determining the fitness of water for potable treatment and in evaluating the efficiency of a treatment process (South African Bureau of Standards 2011).

While pH may not have any direct health effect except at extreme levels; its association with other parameters is of public health and environmental concern. For example, pH mobilises heavy metal elements such as iron, aluminium, cadmium, mercury and lead which then tends to accumulate in living organisms (Oberholster *et al.* 2010). As a result, South Africa’s guidelines for domestic water caution against the use of water with a pH level of less than four (Department of Water Affairs and Forestry 1996a). In water that is prone to sulphur contamination, pH levels below 7 can cause the formation of hydrogen sulphide, which is known as ‘bad egg’ as a result of the odours it produce (Pourbaix 1974). At lower pH, drinking water has been reported to have a bitter taste making it unpleasing for drinking (Department of Water Affairs and Forestry 1996a; South African Bureau of Standards 2011).

❖ ***Effect of pH on coagulation***

pH is a major factor in the hydrolysis of aluminium salts (Ates *et al.* 2007). Inorganic coagulants such as alum are generally acidic and tend to neutralise the alkalinity of water. Raw water with high pH levels requires more coagulant for the complete stabilisation of pollutant charge (Ye *et al.* 2007). However, when too acidic, alkaline reagents such as sodium carbonate or lime can be used to raise the pH of water in order to optimise the coagulation process. When the water is too alkaline, acidic reagents, hydrochloric acid or sulphuric acid, can be used to lower pH level.

Unlike inorganic coagulants, polyelectrolyte are generally insensitive over a range of pH (Lind 1994; Freese, Hodgson and Nozaic 2004). If used correctly, a polyelectrolyte coagulant can significantly reduce the cost arising from the use of a pH adjuster (Walmsely 2003; Freese, Hodgson and Nozaic 2004). Nozaic, Freese and Thompson (2001) reported a 30% decrease in the unit cost in three consecutive financial years (1987-1990) at Umgeni Water as it shifted from alum to polyelectrolyte.

- ***Effect of pH on disinfection***

White (1992) found that the efficiency of chlorine as a disinfectant and oxidant as significantly depended on pH level. Steynberg *et al.* (1996) found that, chlorine was 40 times less effective in killing *Monoraphidium minutum* at a pH of 9.5 than at 7.0. The germicidal efficiency of chlorine depends on the relative proportion of chlorine derivatives in water especially hypochlorous (HOCl) and hypochlorous ion ($HOCl^-$) (Payment, Waite and Dufour 2003). Hypochlorous dominates in low pH while OCl^- tends to increase as the pH rise as illustrated in Figure 2-1.

It have also been reported that HOCl is approximately 100 times more effective than OCl^- (White 1968; Payment, Waite and Dufour 2003; Schutte 2007). This means that as the pH of the water increases, chlorine effectiveness tend to be reduced (Scarpino *et al.* 1972; Kott, Nupen and Ross 1975).

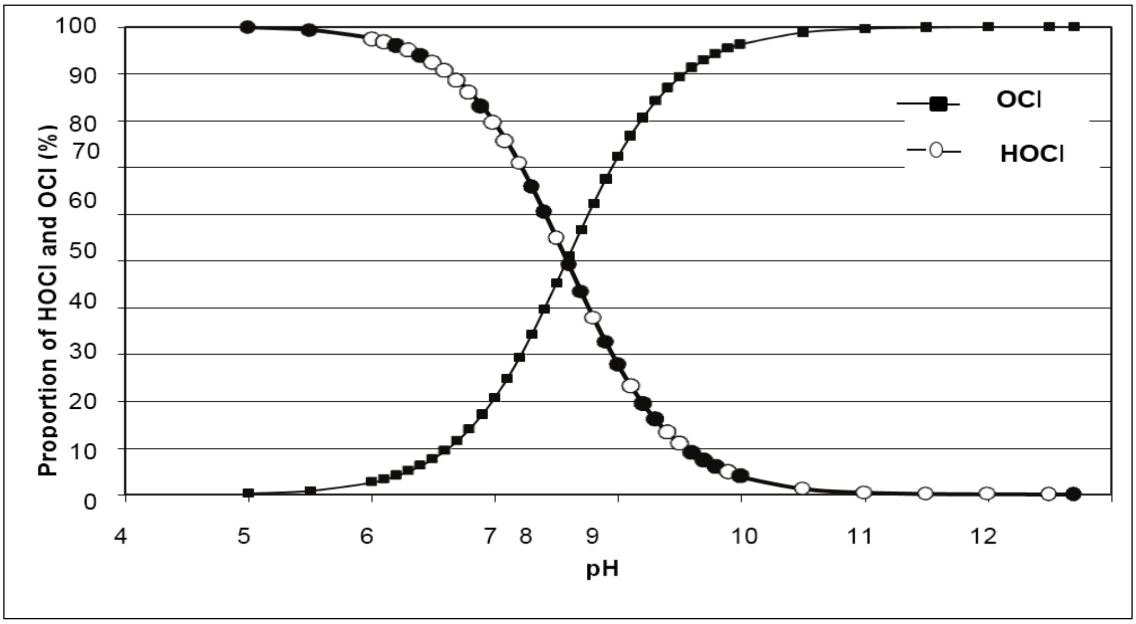


Figure 2-1: Relative proportion of HOCI and OCl- over pH
Source: Leopold and Freese (2009).

2.8.4. Plant nutrients parameters

- ***Effect of nutrients on fresh water ecosystem***

In an aquatic ecosystem, small amounts of nutrients (nitrates and phosphorus) are required for plant growth. However in excess, these parameters cause a phenomenon known as eutrophication which is manifested by a bloom of algae (Graham 2004; Gebremedhin 2009; Dzwairo 2011; United States Environmental Protection Agency n.d.). Wepener *et al.* (2006) recognised that eutrophication is normally observed when the total phosphorus increases to between 40 and 60 mg/L among other factors such as temperature. This tends to influence the type and quantity of living organisms in a catchment (Raw Water Quality 2006).

Depending on the species, algae bloom might subsequently cause odour and taste problems in water systems (Department of Water Affairs and Forestry 1996a). Some species tend to produces toxins, which have been implicated to the death of livestock (Department of Water Affairs and Forestry 1996a). The decomposition of plant material resulting from eutrophication also tend to causes the reduction of dissolved oxygen levels and a rise in the temperature in a water system. These conditions ultimately causes the death of aquatic animals including fish they are generally sensitive to the change in temperature and dissolved oxygen level (Said, Stevens and Sehlke 2004).

Furthermore, it should be highlighted that the effect of nutrient parameters in aquatic ecosystem depends on the form in which it is found in water. For example, dissolved phosphorus is readily available for biological uptake and tend to cause an increase in algal growth (Sonzogni *et al.* 1982). This variation should be taken into consideration when choosing and weighting water quality parameters during index developing.

- ***Effect of nutrient on human health:***

The potential health risk of nitrate arises when it is reduced to nitrite in the human gastrointestinal tract. Upon absorption, nitrite combines with the oxygen-carrying red blood pigment, haemoglobin, to form methaemoglobin, which is incapable of carrying oxygen (Department of Water Affairs and Forestry 1996a; Environmental Protection Agency 2003). This condition also known as the 'blue baby syndrome' is detrimental and can be fatal to pregnant mothers and infants. While considering these effects, SANS 241:2011 stipulated that a nitrite levels in drinking water should not be less than less than 11 mg/L. However, concentrations ranging from 11 to 20 mg/L is only considered safe for seven years (South African Bureau of Standards 2011)**.** Where microbiological data is unavailable, nitrate can be used as crude indicators of faecal pollution (Dzwairo 2011).

- ***Effect of nutrient on chemical process:***

Nutrient pollutants can be removed by the coagulation and flocculation processes (Mohammed and Shanshool 2009). James *et al.* (2003) pointed out pH, coagulant dose and the speed of mixing as main factors affecting the removal of phosphorus compounds in water. Mohammed and Shanshool (2009) noted that a rise in alum dosage up to 80 mg/L increased the removal of phosphorus. Above the optimum level (80 mg/L), the efficiency of phosphorus removal decreases. This reduction in phosphorus removal efficient is caused by the re-stabilisation of colloidal suspension as the dosage shifts the optimum pH (5.8-6.5) to an unfavourable range for phosphate removal (Ahmed, Sumathi and Hameed 2006).

2.8.5. *Escherichia coli*

In relation to human health, the World Health Organisation (WHO) identifies the greatest risk as through the consumption of water contaminated by human or animal faeces (WHO 2004). If the water has been contaminated with faeces from a person suffering from a waterborne disease such as cryptosporidiosis, dysentery, cholera and typhoid among others, the result could be detrimental and sometimes fatal (Momba, Tyafa and Makala 2004; WHO 2011). Disinfection should thus never be compromised at any cost (Department of Water Affairs and Forestry 1996a; WHO 2006b).

Most treatment plants use *Escherichia coli* (*E. coli),* a bacterium found only in warm blooded mammals, as evidence of recent contamination (Staff 1997; Payment, Waite and Dufour 2003; WHO 2004). Water containing *E. coli* is regarded as polluted and unfit for domestic use. While considering the detrimental risk arising from faecal contamination, WHO and DWA standards have stipulated that drinking water must contain 0 colony forming units of *E. coli* per 100 mL of water sampled (0CFU/100mL) (South African Bureau of Standards 2011; WHO 2011).

2.8.6. Taste, odour and colour

In addition to the requirement that water must be biologically and chemically safe to drink, water for domestic use must be aesthetically pleasing, i.e. a clean appearance, taste and odour. Even though odour and colour problem causing substances might not have an adverse effect on human health, South Africa and World Health Organisation potable water guidelines have indicated that the consumer perceptions and aesthetic criteria need to be considered when determining the fitness of water for drinking purposes (Department of Water Affairs and Forestry 1996a; WHO 2011). However, because taste, odour and colour generally have no known health effect, the South Africa National Standards (SANS 241:2011) does not indicate the maximum tolerable exposure but rather, stipulates that water is regarded as Class I if the colour is less than 15 mg/LP and taste of less than 5 FTN (South African Bureau of Standards 2011).

Taste and odour problems usually arise from natural inorganic and organic chemical contaminants, biological sources or processes. Colour in drinking water may be due to the presence of coloured organic matter substances, metals such as iron or manganese, or highly coloured industrial waste (Payment, Waite and Dufour 2003). Colour problems may also result from the corrosion of the distribution pipes or excess chemical dosage of oxidants like potassium permanganate. The removal of the considered causal surrogate parameter is expected to compare favourably to the removal of true colour (Department of Water Affairs and Forestry 1996a).

- ***Effect on chlorine dosage***

When chlorine is added in raw water of high taste and odour pollutants such as metals and sulphides, it tends to also serve as an oxidant. For effective treatment, a water treatment plant should determine the chlorine demand arising from the oxidation of odour, colour and odour producing substances. This can be determined by calculating the chlorine demand point.

2.8.7. Algae

In natural ecosystems, algae serves an important role in the natural purification of surface water, by assimilating inorganic nutrient species, specifically nitrogen and phosphorus. The process produces oxygen, a prerequisite for the survival of aquatic animals. With such a role, algae becomes an important component of the aquatic ecosystem (Department of Water Affairs and Forestry 1996a; Graham 2004).

However, in excess, algae become a nuisance and interfere with the desirable use such as potable treatment. In most of South Africa's catchments, algae bloom is a prominent problem such that several millions of rands are budgeted annually in anticipation of an algae surge (Department of Water Affairs and Forestry 2003). The blue-green algae species also referred to as cyanobacteria dominates in most of South Africa's highly nutrient-enriched waters such as uMngeni Basin (Graham 2004). Depending on the species, some tend to produce a variety of neuro, hepatic and lipopolysaccaride toxins which have been attributed to the death of several livestock and game animal (Department of Water Affairs and Forestry 1996a). Some algae species cause odour and colour problems making the water aesthetically unacceptable for drinking purposes. The cost of addressing these problems is significant and tend to escalate the final treatment cost (Graham 2004; Gebremedhin 2009; Hoko and Makado 2011).

- ***Effect of algae on water treatment***

The removal of algae in the treatment process depends on the species present. However, algae can be removed by coagulation, flocculation and sedimentation process. The Department of Water Affairs pointed out chlorination with 0.5 mg/L chlorine residual for 30 minutes contact time as sufficient to destroy the toxins produced (Department of Water Affairs and Forestry 1996a). Water treatment should thus be designed to limit the risk of post-treatment toxin activity, and production of disinfection by-products such as trihalomethanes (THM).

At Durban Heights Water Treatment Plant, powdered activated carbon (PAC) is used to enhance the removal of algae and its toxins. Personal discussions with the treatment operation personnel revealed that elevated levels of the blue-green algae (cyanobacteria) were significantly affecting the treatment processes at that plant. This was evident by frequent clogging resulting in regular backwashing approximately every 4 to 6 hours, especially during the algae peak period.

2.8.8. Dissolved oxygen

The level of dissolved oxygen (DO) primarily indicates the status of higher aquatic life (Walski and Parker 1974). The level of DO depicts the level of pollution due to various oxygen demanding substances such as algal biomass, dissolved organic matter, ammonia and volatile suspended solids. This gives a reflection of whether biological changes are being brought by aerobic or anaerobic organisms in the measured water column (Parmar and Parmar 2010). Lieven (2007), used DO to evaluate the quality of water in different reservoirs and watersheds.

While considering the importance of DO on aquatic animals, this parameter has been considered in many studies that developed water quality indices that describes the river health status (Boulton *et al.* 1997; Martin, Haniffa and Arunachalam 2000; Dyer *et al.* 2003; Couceiro *et al.* 2007).

2.9. Methods of Determining Chemical Dosage

Optimisation of chemical dosage during treatment is the central key for cost effective treatment plant operation. Excess chemical dosage increases treatment cost and is of public health concern. Under-dosing on the other hand might result in the failure of a treatment plant to meet its final water objectives. Eikebrokk, Juhna and Østerhus (2006) highlighted that chemical dosage optimisation assists in the production of higher quality potable water at a reasonable price.

Both manual and automatic methods have been developed for the purpose of optimising the coagulation process (Lind 1994; Lopaka and Helsel 2005). Black *et al.* (1957) and Schutte (2007) considered the Jar Test as the most widely used manual method of optimising coagulation. The procedure involves the application of different quantities of a coagulant to raw water of the same quality and quantity. After a short period of constant stirring, the different jars are analysed. The condition showing the best flocs is then considered for a large scale.

The main limitation of the Jar Test has been its lack of feedback control mechanism. An operator is thus supposed to continuously monitor the quality of incoming raw water to avoid over or under-dosing (Valentin, Denoeux and Fotoohi n.d.). This procedure tends to be laborious and time consuming. Also, it has been criticised as a subjective technique that is biased since judgement is based on the operator's observation (Valentin, Denoeux and Fotoohi n.d.). In some cases, it may also fail to perfectly simulate the conditions giving the optimum flocs in full scale unit (Fernandez and Gallvis 2002).

To counter the lack of feedback control mechanism during the coagulation process, a streaming current detector (SCD) has been widely used (Dentel, Thomas and Kingery 1989; Ikem *et al.* 2002; Adgar, Cox and Jones). The SCD technique work by measuring the conductivity of incoming raw water and thus determining the amount of coagulant that can be applied to neutralise the charge. The main limitation of the SCD is its inability to adapt to all types of raw water quality.

While considering the limitations of the Jar Test and SCD, studies have of late focused on developing models for forecasting chemical dosage during treatment. Several modelling approaches have been extensively applied for the purpose of forecasting chemical dosage. These models can be categorised based on their approach which can be basically linear, non-linear as well as artificial intelligent (Maier and Dandy 2000; Dzwairo 2011; Evuti *et al.* 2012; Sengul and Gormez 2013; Valentin, Denoeux and Fotoohi n.d.). The following section discusses the common modelling technique applied in the water industry.

2.9.1 Data based modelling techniques

Modelling of treatment processes have been difficult because of the heterogeneous nature of the physical and chemical processes involved (Van Benschoten and Edzwald 1990a; Van Benschoten and Edzwald 1990b; Huang and Shiu 1996). The relationship between water quality determinants is complex with nonlinear mutual relationships (Baxter *et al.* 2001). The application of the normal regression method which assumes linearity, tends to produce biased conclusions.

Different types of models exist depending on the objective and user specialist. So far, evolutionary algorithms, polynomial equations, partial regression, least squares, neural network models, and fuzzy structures have been used for predicting coagulant, lime and chlorine dosage. Statistical models, despite being widely recognised, have of late been slowly replaced by machine learning methods as the former, tend to be restricted by assumptions (Maier and Dandy 2000; Dzwairo 2011; Evuti *et al.* 2012; Sengul and Gormez 2013; Valentin, Denoeux and Fotoohi n.d.)

Dzwairo (2011) developed a model to predict coagulant dosage on treatment plants in the Vaal basin, South Africa, using the hybrid evolutionary algorithm (HEA) technique. Maier, Morgan and Chow (2004) employed the artificial neural networks (ANNs) technique in a study based in Austria to predict optimum alum dosage. Mirsepassi (2004) used the ANNs to model the daily dosage of polymer and alum at Mardi Water Treatment Plant. Sengul and Gormez (2013) also applied ANNs to predict the optimal coagulant dosage during the production of drinking water. The results for these studies shows that artificial intelligence techniques are better predictors as compared with other methods.

Bazer-Bachi *et al.* (1990) developed two separate models to determine coagulant dosage at Clairfont Water Treatment Plant in France based on polynomial equations. Data collected from a modified Jar Test, characterising the physical-chemical (turbidity, temperature, pH, organic matters, etc.,) and chemical analysis (mineralisation) were used. The results showed some non-linearity relationship between the parameters and the coagulant dose. Those findings led to the use of a second degree polynomial to model coagulant dosage.

Even though artificial intelligence methods have been recommended as superior for prediction purposes, their wide use has been hindered by their extensive data requirement which may not be readily available. While methods for interpolating data have been developed and are being widely used, concern has been raised as they tend to lose their accuracy as the number of missing value and data interval increases.

Another major drawback for the wide adoption of artificial intelligence methods has been the high cost of purchasing the software as well as its complexity. One needs to acquire specialised training, which makes it difficult for those who do not have advanced computer skills. The rising cost of training is also a significant limiting factor.

However, for a treatment plant with automated sampling tools and hence producing extensive water quality data-set, it would more plausible to consider artificial intelligence methods. Where monitoring is inconsistent and modelling resources are limited, it would be more plausible to consider statistical techniques. The performance of all the modelling techniques is however improved by data-pre-processing.

2.10. Summary

The objective of this chapter was to review relevant literature related to the four specific objective set for this study. The chapter outlined the South Africa's and uMngeni Basin water quality situation with regards to pollution, river health status, potable use and treatment costs. The effect of specific water quality parameters on the three components were discussed. Methods of pre-processing data-sets and developing water quality index and model development were also reviewed. It is anticipated that the knowledge gained will assist in determining how the variability of water quality in uMngeni Basin influencing chemical dosage. In addition, methods for developing water quality monitoring tools should assist in developing the two indices (1) River Health and (2) Treatability Water Quality Index.

CHAPTER THREE: STUDY AREA

3.1. Introduction

This chapter describes the study area, uMngeni Basin. Emphasis is on pollution sources along the river course in relation to potable water production and the general river health. Furthermore, the chapter outlines the operations of Umgeni Water, a bulk potable water treatment utility which abstracts raw water in the study basin.

3.2. Study Area Outline

The study area, uMngeni Basin, as shown in Figure 1-1 and Figure 3-1 is situated in KwaZulu Natal, an eastern province of the Republic of South Africa. The province has an estimated population of 10.8 million people of which 4.8 million primarily depend on potable water supplied by Umgeni Water (Statistics South Africa 2012). The 230 km long River, uMngeni, is the primary source of water to a population of almost 3.8 million people within, and around Durban and Pietermaritzburg. A consequence of the concentrated development in its catchment area has been the high levels of contaminants entering the water system, which are only flushed out at the sea. A total of 415 million m^3 of potable water is produced annually using raw water supplied by the uMngeni Basin (Umgeni Water 2012c).

The uMngeni River along with others such as Mvoti, Mkomazi, Coastal and Umzimkulu are under the management of Mvoti to Umzimkulu Water Management Area (MUWMA). The MUWMA operations are regulated in terms of the South Africa's Government Gazette Vol. 479 No. 27605 of 2005. Challenges in this catchment area include soil erosion from grazing, intensive cultivation, informal farming and settlement, timber plantations and sand mining operations.

The area receives much of its rain in summer, with occasional snow dustings in some of its high lying areas such as the Drakensberg Mountain (Basson and Rossow 2003). Its rainfall pattern is seasonal, and experienced in summer (October – April). The inland parts of the catchment generally receives from 800 to 1000 ml per annual inland whereas the coastal areas receive 1000-1500 ml per annual (Basson and Rossow 2003). It is underlain by sedimentary rocks of the Karoo and Cape Supergroups (Basson and Rossow 2003). The geology of uMngeni Basin varies from basalts, granites, sandstones, shale and tillites (Wilson 2001). This in turn influences the concentration levels of dissolved ions in the river water as a result of rock weathering and soil erosion. Furness and Richard (1987) observed that the soil in the uMngeni Basin is considerably phosphorus deficient and it would thus be plausible to attribute high levels of phosphate in the river to anthropogenic activities such as the discharge of sewage effluent.

3.3. The uMngeni River and its Major Polluting Activities

The uMngeni River is fully regulated with four major dams, Nagle, Midmar, Albert Falls and Inanda as depicted in Figure 3-1. These were built in 1950, 1965, 1976 and 1988, respectively.

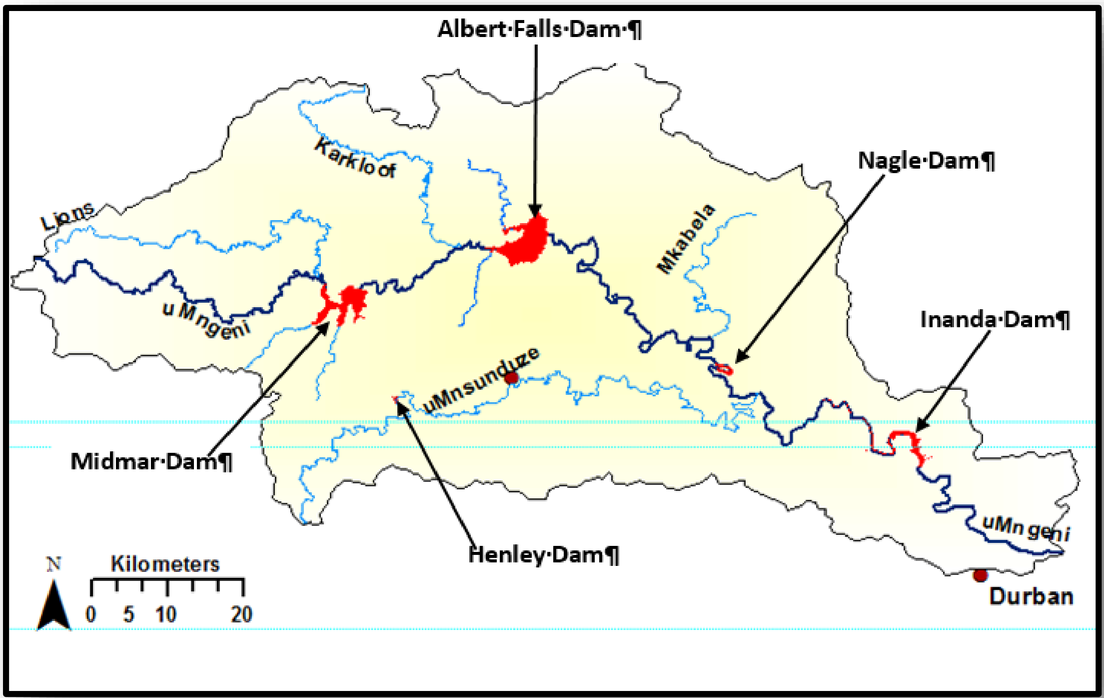


Figure 3-1: The position of uMngeni River, its major dams and tributaries

Three of the dams, Midmar, Nagle and Inanda supply raw water to Midmar, DV Harris, Durban Heights and Wiggins Water Treatment Plants respectively for potable water production as illustrated in Figure 3-12.

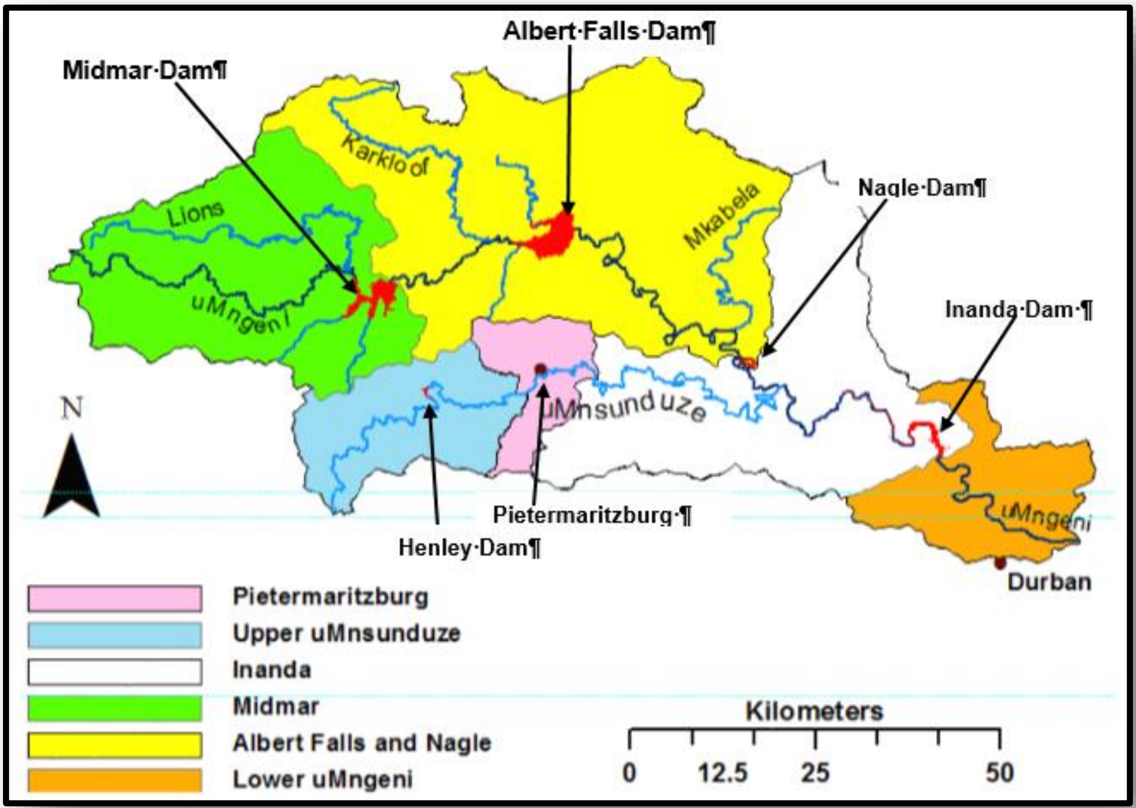


Figure 3-2: Resource units used to describe uMngeni Basin

The uMngeni Basin was considered for this study because it provides the largest portion (90.5%) of raw water for treatment to uMngeni Water as shown in Table 1-1. In addition, the data needed for the study was readily available.

For the purpose of this study, the six resource units proposed by the Department of Water Affairs as part of its River Health program are used to describe the study area and pollution activities along its course. Emphasis is on key pollutants that could influence chemical dosage during potable water production. Figure 3-2 shows the six resource units used to describe the sections making up uMngeni Basin and their pollution activities.

3.3.1. Midmar Resource Unit

The Midmar Resource Unit as shown in Figure 3-3 is positioned in the headwaters of uMngeni River. The river rises from a Vlei in the highland plateau, in the lower mountains of Spioenkop and Lionskop, on either side of Nottingham, at an altitude of 1760 m (Department of Water Affairs and Forestry 2003). It then flows eastward through a pastoral landscape and is joined by the Lions River before flowing into Midmar Dam. The Lions River, serves as a recreational and sporting resource. The Midmar Resource Unit covers an area of about 926 km^2, which is dominated by plantations and animal rearing farms (Roos, Hassan and Coleman 2009; Umgeni Water 2012b). Nutrient pollutants from the piggery, dairy and maize farms surrounding Midmar Dam have been attributed to the high nutrient load in this dam (Department of Water Affairs and Forestry 2003).

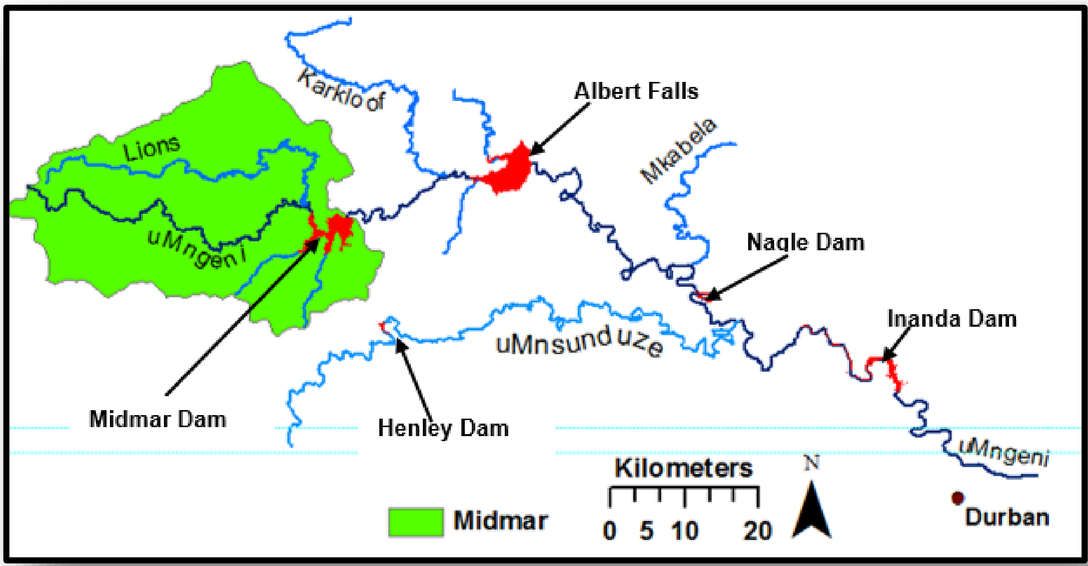


Figure 3-3: The Midmar Resource Unit in uMngeni Basin

The resulting effect of elevated nutrient levels reported in this resource unit has been exhibited by algae bloom. This in turn increases coagulant and chlorine dosages specifically at the DV Harris Water Treatment Plant which abstracts from Midmar Dam (Dennison and Lyne 1997).

Leaking sewers at Mpophomeni, a low-cost housing settlement and poor solid waste disposal methods as shown in Figure 3-4 have been reported as one of the principal polluting activities in this unit (Deventer 2012). Douman (2008) and Deventer (2012) cited sewage effluent from Mphophomeni Waste Water Treatment Plant as significantly causing the deterioration of the upper region of uMngeni River. As a result, GroundTruth (2010) have described Midmar Dam as a highly nutrient content dam with elevated levels of *E. coli.* Even though Mpophomeni's low cost housing area accounts only for 2.4% of Midmar Dam's catchment area, it has been reportedly contributing almost half of the dam's total *E. coli* levels and 15% of its total phosphorous load (GroundTruth 2010)

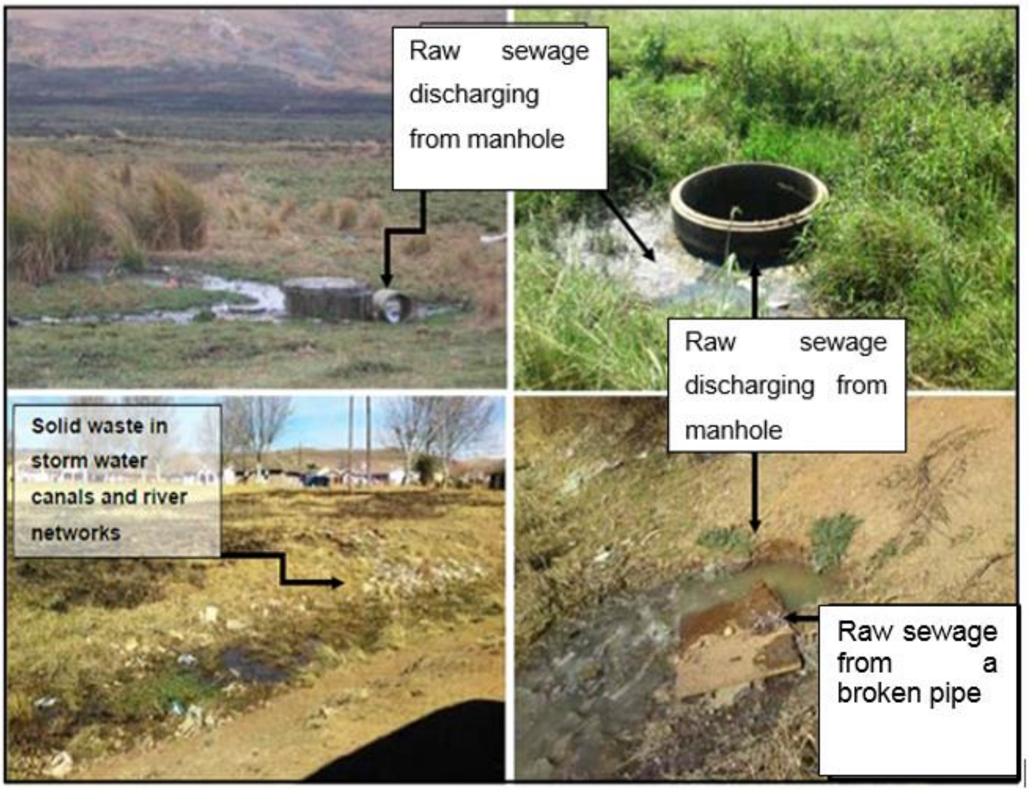


Figure 3-4: Major pollution problems in Mpophomeni Settlement
Source: (Deventer 2012)

As of late, a series of studies have been conducted to determine the phosphorus load in Midmar Resource Unit, suggesting that this parameter could be a major problem in this upper section of the River, uMngeni. For example, Hemens, Simpson and RJ. (1977) studied phosphorus concentration in Midmar Dam over a 10 year period from 1963 to 1973 and reported that an average of 4.81 tons of phosphorus had been deposited annually. Simpson and Dickens (2006), using monitoring data spanning from 1990 to 2005 noted a double increase of phosphorus concentration to 8.3 tons per annum. Roos, Hassan and Coleman (2009) using 1997 to 2006 data-sets reported a 70% increase in the concentration levels of soluble reactive phosphorus (SRP). The presence of such elevated levels of phosphorus suggests anthropogenic activities, specifically agricultural soils and feedlots runoff as well as discharge of sewage effluent, as the principal pollution sources.

3.3.2. Albert Falls and Nagle Resource Unit

Below Midmar Dam, uMngeni River flows over the Howick Falls into a valley, where remnants of plantation forests can be seen. Considerable pollutants emanate from the iMpolweni area, where poor land management and inadequate sanitation contribute turbid and nutrient-rich water (Department of Water Affairs and Forestry 2003). The major tributary, joining uMngeni River before it discharges into Albert Falls Dam, is Karkloof River as shown in Figure 3-5. Karkloof River has been generally described as a river of good quality water.

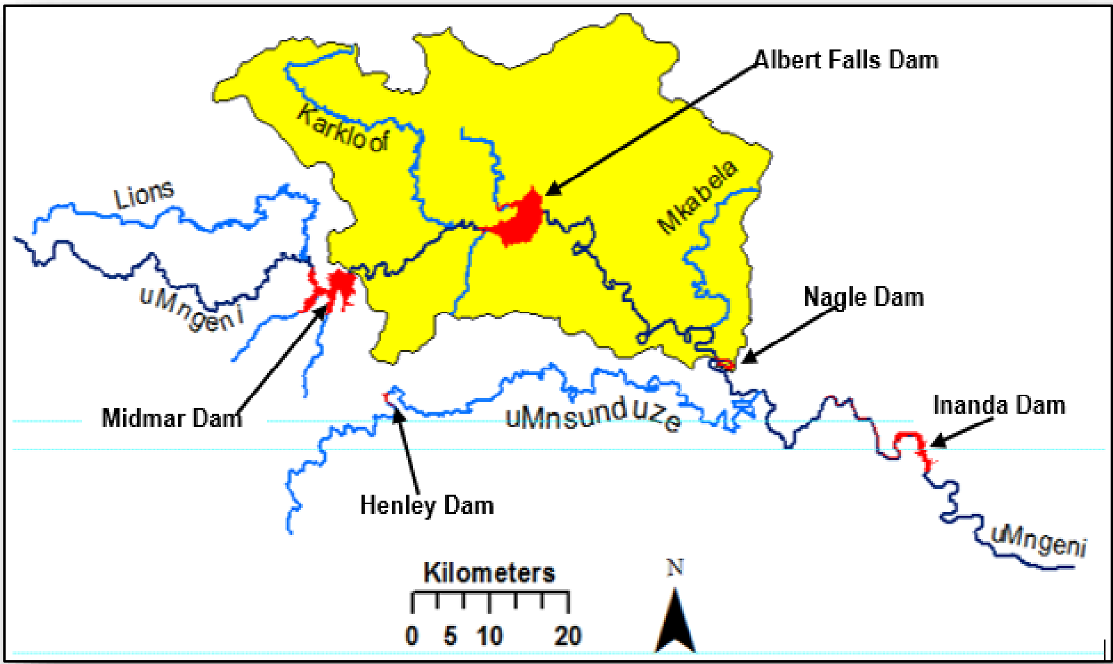


Figure 3-5: Albert Falls and Nagle Resource Unit position in uMngeni Basin

Even though no abstraction occurs at Albert Falls, this dam acts as a reservoir for Nagle Dam, which ultimately provides Durban Heights, the largest treatment plant in the catchment (Department of Water Affairs and Forestry 2003; Graham 2004). Walmsely and Butty (1980) described Albert Falls as a clear and low nutrient dam. Graham (2004) also reported Albert Falls as a low nutrient load with a monthly average total inorganic nitrogen (TIN) and soluble reactive phosphorus (SRP) concentration of 0.400 and 0.004 mg/L respectively. The study attributed the low nutrient levels to the dam's sheer size (capacity of 2.901 x 10^8 m^3) and the resulting long retention time (Umgeni Water 2014). This tends to increase the dilution and settling of suspended particles, which ultimately improve the quality of water.

Of particular note below Albert Falls Dam are two feedlots, housing 25 000 herd of cattle. Other intensive agricultural practices include dairy farming, piggeries and a chicken abattoirs located up and downstream of Albert Falls Dam. These intensive agricultural practices tends to increase the pathogen and eutrophication risk to the Nagle Dam which is downstream Albert Falls.

Midway within the uMngeni Basin is Nagle Dam. Similar to the Albert Falls Resource Unit, Nagle's catchment area is dominated by commercial farms. Walmsely and Butty (1980) studied South Africa's major impoundments and described Nagle Dam as a phosphate limited oligotrophic system. Graham (2004) found its mean monthly conductivity (8.9 mS/m) as slightly higher than for Albert Falls (7.8 mS/m). The study reported periodic algae blooms with a monthly average of 6 100 cell/mL and peaks values of 31 000 cell/mL (Figure 3-6). As a result, Graham (2004) concluded that algae was a significant driver influencing treatment cost at Durban Heights WTP.

Figure 3-6: Cyanobacteria (*Microcystis sp*) bloom in Nagle Dam
Source: (Roos, Hassan and Coleman 2009)

3.3.3. Upper uMsunduze and Pietermaritzburg Resource Unit

UMsunduze is one of the major tributaries of the uMngeni River. It rises near Elandskop on the road to Bulwer (1 500m above sea level) and flows eastward to Henley Dam, Edendale and Pietermaritzburg (Department of Water Affairs and

Forestry 2003). The confluence of the uMsunduze River with the uMngeni River is below Nagle Dam as shown in Figure 3-7.

The river then flows through Pietermaritzburg Central Business District where inadequate sewer systems, industrial waste and the discharge from the Darvill Wastewater Treatment Plant further deteriorates the quality of water (Department of Water Affairs and Forestry 2003). Both legal and illegal effluent discharges from industrial areas such as Willowton, dominate as pollution sources in this resource unit (Neysmith 2008). Willowton is drained by Baynespruit, a tributary that discharges into uMsunduze River. The uMsunduze converges with uMngeni River between Nagle Dam and Inanda Dam.

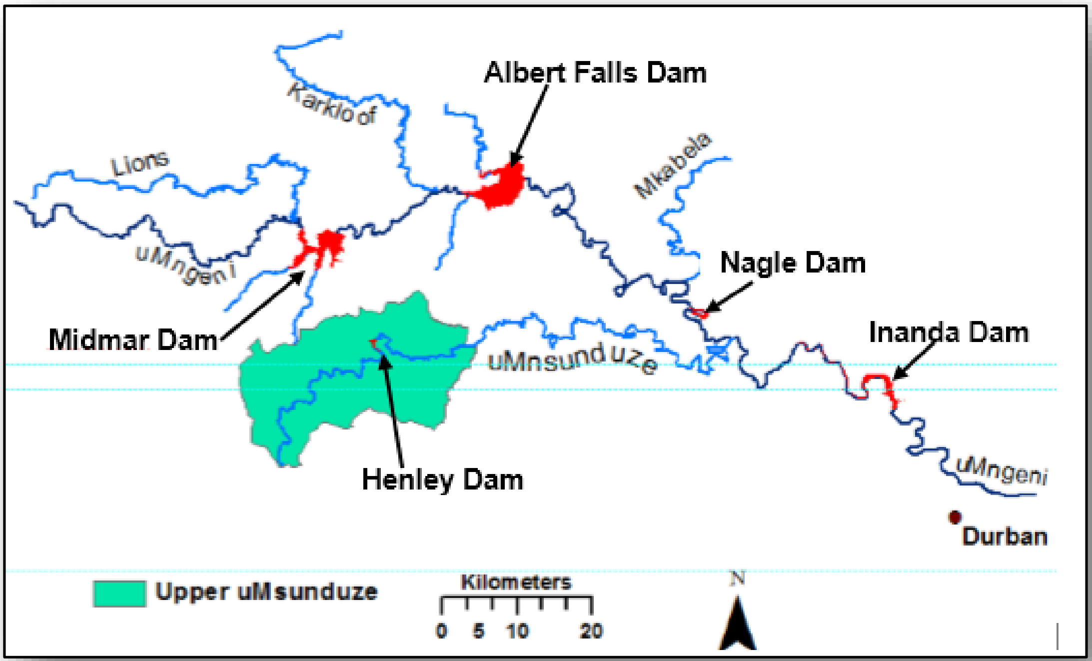


Figure 3-7: Position of the uMsunduze and Pietermaritzburg Resource Unit

Above the Henley Dam area, the quality of the uMsunduze River has been described as fairly good. The retention time at Henley Dam further assists in improving the quality of water (Department of Water Affairs and Forestry 2003). After leaving the dam, uMsunduze passes through the upper Edendale area where several pollution activities start to significantly deteriorate the quality of the water. Serious sewer infrastructure problems such as broken sewers and wash away of sewer lines have been cited as the main polluting activities in this region.

The direct discharge of sewage effluent into the river as shown in Figure 3-8 is of public health concern. Such activities increase the risk of water-borne related diseases especially to the informal settlers staying along the river bank. With regard to treatment, pollution activities in Pietermaritzburg is of concern as they ultimately affect the quality of Inanda Dam. The cost of removing the accumulated pollutants is incurred by Wiggins WTP which abstracts from Inanda Dam.

