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Assessment of groundwater vulnerability in Norton Town, Zimbabwe

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Assessment of groundwater vulnerability in Norton Town, Zimbabwe

By

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MASTER OF SCIENCE THESIS IN INTEGRATED WATER RESOURCES MANAGEMENT

SUPERVISORS:

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A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Integrated Water Resources Management at the University of Zimbabwe

DECLARATION

I, Paidamoyo Mary Vushoma declare that this research is my own work and it has not been submitted before for any other degree of examination at any other University. This thesis is submitted for the Master of Science Degree in Integrated Water Resources Management (IWRM) at the University of Zimbabwe. The findings, interpretations and conclusions expressed in this study neither reflect the views of the University of Zimbabwe, Department of Civil Engineering nor those of the individual members of the MSc Examination Committee, nor of their respective employers.

Signature: ……………………………………………………………………………

Date: ………………………………………………………………………………..

DEDICATION

I would like to dedicate this research with love and gratitude to my husband Eubert, my dearest son Munashe, my mother and my late father for the support they rendered to me right throughout my studies.

ACKNOWLEDGEMENTS

I forward my sincere appreciation to the Almighty God for granting me the opportunity to live this life. I am heavily indebted to my sponsors DAAD for granting me a scholarship that enabled me to undertake this postgraduate study. I also value the effort and assistance provided by my dedicated and patient supervisors Mr. W. Gumindoga and Eng. Z. Hoko. To all my family members and friends, God bless you all for your encouragement. Gratitude is also extended to all the staff members in the Departments of Civil Engineering, Geography and Environmental Science and Geology at the University of Zimbabwe. Finally, to all my 2015/2016 IWRM/WREM colleagues, you will be greatly missed.

ABSTRACT

The current threats of climate change have prompted the dependency on groundwater as a sustainable supply of domestic water. As a result, maintaining groundwater quality has remained a critical intervention for many local authorities especially in developing countries including Zimbabwe. This study assessed the vulnerability of groundwater quality within Norton Town in Zimbabwe, an urban area that dependents partly on groundwater sources for domestic water supplies. The town has a number of potential pollution sources. Potential pollution sources were digitized on Google Earth map using GIS techniques. Ground control points were collected to validate and improve the potential pollution source map. Fifteen (15) systematically selected groundwater points (8 boreholes and 7 wells) located close to potential pollution sources were chosen and water samples collected from them. Four (4) sampling campaigns were undertaken in January and February 2016. The water samples were analysed for selected water quality parameters using standard methods and compared to Zimbabwean and World Health Organization limits to assess drinking suitability. The parameters that were studied include temperature, turbidity, pH, DO, electrical conductivity, TDS, total hardness, iron, sulphates, chlorides, faecal coliform and total coliform. One-way Analysis of Variance was performed using SPSS version 23 to test for any significant differences between parameters and sites. In order to determine parameters that are important in assessing variation in groundwater quality data set, Principal Component Analysis was used. The Moving Average technique in Integrated Land and Water Information System was used to plot spatial and temporal variation of groundwater in the environment. The Aquifer Vulnerability Index Model was used for mapping the vulnerability of groundwater in Norton Town. Six parameters including hydraulic conductivity, soil media, depth to water level, aquifer media, slope and land cover were assigned weights and ratings using ILWIS Software. Statistical data grouping was implemented in order to differentiate five categorical index ranges. Results for mapping potential pollution sources showed that, industrial activities and improper disposal of solid wastes and wastewater are the main causes of groundwater pollution in Norton. Descriptive statistics for the analysed groundwater parameters showed the mean values for temperature, turbidity, pH, DO, electrical conductivity, TDS, total hardness, iron, sulphates, chlorides, faecal coliform and total coliform were 25.7 °C, 6.8 NTU, 7.2, 3.66 mg/L, 580 µS/cm, 280 mg/L, 698 mg/L, 0.05 mg/L, 455 mg/L, 282 mg/L, 1015 cfu/100mL, 991 cfu/100mL respectively. The results showed that temperature, turbidity, DO, TDS, pH, chlorides, total hardness, electrical conductivity and sulphates had significant variation of parameters (spatial and temporal) explained by (p values <0.05). PCA components F1, F2, F3 and F4 had total variability of 80 % with each one of the components having 36 %, 24 %, 11 % and 9 % respectively. The significant parameters were chlorides, dissolved oxygen, electrical conductivity and feacal coliform. From the Aquifer Vulnerability Index Model, five different vulnerability zones were established which were; very low vulnerability (index 63-73), low vulnerability (74-84), moderate vulnerability (85-95), high vulnerability (95-106) and very high vulnerability (107-126). The results showed that 17.8 % of the area had very low vulnerability, 37.2 % low vulnerability, 30 % moderate vulnerability, 12.5 % high vulnerability and 2.5 % very high vulnerability. The study identified the main pollution sources as treatment plant, agriculture, landfill, onsite sanitation and industrial discharge. The study also revealed that potential pollution sources are the main causes of groundwater contamination. The results showed that groundwater sources situated in high density areas had faecal coliform counts greater than 100 cfu/100 mL which could be harmful to human health. Groundwater quality parameters (50 %) exceeded the Zimbabwean and World Health Organisation drinking water limits. At the present moment, the area shows a total of 55 % very low to low vulnerability. It is therefore recommended that water from vulnerable sources be disinfected regularly before human consumption.

Keywords: Aquifer Vulnerability Index model, groundwater quality, Principal Component Analysis, pollution sources, vulnerability

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SYMBOLS, ABBREVIATIONS AND ACRONYM

ADEM	Alabama Department of Environmental Management
APHA	American Public Health Association
AVI	Aquifer Vulnerability Index
DEM	Digital Elevation Model
DO	Dissolved Oxygen
DRASTIC	Depth, Recharge, Aquifer, Soil, Topography, Impact, Conductivity
EC	Electrical Conductivity
EMA	Environmental Management Agency
FC	Feacal Coliform
GIS	Geographic Information System
IDW	Inverse Distance Weight
ILWIS	Integrated Land and Water Information System
NIEHS	National Institute of Environmental Health Science
PCA	Principal Component Analysis
SAZ	Standards Association of Zimbabwe
SWAT	Surface to Well Advection Time
TDS	Total Dissolved Solids
TM	Thematic Mapper
UNEP	United Nations Environment Programme
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WESS	World Economic and Social Survey
WSS	Water Supply and Sanitation
WHO	World Health Organisation

CHAPTER 1
INTRODUCTION

1.1. Background

Groundwater constitutes about 95 per cent of freshwater on this planet making it fundamental to human life and economic development (UNEP, 2003). The inherent qualities of groundwater makes it an immensely important and dependable source of water supplies in all climatic regions including both urban and rural areas of developed and developing countries (Peiffer, 2007). About 50 % of all the underground water used in urban areas of developing countries is derived from wells, springs and boreholes and more than 1 billion inhabitants in Asia and 150 million in Latin America rely on such sources (Ullah et al., 2009). It is estimated that about 70 % of the people in the SADC region rely on groundwater as their only source of drinking water (IGRAC, 2013). In Zimbabwe, 32 per cent of the people rely on relatively unsafe water from unprotected wells, rivers, streams, and dams (Manyanhaire and Kamuzungu, 2009). According to WESS (2013), it is imperative to appreciate the fact that the lack of reliable and good quality water sources is one of the principal constraints to social and economic development in most developing countries.

Kuisi et al. (2014), defined groundwater vulnerability as a measure of the risk placed upon groundwater by human activities and the presence of contaminants. Groundwater vulnerability mapping is based on the idea that some lands are more vulnerable to groundwater contamination than others (Piscopo, 2001). The concept of aquifer vulnerability comes from the fact that geological materials may provide some level of protection to groundwater, with regards to pollution sinking into the ground (Omosuyi and Oseghale, 2012). Approaches such as statistical methods, process-based methods and overlay and index methods have been developed to evaluate groundwater vulnerability (Zhang et al., 2013). Groundwater vulnerability assessment allows the synthesis of complex hydrogeological information that can be used by planners, decision makers and policy makers (Liggett and Talwar, 2009). The development of vulnerability maps is useful for many aspects of water management including, prioritizing areas for protection, community education and the development of risk assessments. Geographic Information Systems are used for predicting areas more likely to become contaminated than others as a result of activities at or near the land surface (Pathak et al., 2009). Such up-to-date and systematic information will be of great importance to researchers, hydro-geologists and decision makers.

According to Samake et al. (2011) groundwater contamination has become one of the serious environmental problems in the world because once polluted it is very difficult to remediate. Industrialization and high population growth are the major sources of industrial and domestic effluents being discharged to the environment, which has led to the pollution of groundwater (Sener and Davraz, 2013). For instance in Africa and Asia around 80 % and 55 % of the population in the largest cities respectively have on-site sanitation such as septic tanks, pour-flush, ventilated improved pit latrines or simple pits (Ojuri and Bankole, 2013). Various sources of contamination have resulted in a decrease in groundwater quality. For example in Nigeria`s Lagos City, groundwater is faced with threats from open waste dumps, petroleum products, landfill sites and underground infrastructure (Ojuri and Bankole, 2013).

In Zimbabwe, freshwater resources are threatened not only by overexploitation but also by poor management and ecological degradation (Chigonda, 2010). Groundwater sources are prone to contamination by seepage from septic systems, pit latrines as well as manure and fertilizers spreading on agricultural lands (UNEP, 2003). This is common in the Norton Community where the majority of the households use fertilizers on their small fields on which they practice urban farming, whilst raw sewers choke pipes due to obsolete infrastructure. A significant proportion of Norton Town community relies on pit latrines and septic tanks which have potentials to contaminate groundwater (Chigonda, 2010) . The impact of inadequate water supply in Norton like in other towns in Zimbabwe has resulted in a high rate of drilling of boreholes, deep and shallow wells as alternative sources of water (Makwara and Tavuyanago, 2012). The water sources are prone to contamination and spread of water borne diseases.