Figure 3-8: The direct discharge of raw sewage into uMngeni River

Source: http://umngeniriverwalk.wordpress.com/2013/08/25/an-overburdened-river/

3.3.4 Inanda Resource Unit

Below Nagle Dam, uMngeni River continues to flow in an easterly direction and is joined by uMsunduze River before Inanda Dam as shown in Figure 3-9. The uMsunduze which has been characterised as a highly polluted water course, converge with uMngeni River before Inanda Dam.

The Inanda Resource Unit is characterised by the rural community in the Valley of a Thousand Hills, a vigorously undulating landscape with hills and valleys. Subsistent farming activities as well as domestic activities (bathing and washing) by this rural community further pollute the river. The DV Wastewater Works which treat domestic effluent from Pietermaritzburg also present a significant pollution challenge.

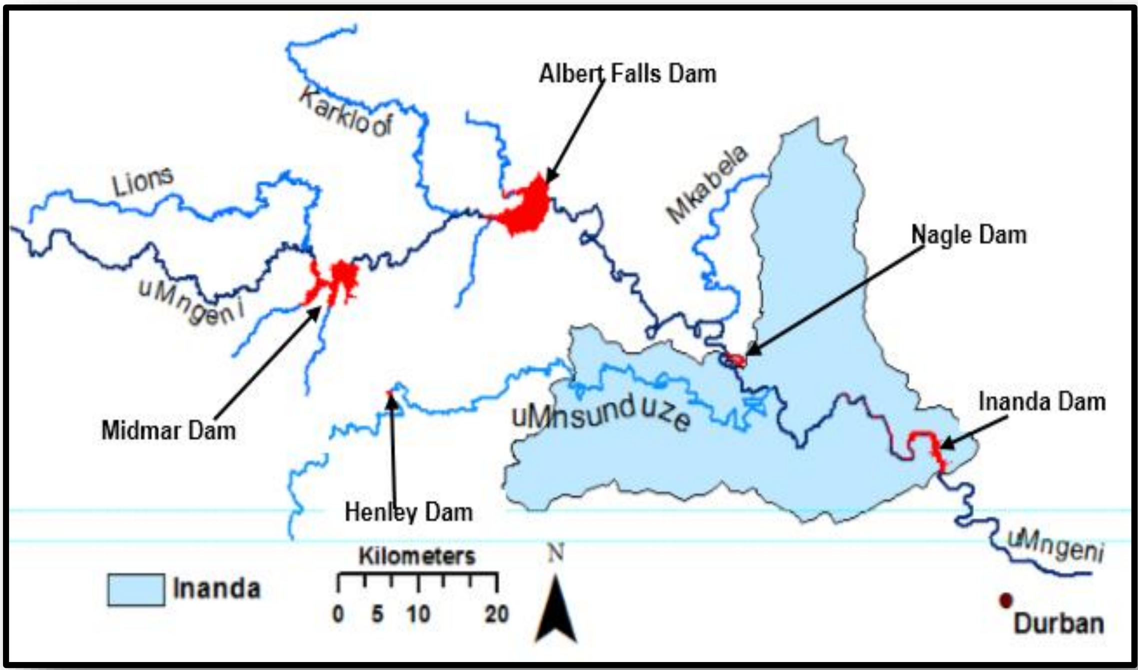


Figure 3-9: The position of Inanda Resource Unit in the uMngeni Basin

A recent study by Ganesh, Lin and Singh (2013) has reported the quality of water stretching from Hillcrest to the mouth of uMngeni River in Durban as heavily contaminated by pathogenic bacteria such as *Salmonella spp, Shigella spp, Vibrio cholerae* and viruses. These findings, have resulted in the uMngeni River being described as one of the 'dirtiest rivers in South Africa' (Carnie 2013). These findings have raised an alarm on the importance of intensifying the protection of this resource. Based on these findings, it can be hypothesised that *E. coli* could be a significant parameter influencing treatment cost at Wiggins WTP.

Beside high levels of *E. coli,* the Inanda Resource Unit also periodically experiences algae and hyacinth bloom as a result of its high nutrient levels (Figure 3-10). Such physical pollutants (algae and hyacinth) tends to increase filtration time, reduces filter's life span and further increase coagulation dosage during treatment.

Figure 3-10: Water Hyacinth bloom at the headwaters of Inanda Dam (2012)

Source:http://cdn.24.co.za/files/Cms/General/d/1787/b1d565531a6a45f8aa865875def140a2.jp

3.3.5 Lower uMngeni Resource Unit

Figure 3-11 depicts the position of Lower uMngeni Resource Unit in the uMngeni Basin. From Inanda Dam, uMngeni River flows passing through the Valley of a Thousand Hills at a gentle gradient for 24 km before flowing out to the Indian Ocean. Pollution activities (e.g. bathing and washing) by the rural population in the Valley of a Thousand Hills has been cited as significantly causing the deterioration of the quality of this section of the basin (Department of Water Affairs and Forestry 1996a). As this rural population continues to rise, the quality of water is expected to deteriorate further.

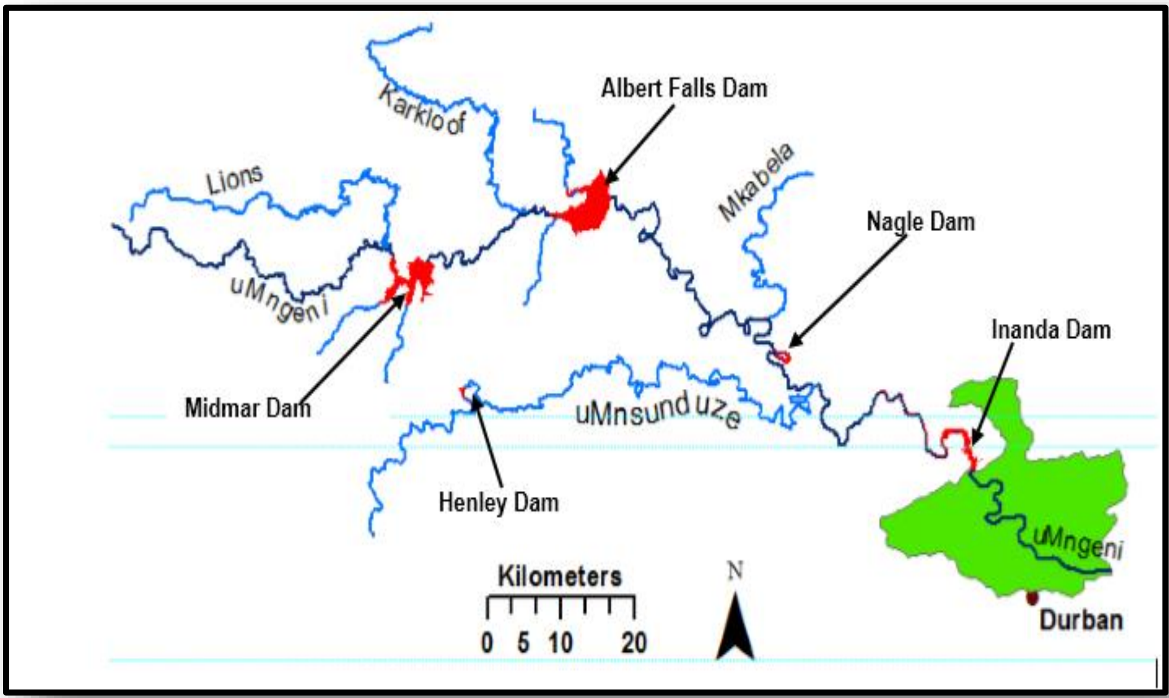


Figure 3-11: The position of Lower uMngeni Resource Unit in the basin

3.4. Umgeni Water

Umgeni Water is a National Government Business Enterprise whose primary mandate is to provide bulk potable water to municipalities in its jurisdiction as pronounced in section 29 of the Water Services Act. The organisation operates in accordance with the Water Services Act (Act 108 of 1997) and the Public Finance Management Act (Act 1 of 1999), amongst others legislations.

Since its establishment in 1974, the utility has over the years grown to become the largest bulk potable supplier in the province of KwaZulu Natal and second in South Africa. The organisation currently serves an estimated 4.8 million customers in an operational area of 21 155 km^2 (Umgeni Water 2012a). Six municipal customers including eThekwini Metropolitan Municipality, Sisonke District Municipality and

Msunduzi depends on potable water supplied by Umgeni Water. A total of 415 million m^3 of potable water is pumped into the municipal's reticulation network. Additionally, the organisation treats a total of 85 000 m^3/year domestic and industrial waste water produced by different stakeholders in its jurisdiction (Tiba and Hodgson 2008).

Among the 12 water treatment plants being operated by Umgeni Water, only Durban Heights and Wiggins were selected in consideration of two main reasons. The first reason being that the two plants produces the largest proportion (63.4%) of the total potable water as shown in Table 1-1. This suggest that they would make a reasonable proportion of the overall operations of Umgeni Water. Secondly, both plants abstract raw water from uMngeni Basin which is being studied as illustrated in Figure 3-12.

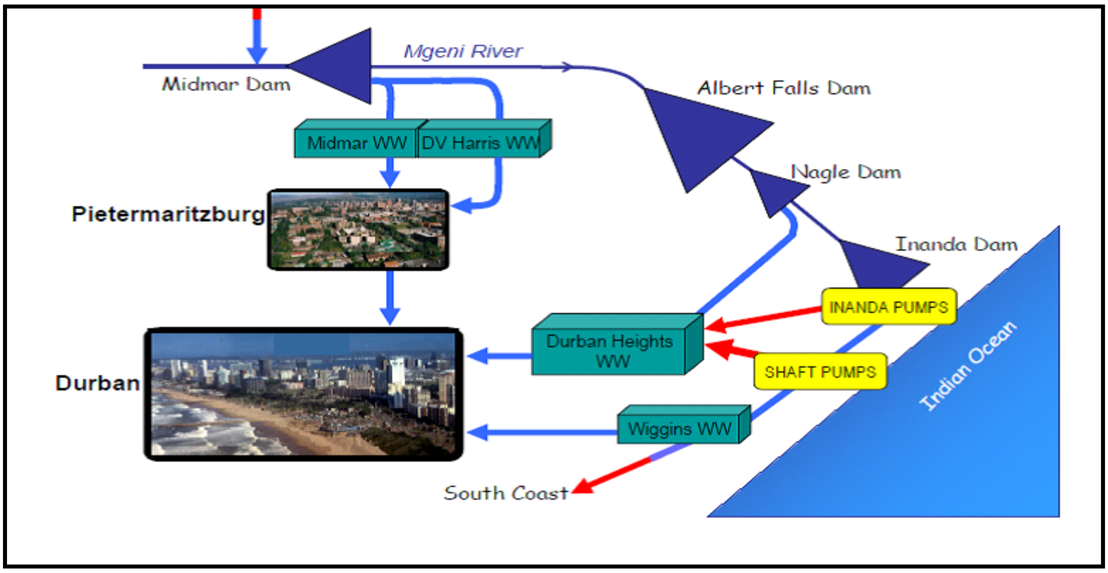


Figure 3-12: Position of water treatment plants and their abstraction dams in uMngeni Basin

Source: (Umgeni Water 2011)

3.4.1. Durban Heights Water Treatment Plant

Durban Heights is situated in Reservior Hills, Durban and is presently the largest treatment plant being operated by Umgeni Water. It currently serves the major northern areas of Durban namely, Newlands, KwaMashu, Ntuzuma, Phoenix, Durban North and Umhlanga (Umgeni Water 2012b). The plant draws its raw water from Nagle Dam by gravity and is designed to produce upto 614 megalitres per day. This make up 43.2% of the total water being produced by the treatment utility. The water levels at Nagle Dam is controlled by Albert Falls Dam which acts as its reservoir. In periods of dry spells, raw water may be pumped from Inanda Dam by gravity (Figure 3-12). The turbidity, pH and temperature level of the incoming raw water are monitored every two hours at the station.

The main treatment processes involve screening, pre-chlorination, lime dosage (pH adjustment), coagulation, sedimentation, filtration and post-chlorination. Facilities exist to dose chlorine, powdered activated carbon, bentonite and cationic polymer. A stream current detector device (SCD) is used to control coagulant dosage.

After dosing the chemicals, water is diverted to sedimentation and filtration facilities. Post-chlorination is done after filtration and before the potable water is stored in the three reservoirs on the site. The pH, free chlorine and turbidity of the final water leaving the reservoirs are also monitored.

3.4.2. Wiggins Water Treatment Plant

Wiggins is the second largest treatment plant being operated by Umgeni Water (Table 1-1). It is located in Cato Manor, Durban and mainly supplies the southern portion of eThekwini Municipality which includes the Amanzimtoti/KwaMakuta areas (Umgeni Water 2012b). The plants receives its raw water from Inanda Dam which is located downstream the uMngeni River (Figure 3-12). It is designed to produce 350 megalitres per day as illustrated in Table 1-1. Even though Inanda has been described as a polluted dam, its sheer size has been playing a role in diluting and improving its quality before abstraction.

The water treatment process consists of pre-chlorination, coagulation, settling/clarification, filtration, post-chlorination and storage. In addition, the plant also have facilities for sludge treatment and waste water recycling. Powdered activated carbon may also be used to remove odour causing algae in the absence of ozone. Lime is then used to adjust the pH. A polymeric coagulant is used to agglomerate fine dirt particles thus forming larger particles (floc) that can settle easily.

Since Umgeni Water's primary business depends on the quality of raw water, the organisation works in conjunction with the Department of Water Affairs (DWA) to monitor and manage the dams. This is to ensure that water resource quality is maintained in a state that allows for sustainable development. The monitoring program has over the years been generating a vast amount of data that can be used in improving the management of the basin. The following sections describe the sampling stations whose data-sets were used in this study.

3.5. Sampling Stations

Six monitoring stations situated along the uMngeni River that are monitored by Umgeni Water were purposely selected for this study. Among these, three were dam inflows while the other three were their respective outflow stations. The inflow stations were assumed to give a reflection of the pollution activities along the river course in relation to the protection of freshwater ecosystem (river health). Findings from these stations should assist in choosing parameters and in developing a water quality index that describes the general river health status.

The dam outflow stations are expected to give a reflection of the treatability of raw water being abstracted in the uMngeni Basin. Findings should also assist in developing a water quality index that gives a reflection of the treatability of the water being abstracted. The stations considered are shown in Figure 3-13 and are discussed in the subsequent sections.

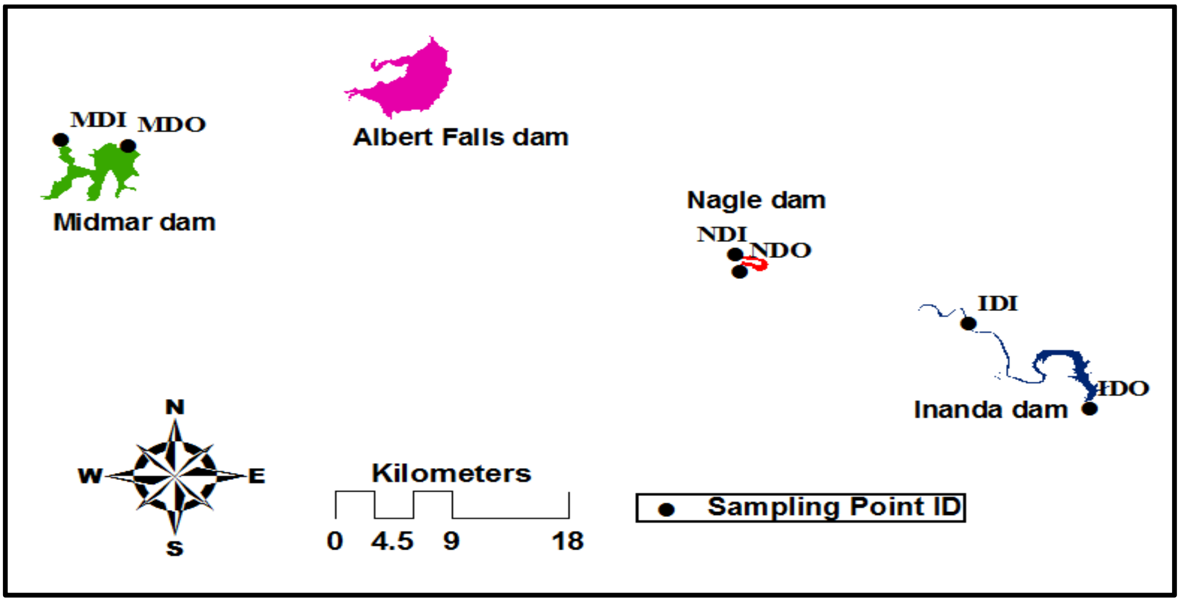


Figure 3-13: The sampling points along uMngeni River that were considered

A. ***Station 1: Midmar Dam Inflow (MDI)***

This sampling station is located at the mouth of Midmar Dam as shown in Figure 3-13. It measures the quality of water flowing into the dam and thus reflects the polluting activities from the river headwaters to Midmar Dam. Literature has cited run-offs from agricultural activities and sewage effluent from Mphophomeni Waste Water Treatment Plant as significant factors impacting the quality of water at this station (Department of Water Affairs and Forestry 2003; Deventer 2012). Since this station measures the quality of river water, findings from data analysis should assist in developing a water quality index for describing the overall river health status of uMngeni River.

B. ***Station 2: Midmar Dam Outflow (MDO)***

This station is located where Midmar Dam re-join uMngeni River as shown in Figure 3-13. Its quality reflects the self-purification capacity of the dam. Since treatment plants generally abstracts water of the best quality, the status of MDO should reflect an overview of the quality expected for treatment at DV Harris.

C. ***Station 3: Nagle Dam Inflow (NDO)***

This station is located downstream Albert Falls. Since the station generally measures the inflow into Nagle Dam, its quality should reflect the pollution activities upstream, specifically between Albert Falls and Nagle Dam. The pollution problems at this station should also assist in choosing parameters for a water quality index that describes the overall river health status of uMngeni River.

D. ***Station 4: Nagle Dam Outflow (NDO)***

This station is located where Nagle discharges into uMngeni River. When the water quality for this station is compared with its subsequent inflow, one can note the self-purification capacity of the dam due to the dilution and retention effect. Reports have indicated that Nagle Dam periodic experience elevated algal counts due to its high nutrient load. The quality of water at this station is expected to give an overview of raw water being abstracted for treatment at Durban Heights. Findings shall influence the formulation of an index for determining the treatability of raw water in the basin.

E. ***Station 5: Inanda Dam Inflow (IDI)***

This station is located at the mouth of Inanda Dam and measures the quality of inflow. This gives a reflection of the pollution activities between Nagle to Inanda Dam. The quality of water flowing through this station is mostly impacted by uMsunduze, a river which drains Pietermaritzburg and surroundings. Also, polluting this section are activities by the rural communities in the Valley of a Thousand Hills. Inanda Dam has been reportedly experiencing periodic algal bloom, which has been attributed to the discharge of sewage effluent of non-compliance quality. The pollution problem of this station is expected to influence the choice of parameters for developing a WQI for determining the river health status.

F. ***Station 6: Inanda Dam Outflow (IDO)***

This station is located where Inanda Dam discharges into uMngeni River. When its quality is compared with its subsequent inflow station, one can deduce the self-purification capacity of the dam. Since treatment plants generally abstract from the best quality point, this station is expected to give a reflection of raw water being treated at Wiggins WTP. Knowledge gained should also assist in developing a water quality index for determining the treatability of water being abstracted from Inanda Dam.

3.6. Summary

This chapter described the study area in relation to water pollution and treatment cost. The discussion was based on the six resource units suggested by the Department of Water Affairs in its River Health programme. The location and operations of the two treatment plants considered, Durban Heights and Wiggins are discussed. The positions of the six dam sampling stations considered in this study were also outlined.

CHAPTER FOUR: METHODS AND MATERIALS

4.1.Introduction

The chapter presents and discuss the methods used to determine the results for the four objectives set for the study. A number of approaches were employed in an effort to determine key water quality parameters influencing chemical dosage on treatment plants abstracting in the basin. In summary, water quality trends, correlations and statistical tests were employed. In addition, the chapter presents the methods used to develop the river health and treatability WQI. Finally, the approach employed in an effort to develop models for predicting chemical dosage is described.

4.2. Data Sources

Eight-year (2005–2012) water quality data-sets for six sampling stations, Midmar Inflow (MDI), Midmar Dam Outflow(MDO), Nagle Dam Inflow (NDI), Nagle Dam Outflow (NDO), Inanda Dam Inflow (IDI) and Inanda Dam Outflow (IDO) were provided by Umgeni Water for analyses. The length of period studied was determined in consideration of a criteria explained by Schertz, Alexander and Ohe (1991) and Lettenmaier, Conquest and Hughes (1982). They stated that at least a five-year monthly data and two-year monthly data should be sufficient for a defensible monotonic and step-trend (abrupt shift) study respectively.

Among the six stations considered, three were dam inflow stations (MDI, NDI and IDI) while the other three were their respective outflow stations (MDO, NDO and IDO). The outflow stations were presumed to give a reflection of the quality of raw water being abstracted for treatment. This was in considering that treatment plants generally abstract from a point showing the best quality, which is normally exhibited by the dam outflow positions. The improvement in water quality is a result of the dam’s retention and dilution effect.

In addition, potable water quality data-sets for Durban Heights and Wiggins WTPs for a period stretching from 2005 to 2012 were also obtained from Umgeni Water for statistical analyses. A comparison of the raw and final water concentrations should help determine parameters whose concentrations are significantly changing due to treatment.

Seven year chemical dosage data for chlorine, polymer and lime for Durban Heights and five year datasets for Wiggins Water Treatment Plant (WTP) were also provided by Umgeni Water for the study.

4.3. Data Pre-processing

Since the study was data-driven, the first step was to select parameters with a considerable data for analyses. Among the 95 water quality parameters that were monitored at the six stations studied, only 23 were considered as they had a reasonable consistent data-sets (Refer to Appendix C and D).

Prior to in-depth statistical analyses and tool formulation, the data were then subjected to pre-processing. The extensive process aimed at treating false values, missing values, outliers and censored values assist in improving the quality of the data-sets. This ultimately helps in the formulation of better water quality management tools such as water quality indices and models.

Obvious errors (e.g. typing error) were corrected, and inexplicable extreme outliers (e.g. pH value of 15) were discarded (Bartram and Ballance 1996). For the reconciliation of detection limits, values below the detection limits (BDL) were multiplied by three-quarters of the BDL (Dzwairo 2011). Where missing values made up less than 5% of the data and were randomly distributed, no action was taken (Helsel and Hirsch 1992; Darken 1999; Montagna n.d). However, where they made up greater than 5% but less than 10% of the data, the missing values were estimated using the simple linear interpolation technique. While considering that a larger proportion of missing values can introduce bias, parameters with missing values, making-up more than 10% of the dataset, were dropped.

Outlying values were treated with a high degree of caution while considering the pollution problems in study area. For example, high values for *E. coli* were retained while considering the irregular sewage effluent pollution pattern in the study area. Both observational (box and whisker) and statistical tests (Dixon) were used to determine outliers (Fu and Wang 2012; Mozejko 2012). Genuine outliers were replaced by the mean of the months with the available data (e.g. mean of Januarys').

The resulting data-set for each parameter were averaged to a monthly mean interval in order to smoothen out the unexpected and inexplicable fluctuations in the datasets. This was necessary while considering that the Seasonal-Kendall technique tests one observation per month (Bartram and Ballance 1996).

- ***Water sampling procedure***

In any water quality study involving the use of secondary data, it is important for the researcher to be aware of the sampling and testing method used to acquire a given data-set. This assists in assessing the integrity of the obtained secondary data. Furthermore, such knowledge assist in suggesting reasons for the presence of outliers, missing values and censored values which are common in water quality data-sets.

For these reasons, the researcher evaluated the sampling and procedures at Durban Heights and Wiggins Water Treatment Plants in order to appraise procedures that generated the given data-sets. Appendix A and B describes the sampling procedure followed.

4.4. Methods for Objective One

Objective 1: To evaluate the spatial and temporal water quality trend along uMngeni River with relation to river health status and potable treatment costs

4.4.1. Parameter selection

Parameters for trend analyses were selected based on three criteria; (1) expert opinion regarding the parameter's significance during treatment and the fitness for aquatic organism survival, (2) data availability and (3) the pollution problems in the study area. For example, Table 4-1 and Table 4-6 outline the effects of different parameters on river health and treatment processes respectively. Furthermore, a review of the effect of common parameters on chemical dosage, freshwater and human health status discussed in Chapter 2 also assisted in choosing the most significant parameters for this objective.

With consideration to the outlined factors in literature, twelve parameters, alkalinity ($CaCO_3$), magnesium (Mg), pH, electrical conductivity (EC), nitrates (NO_3,), total phosphate (TP), temperature, turbidity, total algae count, *Escherichia. Coli (E. coli)*, dissolved oxygen (DO) and ammonia (NH_3) were selected for spatial and temporal trend analyses. Both graphical (time-series and box-plot) and statistical (Seasonal-Kendal test) techniques discussed in the following sections were employed to relate the variability of quality of each parameter to treatment cost, river and human health.

4.4.2. Observational methods

- **Time- series plot**

Eight year (2005-2012) water quality data-sets for 12 parameters monitored at the six stations, MDI, MDO, NDI, NDO, IDI and IDO were plotted against time. Microsoft Excel 2013 program was used for this purpose. The main advantage of this technique is its ability to display the pollution pattern over a period of time. If such pattern is related to chemical dosage one can deduce the effect of each parameter on treatment cost at any given time. This should further assist in forecasting chemical dosage.

Stacked lines were used instead of the normal lines as the former displayed clearer trends for analysis as compared with normal time-series lines. The normal line chart however had congested data points making it difficult to deduce the trends. Even though time-series plot provide an easy and quick method of assessing the pollution patterns, its inability to display the crucial data characteristics specifically; mean, mode and median is a major drawback. While considering the importance of these characteristics in assessing the fitness of the water quality in a catchment for a given use, another method was to be employed along with the time-series plot. The box-plot was such an appropriate alternative.

❖ **Box-plot**

One of the main advantage of a box-plot is its ability to summarise the distribution of data-sets in a way that allows for spatial comparison. The technique gives a visual summary of; (1) the centre of the data (the median = the centre line of the box), (2) the variation or spread (inter-quartile range = the box height), (3) the skewness (quartile skew = the relative size of box halves) and (4) presence or absence of unusual values ('outliers') (Helsel and Hirsch 1992; Antonopoulos, Papamichail and Mitsiou 2001). By allowing the comparison of data without making any statistical assumption, the methods pose a greater advantage as compared with statistical techniques.

In this study, the box-plot was employed to determine the spatial variation of parameters considered among the six stations studied. The variation of water quality among the stations should assist in negotiating for the pricing raw water according to quality variability.

Even though the time series techniques continue to be widely used in water quality resource management, its inability to quantify the magnitude of a trend is a major draw back (Helsel and Hirsch 1992; Antonopoulos, Papamichail and Mitsiou 2001). While considering the importance of such quantifications, especially when forecasting in the water industry, statistical tests had to be employed to counteract this limitation.

4.4.3. Statistical methods for trend analyses

The success of determining the significance and magnitude of a trend depends primarily on the choice of the most appropriate statistical test or method. If the study depends on secondary data, it is reasonable to consider a method that accommodates outliers, missing values and censored values, which tend to be common in secondary water quality data-sets.

In this study, the Seasonal-Kendall (S-K) test was considered for the purpose of determining the significance of trend. One of the main advantages of this method is its ability to override the effects of outliers, missing values and seasonality, which are common in water quality data-sets (Helsel and Hirsch 1992). By only accepting a single observation per month, the S-K method counter-acts serial autocorrelation in a water quality data-set (Cox, Moss and Smyth 2005). In addition, the removal of cross month differences (since the months are 12 apart), tends to reduce the seasonality effect. These characteristics normally affect the analysis and might lead to a wrong conclusion.

A positive S-K value indicates an increasing trend whilst a negative value, shows a decreasing trend. A trend is considered statistically significant if the calculated p- value is less than 0.05 (Hirsch, Slack and Smith 1982b). Where a significant trend was obtained, the Sen's slope test was then employed to determine the magnitude of the trend (Helsel and Hirsch 1992).

Both the S-K and the Sen's slope test were calculated using XLSTAT 2014 software. The program used, which is a Microsoft Excel Add-in does not require programming knowledge by the user, making it simple and user friendly.

4.5. Methods for Objective Two

Objective 2: To produce two water quality indices: one for describing the general river health status and another determining the treatability of raw water being abstracted in uMngeni Basin

Both indices are anticipated to assist in the dissemination of water quality information to the general public and other non-technical stakeholders who have a right to know about the status of their environment. A river health water quality index should assist in evaluating the long term sustainability of a water source for the protection of the freshwater organisms. A treatability water quality index on the other hand should assist a treatment utility evaluate the fitness of raw water for the production of potable water.

4.5.1. River Health Water Quality Index

The rationale was to develop a tool for evaluating the overall river health status to be known as the River Health Water Quality Index (RHWQI). For this purpose, several methods for developing water quality indices reviewed in Chapter 2 were evaluated (Ott 1978; Couillard and Lefebvre 1985; Wepener *et al.* 2006). Among these, the

Weighted Geometric Mean (WQM) method was finally considered in this study. Its ability to counteract ambiguity and eclipsing indexing problems makes the method attractive and widely recommended. As with many popular water quality indices, a WGM is developed following the basic steps outlined below (Couillard and Lefebvre 1985; Hallock 2002; Wepener *et al.* 2006).

i. parameter selection;
ii. data transformation
iii. weight factor assignment and
iv. aggregation of the overall water quality index

1 Parameter selection

The parameters were selected while considering three aspects, (1) expert opinions, (2) data availability and (3) pollution problem in the study area. For example, Bharti and Katyal (2011) reviewed 36 indices that describes the river health status and found that 35 parameters had been frequently used. Among these; dissolved oxygen appeared in 15 indices, pH (11), Biological Oxygen Demand (BOD) (11), total phosphorous and phosphates (11), nitrates (10), total dissolved solid (8) and total hardness (5). Dunnette (1980) suggested that the status of freshwater ecosystem should be described using the five classes. These are; (1) oxygen level depleting substance, (2) eutrophication effect, (3) human health aspects, (4) physical characteristics and (5) dissolved substances level.

With regard to pollution problems in the Basin, it was noted that sewage effluent and runoff from agricultural activities were the major problems. Even though heavy metals are of importance to aquatic animals, literature showed that these were not a problem along the uMngeni River and were thus not considered.

With consideration of these facts, dissolved oxygen, *E. coli*, nitrates, total phosphate, turbidity, conductivity, pH and ammonia were finally selected for this purpose of this objective. Table 4-1 outlines the effect of each of the considered parameters on the river and human health. Appendix C depicts the method and instruments used to monitor these parameters.

Table 4-1: Description of parameters considered for the RHWQI

Parameter	**Category**	**Characteristics**	**Country studied**	**Reference**
(DO)	Oxygen Status	-Regulate the distribution of aquatic flora and fauna. -Essential to aquatic life -Low levels indicate pollution by oxygen demanding substances -low DO increases conversion of nitrate to nitrite and sulphate to sulphide	New Zealand Brazil Philippines India	(Boulton *et al.* 1997) (Couceiro *et al.* 2007) (Dyer *et al.* 2003) (Berzas *et al.* 2000) (Sánchez *et al.* 2007)
E. coli	Health Aspect	-Evidence of human pathogens	-	(WHO, 2006) Waite and Dufour 2003)
NO_3	Eutrophication	-Aquatic plant growth stimulant	India Nigeria	(Kankal *et al.* 2012) (Cude 2001) (Yisa and Jimoh 2010)
TP	Eutrophication	- Indicates eutrophication - Sign of wastewater pollution - Agricultural runoff - Plant and algae limiting factor	Australia UK Kenya Thailand	(Crowns *et al.* 1992) (Hofmann and Mason 2005) (Ndiritu, Gichuki and Triest 2006) (Singkran and Sudara 2005)
EC	Dissolved Substances	-Indicates salinisation - Indicates industrial discharge	Malaysia Australia Brazil Australia	(Azrina *et al.* 2006) (Brainwood and Burgin 2006) (Couceiro *et al.* 2007) Walsh et al. 2001
Temperature		-affects the rate of photosynthesis -affects metabolic rate in aquatic animal Affects the rate of development and reproduction	Malaysia New Colorado England	(Azrina *et al.* 2006) (Clements *et al.* 2000) (Townsend, Hildrew and Francis 1983)
pH			Colorado England	-(Clements *et al.* 2000) -(Townsend, Hildrew and Francis 1983)

2 Data transformation (Rating curves)

Various parameters are measured in different units (ppm, mg/L, mS/m etc.,) and ranges (e.g. pH 1-14) thus making it impossible to directly aggregate them. Thus, prior to aggregation, there is need to convert the data to a common, comparable scale (Couillard and Lefebvre 1985). While there are various methods of transforming water quality data as reviewed in Chapter 2, the rating curves technique was considered in this study due to its wide use and recommendation (Walski and Parker 1974; Smith 1990; Wepener *et al.* 1992).

The following aspects influenced the development of the rating curves in this study.

1. Since guidelines are developed based on scientific findings, with the precautionary principle in consideration, they tends to provide a reasonable baseline for normalising data. National guidelines provides criteria and classes which can be subjectively sectioned and assigned normalised values.

   For this study, the South Africa’s target ranges as stipulated in the fresh water ecosystem guidelines were used as basis for setting the concentration ranges and their respective Q values (Department of Water Affairs and Forestry 1996b).

2. Where the South Africa’s guideline does not state a target range for a given parameter, the Canadian Environmental Quality Guideline for the Protection of Aquatic Life (CCME 2001) and the Austrian and New Zealand guidelines for freshwater ecosystems (ANZECC 1992) were adopted. The latter are always updated and would thus also provide a reasonable comparison. Table 4-2 shows a typical water quality classes for the United Nations Environmental Protection program (UNECE 1994).

3. Since the index was to be site specific, some degree of subjectivity was employed in developing the rating curves. This was done in consideration of the known natural water quality status of the basin under study. For example, analysis of the given data and literature showed that the mean dissolved

oxygen in uMngeni Basin is approximately 8mg/L, suggesting that value as saturation (100%). This analysis was in consideration of South Africa's guidelines for freshwater ecosystem which stipulates that the target range for parameters such as dissolved oxygen should be calculated against the systems natural background (Department of Water Affairs and Forestry 1996b).

Table 4-2: A normalising table for a Water Quality Index
Source: (UNECE 1994)

Variables	Class I	Class II	Class III	Class IV	Class V
DO(mg l^{-1})	>7	7-6	6-4	4-3	<3
Eutrophication					
Total P (µg l^{-1})[1]	<10	10-25 (15-40)	25-50 (40-75)	50-125	>125
Total N (µg l^{-1})[1]	<300	300-750	750-1,500	1,500-2,500	>2,500
Chlorophyll a (µg l^{-1})[1]	<2.5	2.5-10 (4-15)	10-30 (15-45)	30-110	>110
Acidification					
pH[2]	9.0-6.5	6.5-6.3	6.3-6.0	6.0-5.3	<5.3
Alkalinity (mg $CaCO_3$ l^{-1})	>200	200-100	100-20	20-10	<10

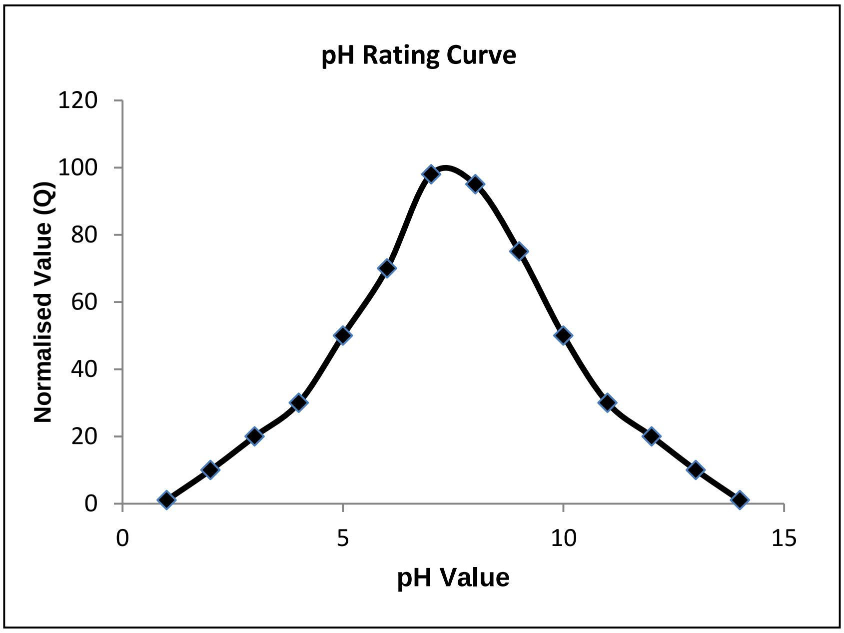
4. A minimum sub-index score (Q-value) of 5 was given instead of zero while considering that water should always have an economic value even when polluted. Also, zero was purposively avoided in order to counteract the eclipsing problem which arise with the WQM. A maximum values of 100 was assigned to signify safe concentration with regard to the protection of freshwater ecosystem.

In this study, the rating curves for the parameters were developed by plotting the different concentration range values against the assigned normalisation values (Q-Values). Transformation equations were determined by curve fitting. All calculations were done in Microsoft Excel 2013.

Since all rating curves were formulated by the same procedure, only pH's rating curve and equations are shown in Table 4-3 as an example. However, Appendix E to L provides a full list of rating tables, curves, equations for the other parameters included in the index.

Table 4-3: Rating curve and normalizing table for pH

pH	Q-Value
14	1
13	10
12	20
11	30
10	50
9	75
8	95
7	98
6	70
5	50
4	30
3	20
2	10
1	1



Rating equations derived from pH's rating curve

Range	**Rating Equation**
1 – 4	$y = -0.1667X^3 + 1.5X^2 + 5.6667X - 6$
4 - 6	$y = 6E\text{-}14X^2 + 20X - 50$
6 - 9	$y = 2.3333X^3 - 64.5X^2 + 570.17X - 1533$
9 - 11	$y = 2.5X^2 - 72.5X + 525$
11 - 14	$y = 0.1667X^3 - 6X^2 + 61.833X - 146$

"IF" statement for calculating the normalised pH value

=IF(pH="","NM",IF(pH<1,"ERR", IF(pH<4, -0.1667*pH^3 + 1.5*pH^2 + 5.6667*pH - 6,IF(pH<6, 0.00000000000006*pH^2 + 20*pH - 50,IF(pH<9, 2.3333*pH^3 - 64.5*pH^2 + 570.17*pH -1533,IF(pH<11, 2.5*pH^2 -72.5*pH + 525,IF(pH<=14, 0.1667*pH^3 - 6*pH^2 + 61.833*pH - 146, IF(pH>14,"ERR")))

3 ***Assigning Weight Factors***

Weight Factors (WFs) are assigned to reflect the significance of parameters relative to others (Wepener *et al.* 2006). Though the criteria for choosing weight factors is often an issue of controversy, a logical approach could improve the interpretability and credibility of an index. For this purpose, the following factors led to the assignment of the weight factors to the different parameters considered for the RHWQI.

1. Expert opinions as reflected in freshwater indices reviewed were considered. Different water quality indices were reviewed and evaluated for this purpose. Their respective WF's assigned on each parameter were evaluated.

2. The WF's assigned ranged from 1 (least) to 5 (most) depending on its relative importance to river health status as highlighted in literature. For example, dissolved oxygen was assigned the highest weight factor amongst the parameters considered while considering its importance to aquatic animals.

3. Even though *E. coli* might not have a significant effect on aquatic ecosystem, it was assigned the second highest weight factor while considering that humans may directly use river water for drinking purposes.

The final weightage were determined by dividing the individual temporary weight of each parameter by the total temporary weights. Table 4-4 shows the full list of the temporary and final weight factors assigned to each if the parameters considered. Having established the rating curves and associated weights, various methods of computing a water quality index were evaluated.

Table 4-4: Weight Factor normalisation table

Parameter Category	Variable	Temporary Weight Rating (out of 5)	$(\frac{temporary\ WF}{Total\ temporal\ WF})$	Final Relative WFs
Toxicity	NH_3	3	$\frac{3}{21.5}$	0.1395
Eutrophication	NO_3	2	$\frac{2}{21.5}$	0.0930
	TP	2.5	$\frac{2.5}{21.5}$	0.1163
Health Implicating	DO	5	$\frac{5}{21.5}$	0.2326
	E. coli	4	$\frac{3}{21.5}$	0.1860
	pH	2	$\frac{3}{21.5}$	0.0930
	EC	1	$\frac{3}{21.5}$	0.0465
	Turbidity	2	$\frac{3}{21.5}$	0.0930
Total		21.5	$\frac{3}{21.5}$	1

4 ***Water Quality Index Aggregation***

Based on the literature review, choice of the appropriate method was in consideration of the three main problems encountered in developing a water quality index namely; ambiguity, eclipsing and rigidity (Singh, Malik and Sinha 2005; Wepener *et al.* 2006). Among the different aggregation methods reviewed in Chapter 2, the Weighted Geometric Mean (WGM) shown in Equation 4-1 has been recommended as a less biased and more viable method for describing the overall river water quality (Walski and Parker 1974; Joung *et al.* 1979; Wepener *et al.* 2006). This method which is nonlinear, has been widely recommended as generally free from the effect of ambiguity.

Equation 4-1

$$WQI = \sum Qi^{wi}$$

Where: *Qi* = Quality rating value (Q-Value) and *Wi*= Weight Factor

I. Qualitative ranking

The description of the calculated WQI score range is generally subjective since indices are normally specific. A thorough literature review was thus conducted to compare the qualitative ranges that have been used in various countries. Table 2-1 outlines various classes that have been used in different countries.

With consideration of other descriptive classes in literature, the RHWQI scores ranging from 0 to 100 were divided into five main categories as shown in Table 4-5. A higher value indicated that the water still supports the biotic communities while a smaller values shows pollution. A narrative score is used to describe each category.

Table 4-5: The different descriptive classes assigned to water quality index score based on RHWQI value

RHWQI- Value	**Class**	**Overall Water Quality Description**
100-91	1	Excellent
71-90	2	Good
51-70	3	Medium
24-50	4	Bad
0-2	5	Very bad

4.5.1.1. *Calculation of the RHWQI on a Microsoft Excel spreadsheet*

To automate the calculation of the index score, the derived rating equations and WFs were manipulated and entered into a Microsoft Excel (Ms Excel) spreadsheet. The “IF” statement, a formula in Ms excel was used to convert a given concentration to its respective Q-Value. The “IF” statement checks to see if a value in a Microsoft excel spreadsheet is true and further gives an action for a given condition. Appendix E to L provide a full list of all the “IF’’ statements, rating curves and equation derived in Ms Excel.

4.5.2. Treatability Water Quality Index

The Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) approach was used to develop an index for determining the treatability of raw water in uMngeni Basin. This method also endorsed by the United Nations Environmental Program (UNEP) has been widely used in many countries to assess the fitness of different water sources in providing drinking water (UNEP and GEMS 2007).

II. Parameter consideration

For this objective, parameters were selected in consideration to their relative effect on treatment especially chemical dosage as well as effect on human health. Knowledge of the existing water quality problems in the uMngeni Basin influenced the choice of parameters. Table 4-6 outlines the parameters selected for this index and their effects implication during treatment.