1.2. Problem Statement

Groundwater is becoming increasingly vulnerable to pollution due to rapid urbanization (Kulabako, 2005). The rapid urbanization and population growth in Norton Town as highlighted by Makwara and Tavuyanago (2012) is not matched with an increase in measures to control pollution resulting from this growth. Furthermore, the limited capacity of the Norton Town

Council Authority to provide basic services to this town has resulted in poor environmental sanitation (Mukuhlani and Nyamupingidza, 2014). Poor sanitation has consequently led to contamination of the deep and shallow groundwater aquifers, a source that is greatly relied on by Norton Town Community (Chigonda, 2010). In this context, groundwater contamination poses direct and immediate health impacts to a huge population. This therefore implies that there is an urgent need to assess groundwater vulnerability for sustainable development in Norton Town.

1.3. Justification

Norton, is facing water quantity and quality problems (Chigonda, 2011). In addition, Norton is premised in close proximity to the seriously polluted Lakes, Chivero and Manyame (Tendaupenyu, 2012). There is an urgent need to thoroughly investigate the impact of groundwater vulnerability to protect water resources for present and future generational needs. Studies done by Dzwairo et al. (2006) showed that groundwater is greatly affected by pit latrines. Musademba Downmore et al. (2011), revealed that Municipality Solid Waste generated amounts to 2.7 kg per household per day. Furthermore, a study done by the Institute of Environmental studies at the University of Zimbabwe in 2008 revealed that Zimbabwe produces 150 000 tonnes of waste per year (EMA, 2011). Groundwater in Norton is greatly affected by the above mentioned pollution sources. However, there is need to put into practice the IWRM Dublin Principle 1 which emphasizes that there is need to protect fresh water since it is a finite and vulnerable resource (Munkonge and Harvey, 2008).

Norton Town experienced an acute cholera outbreak in 2008 due to sanitation problems with choked sewer, unprotected wells, one tanker and a few boreholes available to the population (WHO, 2008). In contrast to the above, since 2008 up to date, Norton Town Council has been unable to match water supply demand by its growing population density (Chigonda, 2010). Demand for groundwater has increased rapidly caused by the failure of local authorities to provide adequate drinking water through the reticulation system (Mukuhlani and Nyamupingidza, 2014). There is need to achieve Sustainable Developmental Goals especially SDG 3 and 6: which state that it is important to ensure healthy lives and promote well beings for all ages, ensure availability and sustainable management of water and sanitation for all. The results from this study will be used for planning against the impact of public health concerns such as cholera and typhoid. Furthermore, this study will be used to raise public awareness on groundwater protection issues.

The use of GIS will enable decision makers to map and differentiate between areas that need protection from potential contamination activities and areas that constitute minor threat to groundwater.

1.4. Objectives

1.4.1. Main objective

The main objective of this study was to assess current groundwater vulnerability in Norton Town, Zimbabwe.

The specific objectives were as follows;

(i) To map potential groundwater pollution sources in Norton Town

(ii) To analyse the spatial-temporal variation of groundwater quality in Norton Town

(iii) To assess current groundwater vulnerability using Aquifer Vulnerability Index (AVI)
(iv) Model

CHAPTER 2
LITERATURE REVIEW

2.1. Status of groundwater globally

According to UNEP (2003) groundwater constitutes about 95 per cent of the freshwater on the planet (discounting that locked in the polar ice caps) making it fundamental to human life and economic development. About 60 % of groundwater withdrawn worldwide is used for agriculture and the rest is divided between the domestic and industrial sector (Margat and Gun, 2013). Over half of the world's population depends on groundwater for drinking water supplies (UNEP, 2003). For example, in the year 2000, over half of the twenty-three cities of the world relied upon groundwater (Mohammad Ibnam Nazir et al., 2014). China has more than 500 cities and two thirds depend on groundwater (Morris et al., 2003). In Angola, about 3.5 million out of the 18.5 million population (approximately 19 %) rely exclusively on groundwater (UNESCO, 2013). In Zambia, in many low-cost areas the Water Supply and Sanitation infrastructure is no longer functional and residents increasingly depend on open wells and pit latrine (UNESCO, 2013). Figure 1 shows cities in Africa that depend on groundwater.

Figure 1:Groundwater dependent cities in Africa*: Adapted from (Morris et al., 2003)*

Large cities in Africa meet their water demands mainly from groundwater (Morris et al., 2003). Akiwumi and Odebunmi (2012), recognized that groundwater has self-purifying properties, hence it is a very good source of drinking water. Groundwater is increasingly being exploited in preference to surface water for drinking water supply (Ferral et al., 2014). Consequently, in arid and semi-arid regions groundwater is the most important source of water supply due to its large volumes and its low vulnerability to pollution when compared to surface water. However, groundwater quality is deteriorating worldwide and a growing concern, often the result of past action (Custodio, 2012).

2.2. Groundwater quality

Groundwater is a major natural resource for drinking purposes in many countries of the world including both developed and developing countries (Afuye et al., 2015). The physical, chemical and bacterial characteristics of groundwater determines its usefulness for various purposes (Adamu and Usman, 2014). Groundwater becomes contaminated from natural sources or human activities. Municipal, residential, commercial, industrial and agricultural activities affect groundwater quality (Abdullahi, 2009). According to Ocheri et al. (2014), African cities have a long history of water supply from surface and groundwater sources. Due to the deteriorating of surface water in terms of quality and quantity groundwater is viewed as a better option (Ocheri et al., 2014). However, once groundwater is contaminated it is difficult to remediate. Groundwater pollution is as a result of high population growth, industrialization and discharge of domestic and industrial effluents (Rahaman, 2009). In recent years, there has been increasing concern on groundwater pollution in the urban areas in the world (Kulabako, 2005).

2.2.1. Groundwater contamination and pollution

According to USGS (1999) groundwater can become contaminated by many of the same pollutants that contaminate surface water. Groundwater becomes unsafe and unfit for human use when man-made products such as oil, gasoline, road salts, and chemicals get into the groundwater. Harter (2003), defined groundwater pollution or groundwater contamination as an undesirable change in groundwater quality resulting from human activities. In many cases the soil can remove bacteria, viruses and chemicals from water that percolates downward but not all soils remove contaminants as effectively as others, and domestic and industrial waste can also exceed the soil's ability to remove chemicals and contaminants. Contaminants can seep into groundwater from leaking underground tanks, septic tanks, cesspools and landfills. Figure 2 shows some of the sources of groundwater contamination.