Table 4-6: Parameters and their effects on treatment processes and human health

Parameter	**permissible limit**	**Effects for drinking fitness**	**Implications on treatment**	**Reference**
Algae	<0.8µg/l*****	-colour and odour problem -toxin produces by some species may have health effect	- high disinfectant demand -potential to form chlorinated organic - high coagulant dose -increase flocculation/ Sedimentation times -harbour microorganisms - reduce filter runs	(Graham 2004) (Widrig, Gray and McAuliffe 1996)
Turbidity	< 1 operational < 5 Aesthetic*****	-Shield bacteria -Aesthetic problem	- high disinfectant demand - potential to form chlorinated organic - high coagulant dose -harbour microorganisms - reduce filter runs	(Apostol, Kouachi, & Constantinescu, 2011)
Conductivity	<170*****	-hardness	- positively correlated to poly ,chlorine and lime	
Alkalinity	-		-Positively correlated to lime and chlorine	(Kang and Cleasby 1995) (Xie et al., 2012)
E. coli	Count per 100ml*****	-Gastrointestinal disease -can cause sensory defects (odour, colour, taste)	-increases chlorine dosage	
Temperature	15 – 25 *		-positively correlated to poly, lime and chlorine	(Kang and Cleasby 1995)

Parameter	permissible limit	Effects for drinking fitness	Implications on treatment	Reference
Ammonia	<1.5*****	-depends on temperature, pH and total dissolved solids	-positively correlates to chlorine	(Brooks 1999) (Argo 1980)

NB: Even though pH is of importance during potable water treatment, it was excluded since its primary effect is also exhibited by alkalinity. The two parameters are positively correlated. However, there is always a need to monitor pH during treatment.

III. *Resource Water Quality Objectives (RWQO)*

In this case, since the adopted CCME WQI was to be site specific, the RWQO set by Durban Heights and Wiggins WTP were considered as benchmarks (objective) for determining the compliance level of a parameter measured. As the proposed index was to serve the uMngeni Basin, the internal warning limits which are calculated as 80 percentile for each parameter's data were averaged to produce a harmonised set of objectives. This was done to provide a fair baseline for comparison of the two treatment plants being studied. CCME (2001) highlighted that any conclusion drawn by comparing indices calculated from different set of objectives will be wrong. Where the parameter's objective was not given, the 80th percentile for the parameter based on the given data-set was used as the benchmark.

Table 4-7 provides the objectives for each treatment plant as well as the calculated harmonised water quality resource objectives.

Table 4-7: Resources water quality objectives for Durban Heights and Wiggins WTP

Durban WTP			**Wiggins WTP**	
Parameter	**Unit**	**Warning Limit**	**Warning Limit**	**Harmonised RWQO**
Total Phosphate	ug/L	55	160	105.2
Nitrates	mg/L	0.4	1.4	0.9
Algae	cell/mL	3 000	1 000	1500
Conductivity	mS/m	10	25	17.5
Turbidity	NTU	25	15	20
Total Organic Carbon	mg/L	4	4	4
Escherichia coli	count/mL	50	50	100*

NB: For *E. coli*, a limit for 100 cell/mL was set was considering the dataset provided and the pollution pattern in the basin.

IV. Aggregation method

Equation 4-2 presents the formula for calculating the CCME-WQI. A detailed description of the CCME-WQI is described by UNEP and GEMS (2007) and comprises three components outlined as follows;

1. Scope - The total number of parameters that failed to meet the set objective (F_1).
2. Frequency - The number of test that failed against the total test done (F_2).
3. Amplitude - The magnitude by which the objectives are not met (F_3).

Equation 4-2

$$WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$$

Where WQI = Water Quality Index

1. F_1 = ***Scope (how many):*** This is the percentage of parameters that exceed the guideline (Equation 4-3). In this study, “failed parameters” are parameters inputs that exceeded the calculated harmonised water resource objective (HWQRO).

Equation 4-3

$$F_1 = \left[\frac{Number\ of\ Failed\ Parameters}{Total\ Number\ of\ parameters}\right] * 100$$

2. F_2 = ***Frequency (How often):*** The percentage of individual tests for each parameter that exceeds the HWQRO as shown in Equation 4-4.

Equation 4-4

$$F_2 = \left[\frac{Number\ of\ \ Failed\ Tests}{Total\ Number\ of\ test} \right] * 100$$

3. F_3 = ***Amplitude (how much).*** The extent (excursion) to which the failed test exceeds the HWQRO is calculated with Equation 4-5.

Equation 4-5

$$F_3 = \left[\frac{nse}{0.01+0.01} \right]$$

The calculation of F_3 involves two steps, (1) calculation of the excursion and the (2) normalised sum of excursion.

The first step of obtaining F_3 involves the calculation of the number of times by which an individual concentration is greater than (or less than, when the objective is a minimum). This is termed an "excursion" and expressed as shown in Equation 4-6.

Equation 4-6

$$\text{Excursion} = \frac{\text{Failed Test Value}}{\text{Objective}} - 1$$

In a case where a test value must not fall below the objective, the "excursion" is calculated using Equation 4-7.

Equation 4-7

$$\text{Excursion} = \frac{\text{Objective}}{\text{Failed Test Value}} - 1$$

The collective amount by which individual tests are out of compliance is calculated by summing the excursions of individual tests from their objectives and dividing by the total number of tests. This stage, also referred to as the normalised sum of excursions, or nse, is calculated as shown in Equation 4-8

Equation 4-8

$$\text{nse} = \sum_{i=1}^{n} \frac{excursions}{number\ of\ test}$$

F_3 is then calculated by a function, shown in Equation 4-5.The formula scales the normalised sum of the excursions from objectives (nse) to yield a range between 0 and 100.

V. Qualitative description of the overall scores

The final water quality scores were assigned narrative description in relation to the expected treatment level. Table 4-8 shows the five classes used to describe the fitness of water for treatment purposes.

Table 4-8: Descriptive classes for the Treatability Water Quality Index scores

Class	WQI score	Treatment Method
I	100-90	- Simple physical treatment and disinfection, - e.g. rapid filtration and disinfection
II	90-75	- Normal physical treatment, chemical treatment and disinfection - e.g. pre-chlorination, coagulation, flocculation, decantation, filtration, disinfection (final chlorina-tion)
III	75-50	- Intensive physical and chemical treatment - e.g. chlorination to break-point, coagulation, flocculation, decantation, filtration
IV	50-30	- , extended treatment and disinfection, - adsorption (activated carbon), disinfection (ozone, final chlorination)
V	0-25	- must undergo waste water treatment

The calculation of the CCME-WQI was done on a Microsoft Excel 2013 spreadsheet. Mathematical functions were developed to automate the calculation.

4.6. Methods for Objective Three

Objective 3: To statistically determine parameters whose concentrations showed significant change due to treatment and correlate them with polymer, chlorine and lime dosage at Durban Heights and Wiggins treatment plants.

For this objective, two distinct statistical methods were employed. The t-test was used along with the correlational analysis. Potable water data-sets from Durban Heights and Wiggins WTP were analysed along with their corresponding raw water data-set for the outflow station of Nagle and Inanda Dams respectively.

4.6.1. One-sample t-test

The first effort was to determine whether the concentration of a given parameter changed significantly due to treatment. For this purpose, potable water monthly mean values denoted by *R* for each of the 23 parameters considered was divided by its corresponding raw water measurement (*Ro*). The calculated, R/Ro were then analysed. An average value (*R/Ro)* close to one suggest that the treatment process had no effect on that parameter's concentration. However, a value close to zero, or far from one, suggested a decrease or increase in the parameter's concentration respectively due to treatment (Haarhoff and Olivier 2002).

Thereafter, a one-sample t-test was performed to determine if the observed change in concentration due to treatment was significant. A test value of one (1) was set to indicate no change in concentration. Thus, for a parameter to be considered significant, two criteria had to be met:

i. The null hypothesis that there was no significant change in the concentration of any given parameter was to be rejected. The mean change was defined as 1. The test was performed at 98% level of confidence using the following equation:

$$t = \frac{\bar{x} - \mu}{s/\sqrt{n}}$$

Where $\bar{x}$ the sample mean, ***s*** is the sample standard deviation of the sample and ***n*** is the sample size

ii. The change in concentration, R/Ro, was considered significant if greater than 5% from the test value of 1. Value less than 0.95 thus indicated a significant decreased while, those greater than 1.05 would be imply an increase in concentration level due to treatment.

4.6.2. Water quality parameter correlations

For the purpose of establishing the relationship between the water quality parameters (independent) and chemical dosed during treatment (dependent), data for the different water quality parameters measured at NDO and IDO stations were correlated to polymer, chlorine and lime dosage at Durban Heights and Wiggins WTP respectively. The Pearson 'R' correlation method was used to determine the presence ($P < 0.05$) and strength (R=value) of the association (Helsel and Hirsch 1992). A parameter was considered significant if the p-value was less than 0.05. Table 4-9 provides the descriptive scale of the correlation coefficient.

Table 4-9: Correlation descriptive scale.

Source: (Rowntree and O'Hehir 1981)

Coefficient ranges	**Correlation description**
0.0	No correlation
+1 and -1	Perfect positive and perfect negative correlation respectively
0.0 to 0.2	Very weak, negligible correlation
0.2 to 0.4	Weak, low correlation
0.4 to 0.7	Moderate correlation
0.7 to 0.9	Strong, high marked correlation
0.9 to 1.0	Very strong, very high correlation

4.7.Methods for Objective Four

Objective 4: To develop models for predicting polymer, chlorine and lime dosage at Durban Heights and Wiggins Water Treatment Plants

While the artificial intelligence methods such as neural networking and genetic algorithms have been recommended as superior for prediction purposes, their wide use has been hindered by their extensive data requirement which may not be readily available. Although methods for interpolating data have been developed and are being widely used, concern has been raised as most of these methods tend to lose their accuracy as the number of missing value and data interval increases.

An additional major drawback for the wide adoption of artificial intelligence methods has been the high cost of purchasing the software as well as the complexity of its programs. One needs to acquire specialised training, which makes it difficult for those who do not have advanced computer skills. The rising cost of training is also a significant limiting factor.

The non-linear polynomial modelling function in XLSTAT 2014 was used to develop three models for each of the two treatment plants studied. The program used, XLSTAT, is a Microsoft Excel Add-in, making it relatively simpler to use. It is also relatively cheap to procure as compared to most artificial intelligent modelling programs. Equation 4-9 depicts the general formula of the model employed using the 23 parameters.

Equation 4-9

Y=pr1+pr2*X1+pr3*X2+pr4*X3+pr5*X4+pr6*X5+pr7*X6+pr8*X7+pr9*X8+pr10*X9+pr11*X10+pr12*X11+pr13*X12+pr14*X13+pr15*X14+pr16*X15+pr17*X16+pr18*X17+pr19*X18+pr20*X19+pr21*X20+pr22*X21+pr23*X22+pr24*X23

Where pr = water quality parameter

Data-set for both treatment plants were divided into two sets, 80% and 20%. The larger proportion (80%) was used for training and the smaller (20%) for model testing. The derived models were manipulated using Microsoft Excel functions to automate the calculations. The predicted and actual dosage values were then compared graphically and statistically. The appropriateness of the models were evaluated using the following aspects:

1) Visual inspection

The predicted values were examined along with the actual dosages on a time-series graph. The fitness of the model was determined by comparing how good the predicted plot fits the actual dosage. Where the predicted values were extremely outside the actual range, it would indicate that either the model is incorrect or the parameter coefficients are poorly estimated.

2) Correlation coefficient

The correlation coefficient (R^2) depicts the predictive power of a model. A value of one (1) implies that the model perfectly predicts while zero might mean that the model is generally irrelevant for predictive purposes.

3) Root Mean Squared Error (RMSE) and Mean Squared Error (MSE)

MSE and RMSE are used to measure the differences between actual values of the outputs and the modelled output values. Therefore, MSE and RMSE value of the model is required to be very low for the accuracy of the model. RSME measures the deviation of the modelled values from the actual observed. An ideal RMSE is zero. Equation 4-10 shows the mathematical formulae for calculating the RMSE.

Equation 4-10

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

Where x_i is the observed value and $\overline{x_i}$ is the predicted model output

4.8. Summary

The purpose of this chapter was to describe the methods and materials employed to determine the four objectives identified for the purpose of this study. The time-series, box-plot and the Seasonal-Kendal test were employed for the first objective. The RHWQI and TWQI were developed using the Weighted Geometric Mean and the Canadian Council of Ministers of Environment Water Quality Index (CCME WQI) respectively. The chapter also discussed how the t-test was employed to determine whether the observed change in the concentration of the considered parameters was significant. The method used to develop the chemical dosage prediction models for the two treatment plants studied were also discussed.

CHAPTER 5: RESULTS AND DISCUSSIONS

5.1. Introduction

This chapter presents and discusses findings of the study in accordance with the four specific objectives outlined in Chapter One. The first section presents the spatial and temporal patterns for parameters measured at the six stations studied, three dam inflows (MDI, NDI and IDI) and their respective outflows (MDO, NDO and IDI), in the uMngeni Basin. The water quality trends are discussed in relation to, (1) potable water treatability and (2) characterisation of the river health status.

The overall water quality status based on the two indices, River Health WQI and Treatability WQI is also presented. Furthermore, the findings of the statistical tests used to determine the significance of the change in concentration of each parameter due to treatment are also presented. The chapter also present results from the different chemical dosage models produced.

5.2. Objective One Findings

To evaluate the spatial and temporal water quality trend along uMngeni River, in relation to river health and potable treatment cost

1. **Turbidity**

Figure 5-1, Figure 5-2 and Table 5-1 shows the time-series, box-plot and descriptive statistics respectively for turbidity at the six stations studied along uMngeni River. As shown in Figure 5-1, a seasonal trend is evident with high values in the wet season (October to April) and low levels in the dry season (May to September).

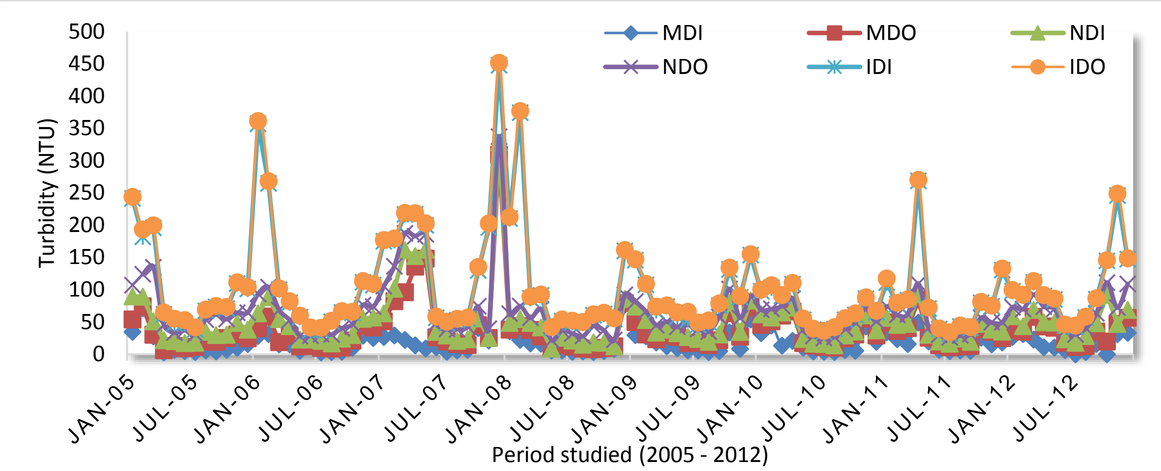


Figure 5-1: Temporal variation of turbidity at stations in uMngeni Basin

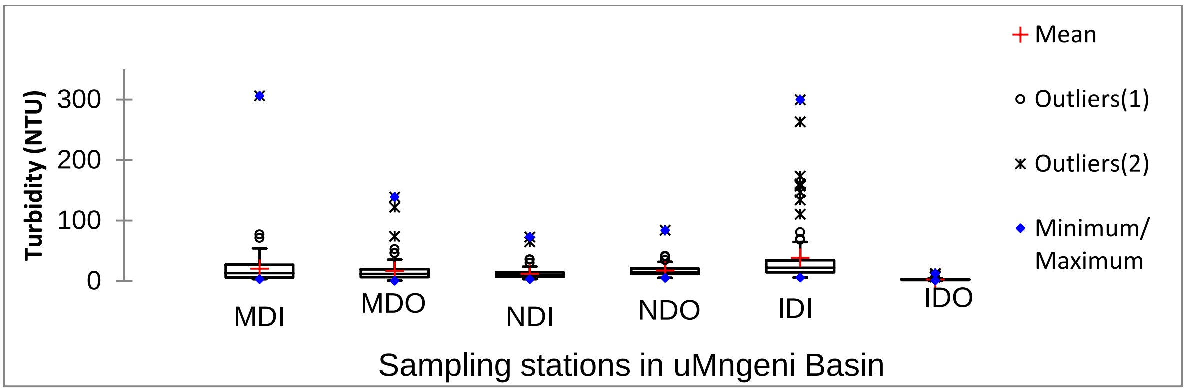


Figure 5-2: Spatial variations of turbidity at station in uMngeni Basin (2005 – 2012)

Table 5-1: Turbidity descriptive statistics for stations in uMngeni Basin

Sample	Minimum	Maximum	SD[2]	Median	Mean	S-K [3] (P-Value)	Sen's slope	Decrease
MDI	2.850	306.000	33.254	12.900	20.361	0.385	0.028	No trend
MDI	0.360	139.000	20.495	11.500	16.577	0.211	0.059	No trend
NDI	3.250	72.740	10.590	9.405	12.160	<0.0001	-0.078	Decrease
NDO	4.910	84.000	10.220	14.650	17.286	0.0495	-0.052	Decrease
IDI	5.635	299.700	50.956	21.563	38.729	0.0351	-0.075	Decrease
IDO	1.040	12.400	1.894	2.060	2.683	< 0.0001	-0.012	Decrease

Where: MDI= Midmar Dam Inflow, MDO=Midmar Dam Outflow, NDI = Nagle Dam Inflow
Nagle Dam Inflow, Inanda Dam Inflow, Inanda Dam Outflow

[2] SD refers to Standard Deviation

[3] S-K refers to Seasonal- Kendal test

The calculated means and medians shown in Table 5-1 depict that turbidity was above South Africa’s target range for domestic use (0-1 NTU) at the six stations studied (Department of Water Affairs and Forestry 1996a). This implies that the water in the uMngeni Basin is not acceptable for drinking purposes without treatment since such levels are of aesthetic concern.

The maximum turbidity level recorded at MDI station (304 NTU) could be explained by intensive farming activities upstream of Midmar Dam as highlighted in Chapter Three. Soil tilling tends to loosen the soil structure exposing it to run-off during the wet season. Chlorination of highly turbid water tends to increase the levels of trihalomethane (THM), which studies have linked to the prevalence of cancerous diseases (WHO 2004; Alkhatib and Peters 2008). Caution need to be taken with regard to THM’s levels in drinking water even though recent studies are disputing such associations (Astel *et al.* 2006; Chen *et al.* 2007).

Turbid particles may also encase pathogenic bacteria thus protecting them from the effect of a disinfectant (Department of Water Affairs and Forestry 1996a). BCWWA (2004) reported that viable *E. coli* bacteria have been detected in water with turbidity levels of 3 NTU, even in the presence of free chlorine residuals.

The relatively low mean turbidity level (2.68 NTU) observed at IDO, possibly due to the dam’s retention effect, tend to pose an advantage by reducing chlorine and polymer dosage. This can explain the low chlorine (Figure 5-34(b)) and polymer dosage (Figure 5-34(c)) observed at Wiggins WTP, which abstract from Inanda Dam compared to Durban Heights, which abstract from Nagle Dam. Thus, it can be that turbidity is a more significant chemical dosage driver at Durban Heights WTP compared to Wiggins.

Regarding river health characterisation, the maximum turbidity levels observed at MDI, MDO and IDI stations tends to reduce light penetration and ultimately photosynthesis in the aquatic ecosystems (Telesnicki and Goldberg 1995). This has a direct effect of reducing food production in the aquatic ecosystem. The abrasive effect of silt particles also tend to damage the delicate fish gills by its abrasive effect.

2. **Algae**

Figure 5-3, Figure 5-4 and Table 5-2 below shows the time-series, box-plot and descriptive statistics respectively for algae levels at the three stations along uMngeni River. Only outflow stations data-sets were available for algae

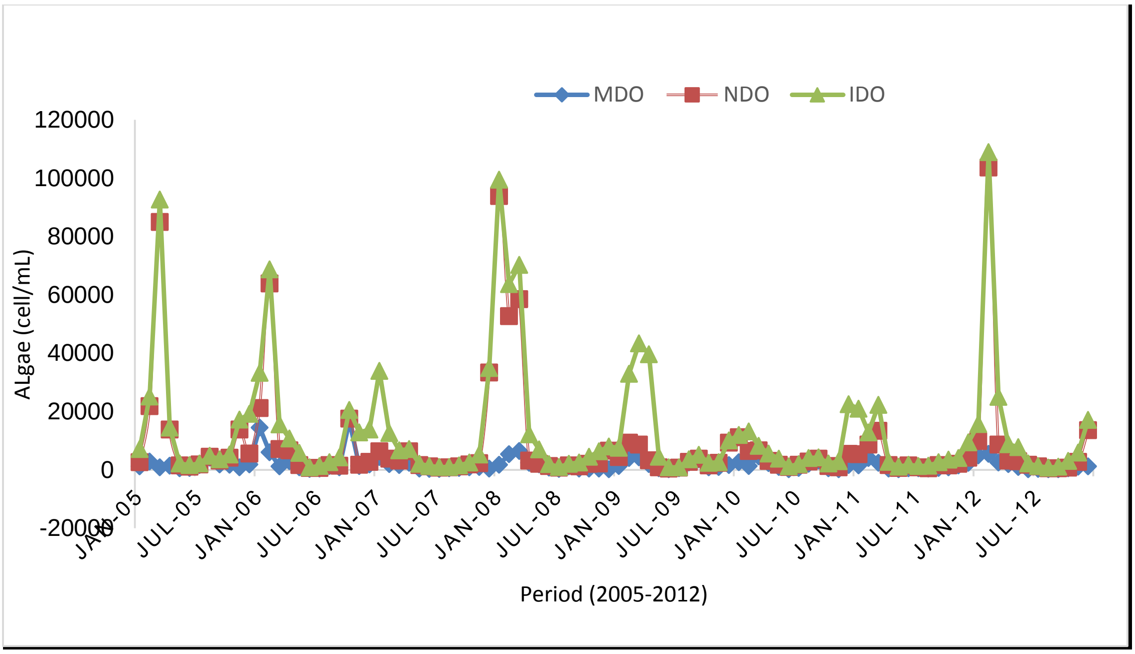


Figure 5-3: Temporal variation of algae at stations in uMngeni Basin (2005 to 2012)

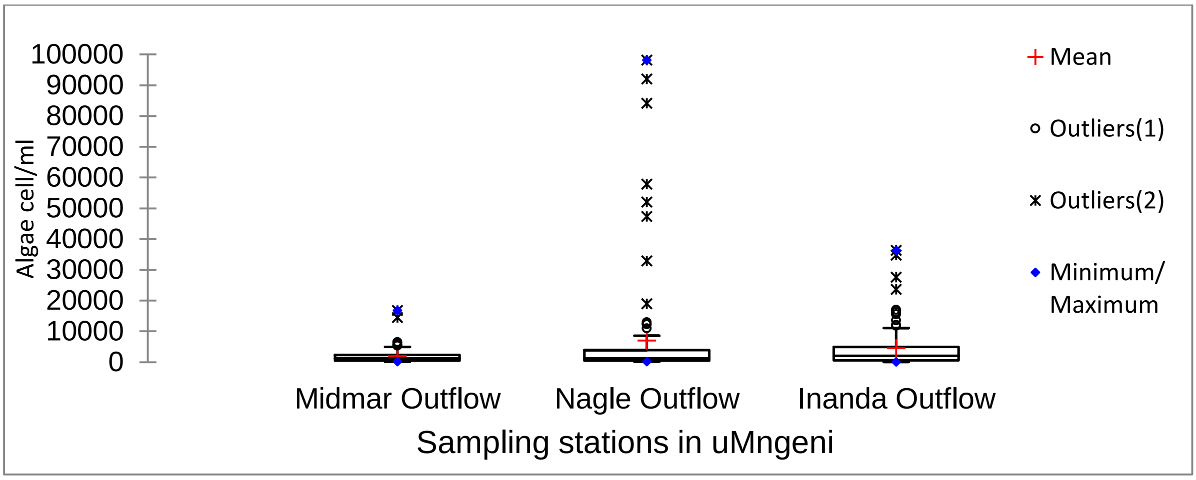


Figure 5-4: Spatial variations of algae at stations in uMngeni Basin (2005 – 2012)

Table 5-2: Descriptive statistics for algae in uMngeni Basin (2005 – 2012)

Station	Minimum	Maximum	SD	Median	Mean	S-K (p value)	Sen’s	Decision trend
MDO	159.50	16760.50	2480.48	1210.00	1900.60	0.125	-4.64	No trend
NDO	124.67	98224.40	18156.64	1155.58	7055.81	0.497	-2.968	No trend
IDO	105.75	36352.33	6833.39	1998.75	4499.09	0.748	-1.766	No trend

As expected, the time-series, Figure 5-3, shows that algae exhibited an annual cyclic pattern with peaks in the wet seasons and low values in winter.

The box-plot, Figure 5-4, shows that algae is a major problem at NDO station. This is of concern to Durban Heights WTP, which abstracts from this dam. High levels of algae tend to cause filter clogging, which in turn increases the frequency of backwashing and filtration time. Even though it was beyond the scope of this study to determine the effects of specific species of algae, it can highlighted that some cause odour and colour. This makes water aesthetically unaccepted and further exacerbates the treatment cost.

The high monthly mean range observed, 1900 to 7055 cell/mL, depicted in Table 5-2 suggest that algae is a significant problem in uMngeni Basin. This is of concern to human health when considering that some species of algae produce neuro, hepatic and lipopolysaccaride toxins whose effects can be fatal. The Department of Water Affairs has attributed the death of several livestock and game animal to toxins produced by specific algae species (Department of Water Affairs and Forestry 1996a). The cost of Powdered Activated Carbon (PAC), which is used to remove algae toxins further exacerbates treatment cost.

The high monthly mean algae level observed at NDO station (7055 cell/mL) suggests that more polymer and chlorine is required to treat water abstracted from this dam as compared to that from Inanda Dam. Algae being organic is oxidised by chlorine. This reaction which is not directly related to disinfection can be considered as wasteful as it increases chlorine dosage which is normally added for disinfection purpose. Formation of potentially harmful disinfection by-products in the presence of organic substances such as trihalomethane is probably the most significant health concern related to the presence of organic matter in treatment water.

A comparison of the median values clearly shows that IDO is more deteriorated among the three stations studied. These findings conform to earlier studies which also reported an upstream to downstream deterioration of water with regard to algae levels (Department of Water Affairs and Forestry 2003; Graham 2004). Graham (2003) using monitoring data that stretched from 1990 to 1999 also pointed out algae as the significant driver influencing treatment cost in uMngeni Basin.

3. **pH**

The time-series, box-plot and descriptive statistics for pH for the six stations studied along uMngeni River are presented in Figure 5-5, Figure 5-6 and Table 5-3 respectively.

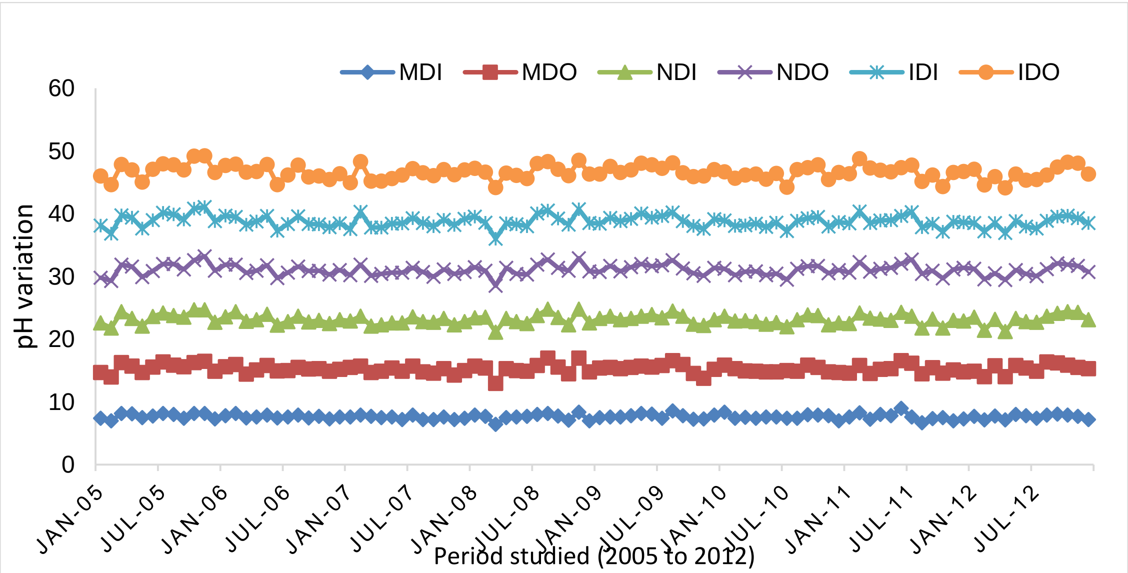


Figure 5-5: pH temporal variation at stations in uMngeni Basin (2005 – 2012)

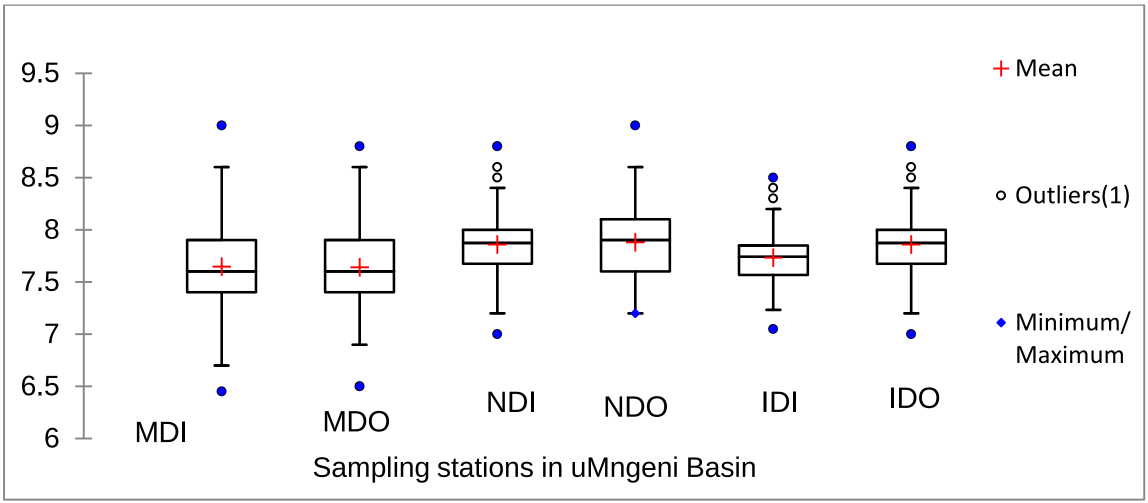


Figure 5-6: Spatial variations of pH at stations in uMngeni Basin (2005 – 2012)

Table 5-3: Descriptive statistics for pH in at stations in uMngeni Basin

Sample	Minimum	Maximum	SD	Median	Mean	S-K (P-value)	Sen's Slope	Decision trend
MDI	6.450	9.000	0.408	7.600	7.646	0.745	0	No trend
MDO	6.500	8.800	0.424	7.600	7.641	0.491	0	No trend
NDI	7.000	8.800	0.348	7.875	7.857	0.77	0	No trend
NDO	7.200	9.000	0.352	7.900	7.880	0.77	0	No trend
IDI	7.050	8.500	0.247	7.742	7.732	0.002	-0.003	Decrease
IDO	7.000	8.800	0.348	7.875	7.857	0.77	0	No trend

Figure 5-5, shows that pH variation is not a major problem in uMngeni Basin. This can be illustrated by the relatively low standard deviation range (SD), ±0.247 to ±0.424, observed. The small variation of pH level illustrated by the box-plots, depicted in Figure 5-6, also supports the notion that pH is a relatively stable parameter in uMngeni Basin.

The observed mean range, 7.641 to 7.857 (Table 5-3) supports that pH levels in uMngeni Basin is still within the target range value that support most freshwater aquatic organisms as stipulated in the South Africa's freshwater ecosystem guidelines (6.0 to 9.0 pH) (Department of Water Affairs 1996). However, at Midmar Dam, the pH varied from slightly acidic to alkalinity while at other stations, its levels ranged from neutral (7) to alkaline (9).

Except for IDI, the Seasonal-Kendal test results reveal that no significant temporal variation was observed at the six stations studied during a period stretching from 2005 to 2012. IDI however recorded a slightly decreasing temporal trend suggesting that the water is becoming acidic at this station. This is of concern to aquatic life especially animals which are generally sensitive to pH change. The maximum values observed at all stations which are above 8 are of concern. Elevated pH levels tends to convert ammonium ion (NH_4^+), a less toxic compound and usable by plants, to a highly toxic unionized ammonia (NH_3).

With regard to treatment, the maximum pH level observed at NDO, 9, suggest a reduction in lime dosage meant to optimise the coagulation process at Durban Heights WTP. This emanates from the fact that slightly alkaline conditions counter acts the pH reductive effect brought by a coagulant thus reducing lime dosage. Regarding disinfection, it is known that chlorine effectiveness is reduced at high pH as observed at NDO (Scarpino *et al.* 1972; Kott, Nupen and Ross 1975). The mean pH values of below 8 noted at all stations tends to promote effective disinfection. Such is in considering that WHO (2006a) highlighted that pH levels of below 8 are effective for disinfection purpose.

4. **Total alkalinity**

Figure 5-7, Figure 5-8 and Table 5-4 shows the time-series, box-plot and descriptive statistics respectively for alkalinity levels at the five stations studied. The time-series plot, Figure 5-7, shows that alkalinity displayed some irregular temporal variability at the stations studied.

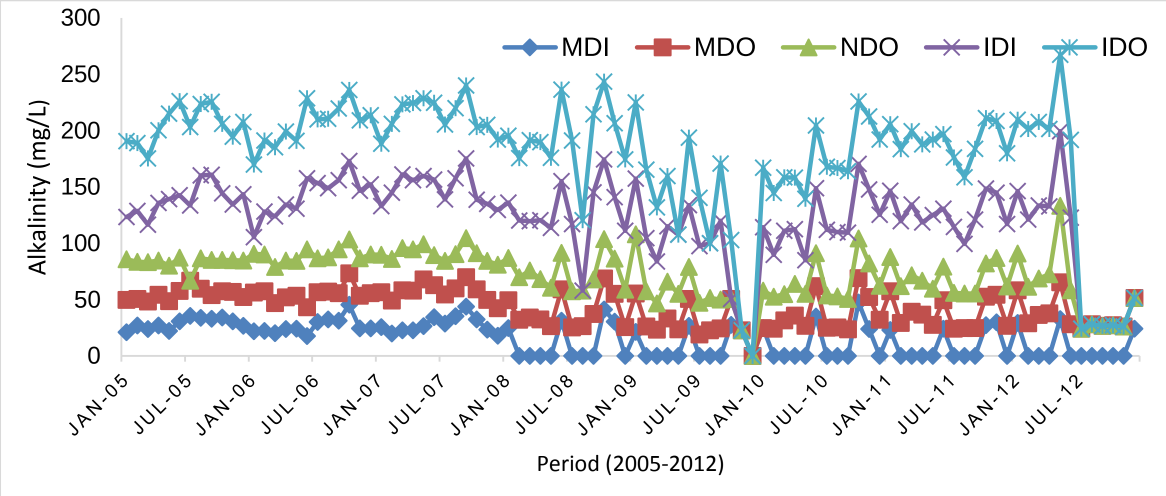


Figure 5-7: Temporal variation of alkalinity at stations in uMngeni Basin

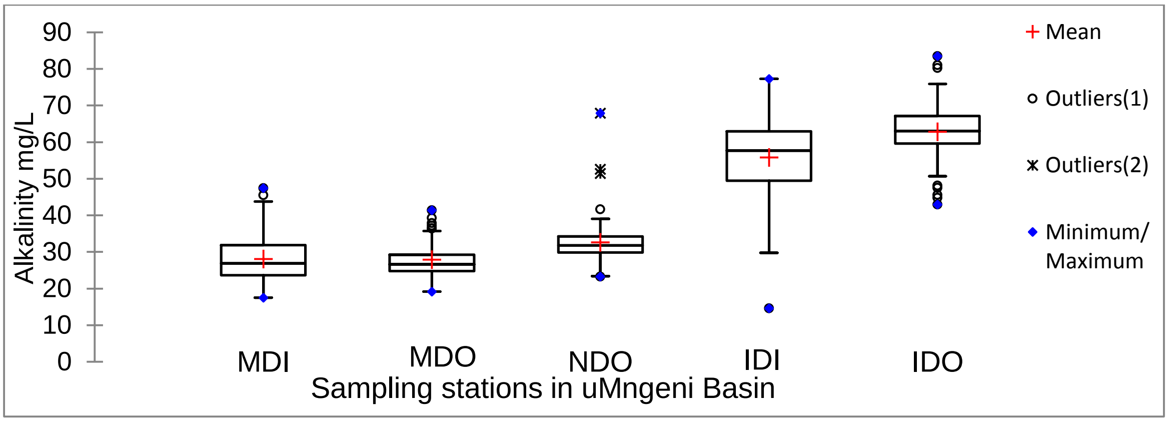


Figure 5-8: Spatial variations of alkalinity at stations in uMngeni Basin (2005 – 2012)

Table 5-4: Descriptive statistics for alkalinity at stations in uMngeni Basin

Sample	No	Minimum	Maximum	SD	Median	Mean	S-K (P-value)	Sen's slope	Decision trend
MDI	96	17.530	47.500	6.564	26.850	28.110	0.492	0.026	No trend
MDO	96	19.160	41.400	4.409	26.650	27.974	1	0.004	No trend
NDO	96	23.280	67.900	5.917	31.815	32.657	0.461	-0.018	No trend
IDI	96	14.600	77.270	10.610	57.695	55.840	0.363	0.077	No trend
IDO	96	42.970	83.500	7.425	62.995	62.842	0.633	-0.015	No trend

The box-plot, Figure 5-8, shows that alkalinity levels increased from upstream station (MDI) to downstream (IDO). The high mean range observed, 27.974 to 62.842 mg/L, suggest that uMngeni Basin still has the ability to buffer pH change to a certain degree. By comparing the mean and median values, as shown in Table 5-4, one can deduce that alkalinity levels increased from upstream to downstream in the uMngeni Basin. The IDI station recorded a monthly mean value of 55.84 mg/L which is twice that of MDI (28.11 mg/L). These results are in agreement with the finding of Dallas and Day (2004) who described South Africa's rivers as naturally alkaline.

The Seasonal-Kendall test results presented in Table 5-4 however shows that alkalinity was generally stable during the period studied (2005 to 2012).

Regarding potable water production, the observed high alkalinity level at IDO (62.842 mg/L) shows the ability of this dam to buffer a reduction in pH level brought by the result from a coagulant dosage as compared to Nagle Dam. These findings should explain the generally low lime dosage observed at Wiggins as compared to Durban Heights WTP as depicted in (Figure 5-34(a)).

5. **Temperature**

Figure 5-9, Figure 5-10 and Table 5-5 show the time-series, box-plot and descriptive statistics respectively for temperature at the six stations studied. As expected, temperature showed annual cyclic variation with lower values in winter (May – August) and high values in summer (September to April) (Figure 5-9).

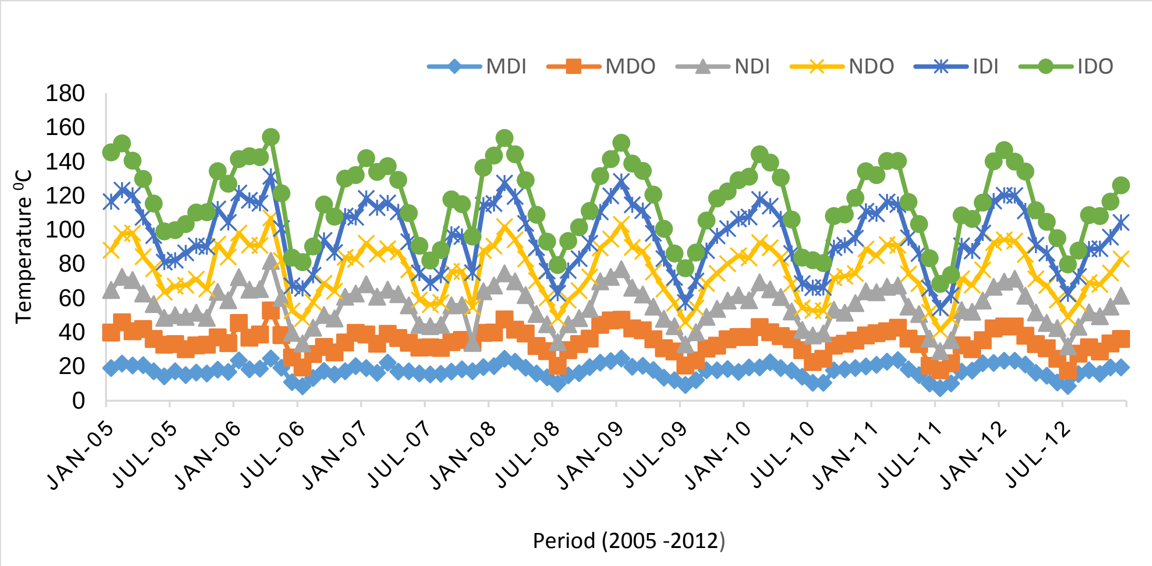


Figure 5-9: Temperature variation at stations in uMngeni Basin (2005 to 2012)

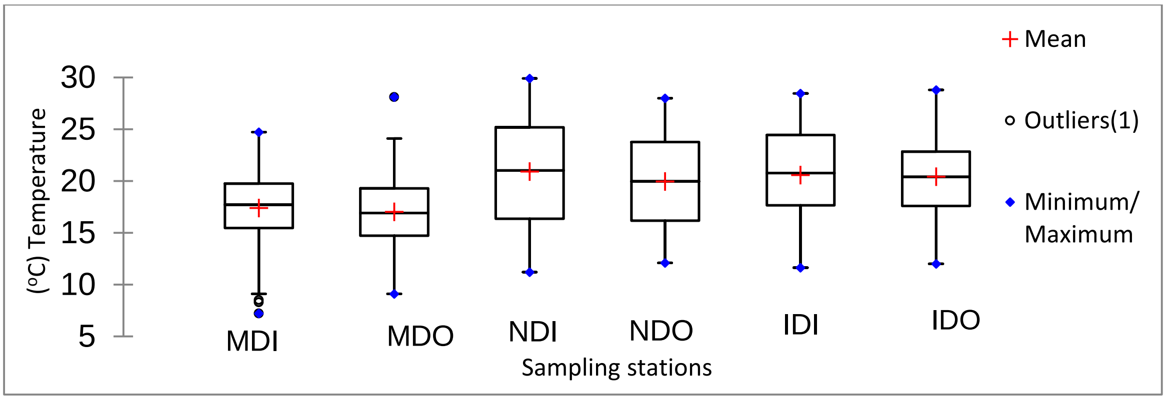


Figure 5-10: Spatial variations of temperature in uMngeni Basin (2005 – 2012)

Table 5-5: Descriptive statistics for temperature in uMngeni Basin

Sample	Minimum	Maximum	SD	Median	Mean	Seasonal-Kendal	Sen's slope	Decision trend
MDI	7.200	24.700	4.012	17.700	17.397	0.83	-0.003	No
MDO	9.100	28.100	3.492	16.900	17.029	<0.0001	-0.038	Decrease
NDI	11.200	29.900	4.946	21.000	20.908	0.0455	-0.029	Decrease
NDI	12.100	28.000	4.286	19.975	19.964	0.001	-0.031	Decrease
IDI	11.633	28.450	4.144	20.750	20.587	0.002997	-0.026	Decrease
IDO	12.000	28.800	3.611	20.400	20.419	0.0379	-0.013	Decrease

Higher temperatures observed in the summer is known to reduce the solubility of dissolved oxygen in water, decreasing its concentration and availability to aquatic organisms (Dallas and Day 2004). These conditions increase stress to aquatic organisms and can be fatal. For an unknown reason, the Seasonal-Kendal and Sen's slope results showed that the water temperature has been slightly decreasing in uMngeni Basin except at the MDO station (Table 5-5).