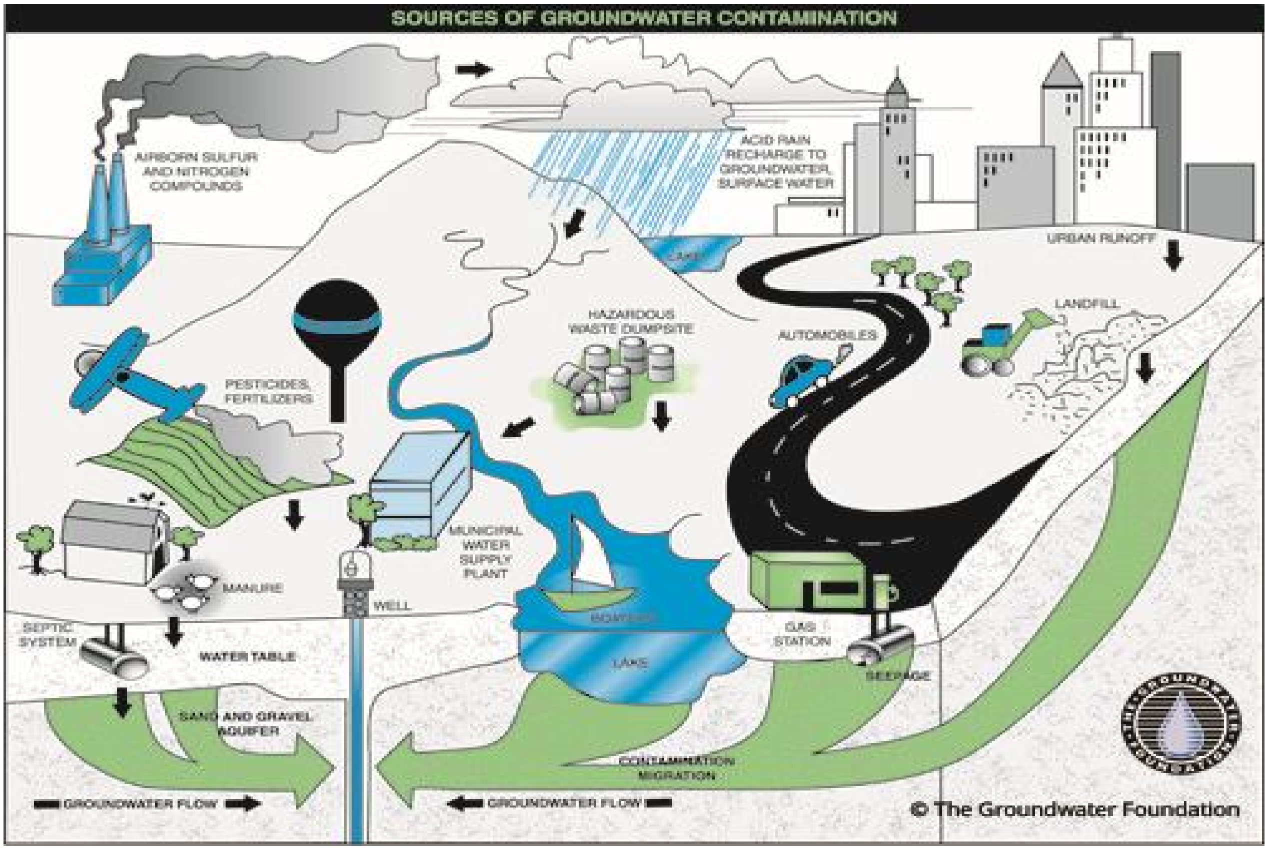

Figure 2: Sources of groundwater contamination*: Adapted from (USGS, 1999)*

According to Kaur and Rosin (2007) groundwater is not easily contaminated, however once contamination occurs it is difficult to remediate. In the developing world, such remediation may prove practically impossible. Surface water resources in Southern Africa are also under pressure from pollution, posing a significant threat to groundwater quality, particularly in urban areas and close to industrial centers as illustrated in Figure 2. In order to solve groundwater contamination problems and mitigate the threats, there is need to understand factors that govern the transport and fate of subsurface pollutants. Moody (1996), asserts that assessment of the extent of groundwater contamination is difficult, due to such factors as limited and inconsistent access to the water supply. According to BGS (2013), risk assessments are defined for three scenarios, that is, very low risk, low risk and significant risk as shown by the table below.

Table 1: Levels of pathogen risk in relation to travel time: ***Adapted from (BSG, 2001)***

LEVEL OF RISK	COMMENTS
Significant risk	Travel time under 25 days (breakthrough of both viral and bacterial pathogens in significant numbers possible)
Low risk	Travel time over 25 days (primarily related to the potential for viral break through) but under 50 days
Very low risk	Travel time over 50 days (unlikely to have significant breakthrough of any pathogens, although low risk of viral breakthrough remains)

Polluted water is regarded as unfit for its intended use (Adeyemo et al., 2002). According to Kaur and Rosin (2007), over three-quarters of freshwater used by the domestic and industrial sector return as domestic sewage and industrial effluents which inevitably end up in surface water bodies or in the groundwater thereby affecting water quality. Pollution of a body of water occurs when an impurity (micro-organism or chemical) is introduced as a result of human activities creating an actual or potential danger to human health or the environment when present at high concentrations (Osei, 2014).

Two types of pollution are point and non-point sources according to USGS (1999) with point sources being identifiable and localized sources of pollution. Examples of point sources that can contaminate groundwater include oil storage tanks, septic system, landfills, buried gasoline, industrial sources and accidental spills. Non-point sources are in the form of pesticides and nutrients that enter the soil as a result of intense agricultural operations or the widespread use of road salts and chemicals (Kumari et al., 2009). Other sources of potential groundwater contamination include unauthorized hazardous waste disposal sites, old landfills, unauthorized dumps, and abandoned wells (Natasha, 2001). The following are some of the sources of groundwater pollution.

2.2.2. Geology and groundwater pollution

Fundamental to the study of groundwater in any place is the geology of the environment. Geology is the main controlling factor in groundwater hydrology. The nature and the properties of the rock aquifer, specific yield, retention, the chemistry of water are governed by the geology of the environment (Ocheri et al., 2014). Rock materials are classified as consolidated and unconsolidated (Hudec, 2005). Consolidated rock consists of limestone, sandstone, granite and other rocks, while unconsolidated consists of granular material such as gravel, sand. Consolidated rocks may contain fractures, fissures, crakes that can hold water. Unconsolidated rocks may contain weathered material, and store large quantities of groundwater. For example, Norton geology is dominated by fractured meta-sediment formations, granite and basaltic formations (Baldock et al., 1991). This means that the Norton area has a mixture of consolidated and unconsolidated rock material. Winter et al. (1999), argued that the quality of groundwater is a function of natural processes as well as anthropogenic activities that include the type, extent and duration of anthropogenic activities on groundwater. According to Meybeck et al. (1996) groundwater quality is controlled by the chemical and physical processes and the hydrological condition present. Studies done by Ocheri et al. (2014) examined groundwater quality in relation to influence of geology in an urban environment and found that water from basement complex contains calcium or sodium bicarbonate and nitrate in high concentration of health implication. It is imperative to realize that the local geology of noticeable stratigraphic variation influences natural attenuation of contaminants their pattern of transfer and subsequent breakthrough into groundwater (Longe and Enekwechi, 2007). Thus groundwater contains some impurities, even if it is unaffected by human activities. The types and concentrations of natural impurities depend on the nature of the geological material through which the groundwater moves and the quality of the recharge water (Samie and Makonto, 2013). Groundwater moving through sedimentary rocks and soils may pick up a wide range of compounds such as magnesium, calcium, and chlorides. Some aquifers have high natural concentration of dissolved constituents such as arsenic, boron, and selenium. The effect of these natural sources of contamination of groundwater quality depends on the type of contaminant and its concentrations (Eberts, 2014).