It can also be noted that high temperature observed in Figure 5-9 coincides with algae bloom (Figure 5-3). Graham (2004), using data stretching from 1990 to 1999 reported algae bloom as a significant driver for treatment cost on plants abstracting in uMngeni Basin. Low water temperatures observed in winter (Figure 5-9) tends to reduce the rate of coagulation and flocculation which ultimately decreases turbidity removal efficient. It is also known that low temperature results in the formation of small and weak flocs which are vulnerable to break up due to fluid shear force (Hanson and Cleasby 1990).

Studies have also attributed the high chlorine dosage in summer as meant to compensate chlorine loss due to sun radiation (Veenstra and Schnoor 1980). Even though, little can be done operationally to remedy temperature variation, a treatment plant should have strategies to take into account the effect of low temperature during the winter months.

6. Dissolved Oxygen

The time-series, box-plot and descriptive statistics for dissolved oxygen (DO) on the five stations (MDI, MDO, NDO, IDI and IDO) during a period stretching from 2005 to 2012 are depicted in Figure 5-11, Figure 5-12 and Table 5-6 respectively. The time-series plot, Figure 5-11, shows that dissolved oxygen (DO) just like temperature and turbidity showed some annual seasonal variation. Except for IDO, the S-K test results depicted in Table 5-6 shows that dissolved oxygen did not exhibit a significantly temporal variation among the stations studied between 2005 and 2012.

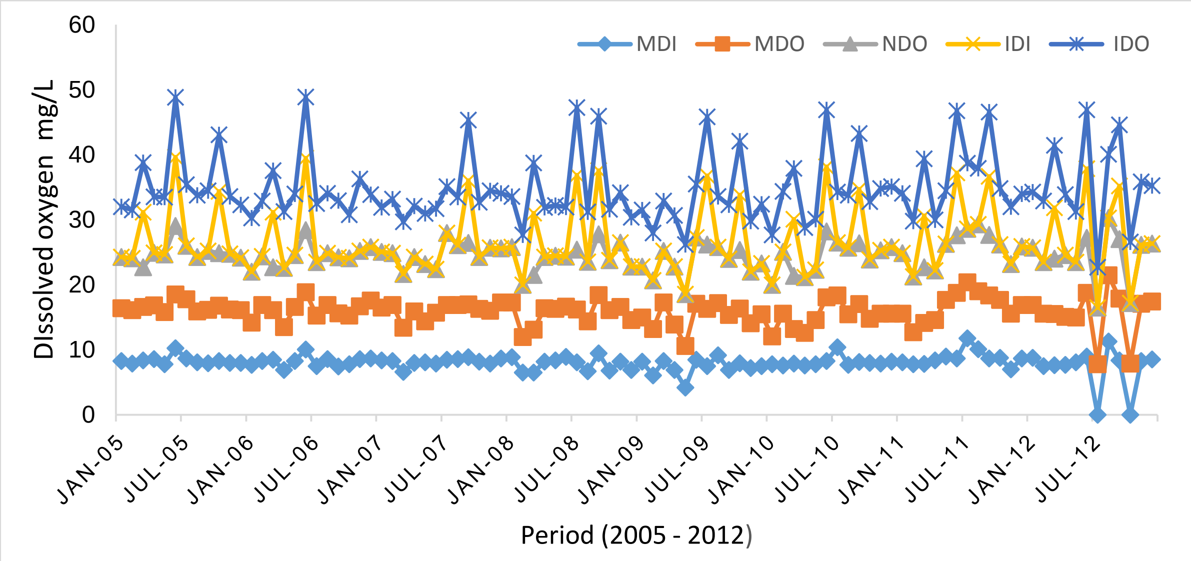


Figure 5-11: Temporal variation of DO at stations in uMngeni Basin (2005 to 2012)

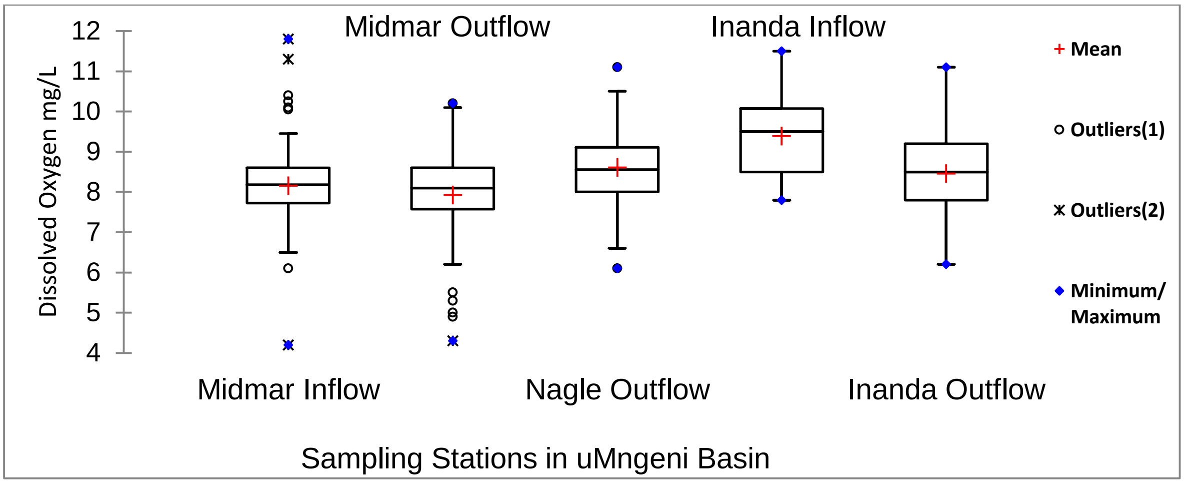


Figure 5-12: Spatial variation of DO in uMngeni Basin (2005 to 2012)

Table 5-6: Descriptive statistics for DO at stations in uMngeni Basin

Sample	Minimum	Maximum	SD	Median	Mean	Seasonal-Kendal	Sen's Slope	Decision
MDI	4.200	11.800	1.014	8.175	8.153	0.6	0.002	No
MDO	4.300	10.200	1.083	8.100	7.926	0.7734	0	No
NDO	6.100	11.100	0.846	8.550	8.608	0.0658	0.007	No
IDI	7.800	11.500	1.092	9.500	9.385		-0.063	
IDO	6.200	11.100	0.877	8.500	8.457	0.036	0.006	Increase

The high monthly mean (7.926 - 9.385 mg/L) and median (8.100 - 9.500 mg/L) range values show that DO levels observed at the stations studied was within South Africa's target range for freshwater ecosystem (Department of Water Affairs and Forestry 1996b). Just like temperature, the DO saturation point is also based on the natural background information and thus tend to be site-specific. For uMngeni Basin, 8mg/L was considered as the saturation point based on literature findings and the analysed data. However, in unpolluted freshwater ecosystems, DO normally ranges between 8 and 10 mg/L (Waston *et al.* 1985).

The minimum values observed at MDI and MDO which are below 5 mg/L are of concern when considering fitness for the survival of aquatic animals. Low dissolved oxygen concentrations tend to adversely affect the performance and survival of aerobic organisms while levels below 2 mg/L, may be fatal to fish.

Regarding treatment, the causal relationship between DO and chemicals used during treatment is not well described in literature. It is however important to remark that oxygen makes floc particles lighter and relatively difficult to attach during the flocculation process (Oyoo n.d). Consequently, the flocs are carried over to the filtration stage and ultimately cause the clogging of the filters. This interrupts the filtration process and increases the frequency of backwashing.

7. **Chlorides**

Figure 5-13**,** Figure 5-14 and Table 5-7 below shows the time-series, box-plot and descriptive statistics respectively for chloride levels at the five stations (MDI, MDO, NDI, NDO, IDI and IDO) studied during a period stretching from 2005 to 2012.

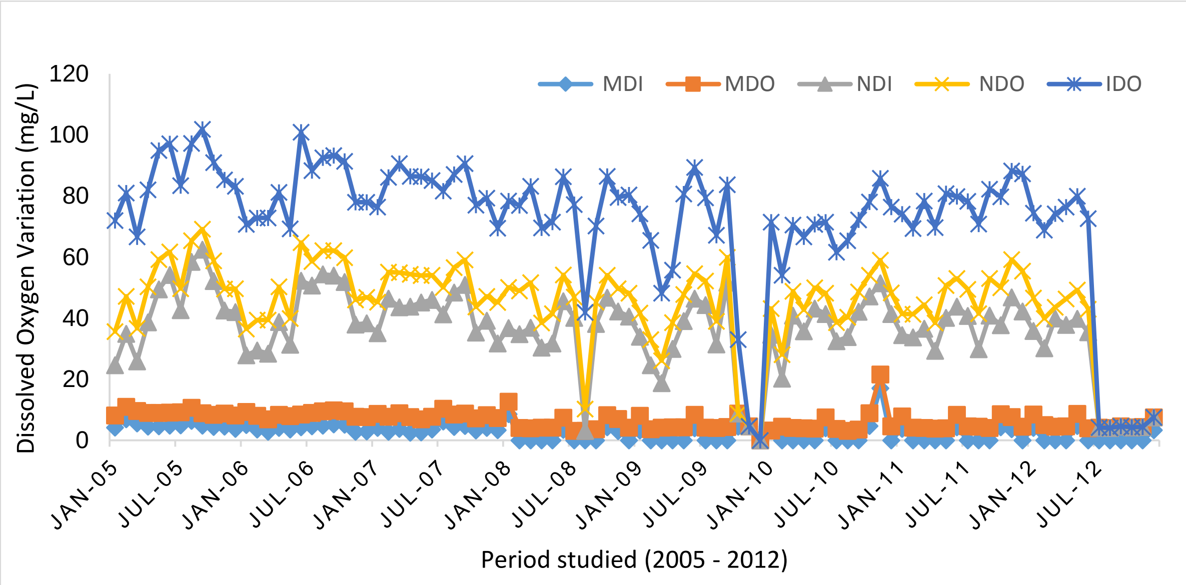


Figure 5-13: Temporal variation of chloride at stations in uMngeni Basin (2005 to 2012)

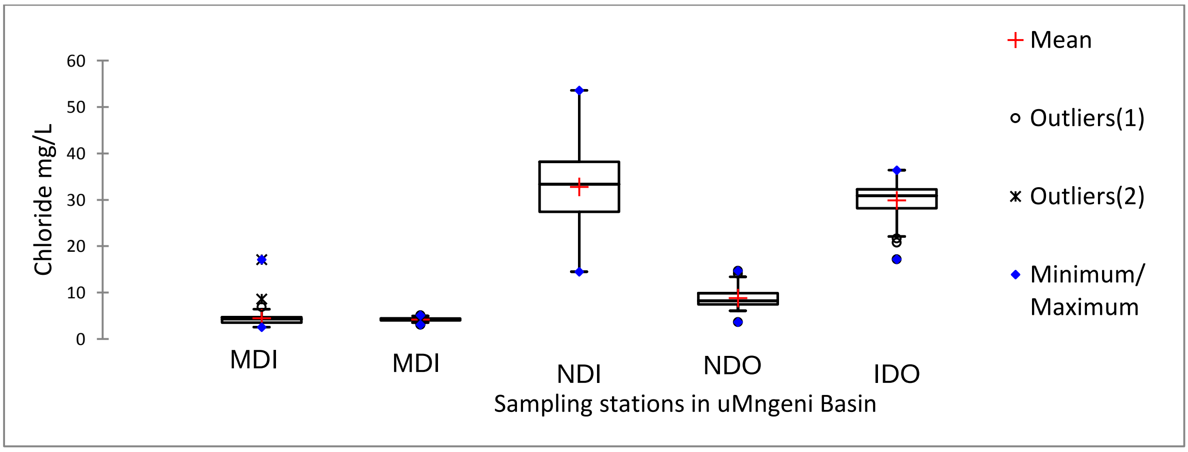


Figure 5-14: Spatial variations of chloride in uMngeni Basin (2005 – 2012)

Table 5-7: Descriptive statistics for chloride at stations in uMngeni Basin

Station	Mean	Median	Minimum	SD	Maximum	S-K (P-value)	Sens's slope	Decision
MDI	4.469	4.290	2.54	2.048	17.1	0.039	-0.013	Decrease
MDO	4.212	4.190	3.11	0.366	5.14	0.062	-0.002	No trend
NDI	32.801	33.350	14.5	7.778	53.6	0.298	-0.026	No trend
IDO	8.845	8.220	3.670	2.070	14.7	0.965	-0.007	No trend
IDO	29.941	30.850	17.2	3.812	36.4	<0.0001	-0.063	Decrease

The variation of chloride depicted in Figure 5-13, illustrates that chloride exhibited irregular temporal variations. Low concentrations observed in the rainy season and more pronounced levels from Nagle Outflow to Inanda Inflow station could be a result of increased river flow which tends to increase the dilution effect of river water. Peaks observed in winter could be a result of reduced flow and discharge which makes the water more concentrated. However, these peaks are not of concern with regard to fitness for drinking purpose as there are within the ‘no effect’ range (0-100 mg/L) (Department of Water Affairs and Forestry 1996a).

The Seasonal-Kendal test results, Table 5-7, indicates that the level of chlorides had been decreasing at MDI and at IDO. This implies an improvement in water quality with regard to chloride levels.

Both the box-plot (Figure 5-14) and the descriptive statistic results (Table 5-7) show that chloride had increased downstream of uMngeni Basin. Even though the available data showed that NDI recorded the highest chloride level, it is more likely that IDI (with missing data) could have contain the highest concentration. This emanates from the fact that IDO station which is located just below Inanda Inflow recorded a relatively high chloride value of 29.94 mg/L despite being expect to exhibit quality improvement due to the retention effect. Thus, it is more likely that its inflow station could have recorded a more concentrated chloride level.

During treatment, chlorides just like other dissolved ion pollutants are removed by the coagulation and filtration process. Thus, the relatively high chlorides levels recorded at IDO as compared to NDO suggest that this parameter could be exhibiting a more effect on coagulant dosage at Wiggins compared to Durban Heights WTP.

8. **Nitrate-N**

The time-series, box-plot and descriptive statistics for nitrate on the six stations (MDI, MDO, NDI, NDO, IDI and IDO) during a period stretching from 2005 to 2012 are depicted in Figure 5-15, Figure 5-16 and Table 5-8.

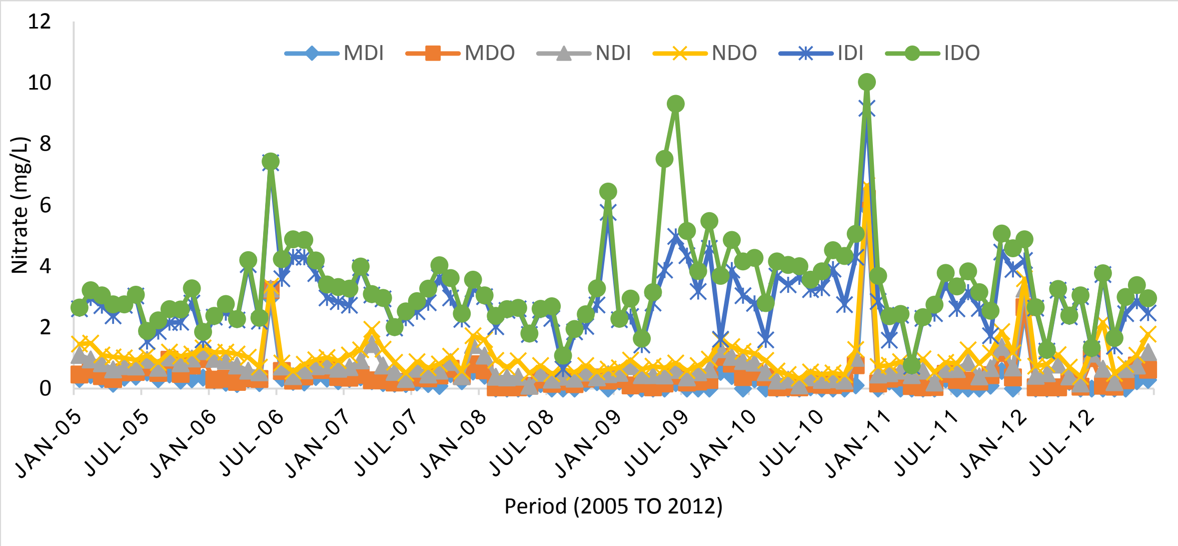


Figure 5-15: Nitrate variation at stations in uMngeni Basin from 2005 to 2012

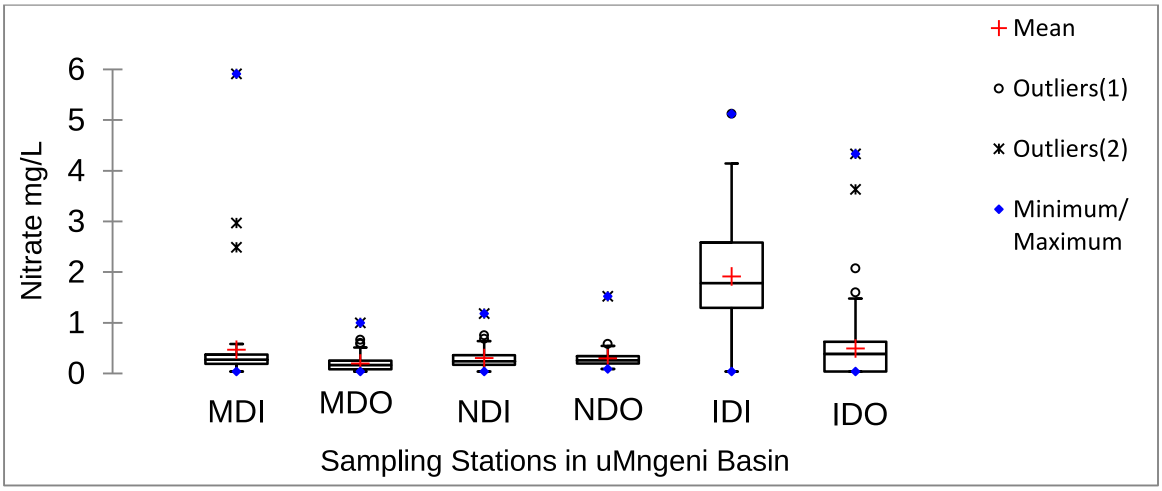


Figure 5-16: Spatial variations of nitrate in uMngeni Basin (2005 – 2012)

Table 5-8: Descriptive statistics for nitrate at stations in uMngeni Basin

Sample Station	No	Minimum	Maximum	SD	Mean	Sen's slope	Decision
MDI	96	0.038	5.910	0.881	0.467	-0.001	No trend
MDO	96	0.038	1.000	0.162	0.197	2.45E-04	No trend
NDI	96	0.038	1.180	0.185	0.299	0	No trend
NDO	96	0.090	1.520	0.169	0.294	8.54E-04	Increase
IDI	96	0.038	5.120	0.958	1.910	0.003	No trend
IDO	96	0.038	4.330	0.634	0.492	0.002	Trend

The time-series plot, Figure 5-15, shows that nitrate exhibited an irregular variation at the six stations studied. This could be attributed to many factors, chief among them the irregular discharge of poor quality sewage effluent. High nitrate concentrations observed in winter could be attributed to a reduction in the river flow which ultimately reduces the dilution capacity (Figure 5-15). Peaks observed in wet season can be explained by increased surface run-off of fertilizers, animal feedlot effluent and sewage effluent discharge into uMngeni River as reported by the Department of Water Affairs and Forestry (2003).

Even though the results shows that nitrate is still within the regulatory limit for potable use (<11 mg/L), it is important to note that levels exceeding 0.5mg/L observed at IDI cause eutrophication (Department of Water Affairs and Forestry 1996b). This could account for algae peaks observed in the wet season which ultimately increase chlorine and coagulant dosage. It is thus plausible to suggest nitrate as a key driver in the basin with regards to its effect on algae levels.

It is also important to note that nitrate level is increasing at NDO station as depicted by the Seasonal-Kendal test results (Table 5-8). This is of concern to treatment cost at Durban Heights as it tends to cause algae bloom as explained earlier on.

9. **Total Phosphate**

Figure 5-17, Figure 5-18 and Table 5-9 shows the time-series, box-plot and descriptive statistics respectively for total phosphate (TP) on the six stations (MDI, MDO, NDI, NDO, IDI and IDO) during a period stretching from 2005 to 2012.

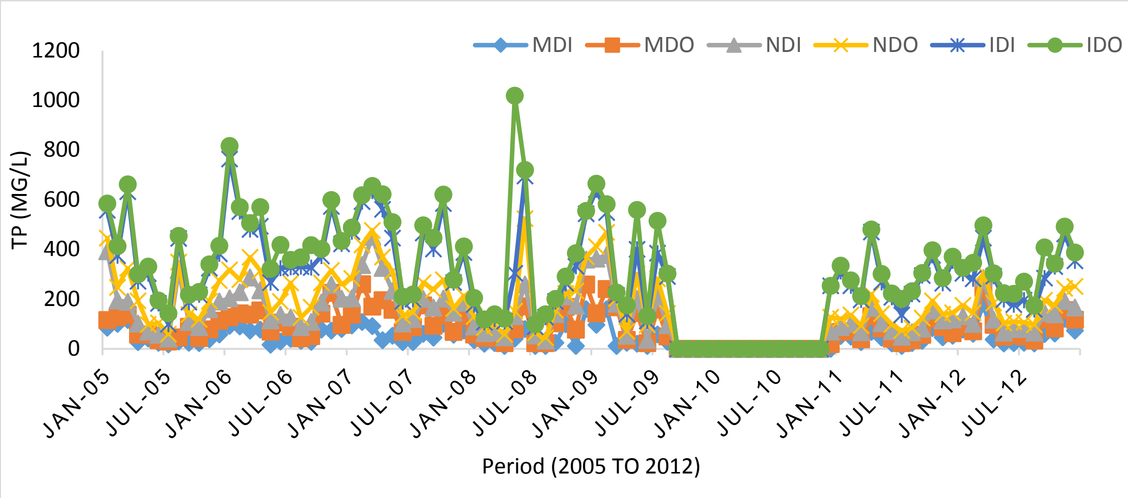


Figure 5-17: Temporal variation of TP at stations in uMngeni Basin (2005 – 2012)

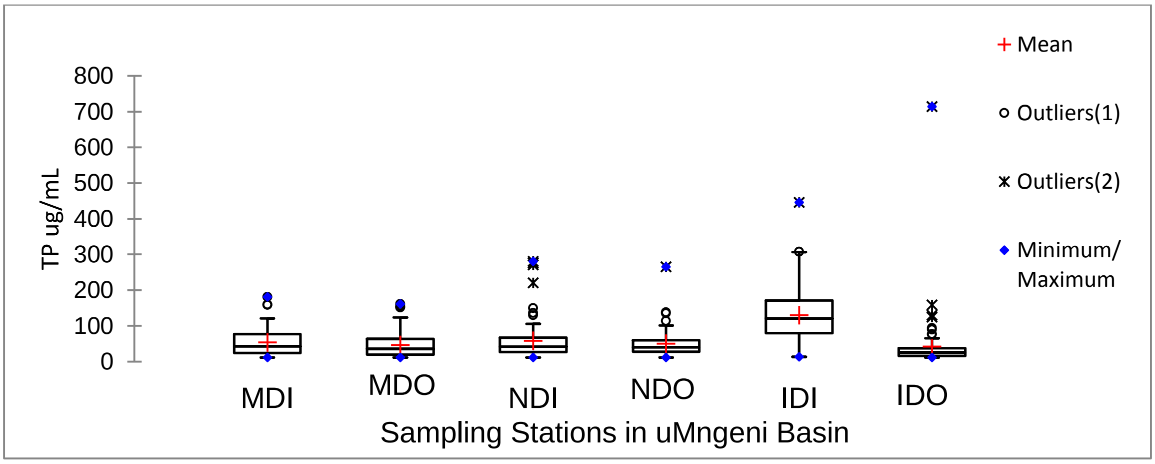


Figure 5-18: Spatial variations of TP in uMngeni Basin (2005 – 2012)

Table 5-9: Descriptive statistics for TP at stations in uMngeni Basin

Sample	Minimum	Maximum	SD	Median	Mean	S-K (P-value)	Sen's Slope	Decision
MDI	11.250	180.977	36.924	42.950	53.238	1	-0.065	No trend
MDO	11.250	161.000	37.192	35.200	46.245	0.913	-0.08	No trend
NDI	11.250	280.550	55.256	41.967	57.798	0.116	-0.389	No trend
NDO	11.250	265.400	36.798	39.700	49.922	0.074	-0.241	No trend
IDI	13.250	445.500	74.555	120.500	130.078	0.704	-0.234	No trend
IDO	11.250	714.300	81.187	26.100	42.012	0.347	-0.002	No trend

The variation of TP, showed a similar irregular pattern as that displayed by nitrate (Figure 5-17). The observed similar pattern suggests that both pollutants could be emanating from the same source. The most plausible sources could be fertilisers and sewage effluent pollutants from human activities along the river course. Furthermore, while considering that the soils of uMngeni catchment have been reported to be generally phosphorus deficient (Furness and Richard 1987), it would be reasonable to consider human activities as causal for the peaks noted. For unknown reasons, TP data stretching from September 2009 to October 2010 was missing. This affects the analysis of water quality pattern variation which can the prediction purpose.

The S-K test results as depicted in Table 5-9 reveals that TP showed no significant trend at any of the stations during the period stretching from 2005 to 2012. Inanda Dam Inflow station recorded twice (130.078 µg/L) the concentration observed at NDI (57.798 µg/L). IDO recorded a relatively high maximal value of 714.30 ug/L. This could further explain intensive algal bloom recorded at this station as shown in Table 5-2.

According to Isikhungusethu Environmental Services (2011), it is more likely that Midmar and Albert Falls Dams could become eutrophic, while Nagle Dam might become hypertrophic by 2019 given the current pollution rate continues. Thus, in order to reduce the treatment cost at treatment plants in uMngeni Basin, attention needs to be focused on the reduction of the nutrient load into the river system.

10. ***Escherichia coli***

Figure 5-19, Figure 5-20 and Table 5-10 show the time-series, box-plot and descriptive statistics for *E. coli* on the six stations (MDI, MDO, NDI, NDO, IDI and IDO) during a period stretching from 2005 to 2012.

The time-series plots, Figure 5-19, indicates a seasonal fluctuation and peaks of *E. coli* levels. Sewage discharge from broken pipes and slurry from intensive livestock farming operation that flow into the river can explain the irregular peaks. The monthly mean range of 97 to 1319 count/100mL as depicted in Table 5-10 show that the quality of water in uMngeni Basin is not fit for drinking purpose without proper disinfection. South Africa’s guidelines stipulates that no *E. coli* count is expected in 100 mL.

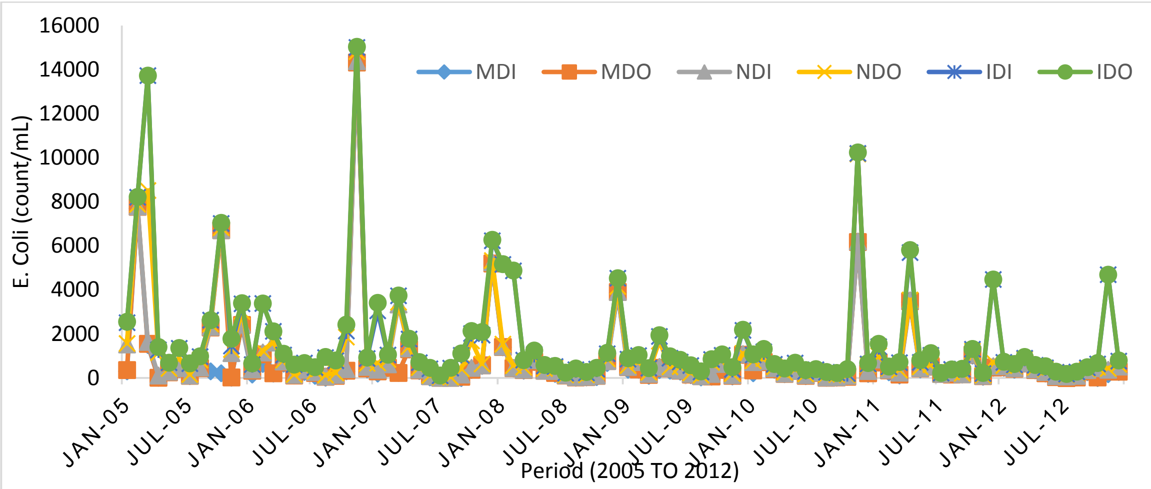


Figure 5-19: Temporal variation of *E. coli* at stations in uMngeni Basin

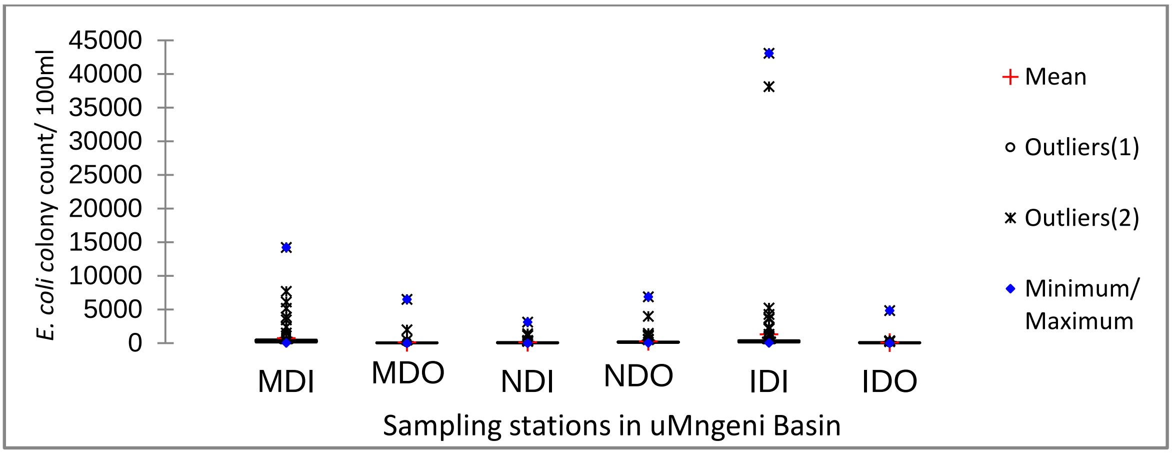


Figure 5-20*: E. coli* spatial variation among the six stations in uMngeni Basin

Table 5-10: Descriptive statistics for *E. coli* at stations in uMngeni Basin

Sampling Station	Minimum	Maximum	SD	Median	Mean	S-K (P-Value)	Sen's slope	Decision
MDI	6.0	14200	1860.96	272.5	745.32	0.572	-0.435	No trend
MDO	0	6490	688.34	23.0	126.73	0.235	-0.143	No trend
NDI	2.0	3100	382.58	38.0	126.25	0.132	0	No trend
NDO	7.75	6870	821.03	100.0	274.299	0.037	-0.47	Decrease
IDI	9.0	43100	978.58	213.0	1319.056	<0.0001	-3.038	Decrease
IDO	0	4838	64.89	26.0	97.917	0.449	0.05	No trend

Among the six stations studied, IDI recorded the highest monthly mean (1319 count/100mL) and maximal values (43100 count/mL) *E. coli* levels. As stated earlier, this could be a result of uMsunduze River, a tributary which joins uMngeni River before Inanda Dam. The uMsunduze River flows passing through Pietermaritzburg where it collects industrial, sewage effluent and storm-water runoff pollutants (Neysmith 2008). The observed high *E. coli* levels recorded at IDI is of concern when considering that the rural communities in the Valley of a Thousand Hill might directly use river water for domestic purposes.

Midmar recorded higher *E. coli* levels than Nagle Dam which is downstream. This could be attributed to sewage effluent flowing into Mthinzima, a tributary river draining Mpophomeni low cost housing scheme. A report by GroundTruth (2010) states that even though Mpophomeni residential area comprised only 2.4% of Midmar dam's catchment area, it was contributing 50.9% of the total *E. coli* concentration. Sewage from measurements between 1 September and 23 November 2009 showed that *E. coli* exceeded safe *E. coli l*evels, reaching 660 000 counts/100mL. This was predominantly attributed to broken sewage, pipes, defected manholes and the direct discharge of raw sewage (GroundTruth 2010).

Regarding potable water treatment costing, the elevated levels of *E. coli* observed downstream at Inanda Dam adds pressure to Wiggins WTP. This suggest that more chlorine is needed at Wiggins compared to Durban Heights WTP.

11. **Ammonia**

Figure 5-21**,** Figure 5-22 and Table 5-11 shows the time-series, box-plot and descriptive statistics for ammonia on the six stations (MDI, MDO, NDI, NDO, IDI and IDO) during a period stretching from 2005 to 2012.

As shown in Figure 5-21, ammonia displayed an irregular cyclic patterns with peaks and low values. The monthly mean range, 0.082 to 3.640 mg/L, shows that ammonia is a major problem in the basin since these values are above South Africa's freshwater ecosystems target range of less than 0.06 mg/L (Department of Water Affairs and Forestry 1996b). Of concern is the high monthly mean (3.640mg/L) recorded at MDO station (Figure 5-22). It is important to remark that such levels are of concern when considering the toxicity of ammonia to aquatic animals. Concentrations above 0.06 mg/L have been reported to cause damage fish gills while those above 0.3 mg/L can be lethal to fish.

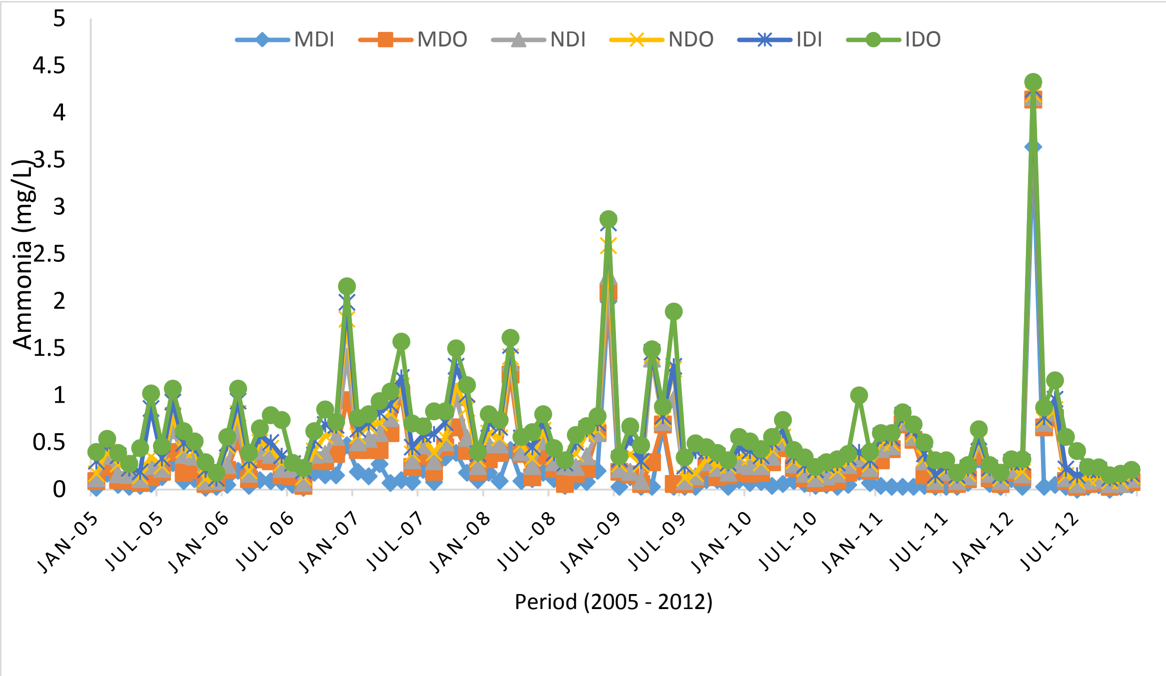


Figure 5-21: Temporal variation of ammonia in uMngeni Basin (2005 to 2012)

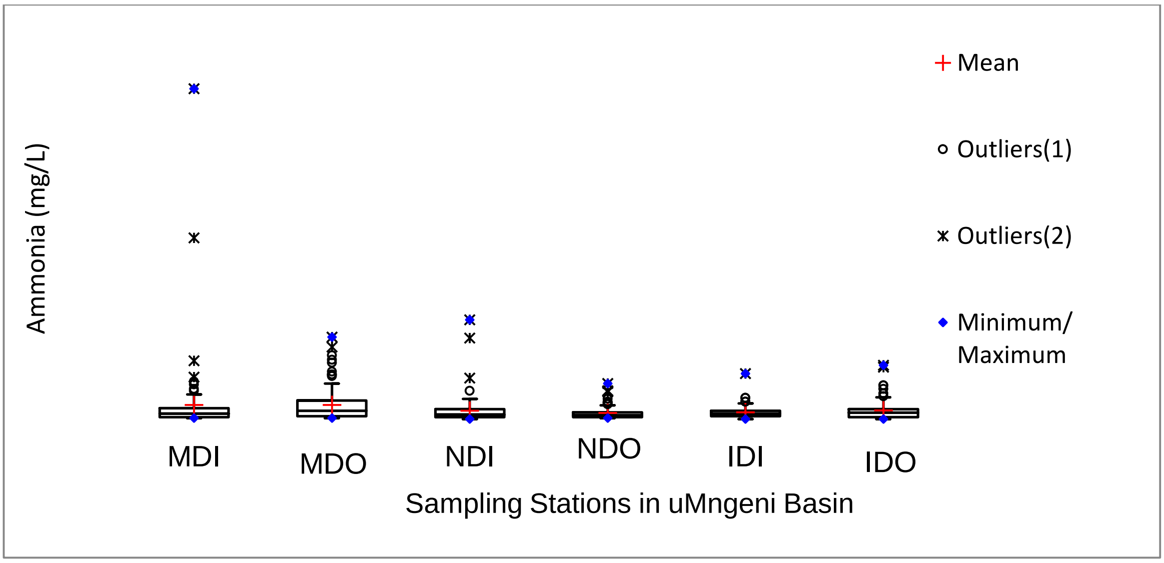


Figure 5-22: Spatial variation of ammonia uMngeni Basin (2005 to 2012)

Table 5-11: Descriptive statistics for ammonia at stations in uMngeni Basin

Sample	Minimum	Maximum	SD	Median	Mean	S-K (P-Value)	Sen's slope	Decision
Midmar Inflow	0.020	3.640	0.426	0.070	0.162	1	-0.065	No trend
Midmar Outflow	0.020	0.910	0.182	0.100	0.165	0.32	-0.08	No trend
Nagle Inflow	0.010	1.100	0.150	0.060	0.100	0.004	-0.389	Decrease
Nagle Outflow	0.020	0.400	0.072	0.050	0.075	0.074	-0.241	No trend
Inanda Inflow	0.008	0.510	0.065	0.070	0.082	0.491	-0.234	No trend
Inanda Outflow	0.008	0.600	0.105	0.080	0.105	0.347	-0.002	No trend

Regarding potable water production, ammonia reacts with chlorine forming mono, di and tri-chloramines, which significantly reduces the bactericidal effect of chlorine. Chloramines are relatively weak oxidant but have a long lasting residual effect. It is however also of concern that water distribution systems with chloramines tends to experience nitrification. The ammonia produced from the nitrification process causes rapid bacterial proliferation, which produce nitrates as a by-product. The disadvantages of chloramines outweigh the merits and there is thus a need to minimise nitrogenous compounds in water sources intended for potable production. It can be suggested that chlorine dosage at Wiggins is more influenced by ammonia as compared to Durban Heights.

12. **Electrical Conductivity**

Figure 5-23, Figure 5-24 and Table 5-12 show the time-series, box-plot and descriptive statistics respectively for electrical conductivity (EC) on the six stations (MDI, MDO, NDI, NDO, IDI and IDO) during a period stretching from 2005 to 2012.

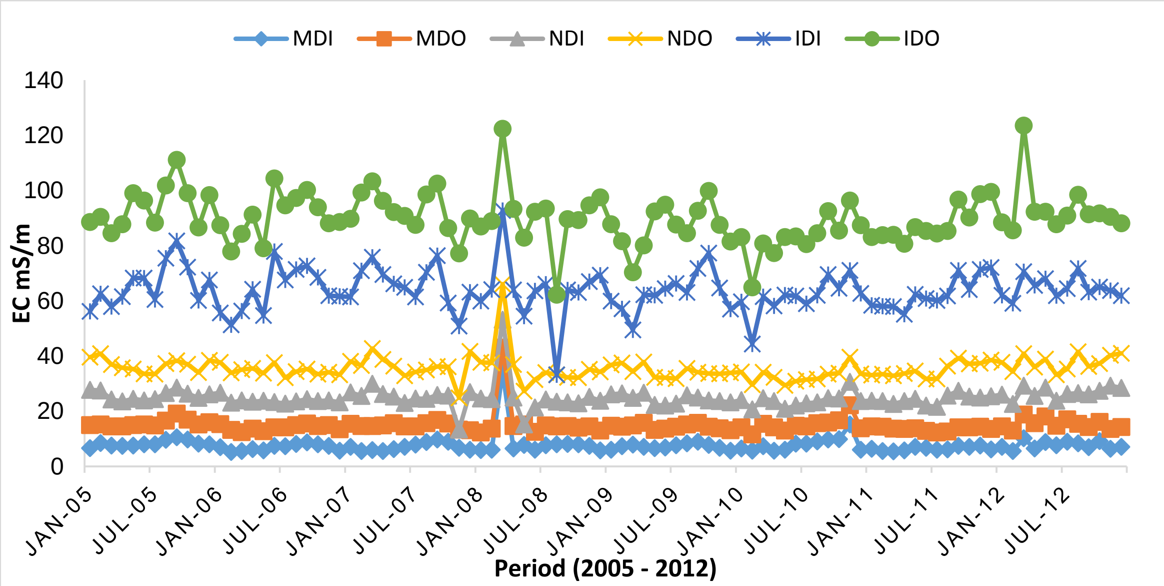


Figure 5-23: Temporal variation of E.C at stations in uMngeni Basin (2005 to 2012)

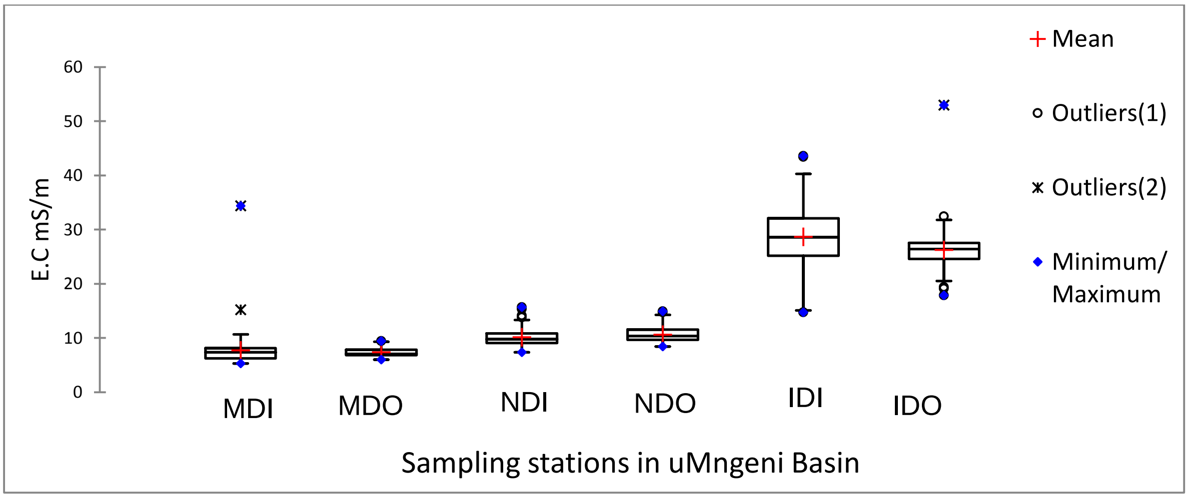


Figure 5-24: Spatial variation of E.C in uMngeni Basin

Table 5-12: Descriptive statistics for E.C at stations in uMngeni Basin

Sample	Minimum	Maximum	SD	Median	Mean	Seasonal Kendal	Sens slope	Decision
MDI	5.280	34.385	3.129	7.338	7.688	0.453	-0.003	No trend
MDO	5.990	9.400	0.815	7.080	7.339	0.248	-8.51E04	No trend
NDI	7.360	15.680	1.559	9.765	10.100	0.179	0.004	No trend
NDO	8.430	14.915	1.419	10.330	10.622	0.045	-0.01	Decrease
IDI	14.740	43.600	5.855	28.600	28.644	0.278	-0.022	No trend
IDO	17.830	52.950	3.919	26.400	26.210	0.003	-0.028	Decrease

As depicted in Figure 5-23, E.C showed irregular temporal variation with peaks and fluctuations. The distinct low E.C levels which were more pronounced in the summer could be explained by an increased river flow and discharge which tend to dilute the water.