2.2.3. Effects of dry and wet season on groundwater pollution

Season is believed to influence the concentration level of the physio-chemical and bacteriological loading in water resources (Efe et al., 2005). Ocheri et al. (2014), investigated seasonal variability of physico-chemical elements in boreholes and the analysis showed that total dissolved solids were lower in the dry season. Ocheri et al. (2014), further found out that 80% of the wells had nitrate concentrations above the WHO allowable limit for drinking water for wet season. Other parameters whose concentrations were higher in the wet season are pH, turbidity, electrical conductivity, chloride, iron, calcium, chromium, biochemical oxygen demand and Feacal coliform bacteria.

2.2.4. Soil characteristics and groundwater pollution

According to Holman et al. (2005) the soil type and hydrogeology influence soil percolation rates and vulnerability of groundwater to nutrient contamination. If the soil has high permeability rainwater will soak into it easily (Custodio, 2012). Norton is dominated by clay and sandy loam soils. Sandy loam soils have higher permeability as compared to clay soils. When groundwater is found at shallow depths pollutants from the surface are not filtered out before reaching the groundwater and pollutants are difficult to remove making the water unsuitable for drinking (EPA, 2003). Soil water and groundwater interaction with sediments and rocks out of the most common soluble minerals involve reactions such as the hydrolysis of carbonates and silicates. This may incorporate solutes that may affect groundwater quality for the intended uses and especially for drinking purposes. Arsenic is widely dispersed in rocks and sediment (NIEHS, 2014). According to NIEHS (2014) arsenic is a naturally occurring element that is widely distributed in the Earth's crust. It is found in rocks, soil, water, air and food. There are two general forms of arsenic, organic and inorganic. Its hydro-geochemical behavior is complex and depends on other factors on ambient redox potential. Arsenic may be released if sulphate and organic-rich sediments are exposed to oxygen, as when recent oxygen-carrying water penetrates deep formations or when air enters formerly saturated formations due to the lowering of the water table by groundwater development (UNEP, 2003). It may be also released when polluted water carrying reactive organic matter produces reducing ambient in oxidized sediments. Thus, arsenic in groundwater is often of natural origin or the result of aquifer development. Figure 3 shows arsenic problems in groundwater.

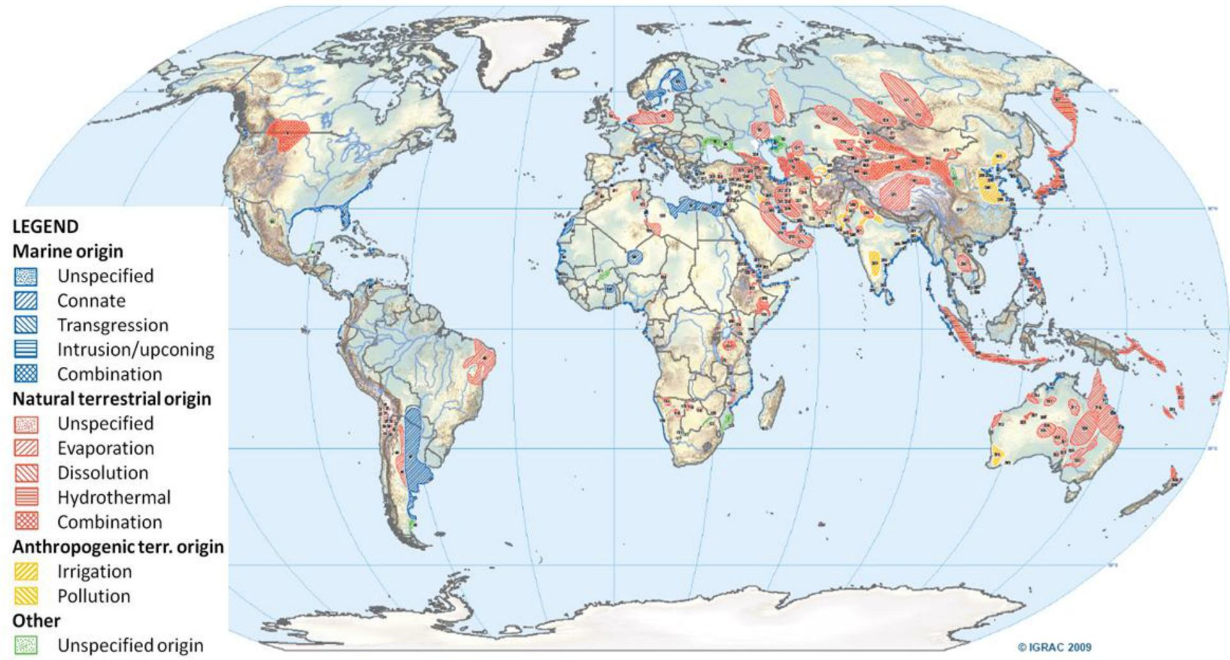

Figure 3: World distribution of major reported problems of arsenic content in groundwater: *Adapted from (Custodio, 2012)*