As presumed, the box-plot (Figure 5-24) shows that E.C increased downstream of the uMngeni Basin. In comparison to South Africa's guidelines for potable use (<170mS/m), the observed overall E.C range (5.280mS/m - 52.95mS/m) was below the set target range. The relatively high maximum values measured at Inanda Dam could be explained by the discharge from uMsunduze River, which has been reported as significantly polluted (Neysmith 2008). However, E.C only showed a decreasing trend only at Nagle and Inanda Outflow station.

Previous studies have also reported uMngeni to be a low E.C River. Graham (2004), using data stretching from 1990 to 1999, noted that Nagle dam had a daily average of conductivity of 8.9 mS/m which is slightly lower than 10.361 mS/m which was observed in this study. This implies that dissolved ions concentration in Nagle dam has increased over time.

With regard to treatment, the relatively high E.C level observed at IDO suggests that conductivity could be influencing coagulant dosage more at Wiggins as compared to Durban Heights.

5.2.1 Summary for the First Objective

As expected, physical parameters namely algae and turbidity displayed an annual cyclic pattern with peaks in the wet season and low values in winter. This implies an increase in treatment cost in the wet season since these parameters directly influence chemical dosage and ultimately cost. The analysis of the water quality pattern variation for each parameter provides a relatively simple way of forecasting chemical dosage with time.

The high *E. coli* levels observed at all stations indicates that the water is not fit for drinking without proper disinfection. In addition, high turbidity levels recorded at all stations indicates that the water is aesthetically unpleasing for drinking purposes. However, the quality of water is still acceptable for other uses such as irrigation, fresh water ecosystem habitat, industrial use and irrigation which requires less stringent quality. The maximum levels of ammonia observed is however of concern to aquatic animals.

Even though the time-series and box-plot are important and informative methods of describing the quality of water in a basin, it is important to highlight that a researcher might end-up concentrating on some individual parameters, leaving others which may also be equally important. In some cases, one may end-up concentrating on data characteristics such as outliers leaving the subtle changes. These factors might lead to a biased conclusion. There is thus need to use a holistic approach in determining the fitness of water for a given use.

5.3. Objective Two Findings:

To produce two water quality indices: one for describing the general river health status and another determining the treatability of raw water being abstracted in uMngeni Basin

With concern that the general public and policy makers should be well informed regarding the status of their water resource, the next objective of the study was to develop two water quality index for describing the fitness of water for the survival of aquatic organism and for determining treatability. These are to be known as;

1. River Health Water Quality Index (RHWQI)
2. Treatability Water Quality Index (TWQI)

5.3.1. River Health Water Quality Index (RHWQI)

Eight water quality variables DO, pH, turbidity, *E. coli*, TP, NO_3, NH_3 and EC were used to give a reflection of the fitness of water for the survival of organisms. The Weighted Geometric Mean depicted in Equation 4-1 was used to calculate the overall water quality scores. Its application resulted in the assessment of the overall water quality of the six stations. Figure 5-25 to Figure 5-30 displays the overall temporal change in water quality for the six stations studied over an eight year period studied (2005 to 2012) with regard to the RHWQI regime.

❖ ***Midmar Dam Inflow station***

Figure 5-25 presents the overall water quality trend at MDI station with respect to the protection of freshwater organisms. The observed fluctuation in the wet season can be attributed to an increase in turbidity (Figure 5-2) and *E. coli (*Figure 5-19) levels observed earlier in the foregoing objective.

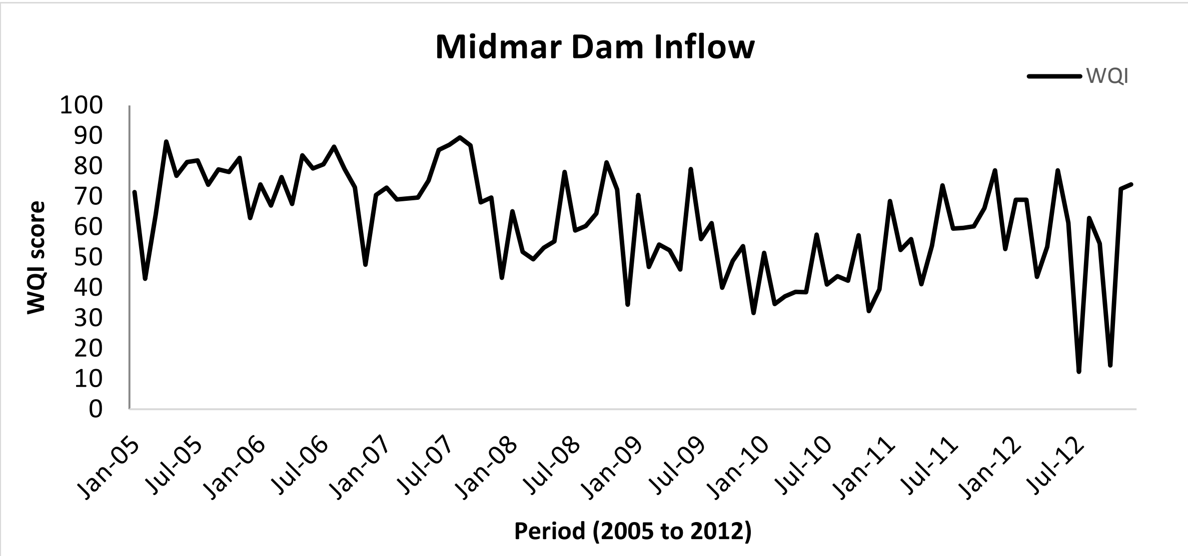


Figure 5-25: Water quality trend (2005 to 2012) at MDI based on RHWQI

Using the descriptive scale outlined in Table 4-8, the study can report that the quality of water at MDO station varied from good to bad quality. However, even though MDO is located upstream of uMngeni Basin near the headwaters, it is of concern to note that its quality is relatively low as compared to that of Nagle Inflow which is below it.

❖ **Midmar Dam Outflow Station**

Figure 5-26 depicts the overall water quality trend at MDO station with respect to the overall river health status. The time-series were calculated based on the RHWQI.

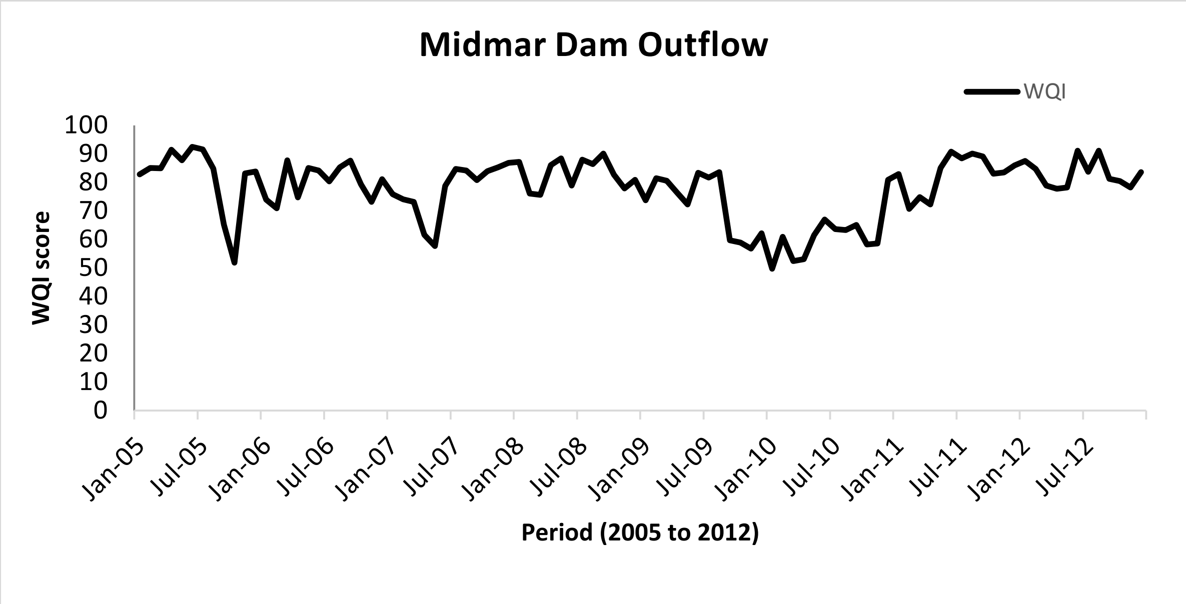


Figure 5-26: Water quality trend (2005 to 2012) at MDO based on RHWQI

Like other outflow stations, Midmar recorded a relatively high water quality scores. This improvement in the quality of water as compared to its upper inflow station could be a result of the retention effect which allows for the settling of suspended particles. The retention effect, along with the dilution effect tends to improve the quality of water.

- **Nagle Dam Inflow Station**

Figure 5-27 shows the variation of water quality at NDI station with regard to the overall river health status. Even though NDI station is located downstream Midmar Dam, it is notable that its quality is relatively high as compared to the later. This observation could be related to the buffering action of Albert Falls, an upstream dam which serves as a reservoir for Nagle Dam.

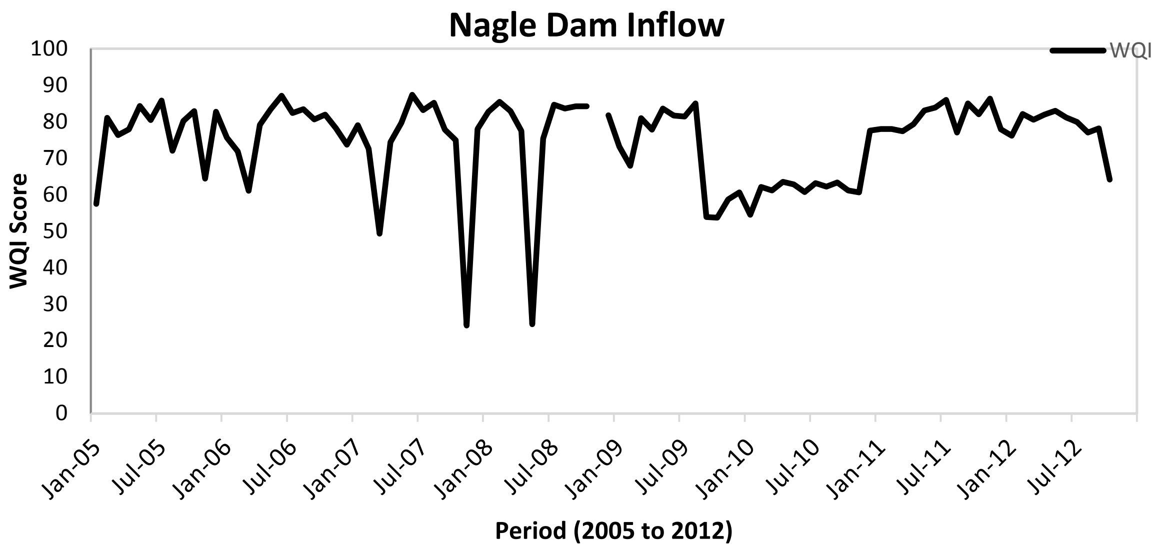


Figure 5-27: Water quality trend (2005 to 2012) at NDI based on RHWQI

- **Nagle Dam Outflow**

Figure 5-28 presents the overall water quality trend at Nagle Dam Outflow station with respect to the protection of freshwater organisms. The trends are drawn using the RHWQI scores. As expect, Nagle Dam Outflow station showed good quality due to its retention effect. The quality is generally good even though some fluctuations were observed in the wet season.

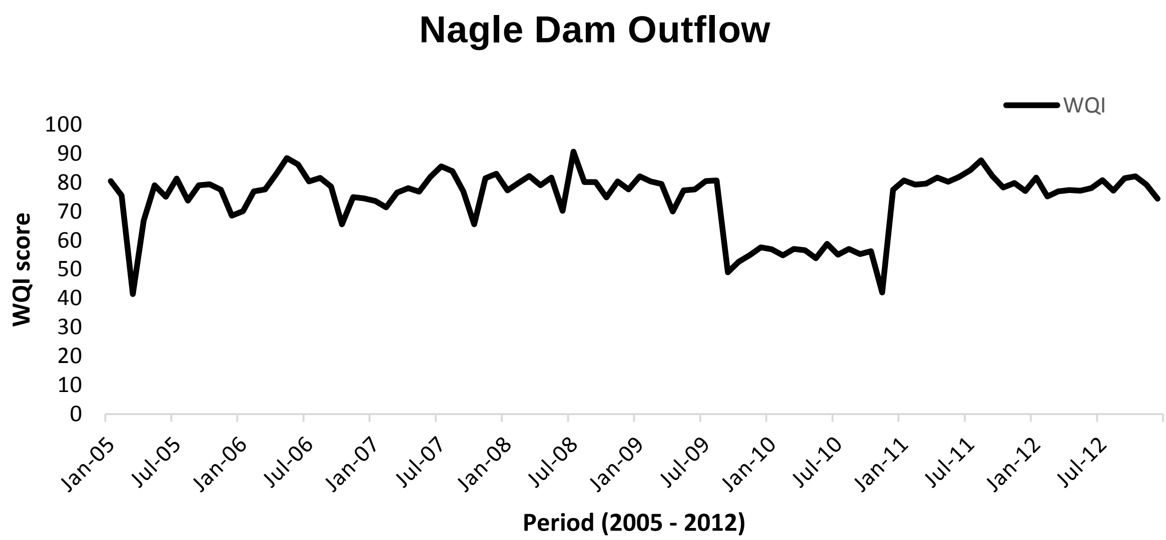


Figure 5-28: Time-series plot of the RHWQI Scores at NDO station (2005 to 2012)

❖ **Inanda Dam Inflow Station**

Figure 5-29 presents the overall water quality trend at Inanda Dam Inflow station with respect to the protection of freshwater organism.

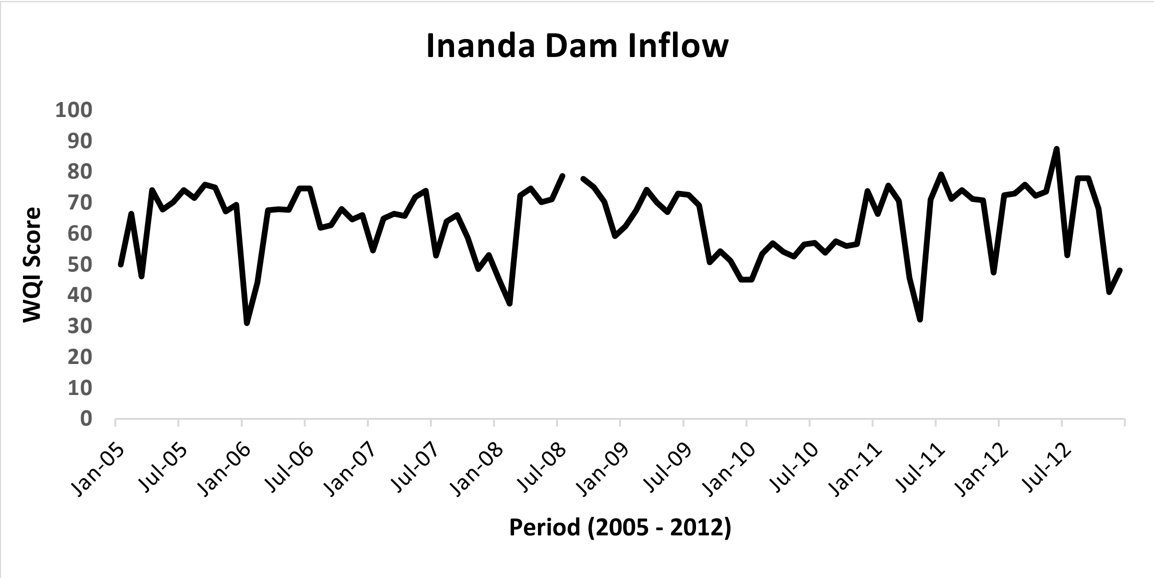


Figure 5-29: Water quality trend (2005 to 2012) at IDI based on RHWQI

This station did not have data for dissolved oxygen and the overall index scores were calculated assuming that dissolved oxygen (DO) Q-value was 80. This was in consideration that the given data-set for other stations showed a mean range of 7.926 mg/L to 9.385 mg/L (Table 5-6) and it would be reasonable to suggest that IDI was also within this range. From the foregoing time-series and descriptive statistics results, it can be noted that *E. coli* and turbidity were the main factors lowering the index score at this station. The fluctuation of RHWQI score in the wet season coincides with the high *E. coli*, turbidity and algae concentrations.

It can be hypothesised that poor quality sewage effluent and rain wash run-off from the arable lands of the rural community of the Valley of a Thousand Hills could be responsible for the deterioration in quality at this station. The effect of uMsunduze, a tributary draining the residential and industrial hub of Pietermaritzburg could also be attributed to the high *E. coli* level which ultimately lowered the index scores. These facts are in agreement with river health water quality status report by Department of Water Affairs and Forestry (2003).

❖ Inanda Dam Outflow Station

Figure 5-30 presents the overall water quality trend at Inanda Dam Outflow station with respect to the overall river health status.

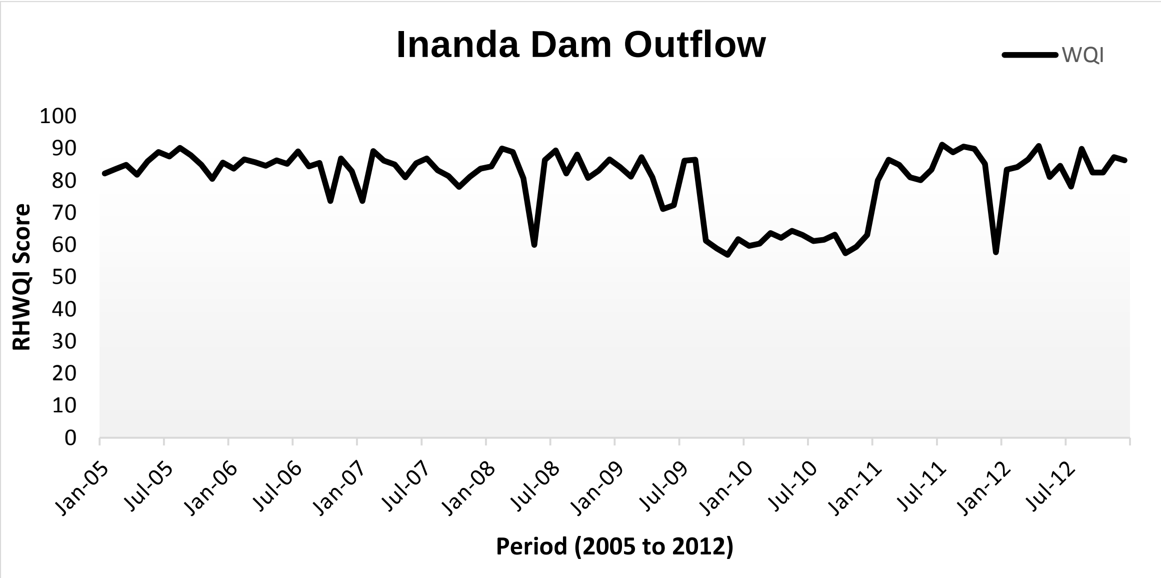


Figure 5-30: Time-series plot of the RHWQI Scores at IDO station (2005 to 2012)

The results displayed in Figure 5-30 shows that the water quality at IDO station can be reported as good with regard to the overall river health status. The general improved water quality at this station can be attributed to the dam's sheer size which helps by the retention and dilution effect.

❖ Spatial variation with respect to the River Health Water Quality Index

Figure 5-31 shows the spatial variation of the quality of water among the six stations studied in uMngeni River with respect to the RHWQI. Table 5-13 further summaries the overall status of water at the six station based on the RHWQI.

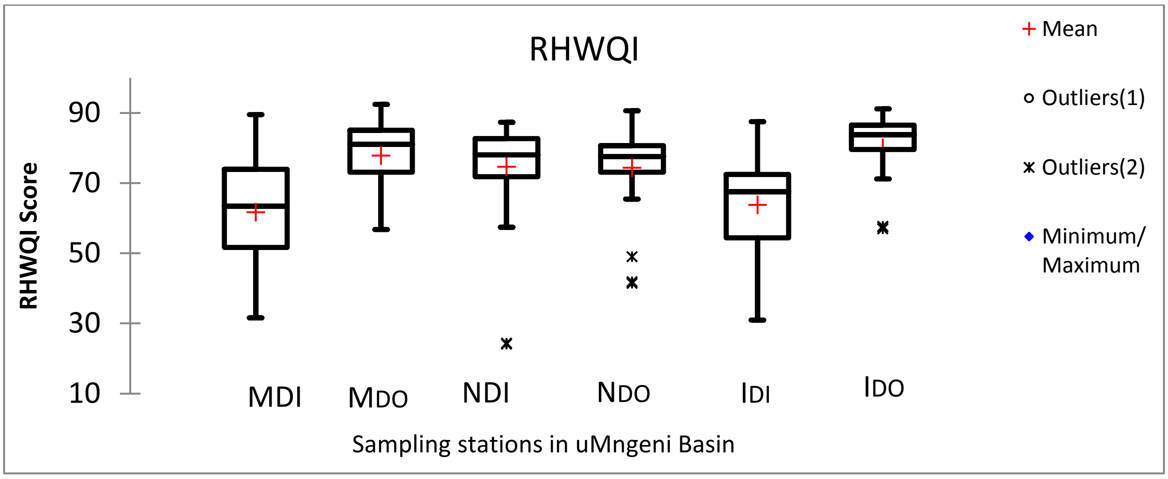


Figure 5-31: Spatial variation of the water quality in uMngeni Basin using the RHWQI

As expected, the outflow stations exhibited a higher water quality as compared to inflow stations. This can be attributed to the retention and dilution effect.

Table 5-13 Summary of water quality along uMngeni with regard to the RHWQI

Variable	Minimum	Maximum	Mean	S.D
Midmar Inflow	12.329	89.483	61.664	16.628
Midmar Outflow	49.644	92.461	77.809	10.691
Nagle Inflow	24.082	87.350	74.624	11.886
Nagle Outflow	41.468	90.650	74.360	10.438
Inanda Inflow	30.949	87.533	63.757	11.591
Inanda Outflow	56.950	91.192	80.015	9.997

By comparing the mean RHWQI score ranges, 61.664 - 80.015, depicted in Table 5-13, it can be concluded that the quality water in uMngeni Basin is generally fit for the survival of aquatic organisms. However, the minimum and maximum values also shows that the quality of water on the stations varies from bad to excellent with regard to the RHWQI.

5.3.2. Treatability Water Quality Index

Figure 5-32 depicts the non-compliance of the concentration levels for selected parameters. The non-compliance proportion at the two treatment plants, Durban

Heights and Wiggins WTP studied were calculated based on the Harmonised Water Quality Resource Objective (HWQRO) shown in Table 4-7. As highlighted in chapter 4, the HWQROs were determined based on each parameter's warning limit. The warning limits were calculated as the 80th percentile of the given data-set.

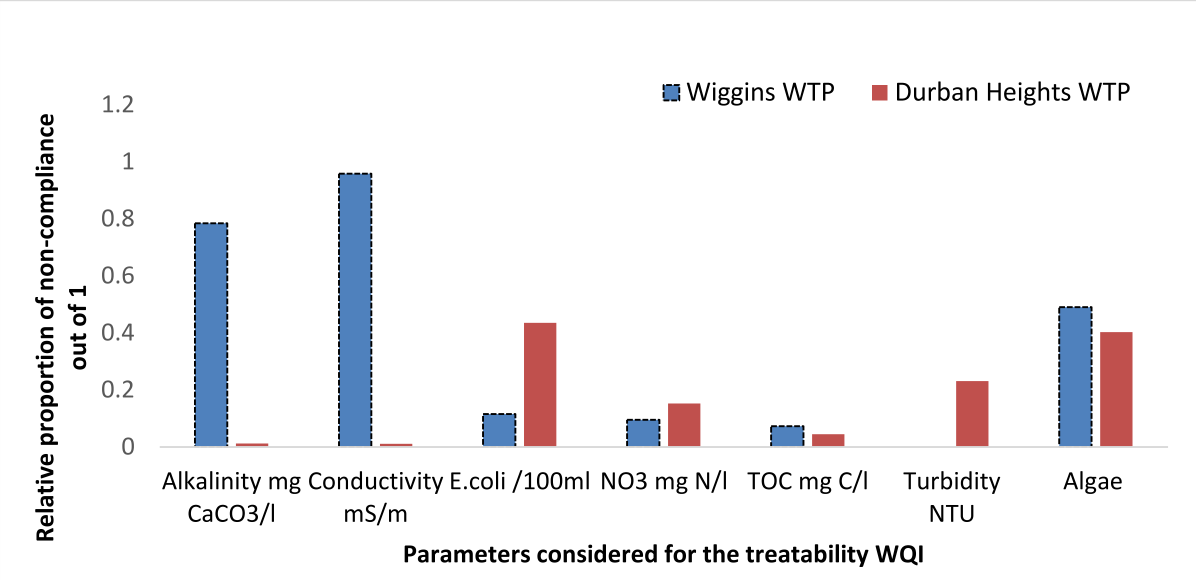


Figure 5-32: Comparison of parameter concentration non-compliance for water being treated at Durban Height and Wiggins

Figure 5-32 illustrates that the water being abstracted at Wiggins WTP is mostly affected by alkalinity, conductivity and algae levels. However, the relatively high alkalinity levels observed at Wiggins WTP pose an advantage during treatment by buffering pH change resulting from coagulant dosage. This observation explains the relatively low lime dosage observed at Wiggins, compared to Durban Heights WTP as shown in Figure 5-34 (a). However, even though Wiggins WTP observed the highest conductivity non-compliance level, it is surprising to note that this treatment plant has been dosing less than Durban Heights WTP. This could be attributed due to the difference in treatment technology among other factors.

Also, even though Wiggins recorded the highest electrical conductivity non-compliance, the descriptive statistics showed that conductivity was below the maximum tolerable lime (<170 mS/m) recommended by the Department of Water

Affairs for drinking purpose at all treatment plants. Algae however showed a higher non-compliance at Wiggins as compared at Durban Heights WTP.

The results in Figure 5-32 show that Durban Heights' polymer dosage is more significantly affected by turbidity than that for Wiggins. This could be the reason for the higher dosage observed at Durban Heights than that at Wiggins WTP (Figure 5-34 (c)). The high non-compliance *E. coli* concentration noted at Durban Heights WTP is a sign of eutrophication and could be the reason for the high chlorine dosage at this plant compared to that for Wiggins WTP.

Figure 5-33 compares the variation of the water with regard to the developed Treatability Water Quality Index. The trends shows that the quality of water being abstracted at Durban Heights is relatively clean as compared to that at Wiggins WTP.

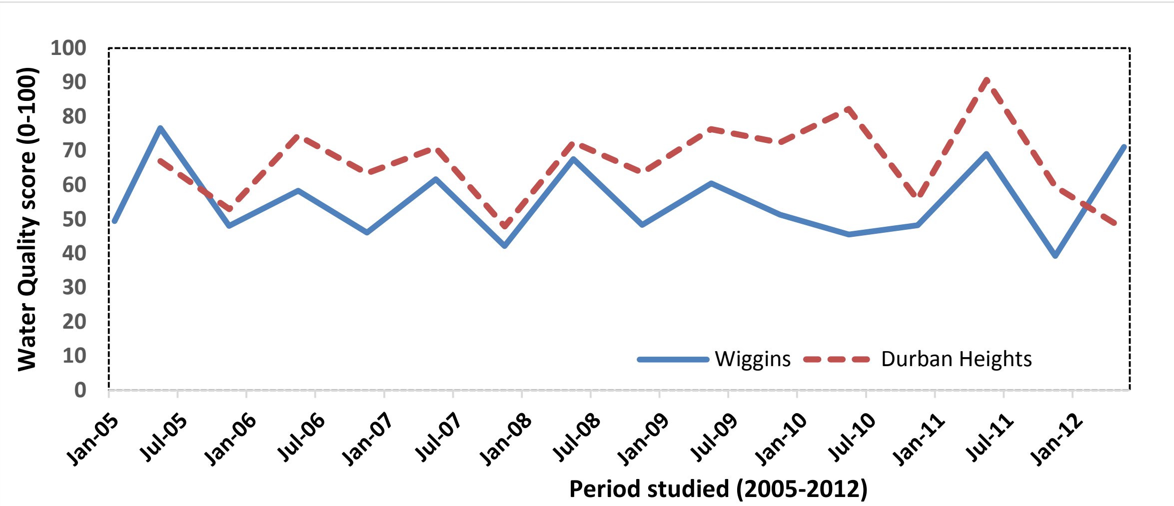


Figure 5-33: Comparison of the treatability of water abstracted for Durban Heights and Wiggins using the TWQI (2005 to 2012)

- **Comparison of chemical dosage at Durban Heights and Wiggins WTP**

Figure 5-34 (a), (b) and (c) compares lime, chlorine and polymer dosage respectively for Durban Heights and Wiggins WTP's.

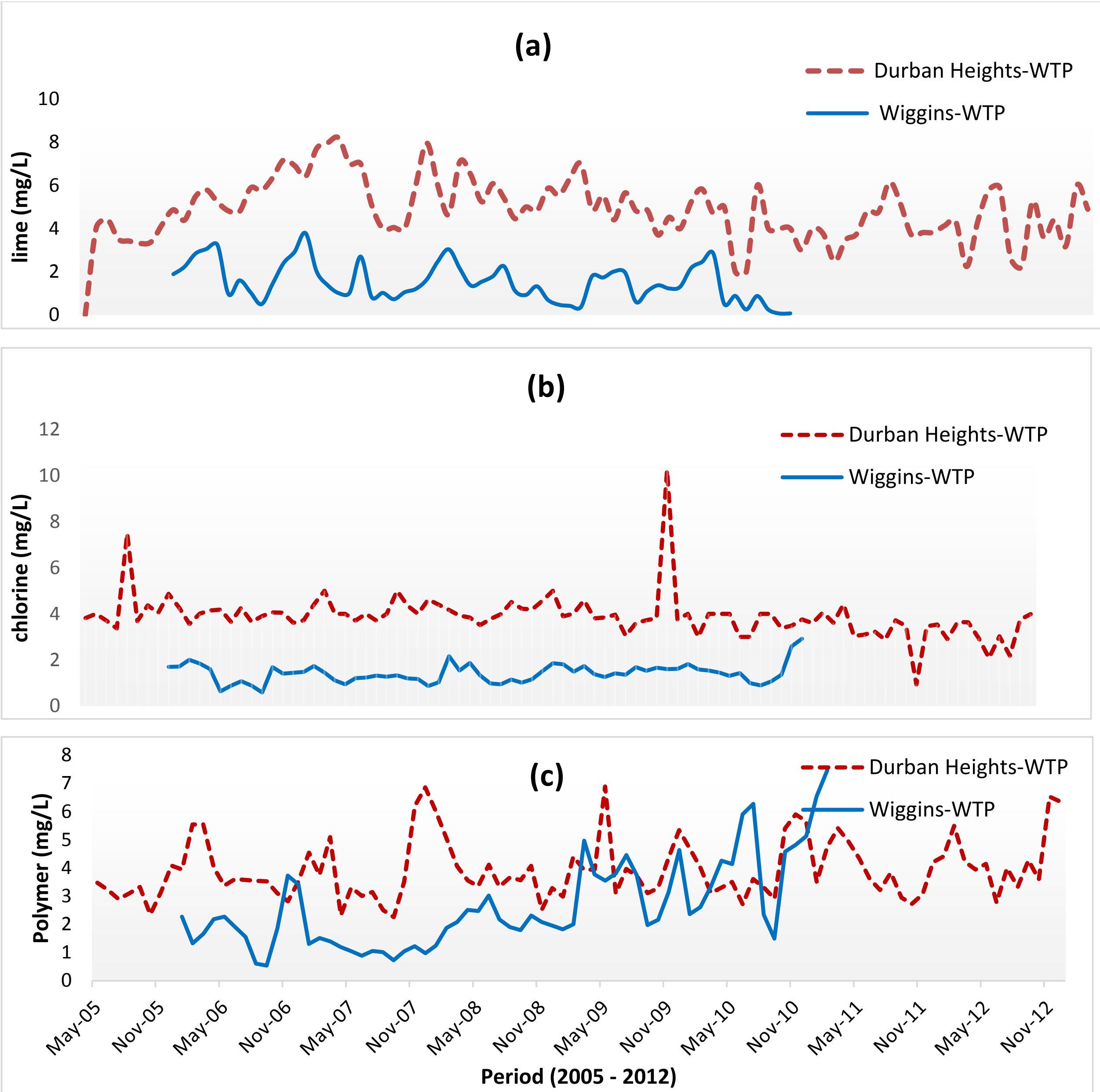


Figure 5-34: Comparison of the time series plot of; (a) lime (b), chlorine and (c) polymer dosage at the Durban Heights and Midmar WTP (May 2005 to December 2012).

Figure 5-34 (a) shows that Wiggins WTP has been dosing less lime as compared to Durban Heights WTP. This could be explained by the relatively high alkalinity levels observed at IDO station as compared to Nagle's (Figure 5-8). The irregular polymer dosage variation (Figure 5-34 (c)) with peaks in the wet season coincides with algae bloom (Figure 5-3) and high turbidity levels (Figure 5-1) observed as explained in the results for objective one.

Regarding disinfection, the relatively low chlorine dosage noted at Wiggins as compared to Durban Heights can be explained the low *E. coli* (Table 5-10) and low turbidity levels (Table 4-1) observed at IDO as compared to NDO which supplies the two respectively.

It can be concluded that Durban Heights WTP uses more chemicals, polymer, lime and chlorine as compared to Wiggins. Even though IDO, which provides raw water to Wiggins WTP is downstream, it is important to note that its quality is relatively good as compared to NDO which is upstream. Its capacity provides a high retention time that allows for dilution and settling of suspended material. Inanda Dam has a capacity of 241.69 x 10^6 m^3, which is ten times that of Nagle (23.237 x 10^6 m^3), thus signifying its high dilution capacity.

5.4. Objective Three Findings

Objective 3. To statistically determine water quality parameters whose concentration showed significant change due to treatment and to correlate them with polymer, chlorine and lime dosage at Durban Heights and Wiggins treatment plants.

The objective was to determine whether the concentration of a given parameter changed significantly due to treatment. For this purpose, monthly potable water measurement averages denoted by *R* for the 23 parameters considered were divided by their corresponding raw water measurement (*Ro*). Thereafter, a one-sample t-test was performed to determine if the observed changes in concentration were statistically significant. A test value of 1 was set to suggest no change. Even though the results depicted in Table 5-14 does not fully reflect the complex behaviour of the chemical interaction during potable water treatment, they allow some conclusion to be reached with the aid of the literature review.

Table 5-14: Average R/Ro and the t-test significant results.

DURBAN HEIGHTS WTP T-TEST RESULTS						WIGGINS WTP T-TEST RESULTS				
	R/Ro	t-test	DF	t-test p-value			R/Ro	t-test	DF	t-test p-value
Alkal	1.1062	3.863	85	0.0002		Alkal	0.9357	-3.291	91	0.0014
Ca	1.5006	13.994	85	0.0000		Ca	0.9981	-0.083	91	0.9338
Cl	1.7943	15.164	85	0.0000		Cl	1.0393	1.711	91	0.0904
EC	1.2983	14.133	85	0.0000		Cond	1.0047	0.625	91	0.5334
F	1.0225	0.645	85	0.5210		F	1.0387	0.734	91	0.4652
K	1.0689	2.054	85	0.0431		K	0 .9322	-2.388	91	0.0190
Mg	1.0458	2.366	85	0.0203						
Na	1.3449	5.679	85	0.0000		Na	1.0009	0.032	91	0.9744
NH_3	5.6232	0.995	85	0.3228		NH_3	0.7615	-2.736	91	0.0075
NO_3	1.2363	4.873	85	0.0000		NO_3	2.2384	3.326	91	0.0013
pH	0.9938	-1.3100	85	0.1938		pH	1.0008	0.038	91	0.9701
SO_4	1.5724	7.200	85	0.0000		SO_4	1.0260	0.821	91	0.4141
SS	0.2435	-53.477	85	0.0000		SS	0.8459	-3.243	91	0.0017
Temp	1.0892	5.760	85	0.0000		Temp	1.0493	4.025	91	0.0001
TOC	0.8300	-3.309	85	0.0014		TOC	0.9018	-1.694	91	0.0937
Turb	0.0113	-1460.881	85	0.0000		Turb	0.1098	-147.434	91	0.0000
Algae	0.0048	-226.4532	85	0.0000		Algae	0.0039	-564.665	91	0.0000

N.B

- The yellow cell indicates parameter satisfying the two conditions to be considered a significant driver for chemical dosage. These parameters average R/Ro showed a greater that 5% change from the set test value of 1 (>1.05 or <0.95) and the change was significance at 98% level of confidence.

- The red cell indicate parameters whose average R/Ro is greater than 5% (<1.05) from the nominal value of 1 while the light green cell indicates those with less that 5% (>0.95) from the nominal value of 1.

- The blue cell indicates parameters whose concentration showed a statistical significant change using the one sample t-test. This indicates a parameter whose change in concentration showed a significant change at 98% level of significance ($\frac{\sigma}{2}$ =0.01).

As anticipated, physical determinants, specifically algae and turbidity showed a marked reduction in their concentrations at the two treatment plants due to treatment. This implies that, physical parameters are key drivers for chemical dosage at the two treatment plants studied except for total organic carbon. These findings agrees with Graham (2004)'s who also reported algae as the main driver for treatment cost among the treatment plants being operated by Umgeni Water. It can thus be anticipated that an effective strategy for controlling physical pollutants should ultimately reduce chemical dosage and ultimately cost

Fluorine and pH showed no significant reduction due to treatment. However, with regard to pH variation, it might be possible that the parameter could have changed during treatment but the lime added could have counter-acted the reduction of pH level normally brought by a coagulant. It would thus be biased to preliminarily conclude that raw water pH did not significantly vary due to treatment.

Alkalinity however, showed a slight significance change at the two treatment plants studied. At Durban Heights, the parameter showed a slight increase (average R/Ro of 1.1062). While considering that Nagle Dam is of relatively low alkalinity value

(32.53mg/L: Appendix C) as compared to Inanda Dam (62.66mg/L: Appendix D) it can be suggested that the current low alkaline level at Nagle could be the reason for high lime dosage at Durban Heights (4.89mg/L: Appendix C) as compared to Wiggins (1.37mg/L Appendix D). These findings are consistent with the non-compliance results depicted in Figure 5-32 which showed alkalinity as a significant driver at Wiggins WTP as compared at Durban Heights WTP. However, the high alkalinity levels observed at IDO station is of an advantage to treatment cost as it counter acts the lime dosage meant to buffer pH change brought by a coagulant.

Nutrient parameters, specifically, nitrates showed a slight increase in concentration at both treatment plants. While it was beyond the scope of this study to interpret the complex nitrogenous stoichiometric pathways, it can be pointed out that some chemically induced oxidation reactions could explain such an increase. It is highly possible that some unstable forms of nitrogenous compounds (e.g. nitrite) could have been oxidised to a more stable form, nitrate. Akoto and Adiyiah (2008) explained that nitrate is a final oxidation product of the nitrogen cycle in natural waters and is considered as the only thermodynamically stable nitrogen compound in waters. However, it is still important to note that the final nitrate levels for both treatment plants were still within the allowable limit for water intended for potable use (<11mg/L) (Department of Water Affairs and Forestry 1996a).

In general, metal parameters specifically sodium, potassium, calcium, sulphate and conductivity for water drawn at Durban Heights (NDO) showed a significant increase in concentration due to treatment as shown by their average R/Ro values of greater than 1.05. This was unexpected, and can be attributed to their relative low concentration in the dam. As shown in Appendix C and D dissolved ion concentrations for water abstracted at the two treatment plants studied were still within the maximum allowable limit for potable use.

5.4.1. Correlation between parameters and chemical dosage

Table 5-15 summaries parameters which showed some significant correlations to polymer, chlorine and lime dosage at 5% level of significant testing.

Table 5-15: Water quality parameters showing statistical significant correlations

Summary of water quality parameters showing statistical significant correlations to polymer, chlorine and lime at 5% level of testing							
DURBAN HEIGHTS WTP					**WIGGINS WTP**		
	Poly	**Lime**	**Chlorine**		**Poly**	**Lime**	**chlorine**
pH							0.274
Alkal					-0.340**		
Ca		0.390**					
Chloride	0.283**	0.243*			-0.400**		
EC		0.264*			-0.426**	0.260*	
K	0.241*	0.410*			-0.437**		
Mg		0.421**			-0.423**		
Na		0.291**			-0.357**		
NH_3		-0.303**	-0.206*				
Si	0.263*						
Sulphate					-0.252*		
Temp	0.350**		0.217*			0.316*	0.374*
TOC	0.282**						
Algae						0.258*	0.2858*

N.B ** Correlation is significant at 0.01 level (2 tailed)

* Correlation is significant at the 0.05 level (2-tailed).

The results show that the correlations coefficients ranged from very weak (0.0 - 0.2) to moderate (0.4 - 0.7) in both direction with regard to the correlation description scale depicted in Table 4-9. The observed relatively weak coefficients could be attributed to many factors, mainly due to collinearity among the parameters, missing values and outliers. Hanushek and Jackson (1977) explained that collinearity can change parameter estimates, increase standard errors, and reduce the power to detect reliable effects of correlated variables in a regression model.

Metal parameters specifically calcium (r = 0. 259), potassium (r= 0. 241) and silicon (r = 0.263) showed some positive correlation to polymer dosage at Durban Heights WTP. This implies that an increase in metal parameter concentration at Nagle Dam Outflow station should result in a proportional increase in polymer dosage at Durban Heights WTP. Thus, methods for controlling metal ion pollution sources should help reduce polymer dosage.

In contrast to NDO station, it is also important to note that metal parameters and their mineral salts namely chloride (r = - 0.40), potassium (r = -0.437), magnesium (r = - 0.423), sodium (r = - 0.357) and conductivity (r = -0.426) measured at IDO station showed some moderate inverse relationship to polymer dosage at Wiggins WTP. Such an unanticipated inverse relationship can be attributed to their relative low content observed at the IDO station. For instant, sodium (27.7mg/L<**100mg/L**), potassium (3.97 mg/L<**50 mg/L**), magnesium (7.30mg/L<30 **mg/L**), sodium (27.7 mg/L<**100mg/L**) monthly averages were below the maximum limit for potable use (bold standard limit) as shown in Appendix D. This unexpected inverse relationship observed can be explained by many factors chief among them collinearity among parameters, missing values and outliers.

The temperature of water at NDO station showed a significant positive correlation with polymer, chlorine and lime dosage at Durban Heights WTP. This coincides with the observed significant R/Ro (1.0892) value which indicates that temperature slightly increased due to treatment. The positive relationship can be explained by the seasonality effect. In South Africa, summer (October to April) is characterised by high temperatures and rainfall. Surface water runoff increased the turbid level which in turn tends to increase polymer dosage. Warm temperatures tend to increase algae growth which in turn increases polymer and chlorine dosage assuming other factors such as nutrient are held constant (American Public Health Association 1998).

Temperature also showed a positive correlation with chlorine dosage at both treatment plants. This again can be explained by the seasonality effect. The increased organic load in summer due to rain wash off could explain the positive relationship with chlorine dosage. Increased chlorine dosage in summer is meant to compensate for loss due to dechlorination by solar rays.

Contrary to the general literature, turbidity did not show a significant correlation to any of the chemicals studied (Dearmont, McCarl and Tolman 1998; Graham 2004; Gebremedhin 2009). The lack of a significant correlation could be explained by the collinearity effect among the water quality parameters. In addition, the low turbidity levels observed at IDO (2.71 mg/L: Appendix D) should also explain the lack of a significant correlation of turbidity with the chemicals used during treatment.

Lime dosage at Durban Heights showed a relatively weak to moderate positive correlation to metal ions; specifically calcium (r=0.390), chloride (r=0.238), potassium (r =0.399) and magnesium (r=0.421), and to conductivity (r=0.264). This was unexpected and could be due to collinearity effect among the parameters.

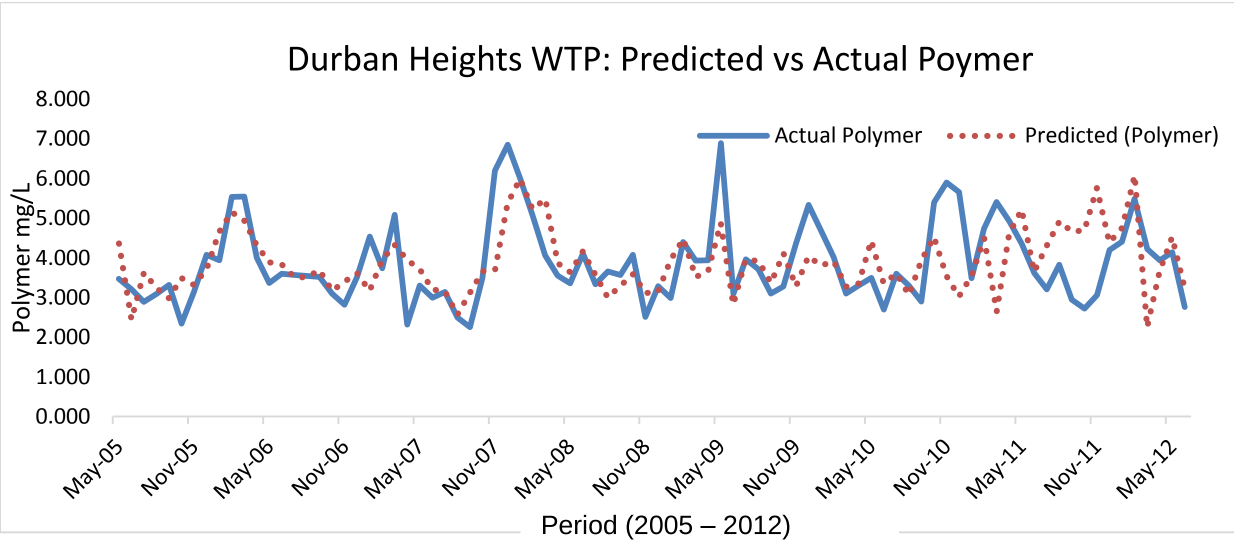
5.5. Objective Four Findings

Objective 4: To develop models for predicting polymer, chlorine and lime dosage at Durban Heights and Wiggins Water treatment plants.

For the purpose of developing models for predicting polymer, chlorine and lime models, eight years (2005 to 2012) water quality monitoring data-set for Nagle Dam Outflow station were used along with their corresponding chemical dosage data-sets. However, only five year (2006 to 2010) chemical dosage data was available for Wiggins WTP. The models where developed using a non-linear polynomial function in XLSTAT program.

5.5.1 Models for chemical dosage prediction at Durban Heights WTP

The predicted and actual dosage values for polymer, lime and chlorine values at Durban Heights WTP are compared in Figure 5-35, Figure 5-36 and Figure 5-37.



Equation of the model:

Poly = -6.90320 - 0.10188*% NH3 %+2.13012E-02*Alkalinity + 0.21185*Cal+0.18894*Cl-7.77593E-02*Conductivity - 0.17870*DO - 2.19087E-04*E.coli - 9.51647E-04*F -0.15826*K -0.4165*Mg - 3.8981E-02*Na+0.26633*NH3+0.37174*NO3 +1.28680*pH+0.191684*Si +3.09153E-02*SO4 - 9.30674E-04*SRP - 1.53839E-02*SS + 2.61246E-02*Temperature + 0.27443*TOC - 1.58704E-04*TP - 8.4378E-03*Turbidity +1.61116E-05*Algae

Goodness of fit statistic

Observations	66.000
DF	42.000
R^2	0.465
SSE	36.364
MSE	0.866
RMSE	0.930

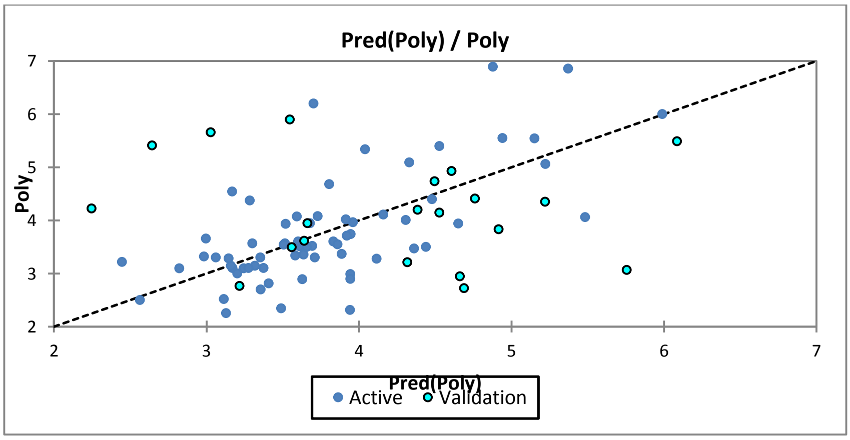
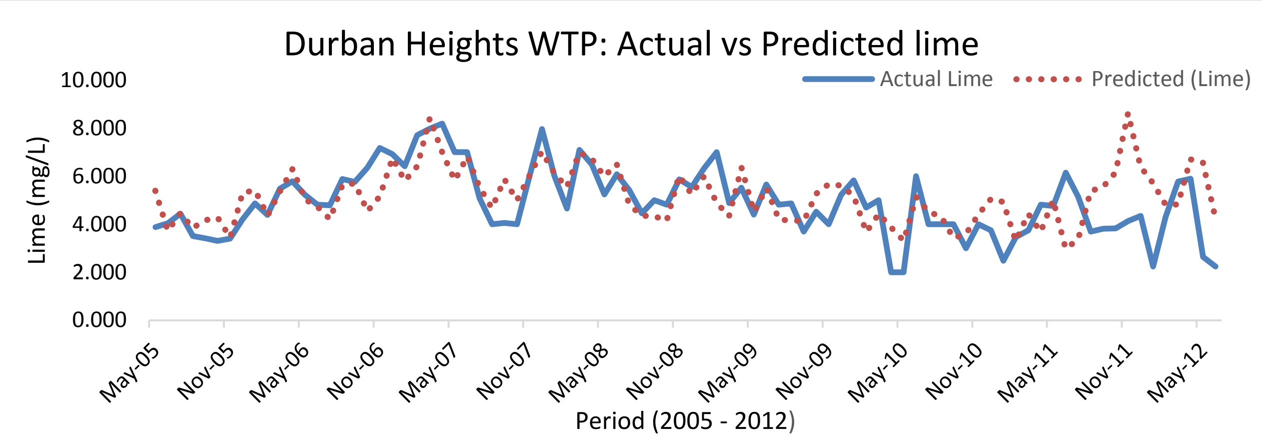


Figure 5-35: Durban Heights WTP Polymer model



Equation of the model:

Lime = -11.07133 - 0.10806*% NH3 %+0.02344*Alkalinity + 0.45062*Ca+0.18223*Cl +0.69046*Conductivity+0.24960*DO+3.34104E-05*E.coli + 3.06994E-03*F -1.71742*K - 1.04456*Mg+8.29506E-02*Na - 0.36904*NH3 + 2.20610*NO3 + 1.07973*pH - 0.25554*Si - 0.22651*SO4 - 0.00411*SRP - 2.52517E-03*SS + 4.38093E-02*Temperature + 0.26853*TOC +3.31286E-03*TP - 1.22752E-02*Turbidity - 4.63897E-07*Algae

Goodness of fit statistics

Observation	66.000
DF	42.000
R^2	0.613
SSE	46.716
MSE	1.112
RMSE	1.055

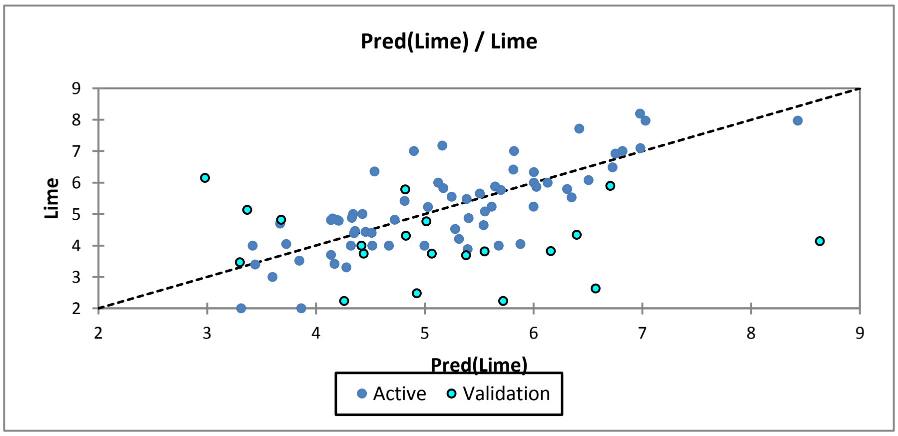
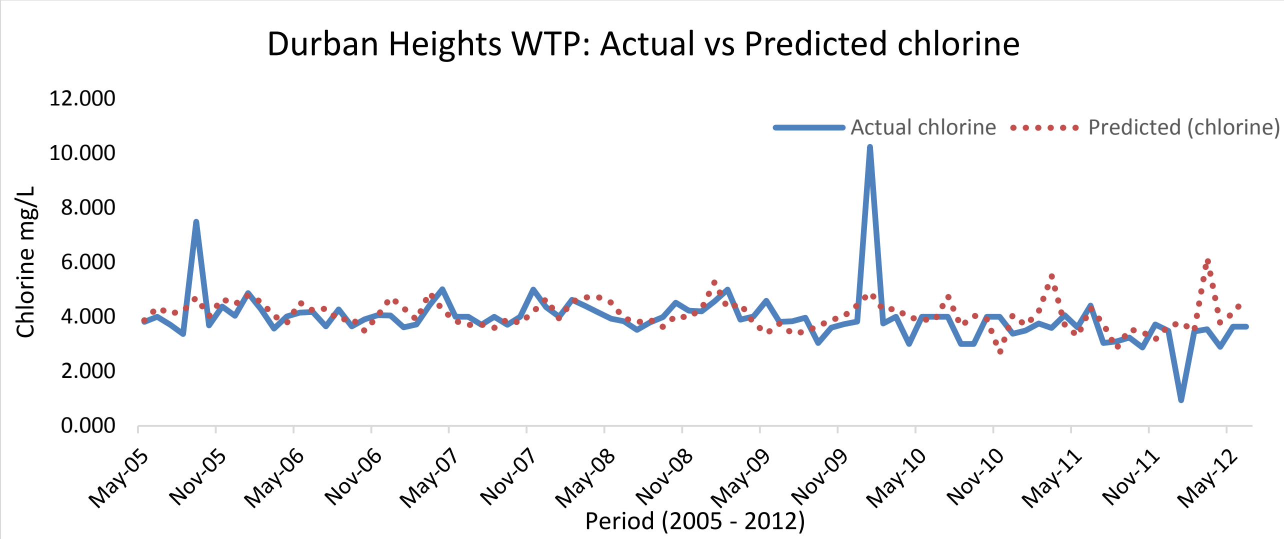


Figure 5-36 Lime dosage prediction model at Durban Heights WTP



Equation of the model:

Chlorine = 14.56146 + 0.10590*% NH3 + 5.92759E-03*Alkalinity+9.63575E-02*Ca - 0.19037*Cl + 9.76097E-02*Conductivity - 0.10480*DO - 2.08752E-04*E.coli + 9.63727E-03*F + 0.35223*K mg/l+0.42265*Mg -0.10465*Na - 3.2363E-02*NH3 + 1.32625E-02*NO3 - 1.48022*pH-0.06121*Si - 8.56738E-02*SO4 +3.43827E-03*SRP - 1.66919E-03*SS + 1.55393E-04*Temperature + 7.31503E-02*TOC -2.43829E-03*TP -1.94032E-02*Turbidity - 9.68238E-07*Algae

Goodness of fit statistics

Observations	66.000
DF	42.000
R^2	0.181
SSE	50.805
MSE	1.210
RMSE	1.100

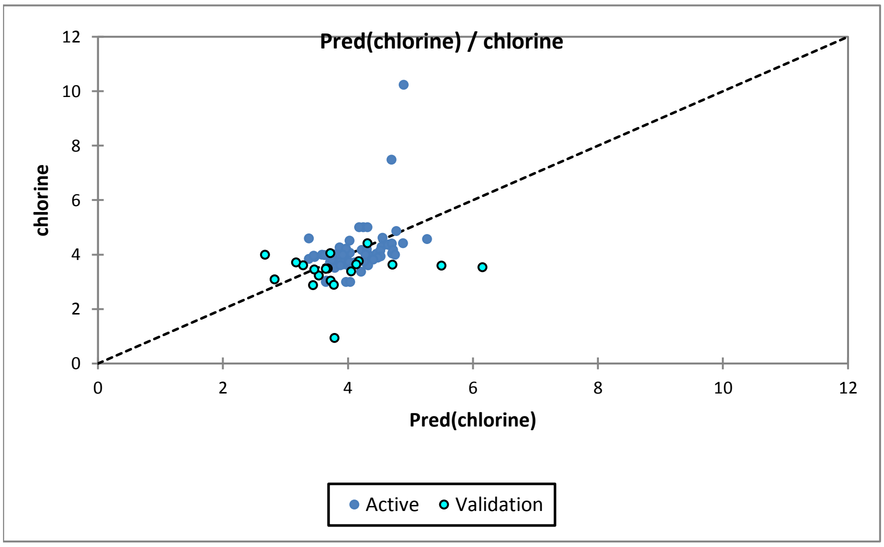


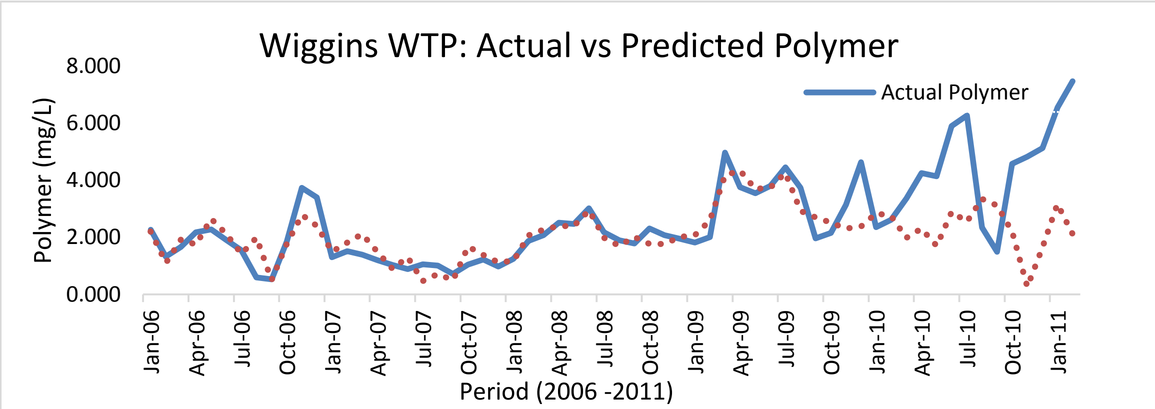
Figure 5-37: Chlorine dosage model at Durban Heights

The figures above shows that performance of the lime (R^2 = 0.613) and polymer (R^2 = 0.465) models with regards to prediction were superior as compared to chlorine (R^2 = 0.181). This could be explained by many factors, such as collinearity among parameters and insufficient data for model validation. Hanushek and Jackson (1977) explained that collinearity can change parameter estimates, increase standard errors, and reduce the power to detect reliable effects of correlated variables in a regression model. It is also evident that the models could not perfectly predict fluctuations and peaks. Dzwairo (2011) however explained that in ecosystem modelling, which is usually characterised by outlying values and missing values, the emphasis should not be on the R^2 values, but whether a model can be able to perform some early warning forecast.

It is further anticipated that increasing the data-set should help improve the prediction power of the models. More data for training and validation generally tends to improve the accuracy of the model (Dzwairo 2011). The observed RMSE of below 1.2 observed for all models indicates that statistically there is a fair deviation of the calculated values from the actual observed values. As discussed in Chapter 4, the ideal RMSE (measure of the deviation of the modelled values from the actual observed values) is zero.

5.5.2. Chemical dosages models for Wiggins WTP

Figure 5-38, Figure 5-39 and Figure 5-40 shows the actual and predicted polymer, lime and chlorine dosage at Wiggins WTP.



Equation of the model:

POLY = 7.45308 + 0.10236*NH3 % - 0.05663*Alkalinity - 4.1608424E-03*Ca + 0.05513*Cl -7.61814E-03*Conductivity + 0.15147*DO + 8.25501E-04*E.coli - 3.70393E-03*F - 0.2726*K +0.90479*Mg -1.72430E-02*Na - 3.34965*NH_3 + 0.50401*NO_3 - 0.61452*pH+0.11251*Si -0.17353*SO4-3.47093E-02*SRP-0.16385*SS - 4.47835E-02*Temperature - 0.14523*TOC + 2.25258E-03*TP + 0.17609*Turbidity+3.3476E-05*Algae

Observations	47.000
DF	23.000
R^2	0.793
SSE	10.331
MSE	0.449
RMSE	0.670

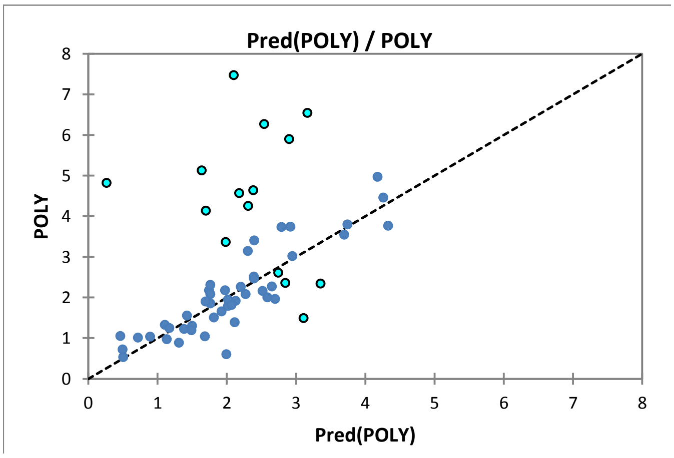
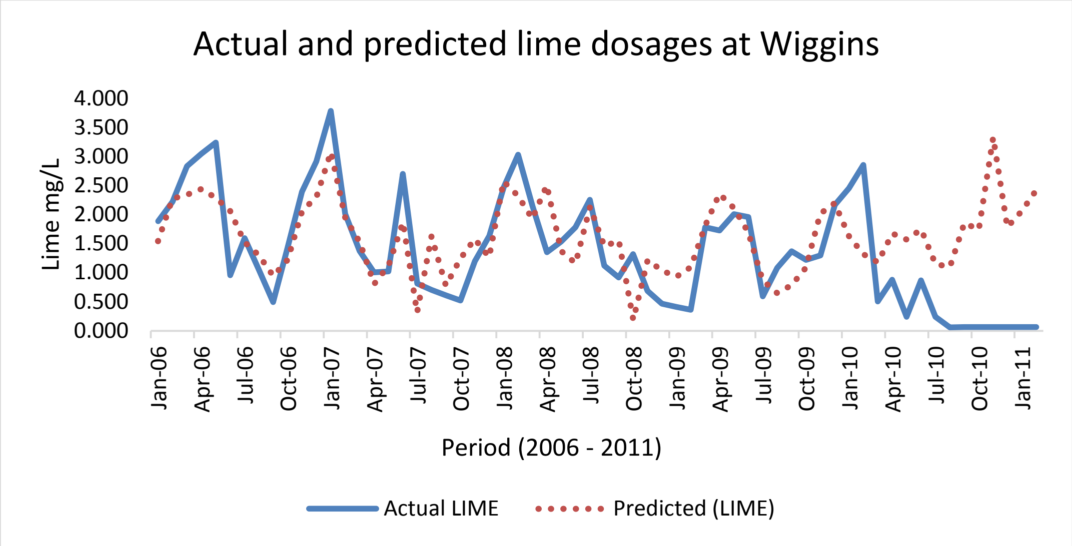


Figure 5-38 : Actual and predicted polymer dosage at Wiggins WTP



Equation of the model:

LIME = 2.75271 + 0.15161*NH3% - 4.17082E - 02*Alkalinity - 0.32043*Ca - 9.65696E-02*Cl + 0.26075*Conductivity + 0.26316*DO + 3.47580E-03*E.coli + 2.58944E-03*F - 0.83190*K +0.33524*Mg mg/l+0.07477*Na + 3.03432*NH_3 - 0.11635*NO_3 - 0.44176+0.19443*Si - 3.71434E-02*SO4l - 3.33113E-02*SRP + 4.75802E-02*SS +7.16637E-03*Temperature+2.76114E-02*TOC +8.84352E-04*TP -5.76550E-02*Turbidity+3.15828E-06*Algae

Observations	47.000
DF	23.000
R^2	0.577
SSE	14.027
MSE	0.610
RMSE	0.781

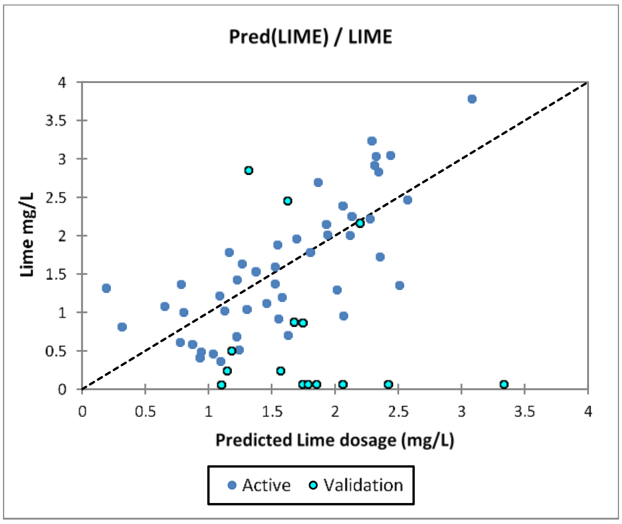
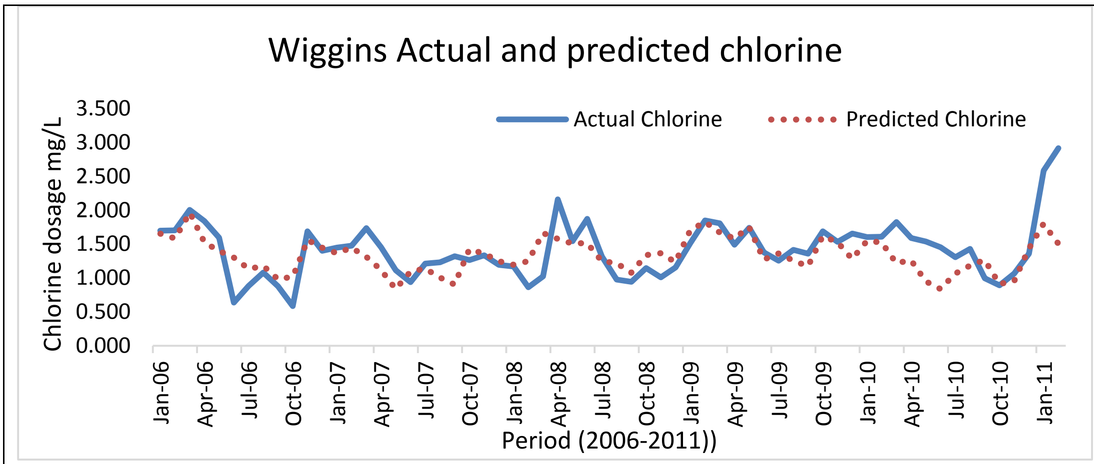


Figure 5-39: Lime model for Wiggins WTP



Equation of the model:

CHLORINE = 4.03081 + 6.54555E-02*NH3 % + 6.98385E-03*Alkalinity - 0.20001*Ca +1.93785E-02*Cl + 1.01063E-02*Conductivity - 1.36445E-02*DO - 2.23040E-04*E.coli - 3.654828E-04*F + 0.78039*K - 0.18304*Mg+4.56613E-02*Na - 1.13501*NH_3 + 0.23038*NO_3 -0.40745*pH + 2.19039E-02*Si - 1.31908E-02*SO4 - 1.21538E-02*SRP - 2.59865E-02*SS - 6.18895E-03*Temperature - 7.75814E-02*TOC + 1.15882E-03*TP + 6.52931E-02*Turbidity + 1.23749E-05*Algae

Observations	47.000
DF	23.000
R^2	0.491
SSE	2.975
MSE	0.129
RMSE	0.360

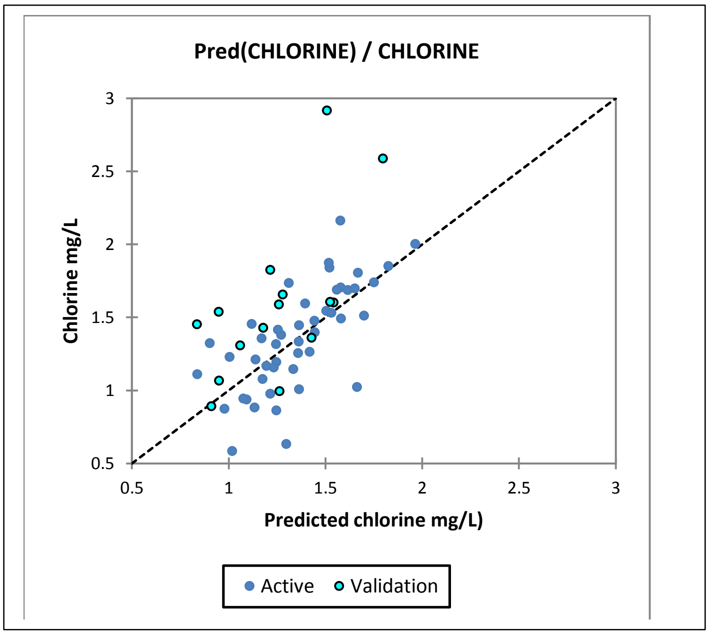


Figure 5-40: Chlorine dosage model for Wiggins WTP

By comparing the predicted power (R^2), it can be stated that polymer model (Figure 5-38) exhibited the highest prediction power of 0.793 as compared to lime (0.577:

Figure 5-39) and chlorine (0.491: Figure 5-40). It is also evident that the models could not perfectly predict fluctuations and peaks in dosage.

The observed RMSE of below 1.2 shows that all models displayed a fair deviation of the calculated values from the actual observed values. However, since RMSE measures the deviation of the modelled values from the actual observed values, a value close to zero illustrates the predictive accuracy of a model (Chen and Mynett, 2004, Kneidinger, 2008), is zero as discussed in Chapter 4.

From these results, it is evident that nonlinear regression model can be an effective tool in early warning against budgeting; improved decision-making and proactive water resource management. However, it is also important to highlight concerns with this modelling technique.

5.5.3. Models applicability

The models developed in this study are site specific, but the method used can be applied for other treatment plants. It should however also be reiterated that the models should be applied with great caution due to their low predictive power (R^2). This stems from the observation that the data exhibited skewness, non-linearity, non-normality and multicollinearity among parameters, which tends to affect the prediction power. The interactions between water quality parameters and the different chemicals during treatment are generally complex and rather difficult to account for each factor in detail. For more precise prediction, it is essential that all a more extensive study on sensitising each parameter on the model is undertaken. This might help optimisation the prediction power (R^2).

As discussed in Chapter 4, water sampling was inconsistent and thus monthly averages were used. This translated to 96 data-set for Durban Height and 60 for Wiggins WTP, which was insufficient for efficient data training and model validation. This limited the performance of the models as extensive data is normally needed for training as explained by Kneidinger (2008).

Finally, it is important to note that models should be used in conjunction with other tools such as water quality indices to enhance the prediction preciseness.

5.6. Summary

The water quality trends showed that algae, *E. coli,* TSS*,* algae and turbidity are the major problem in the Basin. The dam inflow stations exhibited a more deteriorated water quality as compared to outflows. The improvement of water quality at outflow stations should be an effect of the dam's retention effect which allows for the settling of suspended particles. Such pose an advantage to treatment plants since they generally abstract from dam outflow zones since they exhibit improved water quality.

High *E. coli* levels observed in the uMngeni Basin indicates that the water in this system is unfit for drinking without treatment, but can be used for other purposes such as industrial and selected agricultural activities. With regard to the nature of the pollutants, it can be stated that the uMngeni Basin is significantly affected by sewage effluence, agricultural runoff, industrial discharge and other domestic practising such as washing in the river.

The box-plots showed that the pollution load generally increased from upstream to downstream of the uMngeni River. However, the outflow stations clearly showed an improved water quality due to the self-purification capacity of dams. It should also be highlighted that even though IDO station is located downstream the Basin, the station showed an improved water quality. The dam's sheer size could be most plausible reason. Such an improvement of the water quality is of advantage to treatment and could explain the relatively low chemical dosages observed at Wiggins WTP as compared to Durban Heights. This is of importance at Wiggins WTP which even though abstracting from a downstream source, Inanda Dam, has been dosing less as compared to Durban Heights, which abstracts from an upstream Dam, Nagle, which is expected to exhibit less pollution

The results also showed that a water quality index is a better way of displaying monitoring data in an understandable manner as compared to the bulk individual parameters data-sets. The statistical test conducted clearly showed that physical parameters namely turbidity, algae and total suspended solids were significantly driving chemical dosage. The seasonality effect was also evident by a rise in polymer, chlorine and lime dosage at the two treatment plants studied during the rainy season.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1. Introduction

The purpose of this chapter is to conclude findings of the four objectives undertaken in this research. The section concludes findings for each objective undertaken. Finally, the chapter further discuss recommendations for further research work.

6.2. Conclusions

The first objective was to:

- ***To evaluate the spatial and temporal water quality trend along uMngeni River, in relation to river health and treatment cost.***

The time-series plot and box-plot were employed to determine the temporal and temporal water quality trends respectively in the Basin. In addition, the Seasonal-Kendal test was employed to test the significance of each temporal trend noted. All calculations were done using Microsoft Excel and XLSTAT 2014. The trends results showed that water quality along uMngeni River tends to deteriorate from upstream to downstream. This is clearer when comparing the inflow stations. A comparison of the means and box-plots showed that algae, alkalinity, chloride and conductivity exhibited some significant relative to temperature, ammonia, *E. coli,* total phosphate and nitrate.

The dam outflow stations showed an improvement in water quality status as compared to inflows. This can be attributed to the dam's retention and dilution effect. Such an improvement pose an advantage to treatment plants as they basically require high quality raw water in order to produce good quality potable water at a reasonable price. Algae, turbidity and *E. coli* peaks in the wet seasons coincided with the high polymer and chlorine dosage. It can thus be attributed that these parameters are key drivers of treatment cost in the basin.

In view of the high mean *E. coli* count range (98 count/100mL – 1319 colony count/100mL) observed on the six stations studied, it can be concluded that the water in uMngeni Basin is not suitable for drinking without disinfecting. High turbidity levels ranging from 2.68 NTU to 38.73 NTU, also implies that such water is aesthetically unacceptable for drinking purposes.

The S-K test results showed that turbidity, temperature, chlorides and conductivity exhibited some decreasing temporal trends on at least two stations. This implies an improvement of water quality with regard to these parameters. Such improvement can be attributed to several factors such as improved water resource management and the increasing environmental consciousness of the different stakeholders. However, the noted decrease in temperature tends to affect the treatment process as it results in poor floc formation.

Basing on the nature of the pollutant observed, it can be deduced that sewage effluent and runoff from agricultural feedlots and soils are the main polluting activities affecting the quality of water in uMngeni Basin. Knowledge gained from this analysis should help in the implementation of programs that reduces pollution mainly from sewage treatment plants and agricultural activities.

- **Objective two**

The second objective was to:
To produce two water quality indices: one for describing the general river health status and another for determining the treatability of raw water being abstracted in uMngeni Basin.

The results shows that a WQI provides a simple way of summarising water quality information in relation to the fitness for the intended use. The RHWQI clearly showed that the outflow stations showed an improved water quality as compared to the inflow stations. In addition, the RHWQI results generally showed that the quality of uMngeni Water is still acceptable for the survival of fresh water organisms.

The Treatability Water Quality Index allowed for the comparison of the raw water being abstracted at the two treatment plants, Durban Heights and Wiggins. The results showed that, the quality of Inanda Outflow station is relatively low as compared to Nagle. This was expected as Inanda Dam is downstream of Nagle Dam, which Wiggins and Durban Heights WTPs abstracts respectively.

- **Objective three**

To statistically determine parameters whose concentrations showed significant change due to treatment and to correlate them with polymer, chlorine and lime dosage at Durban Heights and Wiggins treatment plants.

The t-test and correlational results showed that the concentration of physical parameters namely algae, turbidity and total organic carbon were significantly reduced due to treatment. This findings implies that algae and turbidity are significant drivers for chemical dosage along uMngeni River. It can thus be hypothesised that methods for controlling physical pollutant sources should help reduce chemical dosage.

- **Objective four**

To develop models for forecasting polymer, chlorine and lime dosage at Durban Heights and Wiggins treatment plants.

The models for the two treatment plants, Wiggins and Durban Heights WTP, showed a relatively low to high prediction power (R^2). On both treatment plants, chlorine recorded the lowest prediction power. This could be due to the interaction effect of parameters being modelled. It can thus be concluded that this model can serve as a tool for early forecasting. Dzwairo (2011) explained that in ecosystem modelling emphasis should not be on R^2 values, but on whether a model can be able to perform some early warning forecasting.

This study serves as a reminder of the importance of continuously assessing of the fitness of a basin for potable water treatment and for the protection of freshwater ecosystems.

6.3. Recommendations

The conclusions of this research suggest the four recommendations.

1. A multisectoral approach is recommended in order to protect the fitness of water for various uses. One of the recommendations is to start pricing raw water according to quality variability. This will imply that treatment plants located downstream of uMngeni Basin, such as Wiggins and receiving poor quality water will have to pay less according to the variability of their raw water. This will ensure a cost-effective operation of the treatment plant and results in the production of high quality potable water at a reasonable price. Such a move will also force the Department of Water Affairs (DWA) and other interested stakeholders to intensify pollution control measured in the basin as the pricing strategy will now be offloading the cost of diminishing quality to them.

2. Industries need to conform to the given minimum effluent quality before discharging into river systems. This is important especially for sewage treatment works which have been noted to be significantly affecting the quality of water in uMngeni Basin. Simply giving industries a fine for polluting activities does not really force them to mitigate the contamination problem but they should actively minimise the amount of waste.

   In addition, the most effective means of reducing algae levels in uMngeni Basin would be to reduce the nutrient pollution source to the river and its dams. An example would be upgrading and improving the efficiency and capacity of sewage treatment plants along the river. Even though such action may require a huge capital injection, its long-term effect is the sustainable improvement of the river water quality status which ultimately reduces chemical dosage and cost. This will ensure the availability of high quality potable water at a reasonable price.

3. Residential areas need to be educated on the importance of minimising water pollution as it has costing implication which is normally incorporated into the

tariffs. Informal settlers need to be relocated from the riverbank area to proper serviced sites. Furthermore, communities residing near basin should be educated about the ecological impact of pollution. Furthermore, there is also needs to be provided to sanitation at micro level communities such as informal settlement which are a big concern in South Africa.

4. The use of multiple modelling approach to determine the best approach of predicting chemical dosage during treatment is hereby encouraged, rather than reliance on a single model. In particular, a study that would take into consideration the collinearity among the parameters should give a good comparison. The variability of results produced by different models give a wide range of choice for the most effective approach to predict chemical dosage. Furthermore, an extensive data-set for analysis such as daily or weekly interval should help produce better models.

REFERENCES

Abdullah, M. P., Yee, L. F., Ata, S., Abdullah, A., Ishak, B. and Abidin, K. N. Z. 2009. The study of interrelationship between raw water quality parameters, chlorine demand and the formation of disinfection by-products. *Physics and Chemistry of the Earth, Parts A/B/C*, 34 (13–16): 806-811.

Adedeji, A. A. and Ako, R. T. 2009. Towards achieving the United Nations' millennium development goals: The imperative of reforming water pollution control and waste management laws in Nigeria. *Desalination*, 248 (642): 649.

Adgar, A., Cox, C. and Jones, C. n.d. Coagulation control using the streaming current detector: Problems and a possible solution. Available: http://www.nt.ntnu.no/users/skoge/prost/proceedings/ecc03/pdfs/494.pdf (Accessed 24 August 2013).

Ahmed, A. L., Sumathi, S. and Hameed, B. H. 2006. Coagulation of Residue Oil and Suspended Solids in Palm Oil Mill Effluent by Chitosan, Alum and PAC. *Chemical Engineering Journal*, 118

Akoto, O. and Adiyiah, J. 2008. Dissolved nitrogen in drinking water resources of farming communities in Ghana. *African Journal of Environmental Science and Technology* 2(2): 31-35.

Al-Layla, M. H., Middlebrooks, E. J. and Porcella, D. B. 1974. *Effect of Temperature on Algal Removal by Alum Coagulation*. UtahStateUniversity

Alexander, R. B. and Smith, R. A. 2005. Moving from Monitoring to Prediction: The Quality of the Nation's Streams. In. Washington, D.C., U.S.Geological Survey,

Alkhatib, E. and Peters, R. 2008. Wet weather impact on trihalomethane formation potential in tributaries to drinking water reservoirs. *Environmental monitoring and assessment*, 139 (1-3): 173-181.

American Public Health Association. 1998. Standard methods for the examination of water and wastewater. *American Public Health Association, Washington, DC*, 1268

Ames, M. and Whitney-Smith, W. J. 1944. Bacteriology *47*, 445

Antonopoulos, V. Z., Papamichail, D. M. and Mitsiou, K. A. 2001. Statistical and trend analysis of water quality and quantity data for the Strymon River in Greece. *Hydrology and Earth System Sciences*, 5 (4): 679-691.

Antweiler, R. C. and Taylor, H. E. 2008. Evaluation of Statistical Treatments of Left-Censored Environmental Data using Coincident Uncensored Data Sets. *Environmental Science and Technology*, 42 (10): 3732-3738.

ANZECC. 1992. *Australian Water Quality Guidelines for Fresh and Marine Waters*. Canberra Australian and New Zealand Environment and Conservation Council.

Argo, D. G. 1980. Cost of Water Reclamation by Advanced Wastewater Treatment. *Journal (Water Pollution Control Federation)*, 52 (4): 750-759.

Arnell, N. W. 1999. Climate change and global water resources. *Global environmental change*, 9: S31-S49.

Assessment, M. E. 2005. *Ecosystems and human well-being*. Island Press Washington, DC.

Astel, A., Biziuk, M., Przyjazny, A. and Namieśnik, J. 2006. Chemometrics in monitoring spatial and temporal variations in drinking water quality. *Water Research*, 40 (8): 1706-1716.

Ates, N., Kaplan, S. S., Sahinkaya, E., Kitis, M., Dilek, F. B. and Yetis, U. 2007. Occurrence of disinfection by-products in low DOC surface waters in Turkey. *Journal of Hazardous Materials*, 142 (1–2): 526-534.

Autio, L., Juhola, M. and Laurikkala, J. 2007. On the neural network classification of medical data and an endeavour to balance non-uniform data sets with artificial data extension. *Computers in Biology and Medicine*, 37 (3): 388-397.

Azrina, M., Yap, C., Rahim Ismail, A., Ismail, A. and Tan, S. 2006. Anthropogenic impacts on the distribution and biodiversity of benthic macroinvertebrates and water quality of the Langat River, Peninsular Malaysia. *Ecotoxicology and Environmental Safety*, 64 (3): 337-347.

Ball, R. O. and Chruch, R. L. 1980. Water quality indexing and scoring. *Journal of Environmental Engineering Division*, 106: 757-771.

Barnett, V. and Lewis, T. 1995. Outliers in Statistical Data. *International Journal of Forecasting*, 12 (1): 175-176.

Baron, J. S., Poff, N. L., Angermeier, P. L., Dahm, C. N., Gleick, P. H., Hairston Jr, N. G., Jackson, R. B., Johnston, C. A., Richter, B. D. and Steinman, A. D. 2002. Meeting ecological and societal needs for freshwater. *Ecological Applications*, 12 (5): 1247-1260.

Bartram, J. and Ballance, R. 1996. *Water quality monitoring: a practical guide to the design and implementation of freshwater quality studies and monitoring programmes*. CRC Press.

Basson, M. S. and Rossow, J. D. 2003. *Mvoti to Umzimkulu Water Management Area Overview of Water Resource Availability and Utilisation*. Department of Water Affairs (DWAF).

Bates, B., Kundzewicz, Z. W., Wu, S. and Palutikof, J. 2008. *Climate change and water*. Intergovernmental Panel on Climate Change (IPCC).

Baxter, C. W., Zhang, Q., Stanley, S. J., Shariff, R., Tupas, R. R. T. and Stark, H. L. 2001. Drinking water quality and treatment: the use of artificial neural networks. *Canadian Journal of Civil Engineering*, 28 (1): 26-35.

Bazer-Bachi, A., Puech-Coste, E., Aim, R. B. and Probst, J. 1990. Mathematical modelling of optimal coagulant dose in water treatment plant. *Revue des sci. de l'eau*, 3: 377-397.

BCWWA. 2004. *Best Management Practices, Turbidity Monitoring and Reporting.* British Columbia: Ministry of Health Services.

Berzas, J. J., GarcÍa, L. F., RodrÍguez, R. C. and MartÍn-Alvarez, P. J. 2000. Evolution of the water quality of a managed natural wetland: Tablas de Daimiel National Park (Spain). *Water Research*, 34 (12): 3161-3170.

Bharti, N. and Katyal, D. 2011. Water quality indices used for surface water vulnerability assessment. *International Journal of Environmental Science*, 2 (1)

Black, A., Buswell, A. M., Eidsness, F. A. and Black, A. 1957. Review of the jar test. *Journal (American Water Works Association)*, 49 (11): 1414-1424.

Bolto, B. and Gregory, J. 2007. Organic polyelectrolytes in water treatment. *Water Research*, 41 (11): 2301-2324.

Boulton, A. J., Scarsbrook, M. R., Quinn, J. M. and Burrell, G. P. 1997. Land-use effects on the hyporheic ecology of five small streams near Hamilton, New Zealand. *New Zealand journal of marine and freshwater research*, 31 (5): 609-622.