2.2.5. Agricultural activities and groundwater pollution

According to Moody (1996) agriculture is one of the most widespread human activities that affects the quality of groundwater. Pesticides, fertilizers, herbicides and animal waste are agricultural sources of groundwater contamination. According to (BSG, 2001) discharge of effluent from intensive livestock units and leachate from manure stores and leaking slurry pits and slurry or manure spreading on land as organic fertilizer can all be sources of groundwater pollution. The agricultural contamination sources are varied and numerous and also include, spillage of fertilizers and pesticides during handling, runoff from the loading and washing of pesticide sprayers or other application equipment using chemicals uphill from or within a few hundred meters of a well. Use of partially treated or untreated wastewater in irrigation can also cause deterioration in the quality of the underlying groundwater (BSG, 2001). Storage of agricultural chemicals near conduits to groundwater such as open and abandoned wells, sink holes or surface depressions where ponded water is likely to accumulate. Contamination may also occur when chemicals are stored in uncovered areas, unprotected from wind and rain, or are stored in locations where the groundwater flows from the direction of the chemical storage to the well (Juma, 2014). Error! Reference source not found.illustrates fractured aquifer pollution by chlorinated solvents spillage. Farmers consider agricultural land that lacks sufficient drainage to be lost income land. So they may install drain tiles or drainage wells to make the land more productive.

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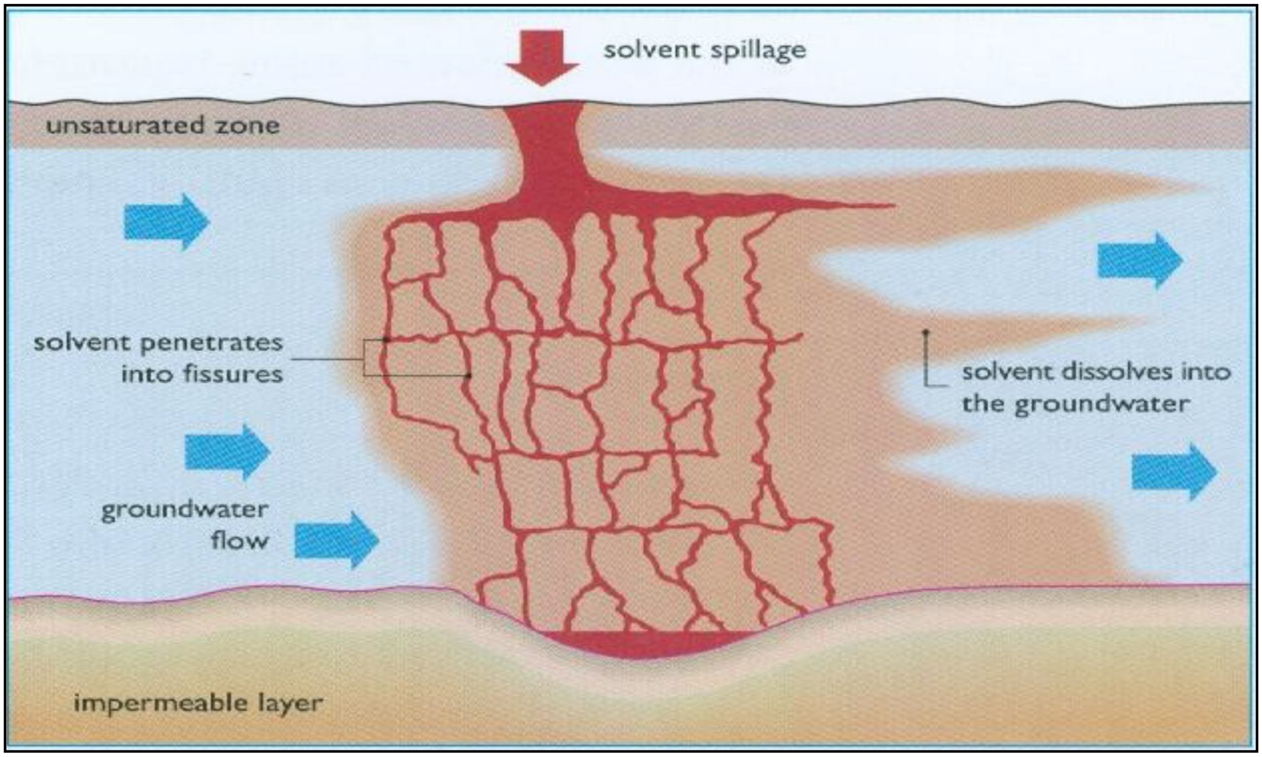

Figure 4: Soil and fractured aquifer pollution by chlorinated solvents spillage: ***Adapted from (Custodio, 2012)***