Boyacioglu, H. 2007. Development of a water quality index based on a European classification scheme. *Water SA*, 33 (1): 101-106.

Brainwood, M. and Burgin, S. 2006. An exploration of the relationships betweenmacroinvertebrate community composition and physical andchemical habitat characteristics in farm dams. *Environmental monitoring and assessment*, 119 (1-3): 459-480.

Bratby, J. 2006. Coagulation and flocculation in water and wastewater treatment. *IWA Publishing*,

Brooks, M. A. 1999. Breakpoint Chlorination as an Alternate Means of Ammonia-Nitrogen Removal at a Water Reclamation Plant. Virginia Polytechnic Institute and State University.

Brown, R. M., McClleland, N. I., Deininger, R. A. and Tozer, R. G. 1970. A Water quality index do we dare? *Water . Sewage Work*: 339-343.

Butterfield, C. T. and Wattie, E. 1946. Influence of pH and temperature on the survival of coliforms and enteric pathogens when exposed to chloramine. *Public Health Reports (1896-1970)*: 157-192.

Calcagno, G., Staiano, A., Fortunato, G., Brescia-Morra, V., Salvatore, E., Liguori, R., Capone, S., Filla, A., Longo, G. and Sacchetti, L. 2010. A multilayer perceptron neural network-based approach for the identification of responsiveness to interferon therapy in multiple sclerosis patients. *Information Sciences*, 180 (21): 4153-4163.

Camp, T. R., Root, D. A. and Bhoota, B. 1940. Effects of Temperature on Rate of Floe Formation. *Journal of the American Water Works Association*, 32 (11): 1913-1927.

Campell, A. 2006. The role of aluminium and copper on neuroinflammation and Alzheimer's disease. *Journal of Alzheimer's Disease*, 10: 165-172.

Cannata, S., Engle, T. E., Moeller, S. J., Zerby, H. N., Radunz, A. E., Green, M. D., Bass, P. D. and Belk, K. E. 2010. Effect of visual marbling on sensory properties and quality traits of pork loin. *Meat Science*, 85 (3): 428-434.

Carnie, T. 2013. *Umgeni River 'one of dirtiest' in SA*. Available: http://www.iol.co.za/scitech/science/environment/umgeni-river-one-of-dirtiest-in-sa-1.1529000#.Ukq3Py8aLIU (Accessed 1 October 2013).

Caspers, H. 1981. J. S. Alabaster and R. Lloyd: Water Quality Criteria for Freshwater Fish. – 297 pp. London-Boston: Butterworth 1980. ISBN 0 408 10673 5. £ 18.00. *Internationale Revue der gesamten Hydrobiologie und Hydrographie*, 66 (3): 443-443.

CCME. 2001. *Canadian water quality guidelines for the protection of aquatic life*. Winnipeg, Manitoba:

Chambers, C. W. 1976. An overview of the problems of disinfection. In: Davis, E. ed. Proceedings of *International Symposium on Wastewater Treatment in Cold Climates*. Ottawa, Water Pollution Control Directorate, 396. Available: http://dx.doi.org/10.1002/iroh.19760610316 (Accessed 6 June 2013).

Chandler, R. and Scott, M. 2011. *Statistical Methods for Trend Detection and Analysis in the Environmental Sciences*. Wiley.

Chatterjee, T., Chatterjee, S. and Woo, S. H. 2009. Enhanced coagulation of bentonite particles in water by a modified chitosan biopolymer. *Chemical Engineering Journal*, 148 (2–3): 414-419.

Chen, Q. and Mynett, A. E. 2004. Predicting Phaeocystis globosa bloom in Dutch coastal waters by decision trees and nonlinear piecewise regression. *Ecological Modelling*, 176: 277-290

Chen, C.-Y., Wen, T.-Y., Wang, G.-S., Cheng, H.-W., Lin, Y.-H. and Lien, G.-W. 2007. Determining estrogenic steroids in Taipei waters and removal in drinking water treatment using high-flow solid-phase extraction and liquid chromatography/tandem mass spectrometry. *Science of The Total Environment*, 378 (3): 352-365.

Chiang, L. H., Pell, R. J. and Seasholtz, M. B. 2003. Exploring process data with the use of robust outlier detection algorithms. *Journal of Process Control*, 13 (5): 437-449.

Chua, L. H. C., Tan, S. B. K., Sim, C. H. and Goyal, M. K. 2012. Treatment of baseflow from an urban catchment by a floating wetland system. *Ecological Engineering*, 49 (0): 170-180.

Clements, W. H., Carlisle, D. M., Lazorchak, J. M. and Johnson, P. C. 2000. Heavy metals structure benthic communities in Colorado mountain streams. *Ecological Applications*, 10 (2): 626-638.

COHRE, AAAS, SDC and UN-HABITAT. 2007. *Manual of the Right to Water and Sanitation*. Switzerland COHRE, AAAS. SDC andUN-HABITAT.

Couceiro, S. R., Hamada, N., Luz, S. L., Forsberg, B. R. and Pimentel, T. P. 2007. Deforestation and sewage effects on aquatic macroinvertebrates in urban streams in Manaus, Amazonas, Brazil. *Hydrobiologia*, 575 (1): 271-284.

Couillard, D. and Lefebvre, Y. 1985. Analysis of water indices. *Journal of Environmental Management*, 21 (2): 161-179.

Cox, M. E., Moss, A. and Smyth, G. K. 2005. Water quality condition and trend in North Queensland waterways. *Marine Pollution Bulletin*, 51 (1–4): 89-98.

Crowns, J., Davis, J., Cheal, F., Schmidt, L., Rosich, R. and Bradley, S. 1992. Multivariate pattern analysis of wetland invertebrate communities and environmental variables in Western Australia. *Australian Journal of Ecology*, 17 (3): 275-288.

CSIR. 2010. *A CSIR perspective on water in South Africa*. Pretoria, South Africa. Available: https://www.google.co.za/#fp=b9e55bd8b1c2efe7&q=Deterioration+of+water+quality+can+adversely+affect+human+health%2C+aquatic+ecosystem+and+has+implications+on+various+economic+sectors+(Oberholster+and+Ashton%2C+2008). (Accessed 23 Auguast 2013).

Cude, C. 2001. Oregon Water Quality Index: a tool for evaluating water quality management effectiveness. *Water Resource Association*, 37 (1): 125-137.

Daily, G. C., Alexander, S., Ehrlich, P. R., Goulder, L., Lubchenco, J., Matson, P. A., Mooney, H. A., Postel, S., Schneider, S. H. and Tilman, D. 1997. *Ecosystem services: benefits supplied to human societies by natural ecosystems*. Ecological Society of America Washington (DC).

Dallas, H. F. and Day, J. A. 2004. *The effect of water quality variables on Aquatic Ecosystems: A Review*. Pretoria, South Africa:

Dallas, H. F., Pay, J. A. and Reynolds, E. G. 1994. *The effects of water quality variables on riverine biotas.* Pretoria: Water Research Commission (WRC)

Darken, P. F. 1999. Testing for changes in trend in water quality data. Doctor of Philosophy in Statistics, Virginia Polytechnic Institute and State University. Available: http://scholar.lib.vt.edu/theses/available/etd-091099-132201/unrestricted/PatDarken1.pdf (Accessed 15 February 2013).

Data Analysis and Interpretation. 2000. In: *Rhe Monitoring Guideline*. Austria.

Davis, A. P. and McCuen, R. H. 2005. *Stormwater Management for Smart Growth*. Springer.

Dearmont, D., McCarl, B. A. and Tolman, D. A. 1998. Costs of water treatment due to diminished water quality: a case study in Texas. *Water Resources Research*, 34 (4): 849-854.

Dennison, D. B. and Lyne, M. C. 1997. Analysis and prediction of water treatment costs at the DV Harris Plant in Umgeni Catchment Area. *Agrekon*, 36: 40.

Dentel, S. K., Thomas, A. V. and Kingery, K. M. 1989. Evaluation of the streaming current detector—I. Use in jar tests. *Water Research*, 23 (4): 413-421.

South Africa. Department of Irrigation and Drainage 2009. *Study on the river water quality trends and indexes in Penninsular Malaysia*. Malaysia: Department of Irrigation and Drainage.

South Africa. Department of Water Affairs and Forestry. 1996a. *South African Water Quality Guidelines. Volume 1: Domestic Use.* Pretoria, South Africa: Department of Water Affairs and Forestry.

South Africa. Department of Water Affairs and Forestry. 1996b. *South African Water Quality Guidelines. Volume 7: Aquatic Ecosystems*. Pretoria, South Africa: Department of Water Affairs and Forestry

South Africa. Department of Water Affairs and Forestry. 2000. *Quality of Domestic Water Supplies Volume 2: Sampling Guide*. Pretoria, South Africa: Department of Water Affairs and Forestry.

South Africa. Department of Water Affairs and Forestry. 2001. *Quality of Domestic Water Supplies. Voume 3. Analysis Guide*. Pretoria: Department of Water Affairs and Forestry, Department of Health, Water Research Commission.

South Africa. Department of Water Affairs and Forestry. 2003. *uMngeni River and Neighbouring Rivers and Streams: State of the Rivers Report* Pretoria:

Deventer, R. v. 2012. Impact of land use on water quality and aquatic ecosystem health of stream network in the upper uMngeni catchment feeding Midmar Dam, KwaZulu-Natal, South Africa (Masters). Masters of Science degree in Environmental Science, University of KwaZulu-Natal.

Diaz, A., Rincon, N., Escorihuela, A., Fernandez, N., Chacin, E. and Forster, C. F. 1999. A preliminary evaluation of turbidity removal by natural coagulants indigenous to Venezuela. *Process Biochemistry*, 35 (3–4): 391-395.

Díaz Muñiz, C., García Nieto, P. J., Alonso Fernández, J. R., Martínez Torres, J. and Taboada, J. 2012. Detection of outliers in water quality monitoring samples using functional data analysis in San Esteban estuary (Northern Spain). *Science of The Total Environment*, 439 (0): 54-61.

Dinius, S. H. 1987. Design of an index of water quality. *Water Resources Bulletin*, 23 (5): 833-843.

Donkor, S. M. K. 2003. Development challenges of water resources management in Africa. *African Water Journal*, Pilot edition (December 2003)

Douman, M. 2008. Midmar Dam will be contaminated, experts warn,. *The Witness*, 30 July 2008

Driscoll, C. T. and Letterman, R. D. 1995. Factors regulating residual aluminium concentrations in treated waters. *Environmetrics*, 6 (3): 287-305.

Dunnette, D. A. 1980. A geographically variable water quality Index used in Oregon. *Journal of Water Pollution Control Federation,*, 51 (1): 53-61.

Dyer, S. D., Peng, C., McAvoy, D. C., Fendinger, N. J., Masscheleyn, P., Castillo, L. V. and Lim, J. M. U. 2003. The influence of untreated wastewater to aquatic communities in the Balatuin River, The Philippines. *Chemosphere*, 52 (1): 43-53.

Dzwairo, B. 2011. Modelling raw water quality variability in order to predict cost of water treatment. Doctor Technologiae, Tshwane University of Technology.

Dzwairo, B., Otieno, F. A. O. and Ochieng', G. M. 2010. Incorporating surface raw water quality into the cost chain for water services: Vaal catchment, South Africa. *Research Journal of Chemistry and Environment*, 14 (1): 29-35.

Dzwairo, B., Otieno, F. A. O. and Ochieng, G. M. 2011. Towards a more sustainable surface raw water tariff structure in the Vaal basin: A situational analysis. *International Journal of the Physical Sciences*, 6 (29): 6751 - 6758.

Dzwairo, B., Otieno, F. A. O., Ochieng, G. M. and Bezuidenhout, J. J. 2012. Raw water quality weight factors: Vaal basin, South Africa. *Water Science & Technology*, 66 (5): 1061-1068.

Eaton, A. D., Franson, M. A. H., Association, A. P. H., Association, A. W. W. and Federation, W. E. 2005. *Standard Methods for the Examination of Water & Wastewater*. American Public Health Association.

Ebeling, J. M., Sibrell, P. L., Ogden, S. R. and Summerfelt, S. T. 2003. Evaluation of chemical coagulation flocculation aids for the removal of suspended solids and phosphorus from intensive recirculating aquaculture effluent discharge. *Aquacultural Engineering*, 29: 23-42.

Eikebrokk, B., Juhna, T. and Østerhus, S. W. 2006. *Water treatment by enhanced coagulation – Operational status and optimization issues*. Techneau.

Elder IV, J., Hill, T., Delen, D. and Fast, A. 2012. *Practical text mining and statistical analysis for non-structured text data applications*. Academic Press.

Environmental Protection Agency. 1999. *Guidance Manual for Compliance with the Interim Enhanced Surface Water Treatment Rule: Turbidity Provisions*. United States Environmental Protection Agency

Environmental Protection Agency. 2006. *Data Quality Assessment: Statistical Methods for Practitioners*. Washington: United States Environmental Protection Agency, Office of Environmental Information, 2006.

Environmental Protection Agency. 2009. Exploratory Tools. In: *Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities-Unified Guidance*.

Environmental Protection Agency. 2012. *What is Nonpoint Source Pollution?* Available: http://water.epa.gov/polwaste/nps/whatis.cfm (Accessed 24 Sepetmber 2013).

Evuti, A. M., Folorunsho, A. D., Agaie, G. B. and Jibri, M. 2012. Predictive Model for Lime Dosage in Water Treatment Plant. *International Journal of Science and Research Publications*, 2 (12)

Falkenmark, M. 1989. The massive water scarcity now threatening Africa – Why isn't being addressed? *Ambio*, 18 (2): 112-118.

Fataei, E., Seyyedsharifi, S. A., Seiiedsafaviyan, S. T. and Nasrollahzadeh, S. 2013. Water Quality Assessment Based on WQI and CWQI Indexes in Balikhlou River, Iran.

Fernandez, E. and Gallvis, A. 2002. Artificial Neural Networks Model Used for Clear Water Treatment Plants. *Instituto Cinara, Universidad del Valle*,

Flores, J. C. 2002. Comments to the use of water quality indices to verify the impact of Cordoba City (Argentina) on Suquia river. *Water Research*, 36 (18): 4664-4666.

Fogarty, D. J. 2006. Multiple imputation as a missing data approach to reject inference on consumer credit scoring. *Intersat*,

Forster, D. L., Chris, P. B. and Douglas, D. S. 1987. Soil Erosion and Water Treatment Costs. *Journal of Soil and Water Conservation*, 42: 349-359.

Forster, D. L. and Murray, C. 2001. *Farming Practices & Community Water Treatment Costs* Ohio Stat University: Ohio State University Department of Agricultural, Environmental, and Developmental Economics.

Freese, S. D., Hodgson, K. and Nozaic, D. J. 2004. Factors affecting coagulation with polelectrolytes: Are these quantifiable? In: Proceedings of *Water Institute of Southern Africa (WISA)*. Capetown, 1154-1163.

Fresh Water Resources : State. 1999. Available: http://www.ceroi.net/reports/durban/issues/fshwater/state.htm (Accessed 14 September 2012).

Fu, L. and Wang, Y.-G. 2012. *Statistical tools for analysing water quality data*. Water Quality Monitoring and Assesment. Available: http://cdn.intechopen.com/pdfs/35050/InTech-Statistical_tools_for_analyzing_water_quality_data.pdf (Accessed 27 May 2013).

Furness, H. D. and Richard, W. N. 1987. South Africa: eWISA. Available: http://www.ewisa.co.za/literature/files/1989%20-%2017.pdf (Accessed 23 September 2013).

Ganesh, A., Lin, J. and Singh, M. 2013. Detecting Virus-Like Particles from the Umgeni River, South Africa. *CLEAN–Soil, Air, Water*,

GE Power and Water. 2012. *Chlorine and Chlorine Alternatives*. Available: http://www.gewater.com/handbook/cooling_water_systems/ch_27_chlorine.jsp (Accessed 22 September 2013).

Gebremedhin, S. K. 2009. Analysis and Prediction of Chemical Treatment Cost of Potable Water in the Upper and Middle Vaal Water Management Areas. Master of Science in Agriculture, University of KwaZulu-Natal.

Gidde, M. R. and Bhalero, A. R. 2011. Optimisation of physical parameters of coagulation-flocculation process in water treatment. *Journal of Environmental Research And Development*, 6 (1): 99-110.

Gleick, P. H. 2010. *Bottled and Sold: The Story Behind Our Obsession with Bottled Water*. Washington D.C: Island Press.

Global Water Intelligence. 2010. *Water tariffs continue upward momentum*. Global Water Intelligence. Available: http://www.globalwaterintel.com/archive/11/9/market-insight/water-tariffs-continue-upward-momentum.html (Accessed 12 May 2013).

Graham, P. 2004. Modelling the water quality in dams within the Umgeni Water operational area with emphasis on algal relations. Philosophiae Doctor, North West University.

GroundTruth. 2010. *Draft Upper uMngeni Integrated Catchment Management Plan. Report prepared by GroundTruth for the uMngeni Local Municipality as a requirement of the Record of Decision by the Department of Environmental Affairs for authorization of the Khayalisha housing development*. Pietermaritzburg: GroundTruth Water, Wetlands and Environmental Consultants,.

Güler, C., Thyne, G. D., McCray, J. E. and Turner, A. K. 2002. Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. *Hydrogeology* 10: 455–474.

Haarhoff, J. and Olivier, J. 2002. GAC performance at three Southern African water treatment plants. Paper presented at the *Biennial Conference of the Water Institute of Southern Africa (WISAi*. Durban, Water Research Commission, 37-42.

Hallock, D. Department of Ecology. Ecology, D. o. 2002. *A Water Quality Index for Ecology's Stream Monitoring Program*. Washington: Department of Ecology Publications. Available: http://www.ecy.wa.gov/biblio/0203052.html (Accessed 20 September 2012).

Hanson, A. and Cleasby, J. 1990. The effects of temperature flocculation: Fluid dynamics. . *Journal of America Water Works Association*, 82 (1): 56-72.

Hanushek, E. A. and Jackson, J. E. 1977. *Statistical methods for social scientists*. New York: Academic Press.

Health-Canada. Branch, H. E. a. C. S. 2003. *Guidelines for Canadian Drinking Water Quality: Supporting Document-Turbidity*. Ottawa, Ontario: Health Canada.

Helsel, D. 1990. Less than obvious-statistical treatment data below the detection limit. *Environmental Science and Technology*, 24 (12): 1766-1744.

Helsel, D. 2006. Fabricating data: How substituting values for nondetects can ruin results, and what can be done about it. *Chemosphere*, 65: 2434-2439.

Helsel, D. R. and Cohn, T. 1988. Estimation of description statistics for multiply censored water quality data. *Water Resource Research*, 24: 1997-2004.

Helsel, D. R. and Hirsch, R. M. 1992. *Statistical Methods in Water Resources*. Amsterdam, Netherlands: Elsevier Science Publisher B.V.

Hemens, J., Simpson, D. E. and RJ., W. 1977. Nitrogen and phosphorus input to the Midmar Dam, Natal. *Water SA*, 3 (4): 193-201.

Herold, C. E. 2009. The Water Crisis in South Africa. Paper presented at the *14th SANCIAS SYMPOSIUM*. Umfula Wempilo Consulting,

Hewett, P. and Ganser, G. H. 2007. A Comparison of Several Methods for Analyzing Censored Data. *British Occupational Hygiene*, 57 (7): 611-632.

Hirsch, R. M., Alexander, R. B. and Smith, R., A. 1991. Selection of Methods for the Detection and Estimation of Trends in Water Quality. *Water Resource Resarch* 27 (5): 803-815.

Hirsch, R. M., Slack, J. R. and Smith, R. A. 1982a. Techniques of trend analysis for monthly water quality analysis. *Water Resource Research* 18 No 1: 107-121.

Hirsch, R. M., Slack, J. R. and Smith, R. A. 1982b. Techniques of trend analysis for monthly water quality data. *Water resources research*, 18 (1): 107-121.

Hofmann, T. A. and Mason, C. F. 2005. Habitat characteristics and the distribution of Odonata in a lowland river catchment in eastern England. *Hydrobiologia*, 539 (1): 137-147.

Hoko, Z. and Makado, P. K. 2011. Optimization of algal removal process at Morton Jaffray water works, Harare, Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C*, 36 (14–15): 1141-1150.

Holmes, T. P. 1988. The Offsite Impact of Soil Erosion on the Water Treatment Industry. *Land Economic*, 64: 356-366.

Horton, R. K. 1965. An index-number system for rating water quality. *Journal of Water Pollution Control Federation*, 37 (3): 300-306.

House, M. A. and Ellis, J. B. 1980. Water quality indices: an additional management tool? *Progress in Water Technology*, 13: 413-423.

Huang, C. and Shiu, H. 1996. Interactions between alum and organics in coagulation. *Colloids and Surfaces A*, 113 (1-2): 155-163.

Hulton, G. and Organization, W. H. 2012. Global costs and benefits of drinking-water supply and sanitation interventions to reach the MDG target and universal coverage.

Huntley, B., Siegfried, R. and Sunter, C. 1982. South African Environments into the 21st Century, Human and Rousseau. *Human and Rousseau*,

Hurst, A. M., Edwards, M. J., Chipps, M., Jefferson, B. and Parsons, S. A. 2004. The impact of rainstorm events on coagulation and clarifier performance in potable water treatment. *Science of The Total Environment*, 321 (1–3): 219-230.

Iglewicz, B. and Hoaglin, D. C. 1993. How to Detect and Handle Outliers.

Ikem, A., Odueyungbo, S., Egiebor, N. O. and Nyavor, K. 2002. Chemical quality of bottled waters from three cities in eastern alabama. *Science of The Total Environment*, 285: 165-175.

Isikhungusethu Environmental Services. 2011. *Status Quo Report for the uMgungundlovu DistrictMunicipality Strategic Environmental Assessment and Strategic Environmental Management*. Pietermaritzburg: Isikhungusethu Environmental Services (Pty) Ltd

James, M., Ebeling-Sibrell, P. L., Ogden, S. R. and Steven S. T. 2003. Evaluation of Chemical Coagulation-Flocculation Aids for the removal of Suspended Solids and Phosphorus from Intensive Recirculating Aquaculture Effluent Discharge. *Aquacultural Engineering*, 29: 23-42.

John, W. and Trollip, D. 2009. *National Standards for drinking water treatment*. South Africa: Water Research Commission (WRC).

Jonnalagaddai, S. B. and Mhere, G. 2001. Water Quality of the Odzi River in the Eastern Highlands of Zimbabwe. *Water Research*, 35 (1): 2371-2376.

Joung, H. M., Miller, W. W., Mahannah, C. N. and Guittjens, J. C. 1979. A generalized water quality index based on multivariate factor analysis. *Journal of Environmental Qualiity* 8(1): 95-100.

Kalderstam, J., Edén, P., Bendahl, P.-O., Strand, C., Fernö, M. and Ohlsson, M. 2013. Training artificial neural networks directly on the concordance index for censored data using genetic algorithms. *Artificial Intelligence in Medicine*, 58 (2): 125-132.

Kang, L. S. and Cleasby, J. L. 1995. Temperature effects on flocculation kinetics using Fe (III) coagulant. *Journal of environmental engineering*, 121 (12): 893-901.

Kang, P. 2013. Locally linear reconstruction based missing value imputation for supervised learning. *Neurocomputing*, (0)

Kankal, N., Indurkar, M., Gudadhe, S. and Wate, S. 2012. Water quality index of surface water bodies of Gujarat, India. *Asian J. Exp. Sci*, 26 (1): 39-48.

Khan, F., Husain, T. and Lumb, A. 2003. Water quality evaluation and trend analysis in selected watersheds of the Atlantic Region of Canada. *Environmental Monitoring and Assessment*, 88: 221-242.

Khan, S. and Simpson, D. 2002. Displaying Water Data using GIS. Paper presented at the *Biennial Conference of the Water Institute of Southern Africa (WISA*. Durban, Water Research Commission,

Kneidinger, T. M. 2008. A basic model to predict water quality changes in the Vaal Dam. Master of Science in Environmental Management, University of Johannesburg

Köster, D. and Hutchinson, N. 2008. *Review of Long-Term Water Quality Data for the Lake System Health Program*. Ontario:

Kott, Y., Nupen, E. M. and Ross, W. R. 1975. The effect of pH on the efficiency of chlorine disinfection and virus enumeration. *Water Research*, 9 (869)

Kumar, A. and Dua, A. 2009. Water Quality Index for assessment of water quality of river Ravi at Madhopur (India). *Global journal of Environmental Sciences*, 8 (1): 49-57.

Lakshminarayan, K., Harp, S. and Samad, T. 1999. Imputation of missing data in industrial databases. *Applied Intelligence*, 11 (3): 259-275.

Landwehr, J. M. and Deininger, R. A. 1976. A comparison of several water quality indexes. *Journal of Water Pollution Control Federation*, 48 (5): 954-950.

Lange, G. M. and Hassan, R. 2006. *The Economics of Water Management in Southern Africa: An Environmental Accounting Approach*. Cheltenham, UK.: Edward Elgar Publishing Ltd.

Laurent, P. and Prevost, M. 2005. *Biodegradable Organic Matter in Drinking Water Treatment and Distribution*. Denver: American Water Works Assocication & Servais.

LeChevallier, M. W., Evans, T. M. and Seidler, R. J. 1981. Effect of turbidity on chlorination efficiency and bacterial persistence in drinking water. *Applied Environmental Microbiology*, 42 (159)

Legay, C., Rodriguez, M. J., Sérodes, J. B. and Levallois, P. 2010. Estimation of chlorination by-products presence in drinking water in epidemiological studies on adverse reproductive outcomes: A review. *Science of The Total Environment*, 408 (3): 456-472.

Leopold, P. and Freese, S. D. 2009. *A simple guide to the chemistry, selection and use of chemicals for water and wastewater treatment*. South Africa: Water Research Commission.

Lettenmaier, D. P., Conquest, L. L. and Hughes, J. P. 1982. *Routine streams and rivers water quality trend monitoring review*. Washington: University of Washington.

Li, J., Li, H., Shen, B. and Li, Y. 2011. Effect of non-point source pollution on water quality of the Weihe River. *International Journal of Sediment Research*, 26 (1): 50-61.

Lieven, C. 2007. Statistical validation and spatio-temporal modelling of river monitoring networks. PhD in Applied Biological Sciences, Ghent University.

Lin, P.-E. and Niu, X.-F. 1998. *Comparison of Statistical Methods In Handling Minimum Detection Limits*. Department of Statistics,, Florida State University.

Lind, C. 1994. Coagulation control and optimization: Part two. *Public Works*, 125 (12)

Liou, S. M., Lien, S. and Wang, S. H. 2004. General water quality index for Taiwan. *Environmental Monitoring and Assessment*, 96: 35-52.

Lohani, B. N. and Todino, G. 1984. Water Quality Index for Chao Phraya River. *Journal of Environmental Engineering*, 110 (6): 1162-1177.

Lopaka, L. and Helsel, D. 2005. Statistical analysis of water-quality data containing multiple detection limits: S-language software for regression on order statistics. *Computers & Geosciences*, 31: 1241-1248.

Loucks, D. P. and Van Beek, E. 2005. Water Quality Modelling and Prediction. In: *Water Resources Systems Planning and Management: An introduction to methods, models, and Applications*. Paris, France: United Nations Educational. Available: http://ecommons.library.cornell.edu/handle/1813/2798. (Accessed 14 October 2013).

Lumb, A., Halliwell, D. and Sharma, T. 2006. Application of CCME Water Quality Index to monitor water quality: A case study of the Mackenzie River basin, Canada. *Environmental Monitoring and Assessment*, 113 (1-3): 411-429.

Maasdam, R. 2000. Exploratory Data Analysis in Water Quality Monitoring Systems. Master of Science in Geographical Information Systems, University of Salford. Available: http://www.unigis.nl/downloads/msc/Ruurd%20Maasdam.pdf (Accessed 21 July 2012).

Magadza, C. H. D. 2003. Lake Chivero: A management case study. *Lakes & reservoirs : research and management*, 8 (2): 69-81.

Maier, H. R. and Dandy, G. C. 2000. Neural networks for the prediction and forecasting of water resources variables: a review of modelling issues and applications. *Environmental Modelling and Software*, 15 (1): 101-124.

Maier, H. R., Morgan, N. and Chow, C. W. K. 2004. Use of artificial neural networks for predicting optimal alum doses and treated water quality parameters. *Environmental Modelling and Software*, 19 (5): 485-494.

Mancini, G., Roccaro, P. and Vagliasindi, F. G. A. 2004. Water intended for human consumption- Part II: Treatment alternatives, monitoring issues and resulting costs. *Desalination*, 176: 143-153.

Martin, P., Haniffa, M. and Arunachalam, M. 2000. Abundance and diversity of macroinvertebrates and fish in the Tamiraparani river, South India. *Hydrobiologia*, 430 (1-3): 59-75.

Maya, R. S. 1996. *Perspectives on Water Quality and Conservation in Zimbabwe's Urban Centres: Southern Centre, Natural Resource Programme, Phase 1 Report, Urban Water Quality and Conservation Project.* Harare, Zimbabwe: Natural Resources Forum,Centre for Natural Resources, Energy, and Transport (United Nations).

McClleland, N. I. US Environmental Protection Agency. Agency, U. E. P. 1974. *Water Quality Index Application in the Kansas River Basin*. Kansas City: Environmental Protection Agency.

McLaren, S. J. and Kim, N. D. 1995. Evidence for a seasonal fluctuation of arsenic in New Zealand's longest river and the effect of treatment on concentrations in drinking water. *Environmental Pollution*, 90 (1): 67-73.

Mirsepassi, A. 2004. Application of Intelligent System for Water Treatment Plant Operation. *Iranian Journal of Environmental Health Science and Engineering*, 1 (2): 51-57.

Mohammed, S. A. M. and Shanshool, H. A. 2009. Phosphorus Removal from Water and Waste Water by Chemical Precipitation Using Alum and Calcium Chloride. *Iraqi Journal of Chemical and Petroleum Engineering*, 10 (2): 35-42.

Momba, M. N. B., Tyafa, Z. and Makala, N. 2004. Rural water treatment plants fail to provide potable water to their consumers: the Alice water treatment plant in the Eastern Cape Province of South Africa. *South African Journal of Science*, 100: 307-310.

Montagna, P. A. n.d. Using PROC STANDARD and PROC SCORE to impute missing multivariate values. Harte Research Institute for Gulf of Mexico Studies.

Moore, W. B. and M., B. A. 1987. Off-Site Costs of Soil Erosion: A Case Study in the Willamette Valley. *Western Journal of Agricultural Economics*, 12: 42-49.

Morris, R. D., Naumova, E. N., Levin, R. and Munasinghe, R. L. 1996. Temporal variation in drinking water turbidity and disguised gastroenteritis in Milwaukee. *America Journal of Public Health*, 86 (2): 237-239.

Mozejko, J. 2012. Detecting and Estimating Trends of Water Quality Parameters. In: Voudouris, D. ed. *Water Quality Monitoring and Assessment*. Croatia: InTech, 95-120. Available: http://www.intechopen.com/books/water-quality-monitoring-and-assessment/detecting-and-estimating-trendsof-water-quality-parameters (Accessed 21 July 2012).

Muller, M., Schreiner, B., Smit, L., Koppen, B., Sally, H., Aliber, M., Cousins, B., Tapela, B., Merwe-Botha, M., Karar, E. and Pietersen, K. 2009. Water security in South Africa. Development bank of Southern Africa. Midrand. Available: http://www.dbsa.org/Research/DPD%20Working%20papers%20documents/DPD%20No12.pdf (Accessed 27 July 2012).

Nasirian, M. 2007. A New Water Quality Index for environmental contamination contributed by mineral processing: A case study of Amang (tin tailing) Processing activity. *Applied Sciences*, 7 (20): 2977-2987.

Nieh, C. 2011. Using Mass Balance, Factor Analysis, and Multiple Imputation to Assess Health Effects of Water Quality. Doctor of Philosophy in Public Health Sciences, University of Illinois

NBI. 2012. *Companies need to act now to combat water risks*. National Business Innitiative: Available: http://www.nbi.org.za/Pages/Publication-Details.aspx?NBIweb=e586ac5b-bcad-49be-ba41-81b0f1fa2ba3&NBIlist=64654bc6-d34d-4582-999b-0778898cb878&NBIitem=97 (Accessed 1 July 2013).

Ndabigengesere, A. and Subba Narasiah, K. 1998. Quality of water treated by coagulation using Moringa oleifera seeds. *Water Research*, 32 (3): 781-791.

Ndiritu, G. G., Gichuki, N. N. and Triest, L. 2006. Distribution of epilithic diatoms in response to environmental conditions in an urban tropical stream, Central Kenya. *Biodiversity & Conservation*, 15 (10): 3267-3293.

Netshidaulu, A. E. 2007. *Personal Communication* Bothaville: Sedibeng Water.

Neysmith, J. 2008. Investigating non-regulatory barriers and incentives to stakeholder participation in reducing water pollution in Pietermaritzburg's Baynespruit (Masters Degree). Master of Environment and Development (Environmental Management), University of KwaZulu-Natal.

NHMRC. n.d. Drinking water treatment chemicals. In: *Australian Drinking Water Guidelines*. Australia.

Nishanth, K. J., Ravi, V., Ankaiah, N. and Bose, I. 2012. Soft computing based imputation and hybrid data and text mining: The case of predicting the severity of phishing alerts. *Expert Systems with Applications*, 39 (12): 10583-10589.

Noor, N. M. and Zainudin, M. L. 2008. A Review: Missing Values in Environmental Data Sets. Paper presented at the *International Conference on Environment 2008 (ICENV 2008)*. Pulau Pinang,

Nozaic, D. 2004. Chlorine: Is it really so bad and what are the alternatives? *Water Sa*, 30 (5): 18-24.

Nozaic, D. J., Freese, S. D. and Thompson, P. 2001. Longterm experience in the use of polmeric coagulants at Umgeni Water. *Water Science and Technology*, 1: 43-50.

NRC. 1980. *Drinking Water and Health*. Washington, D.C.: National Academy Press.

NWQMS. 2000. *Australian Guildeline for Water Quality Monitoring and Reporting*.

O'Keeffe, J., Uys, M. and Bruton, M. N. 1992. *Freshwater Systems*. 2 ed. Capetown: Juta & Co Ltd.

Oberholster, P. J., Myburgh, J. G., Ashton, P. J. and Botha, A.-M. 2010. Responses of phytoplankton upon exposure to a mixture of acid mine drainage and high levels of nutrient pollution in Lake Loskop, South Africa. *Ecotoxicology and Environmental Safety*, 73: 326-335.

Olness, A. 1995. Water quality: prevention, identification and management of diffuse pollution. *Journal of Environmental Quality*, 24 (2): 383-383.

Oston, R., Williams, D. T. and Bothwell, P. D. 1981. Comparison of the trihalomethane levels and other water quality parameters for three treatment plants on the Ottawa River. *Environmental Science Technology*, 15 (1075)

Ott, W. R. 1978. *Environmental Indices Theory and Practice* Michigan: Ann Arbor Science

Oyoo, R. n.d. Deteriorating Water Quality in the Lake Victoria Inner Murchison Bay and its impact on the drinking water supply for Kampala, Uganda.

Palani, S., Liong, S. and Tkalich, P. 2008. An ANN application for water quality forecasting. *Marine Pollution Bulletin*, 56: 1586-1597.

Parmar, K. and Parmar, V. 2010. Evaluation of water quality index for drinking purposes of river Subernarekha in Singhbhum District. *international Journal of Environmental Science*, 1 (1): 77-81.

Parsons, S. A. and Jefferson, B. 2006. Introduction to Potable Water Treatment Processes. Cranfield University.

Payment, P. 1999. Poor efficacy of residual chlorine disinfectant in drinking water to inactivate waterborne pathogens in distribution systems. *Canadian journal of Microbiology*, 45 (8): 709-715.

Payment, P., Waite, M. and Dufour, A. 2003. Introducing parameters for the assessment of drinking water quality. *Assessing Microbial Safety of Drinking Water*: 47.

Pernitsky, D. J. and Eng, P. 2003. Coagulation 101. In: Proceedings of *P:\ OFFICE\ Conferences\ 2003TechTrans\ Dave P\ DAVE_paper. doc (consulted 25/07/05)*.

Pesce, S. F. and Wunderlin, D. A. 2000. Use of water quality indices to verify the impact of Córdoba City (Argentina) on Suquía River. *Water Research*, 34 (11): 2915-2926.

Pourbaix, M. 1974. *Atlas of electrochemical equilibria in aqueous solutions*. Houston: National Association of Corrosion Engineers.

Prakirake, C., Chaiprasert, P. and Tripetchkul, S. 2009. Development Of Specific Water Quality Index For Water Quality Supply In Thailand. *Songklanakarian Journal of Science and Technology*, 31 (1): 91-104.

Pretty, J. N., Mason, C. F., Nedwell, D. B. and Hine, R. E. 2002. *A Preliminary Assessment of the Environmental Costs of Fresh Waters in England and Wales*.

Pryor, M., Naidoo, P., Bahrs, P. and Freese, S. 2002. Ozone experiences at Umgeni Water. Paper presented at the *Biennial Conference of the Water Institute of Southern Africa (WISA)*. Durban, South Africa, Water Research Commission,

Raw Water Quality. 2006. In: *Audit of the Sydney Drinking Water Catchment 2005*.

Reckhow, K. D., Kepford, K. and Hicks, W. W. 1993. *Methods for the Analysis of Lake Water Quality Trends*.

Recknagel, F., Bobbin, J., Whigham, P. and Wilson, H. 2002. Comparative application of artificial neural networks and genetic algorithms for multivariate time-series modelling of algal blooms in freshwater lakes. *Journal of Hydroinformatics*, 4 (2): 125-134.

Richardson, A. M. 1997. Development of an estuarine water quality index (eWQI) for New South Wales. Dissertation, University of Sydney.

Rietveld, L. C., Haarhof, J. and Jagals, J. 2009. A tool for technical assessment of rural water supply systems in South Africa. *Physics and Chemistry of the Earth*, 34: 43-49.

Roos, J., Hassan, F. and Coleman, T. 2009. *Water Reconciliation Strategy Study of the Kwazulu Natal Coastal Metropplitan Areas. Water Quality Review Report*. Department of Water Affairs and Forestry (DWAF).

Rousseeuw, P. J. and Leroy, A. M. 1987. *Robust Regression and Outlier Detection*. New York: John Wiley & Sons.

Rowntree, D. and O'Hehir, R. 1981. *Statistics without tears: A primer for non-mathematicians*. Penguin Har-mondsworth.

Said, A., Stevens, D. K. and Sehlke, G. 2004. An innovative index for evaluating water quality in streams. *Environmental Management*, 34 (3): 406-414.

Sánchez, E., Colmenarejo, M. F., Vicente, J., Rubio, A., García, M. G., Travieso, L. and Borja, R. 2007. Use of the water quality index and dissolved oxygen deficit as simple indicators of watersheds pollution. *Ecological Indicators*, 7 (2): 315-328.

Sanford, R. F., Pierson, C. T. and Crovelli, R. A. 1993. An objective replacement method for censored geochemical data. *Math Geol*, 25: 59-80.

Sauer, P. and Kimber, A. 2002. *Energy Consumption and Costs to Treat Water and Wastewater in Iowa*. Report to the Iowa Association of Municipal Utilities (IAMU). Available: http://www.iamu.org/main/studies_reports/reports/WWWPartI/part%20I%20Energy%20and%20costs%20Treat%20(Cover%20-Pg%206).pdf (Accessed 13 November 2012).

Scarpino, P. V., Berg, G., Chang, S. L., Dahling, D. and Lucas, M. 1972. A comparative study of the inactivation of viruses in water by chlorine. *Water Research*, 9 (959)

Scheibe, O. K. and Konasewich, D. E. 1981. *Ultraviolet Disinfection in a Secondary Wastewater Treatment Plant Effluent*. Ohio: U. S. EPA,.

Schertz, T. L., Alexander, R. B. and Ohe, D. J. 1991. *The computer program estimate trend (estrend), a system for the detection of trends in water-quality data*. Reston, Virginia: U.S. Geological Survey, Water-Resources Investigations.

Schutte, F. 2007. *Handbook for the Operation of Water Treatment Works* Pretoria: Water Research Commission.

Sengul, A. B. and Gormez, Z. 2013. Prediction of Optimal Coagulant Dosage in Drinking Water Treatment by Artificial Neural Network. In: Proceedings of *1st EWaS-MED International Conference, "Improving Efficiency of Water Systems in a Changing natural and financial Environment",* . Greece,

Silva-Ramírez, E.-L., Pino-Mejías, R., López-Coello, M. and Cubiles-de-la-Vega, M.-D. 2011. Missing value imputation on missing completely at random data using multilayer perceptrons. *Neural Networks*, 24 (1): 121-129.

Simpson, D. and Dickens, C. 2006. *Potential water quality impacts on Midmar Dam from the proposed Khayelisha social housing project* Gauteng, South Africa: Institute of Natural Resources.

Singh, K. P., Malik, A. and Sinha, S. 2005. Water quality assessment and apportionment of pollution sources of Gomti river (India) using multivariate statistical techniques—a case study. *Analytica Chimica Acta*, 538 (1–2): 355-374.

Singkran, N. and Sudara, S. 2005. Effects of changing environments of mangrove creeks on fish communities at Trat Bay, Thailand. *Environmental Management*, 35 (1): 45-55.

Smith, D. G. 1990. A better water quality indexing system for rivers and streams. *Water Research*, 24 (10): 1237-1244.

Snyman, H. G., Van Niekerk, A. M. and Rajasakran, N. 2006. Sustainable wastewater treatment – What has gone wrong and how do we get back on track. In: Proceedings of *Water Institute of South Africa (WISA) Conference,* . Durban, 21-25 May 2006.

Sonzogni, W., Chapra, S., Armstrong, D. and Logan, T. 1982. Bioavailability of phosphorus inputs to lakes. *Journal of Environmental Quality*, 11 (4): 555-563.

South Africa. South Africa Bureau of Standards. 2006. *South African National Standard 241:2006*. Pretoria: South Africa Beareau of Standards.

South Africa. South African Bureau of Standards. 2011. *South Africa National Standard 241:2011*. Pretoria: South African Bureau of Standards

South Africa. Statistics South Africa. 2012. *South African Statistic 2012*. Pretoria, South Africa: Statistics South Africa.

South Africa. Statistics South Africa. 2013. *Mid year population estimates 2013*. Pretoria, South Africa: Statistics South Africa.

Ssali, G. and Marwala, T. n.d. Estimation of Missing Data Using Computational Intelligence and Decision Trees.

Staff, W. H. O. 1997. *Guidelines for drinking-water quality: Surveillance and control of community supplies*. World Health Organization.

Stambuk-Gijanovic, N. 1999. Water quality evaluation by index in Dalmatia. *Water Research*, 33 (16): 3423-3440.

Steynberg, M. C., Guglielmi, M. M., Geldenhuys, J. C. and Pieterse, A. J. H. 1996. Chlorine and chlorine dioxide; pre-oxidants used as algaecide in potable water plants. *Journal Water SRT-Aqua*, 45 (4): 162-170.

Steel, A., Clarke, M. and Whitfield, P. 1996. Use and Reporting of Monitoring Data. In: Bartram, J. and Ballance, R. eds. *Water Quality Monitoring - A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes*. United Nations Environment Programme and the World Health Organization.

Stoimenova, E., Mateev, P. and Dobreva, M. 2006. Outlier detection as a method for knowledge extraction from digital resources. *Review of the National Center for Digitization*, 9: 1-11.

Swamee, P. K. and Tyagi, A. 2000. Describing water quality with aggregate index. *Journal of Environmental Engineering*, 126: 451-455.

Swatuk, L. A. 2005. Political challenges to implementing IWRM in Southern Africa. *Physics and Chemistry of the Earth*, 30: 872-880.

Sweeney, B. W. and Vannote, R. L. 1981. Ephemerella mayflies of White Clay Creek: bioenergetic and ecological relationships among six coexisting species. *Ecology*: 1353-1369.

Tasić, S. and Feruh, M. B. 2012. Errors and Issues in Secondary Data used in marketing research. *The Scientific Journal for Theory and Practice of Socioeconomic Development*, 1 (2)

Taylor, J. S., Dietz, J. D., Hong, S. K., Mulford, L. A. and Randal, A. A. 2001. Required Treatment and Water quality criteria for distribution system blending of treated surface, ground and saline sources. University of Florida. Orlando.

Telesnicki, G. J. and Goldberg, W. M. 1995. Effects of Turbidiy on the Photosynthesis and Respiration of Two South Florida Reef Coral Species. *Bulletin of Marine Science*, 57 (12): 527-539.

Tiba, F. and Hodgson, K. 2008. Development of Resource Water Quality Objectives for Potable water treatment at Umgeni Water. Paper presented at the *WISA*. Sun City, South Africa, Water Institute of South Africa,

Townsend, C. R., Hildrew, A. G. and Francis, J. 1983. Community structure in some southern English streams: the influence of physicochemical factors. *Freshwater Biology*, 13 (6): 521-544.

Umgeni Water. 2012a. *The Umgeni Annual report 2011/2012*. Pietermaritzburg:

Umgeni Water. 2012b. *Umgeni Water Infrastructure Master Plan 2012 (2012/2013-2042-2043)*. Pietremarizburg, South Africa: Umgeni Water (UW).

Umgeni Water. 2012c. *Umgeni Water Policy Statement and Five-Year Business Plan. Volume 2: Business Plan . 2012/13 to 2016/17*. Pietermarizburg: Umgeni Water.

Umgeni Water. 2014. *Dam and Rainfall* 2014. Available: http://www.umgeni.co.za/media_centre/drd.asp (Accessed

UN. 2007. *Coping with water scarcity. Challenge of the twenty-first century*. Food and Agriculture Organisation.

UNECE. 1994. *Standard Statistical Classification of Surface Freshwater Quality for the Maintenance of Aquatic Life.* New York, Geneva: United Nations Economic Commission for Europe (UNECE).

UNEP and GEMS. 2007. *Global Drinking Water Quality Index Development and Sensitivity Analysis Report*. Canada: United Nations Environment Programme Global Environment Monitoring System /Water Programme. Available: http://www.gemswater.org (Accessed 20 June 2013).

UNICEF. 2012. *Progress on Sanitation and Drinking-Water: 2012 Update*. New York: UNICEF.

United States Environmental Protection Agency. 2003. *Water on Tap: what you need to know*. DIANE Publishing.

United States Environmental Protection Agency. n.d. *Water: Monitoring and Assessment.Nitrates*. Available: http://water.epa.gov/type/rsl/monitoring/vms57.cfm (Accessed 16 September 2012).

USEPA. and Department of Ecology: 2011. *Technical Guidance for Exploring TMDL Effectiveness Monitoring Data*.

UNNWWAP. 2003. *The World Water Development Report 1: Water for people, Water for Life*. Paris, France: UNESCO.

UNWWAP. n.d. *Water and Industry*. Available: http:/www.unesco.org/water/wwap/facts_figures/water_industry.shtml (Accessed 13 October 2013).

United State Environmental Protection Agency. 1976. *Quality criteria for water. Office of Water Planning and Standards*. Washington D.C.: United States Environmental Protection Agency.

Valentin, N., Denoeux, T. and Fotoohi, F. n.d. Modelling of Coagulant dosage in a water treatment plant.

Van Benschoten, J. E. and Edzwald, J. K. 1990a. Chemical aspects of coagulation using aluminum salts - I. Hydrolytic reactions of alum and polyaluminum chloride. *Water Research*, 24 (12): 1519-1526.

Van Benschoten, J. E. and Edzwald, J. K. 1990b. Chemical aspects of coagulation using aluminum salts - II. Coagulation of fulvic acid using alum and polyaluminum chloride. *Water Research*, 24 (12): 1527-1535.

Van Duuren, F. 1998. Water purification works design. *SA Waterbulletin*, 24

Veenstra, J. N. and Schnoor, J. L. 1980. Seasonal-Variations in Trihalomethane Levels in an Iowa River Water-Supply. *Journal American Water Works Association*, 72 (10): 583.

Voortman, W. J. and Reddy, C. D. 1997. *Package Water Treatment Plant Selection,* . South Africa: WRC.

Walmsely, R. D. 2000. *Perspectives on eutrophication of surface water: Policy Research needs in South Africa.* Pretoria, South Africa: Water Research Comission.

Walmsely, R. D. 2003. *Project 1: Phase 1. Development of a strategy to control eutrophication in South Africa. A review and discussion document. Water Quality Management Series.* Pretoria, South Africa: Department of Water Affairs and Forestry.

Walmsely, R. D. and Butty, M. 1980. *Limnology of some selected South African impoundments*. Water Research Commission ,
National Institute for Water Research Council for Scientific and Industrial Research.

Walsh, C. J., Sharpe, A. K., Breen, P. F. and Sonneman, J. A. 2001. Effects of urbanization on streams of the Melbourne region, Victoria, Australia. I. Benthic macroinvertebrate communities. *Freshwater Biology*, 46 (4): 535-551.

Walsh, P. and Wheeler, W. 2012. Water Quality Index Aggregation and Cost Benefit Analysis. National Center for Environmental Economics. Wshington. Available: http://www.epa.gov/economics (Accessed 16 October 2013).

Walski, T. M. and Parker, F. L. 1974. Consumers Water Quality Index. *Journal of the Environmental Engineering Division,*, 27 (593-611)

Ward, R. C., Loftis, J. C. and McBride, G. B. 1986. The “data-rich but information-poor” syndrome in water quality monitoring. *Environmental Management*, 10 (3): 291-297.

Waston, I. M., Robinson, J. O., Burke, V. and Grace, M. 1985. Invasive of Aeromonas spp. In relation to biotype virulence factors and clinical features. *J. Clin. Microbiol*, 22 (1): 48-51.

Water, U. 2011. *Umgeni Water Infrastructure Master Plan 2011*. Pietermaritzburg: Available: http://www.umgeni.co.za/projects/infra-structuremasterplans/docs/IMP_2011_Vol1.pdf (Accessed 23 September 2013).

Wepener, V., Cyrus, D. P., Vermeulen, L. A., O`Brien, G. C. and Wade, P. Commission, W. R. 2006. *Development of a Water Quality Index for Estuarine Water Quality Management in South Africa*.(Notice 1163/1/06). Pretoria

Wepener, V., Euler, N., Van Vuren, J. H. J., Du Preez, H. H. and Kohler, A. 1992. The development of an aquatic toxicity index as a tool in the operational management of water quality in the Olifants River (Kruger National Park). *Koedoe*, 35 (2): 1-9.

White, G. C. 1968. Chlorination and dechlorination: a scientific and practical approach. *J. Am. Water Works Assoc.,*, 60 (540)

White, G. C. 1992. *The Handbook of Chlorination and Alternative Disinfectants*. Van Nostrand Reinhold.

WHO. 2003a. *Assessing Microbial Safety of Drinking Water Improving Approaches and Methods: Improving Approaches and Methods*. OECD Publishing.

WHO. 2003b. Relationships between common water bacteria and pathogens in drinking-water. In: Bartram, J., Cotruvo, J., Exner, M., Fricker, C. and Glasmacher, A. eds. *Heterotrophic Plate Counts and Drinking-water Safety*. London, UK: IWA Publishing.

WHO. 2004. *Guidelines for Drinking Water quality*. Geneva: World Health Organisation.

WHO. 2006a. *Guidelines for Drinking –Water Quality. seconded, Health Criteria and Other Supporting Information*. Geneva, Switzerland: World Helath Organisation.

WHO. 2006b. *Guidelines for drinking water quality: first addendum to third edition*. Geneva: World Health Organisation.

WHO. 2007. *Global task force on cholera control. Cholera country profile: Angola.* Available: http://www.who.int/cholera/countries/Angola%20country%20profile%202007.pdf (Accessed 3 September 2009).

WHO. 2011. *Guidelines for drinking-water quality*. WHP Press: World Health Organisation.

WHO and UNICEF. 2012. *Progress on Drinking Water and Sanitation 2012 update*. United States of America: UNICEF and World Health Organisation

Widrig, D. L., Gray, K. A. and McAuliffe, K. S. 1996. Removal of algal-derived organic material by preozonation and coagulation: monitoring changes in organic quality by pyrolysis-GC-MS. *Water research*, 30 (11): 2621-2632.

Wilson, A. J. 2001. *Mvoti to Mzimkulu Water Management Area Situational Assessment* South Africa: A.J. Wilson & Associates International cc.

Wyk, V. F. 2001. An integrated manual for the management, control and protection of the Vaal River barrage reservoir. Magister Scientae, Rand Afrikaans University.

Ye, C., Wang, D. S., Shi, B., Yu, J. F., Qu, J., Edwards, M. and Tang, H. 2007. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 294 (1-3): 163-117.

Yiasoumi, W., Evans, L. and Rogers, L. 2005. Farm water quality and treatment. *Agfact*,

Yip, R. W. and Konasewich, D. E. 1972. Ultraviolet Sterilasation of water-Its potential and Limitations. *Water and Pollution Control*, 110 (6)

Yisa, J. and Jimoh, T. 2010. Analytical Studies on Water Quality Index of River Landzu. *American Journal of Applied Sciences*, 7 (4)

Zetland, D. 2011. Global water tarrifs continue upward trend. 12(9). Available: http://www.globalwaterintel.com/archive/11/9/market-insight/water-tariffs-continue-upward-momentum.html

APPENDICES

Appendix A: Summary of sampling procedure by Umgeni Water

Appendix A and B provides an overview for the sampling procedure done by Umgeni Water. The aim is to assist in evaluating the validity of the characteristic (e.g. outliers and censored values) observed in the data-sets obtained for this study.

Sampling was done in accordance with the South Africa's water sampling guidelines (Department of Water Affairs and Forestry 2000, 2001). These guidelines outline how water samples are required to be collected, handled, preserved, transported, and tested.

Before sampling, containers for microbial and operational parameters samples were thoroughly scrubbed, rinsed with tap water and de-ionised. All sampling containers were labelled to inform the name of the determinand, sampling date and station as stipulated in the South Africa's sampling guide (Department of Water Affairs and Forestry 2000). Samples for microbial analysis were collected in a 500ml sterilised glass bottle that was thoroughly sterilised before sampling. Samples for metal analysis were collected in a 500 ml polyethylene bottle containing nitric acid to stabilise the sample. Just like for microbial analysis, samples for physico-chemical analysis (e.g. turbidity, BOD, etc.) were also collected in a 500 ml polythene bottle

Thereafter, samples were transported in a cooler bag containing ice cubes to the main Umgeni Water's laboratory in Pietermaritzburg for analysis. Analysis was done within 24 hours in order to reduce bias that may arise due to biochemical reactions in the sample. Temperature and pH were however measured in-situ as they rapidly change (Department of Water Affairs and Forestry 2000). Methods and instruments used for monitoring the major parameters are outlined in appendix B

Appendix B. Determinants monitored and their methods of analysis

Determinand	**Abbreviation**	**Unit**	**Test instrument**	**Method**	**SANS**
pH	pH		PH meter		SANS 5011
Electrical conductivity	EC	microsiemens	Conductivity Meter		SANS7888
Temperature	Temp	^{0}c	thermometer		
Escherichia .coli	*E. coli*	per 100ml		Seven-Hour Fecal Coliform Test	SANS9308
Total algae count	algae	cellcount/100ml			
Turbidity	Turb	Nephelometer Turbidity Units (NTU)	turbid meter	Nephelometric Method	SANS375
Nitrates	NO_3	mg/L		Colorimetric Method	SANS5210
Dissolved oxygen	DO	% saturation		Iodometric	
Ammonia	NH_3	mg/L			SANS5217
Total Phosphorus	TP	mg/L		Colorimetric Method	
Magnesium	Mg	mg/L			

ug = microgram or ppb
mg= milligram or ppm

Appendix C and D below provides the summary of the raw and treated water quality status at the two treatment plants studied. Nagle and Inanda Dam Outflow station were used to give a reflection of the raw water being abstracted at the two treatment plants.

The blue cell shows the mean of the treated water and limits for drinking water as stipulated in SANS 241:2011. The orange cell shows parameters whose mean exceeded the limits set stipulated in the SANS 241: 2011. In addition, the table also summaries the dosage of polymer, chlorine and lime.

Appendix C. Summary of water quality at Durban Heights and Wiggins WTP

STATISTICAL SUMMARY OF DURBAN HEIGHTS WATER TREATMENT PLANT									
	Raw water							Potable water	
	Unit	Valid	Mean	Median	SD	Min	Max	Mean	DWAF limit
Polymer	mg/ℓ	92	3.93	3.60	1.06	2.25	6.89		
Lime	mg/ ℓ	92	4.89	4.82	1.37	2.00	8.20		
Chlorine	mg/ℓ	92	3.89	3.86	.98	0.94	10.23		
Alk	mg/ℓ	82	32.53	31.64	5.86	23.28	67.90	36.41	
Ca	mg/ℓ	82	6.59	6.18	2.11	4.76	20.60	9.58	<32
Chloride	mg/ℓ	83	8.71	8.15	2.01	3.67	14.70	15.45	<300
EC	mg/ℓ	92	10.64	10.24	1.71	8.43	20.31	13.74	<170
DO	mg/ℓ	92	8.66	8.60	.83	6.60	11.10		
E. coli	mg/ℓ	92	199.34	100.00	461.35	7.50	3972.00	0	0
F	ug/ℓ	83.	79.41	75.00	14.15	75.00	156.00	82.45	<1.7
K	mg/ℓ	82.	1.92	1.86	.48	.63	4.22	2.01	50
Mg	mg/ℓ	82.	4.13	3.98	.71	3.12	7.41	4.29	<30
Na	mg/ℓ	82.	8.50	7.53	4.85	5.55	47.30	10.67	<100
NH_3	mg/ℓ	92	0.79	.08	1.25	.01	3.00	0.010	<1.5
NO_3	mg/ℓ	92	0.29	.25	.17	.10	1.52	0.33	<11
pH		92	7.91	7.90	.34	7.20	9.00	7.85	Lower 5 Upper 9.7
Si	mg/ℓ	84	3.57	3.54	1.03	.08	5.61		
SO_4	mg/ℓ	83	3.67	3.40	2.10	.78	20.97	5.39	
SS	mg/ℓ	91	14.89	13.60	7.96	3.00	55.20	3.12	
Temp	^{0}C	92	19.83	19.75	4.31	12.10	28.00	21.19	21.098
TOC	mg/ℓ	91	2.89	2.83	.81	.53	7.30	2.27	<10
TP	ug/ℓ	76	47.72	37.95	36.12	11.25	265.40		
Turb	NTU	91	16.24	14.20	7.46	4.91	41.70	0.16	<1 operation <5 aesthetic
Algae	mg/ℓ	96	7055.89	1155.59	18156.64	124.67	98224.40	1.07	<0.8

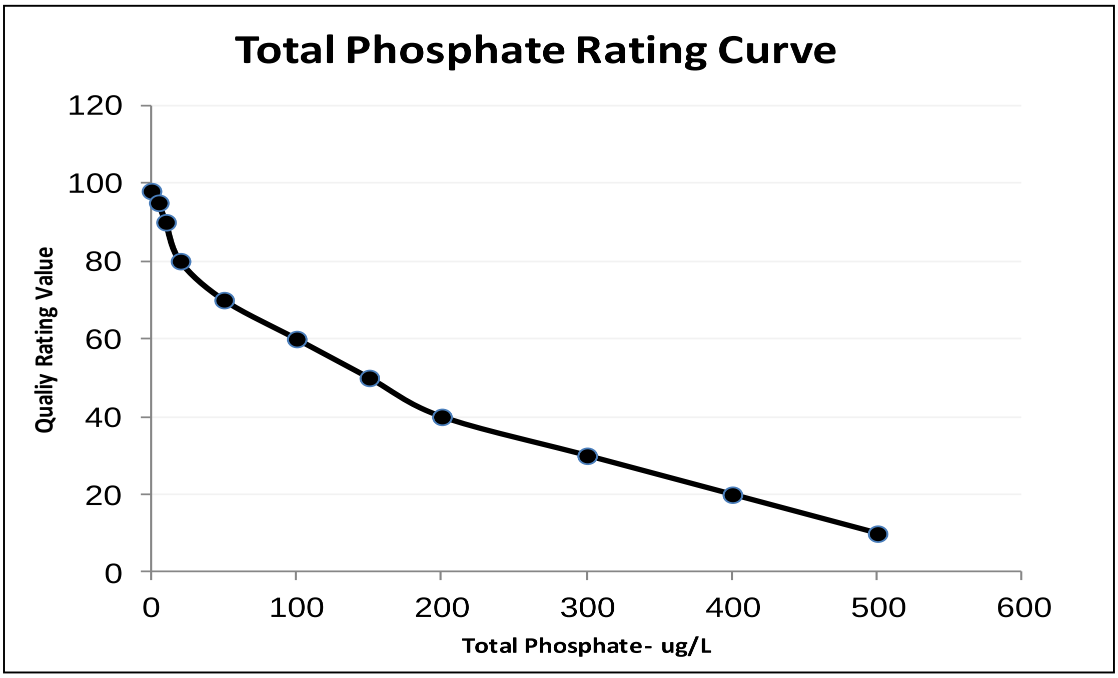
Appendix D: Descriptive statistic of Wiggins Water Treatment Plant

STATISTICAL SUMMARY OF WIGGINS WATER TREATMENT PLANT									
	Raw water							**Potable water**	
		Valid	Mean	Median	SD	Min	Max	Mean	DWAF Limit
Chlorine	mg/ℓ	62	1.41	1.41	0.42	0.58	2.91		
Lime	mg/ℓ	62	1.37	1.26	0.95	0.06	3.79		
Polymer	mg/ℓ	62	2.63	2.17	1.58	0.53	7.47		
Alkal	mg/ℓ	88	62.66	62.86	7.38	44.80	83.50	59.31	
Ca	mg/ℓ	90	13.87	14.09	1.66	9.10	20.60	14.06	<32
Chloride	mg/ℓ	90	29.91	30.70	3.77	17.20	36.40	31.36	<300
EC	mg/ℓ	96	26.21	26.40	3.92	17.83	52.95	25.94	<170
DO	mg/ℓ	96	8.46	8.50	0.88	6.20	11.10		
E. coli	count/ 100m ℓ	96	98.31	28.00	493.0 2	0.00	4838. 00	0	0
F	mg/ℓ	90	1.54	163.00	47.92	60.50	311.0 0	149.29	<1.7
K	mg/ℓ	90	3.97	3.00	5.36	2.21	45.33	21.0889	
Mg	mg/ℓ	90	7.30	6.74	3.46	4.94	30.16	6.42	<30
Na	mg/ℓ	90	27.70	28.75	4.62	14.98	36.90	27.70	<100
NH_3	mg/ℓ	96	0.10	0.08	.11	0.19	.60	0.04	<1.5
NO_3	mg/ℓ	96	0.34	.39	1.74	1.36	4.33	0.45	<11
pH	mg/ℓ	96	7.86	7.88	.35	7.00	8.80		Lower 5 Upper 9.7
Si	mg/ℓ	96	3.22	3.32	1.34	0.75	8.21		
SO_4	mg/ℓ	90	15.05	14.85	3.04	6.49	21.80	15.11	<200 aesthetic <500acute
SS	mg/ℓ	96	4.66	3.00	2.51	3.00	16.40	3.12	
Temp	^{o}C	96	20.37	20.40	3.65	12.00	28.80	21.0889	
TOC	mg/ℓ	96	2.98	2.91	.87	.53		<10	
TP	ug/ℓ	96	37.65	22.59	74.31	11.25			
Turb	NTU	96	2.71	2.06	1.92	1.04	12.40	0.23	<1 <5aesthatic
Algae	mg/ℓ	96	4499. 08	1998.7 5	6833. 39	105.7 5	36352 .33	6.20	<0.8

Rating Curves and equations for the River Health Water Quality Index

The graphs below, appendix E to L provides the normalising tables, rating curves, rating equation and the “IF” statement for automatic River Health Water Quality Index (RHWQI) calculation in Microsoft Excel.

Appendix E: Rating curve and normalising table for Total Phosphate



Rating equations for TP derived from the rating curve

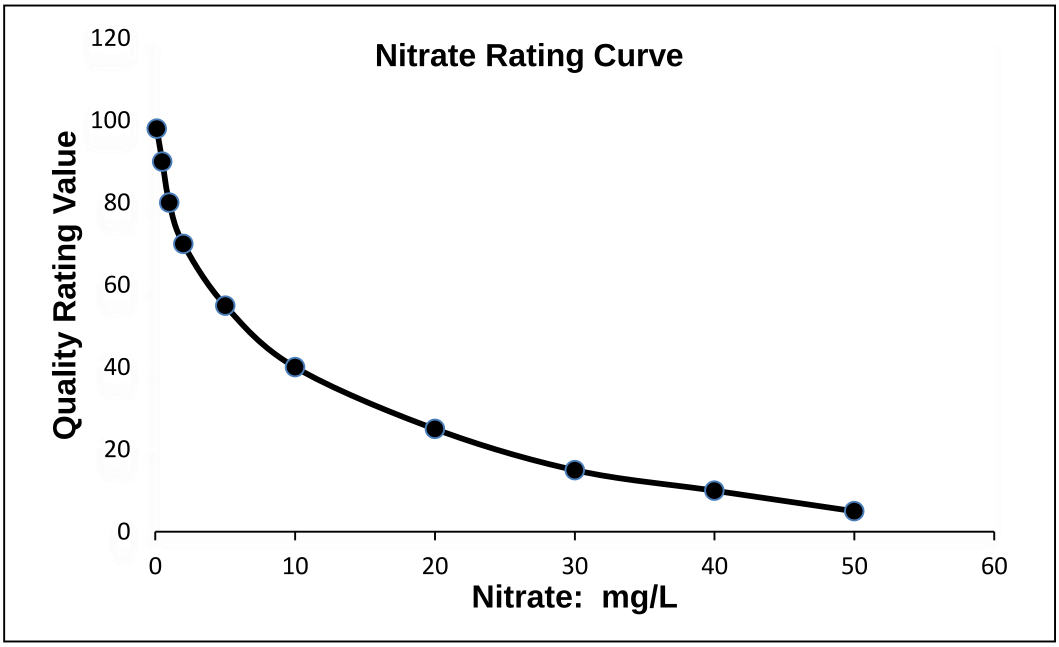
Range	Rating Equation
0-20	$y = 0.002x^3 - 0.07x^3 - 0.3x + 98$
20-200	$y = -5E{-}06x^3 + 0.0019x^2 - 0.4204x + 87.477$
200-500	$y = 1E{-}19x^3 - 8E{-}17x\ 2 - 0.1x + 60$
x>500	$y = 5$

Where X is the value of TP

“IF”_ Statement in computing the Q Value in Microsoft Excel

=IF(TP="","NM",IF(TP<0,"ERR",IF(TP<20,0.002*TP^3-0.07*TP^2 0.3*TP+98,IF(TP<200,-0.000005*TP^3+0.0019*TP^2-0.4204*TP +87.477, IF(TP<500,0.0000000000000000001*TP^3-0.00000000000000008*TP^2-0.1*TP+60,IF(TP>500,5))))

Appendix F: Rating curve and normalising table for nitrate



Rating equations for NO_3 developed from the rating curve

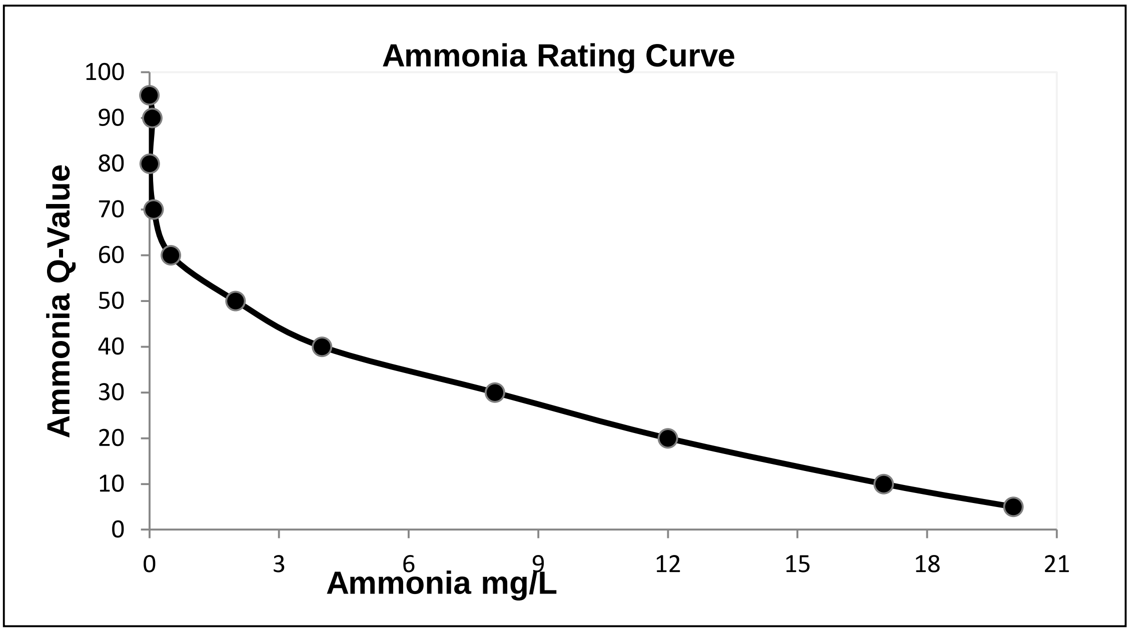
Range	Equation
0.1 - 1	$y = -20x + 100$
1—5	$y = -15.58\ln(x) + 80.289$
5--20	$y = -21.64\ln(x) + 89.829$
20 - 50	$y = -0.0008x^3 + 0.1x^2 - 4.4167x + 80$

Where X is the value of NO_3

"IF"_ Statement for computing nitrate Q-Value in Microsoft Excel

=IF(NO3="","NM",IF(NO3<0,"ERR",IF(NO3<1,-20*NO3+100,IF(NO3<5, 15.58*LN(NO3) +80.289,IF(NO3<5,-21.64*LN(NO3)+89.829,IF(NO3<50,-0.0008*NO3^3+0.1*NO3^2-4.4167*NO3+80,IF(NO3>50,1)))))))

Appendix G: Rating curve and normalising table for ammonia



Rating equations for NH_3 derived from the rating curves

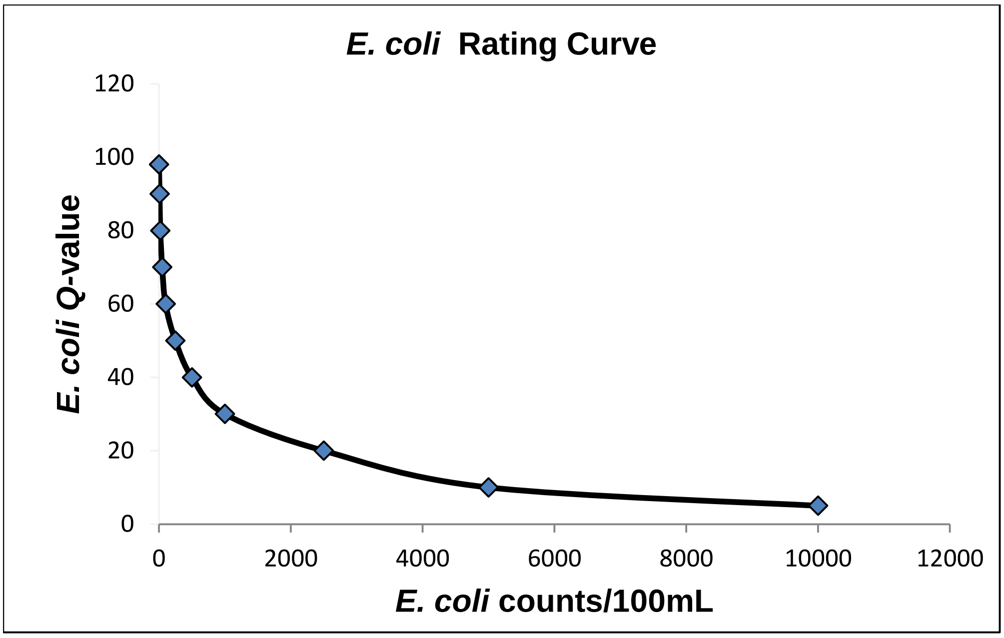
Range	Rating Curve
0.005 - 0.1	$y = -373545x^3 + 57979x^2 - 2342.4x + 98$
0.1 - 2	$y = -6.664\ln(x) + 54.885$
2 – 8	$y = -14.43\ln(x) + 60$
8 – 20	$y = -0.0012x^3 + 0.0984x^2 - 4.1157x + 57.222$

Where X is the value of NH_3

IF_ Statement for computing ammonia Q Value in Microsoft Excel

=IF(NH3="","NM",IF(NH3<0,"ERR",IF(NH3<0.1, -373545*NH3^3 +57979*NH3^2-2342.4*NH3+98,IF(NH3<2, -6.664*LN(NH3)+54.885, IF(NH3<8, -14.43*LN(NH3)+60,IF(NH3<20, -0.0012*NH3^3 + 0.0984*NH3^2 -4.1157*NH3 + 57.222,IF(NH3>20,5)))))))

Appendix H: Rating curve and normalising table for *Escherichia* coli



Rating equations for *E. coli* derived from the rating curves

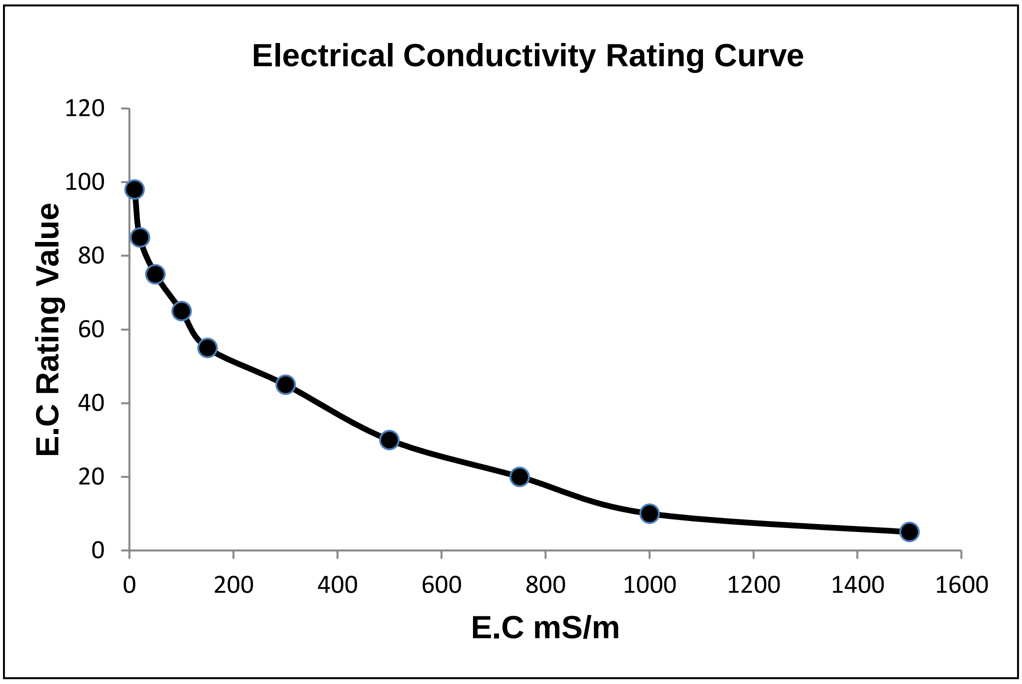
0 – 20	$y = -0.01x^2 - 0.7x + 98$
20 – 100	$y = -12.35\ln(x) + 117.39$
100 – 500	$y = 7E\text{-}05x^2 - 0.09x + 68.333$
500 - 2500	$y = 585.99x^{-0.431}$
2500 – 10 000	$y = 4E\text{-}07x^2 - 0.007x + 35$

Where X is the value of *E. coli*

IF_ Statement for computing *E. coli* in Microsoft Excel

=IF(*E. coli*="","NM",IF(*E. coli*<0,"ERR",IF(*E. coli* <20, -0.01* *E. coli*^2 - 0.7* *E. coli* + 98,IF(*E. coli* <100, -12.35*LN(*E. coli*) + 117.39,IF(*E. coli*<500,0.00007* *E. coli*^2-0.09* *E. coli*+68.333,IF(*E. coli* <2500, 585.99* *E. coli* ^(-0.431), IF(*E. coli*<10000,0.0000004* *E. coli*^2-0.007* *E. coli*+35,IF(*E. coli*>10000, 5))))))))

Appendix I: Rating curve and normalising table for Electrical Conductivity



Rating equations derived from conductivity's rating curve

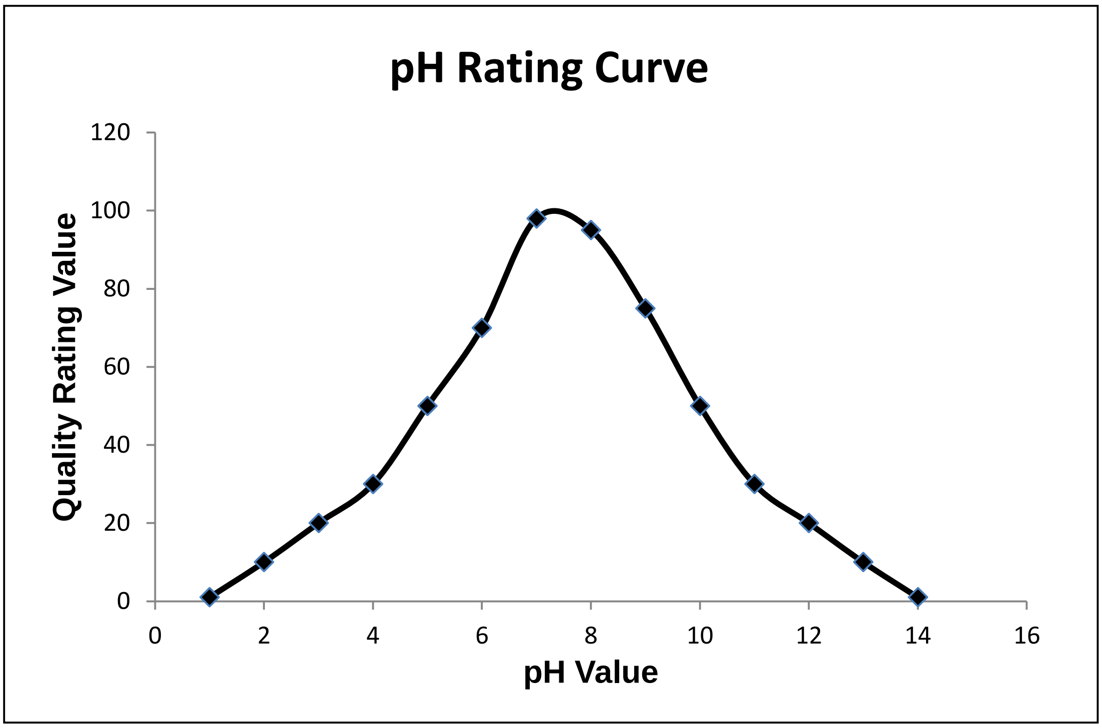
RANGE	RATING EQUATION
10 - 50	$y = 0.0242x^{2} - 2.025x + 115.83$
50 - 150	$y = 6E\text{-}17X^{2} - 0.2X + 85$
150 - 500	$y = -2E\text{-}05X^{2} - 0.056X + 63.929$
500 - 750	$y = -24.66\ln(X) + 183.27$
750 - 1500	$y = 9E+06X^{-1.981}$

Where X is the value of conductivity

"IF"_ Statement for conductivity Q-Value in Microsoft Excel

IF(EC="","NM",IF(EC<0,"ERR",IF(EC<10,98,IF(EC<50,0.024*EC^2-2.0242*EC+115.83,IF(EC<150,0.00000000000000006*EC^2-0.2*EC+85,IF(EC<500,-0.00002*EC^2-0.056*EC+63.929,IF(EC<750,-24.66*LN(EC)+183.27,IF(EC<1500,0.000009*EC^-1.981,IF(EC>1500,5)))))))))

Appendix J: Rating curve and normalising table for pH



Rating equations derived from pH's rating curve

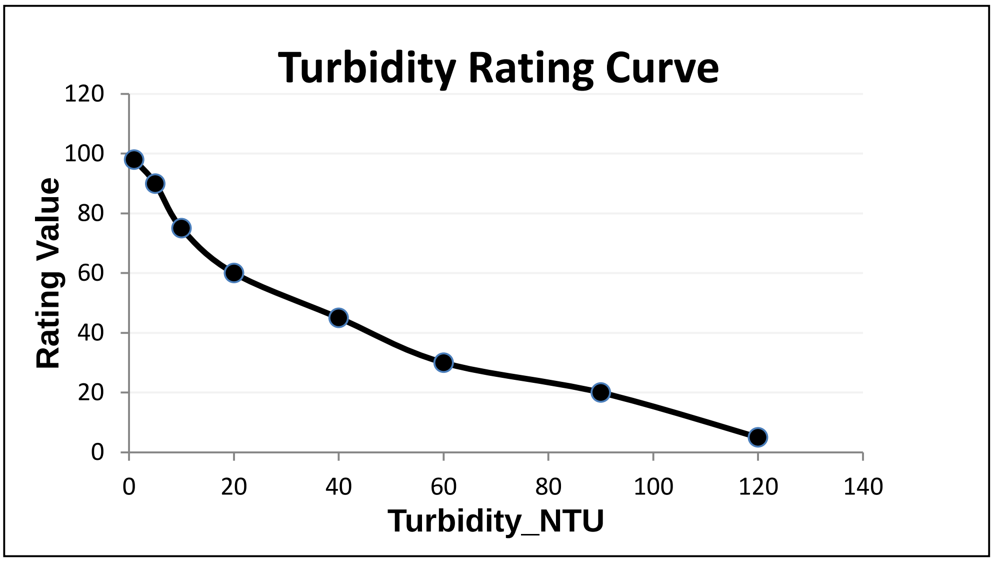
Range	Rating Equation
1 – 4	$y = -0.1667X^3 + 1.5X^2 + 5.6667X - 6$
4 - 6	$y = 6E\text{-}14X^2 + 20X - 50$
6 - 9	$y = 2.3333X^3 - 64.5X^2 + 570.17X - 1533$
9 - 11	$y = 2.5X^2 - 72.5X + 525$
11 - 14	$y = 0.1667X^3 - 6X^2 + 61.833X - 146$

Where X is the value of pH

IF_ Statement for computing the Q Value in Microsoft Excel

=IF(pH="","NM",IF(pH<1,"ERR", IF(pH<4, -0.1667*pH^3 + 1.5*pH^2 + 5.6667*pH - 6,IF(pH<6, 0.00000000000006*pH^2 + 20*pH - 50,IF(pH<9, 2.3333*pH^3 - 64.5*pH^2 + 570.17*pH -1533,IF(pH<11, 2.5*pH^2 -72.5*pH + 525,IF(pH<=14, 0.1667*pH^3 - 6*pH^2 + 61.833*pH - 146, IF(pH>14,"ERR")))

Appendix K: Rating curve and equations turbidity



Rating table and curve for turbidity

Rating equations derived from turbidity's rating curve

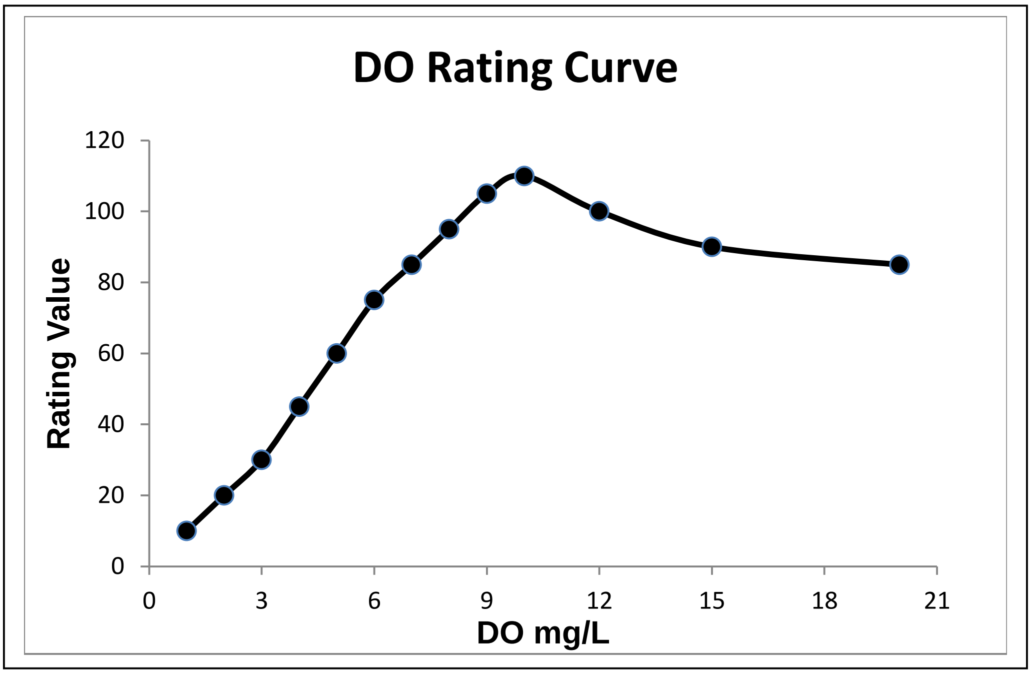
Range	Rating Equation
1 - 10	$y = -0.1111X^2 - 1.3333X + 99.444$
10 – 40	$y = -21.64\ln(X) + 124.83$
40 -60	$y = -36.99\ln(X) + 181.47$
60 - 120	$y = -0.0028X^2 + 0.0833X + 35$

Where X is the value of Turbidity

"IF"_ Statement for computing turbidity Q-value in Microsoft Excel

=IF(Turbidity="","NM",IF(Turbidity<0,"ERR",IF(Turbidity <10, -0.1111* Turbidity^2 - 1.3333*Turbidity+99.444,IF(Turbidity<40,-21.64*LN(Turbidity)+ 124.83,IF(Turbidity <60,-36.99*LN(Turbidity)+181.47,IF(Turbidity<120,-0.0028* Turbidity^2+ 0.0833* Turbidity+ 35,IF(Turbidity>120,5)))))

Appendix L: Rating curve and normalizing table for Dissolved Oxygen



Rating equations for DO derived from the rating curve

Ranger	Equation
1 – 3	$y = 3E\text{-}14X^2 + 10X + 1E\text{-}13$
3 - 6	$y = 2E\text{-}13X^3 - 2E\text{-}12X^2 + 15X - 15$
6 - 10	$Y = -0.2083X^4 + 6.25X^3 - 69.792X^2 + 353.75X - 615$
10 – 20	$Y = -0.0042X^3 + 0.4875X^2 - 14.208X + 207.5$

Where X is the value of DO

IF_ Statement for dissolved oxygen in computing an index

=IF(DO="","NM",IF(DO<0,"ERR",IF(DO<1,5,IF(DO<3,0.0014*DO^2+10*DO+0.13,IF(DO<6,0.013*DO^3-0.012*DO^2+15*DO-15,IF(DO<10,-0.2083*DO^4+6.25*DO^3-69.79*DO^2+353*DO-615,IF(DO<20,-0.0042*DO^3+0.4875*DO^2-14.208*DO+207.5,IF(DO>20,85)))