2.2.6. Industrial activities and groundwater pollution

Leachate from Landfill and Industrial activities

Leachate was defined by Raghab et al. (2013), as a liquid that passes through landfill and has extracted dissolved and suspended matter from it. Leachate results from precipitation entering the landfill from moisture that exists in the waste when it is composed. According to Hamidi and Salem (2005) leachate pollution is one of the main problems in groundwater and researchers have yet to find an effective solution to this problem. Ocheri et al. (2014), recognized the increase in industrial activities has intensified environmental pollution problems and the deterioration of several aquatic ecosystems with the accumulation of metals in biota and flora. These trace metals are dangerous because they tend to bio-accumulate resulting in heavy metal poisoning. According to Raghab et al. (2013), industrial solid waste gives rise to a very polluting leachate and solid waste landfills may cause severe environmental impacts if leachate and gas emissions are not controlled. In addition, Water resources and environmental pollution is as a result of leachate from Municipal solid waste landfills (Aljaradin, 2012). However, of late engineered landfills are being encouraged. Figure 5 shows a cross-section of an engineered modern landfill. The design incorporates a synthetic membrane liner (about 2.5-millimeter-thick) on a layer of low-permeability clay (about 1 meter thick).

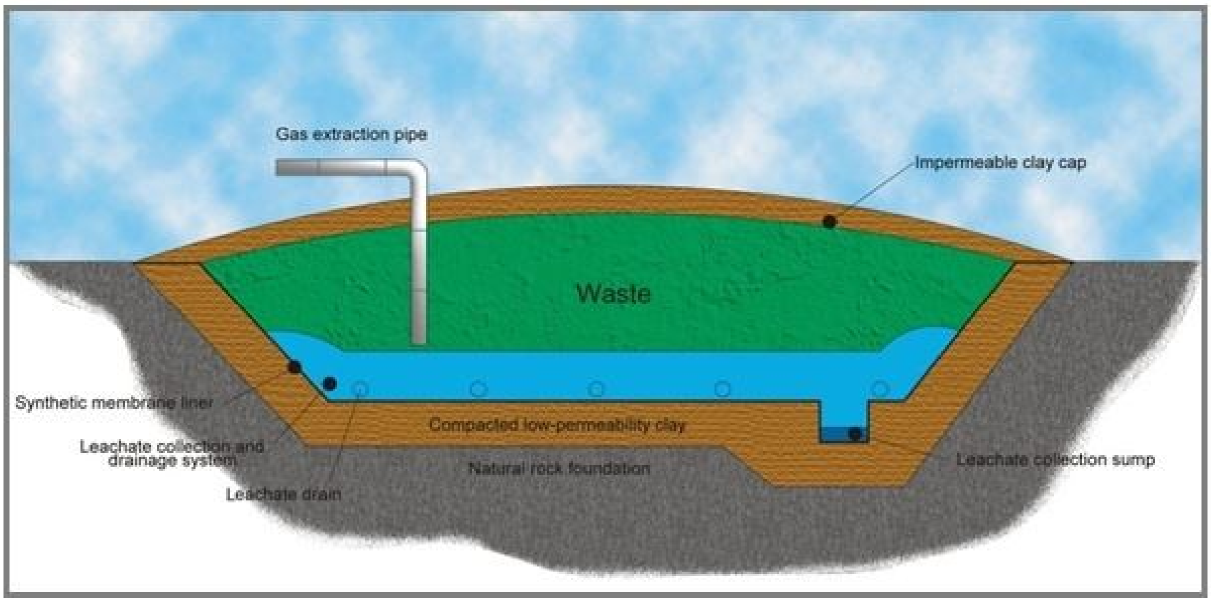

Figure 5: Cross-section of a modern landfill*: Adopted from (BGS, 2013)*

A network of pipes drains leachate into a sump and the same pipes collects any gas generated. According to Afalayan et al. (2012), the primary method of waste disposal is the use of landfills because this method is the most convenient. However, it is important to prevent contamination of groundwater, unconfined aquifer, surface water and the surrounding from landfills (Ismail and Manaf, 2013). In many developing countries the use of landfills is far from standard recommendations. For example in Harare Zimbabwe, a study done by Chihanga (2015) concluded that, leachate quality is significantly influenced by the waste age. This is caused by leachate impacts to bacterial growth and chemical reaction in the waste mass of landfill giving rise to various pollutants that pose pollution to groundwater. The investigation of impacts of landfill leachate on groundwater is important to the management and disposal of municipal waste.

Abattoir wastes and groundwater pollution

Abattoir also known as slaughter house have been defined as a premise approved and registered by the controlling authority for hygienic slaughtering and inspection of animals, processing and effective preservation and storage of meat products for human consumption (Adio et al., 2014). According to Chukwu (2008) abattoir wastes are hazardous as many contain small quantities of components which are potentially dangerous to man and the environment. These wastes can seep through the ground and contaminate groundwater with nitrate and bacteria whilst the slaughtering of animals results in significant meat supplies and production of useful by product such as leather and skin (Chukwu, 2008). The processing activities involved sometimes result in environmental pollution and other health hazard that may threaten animal and human health. These leachates consist largely of solids, microbial organisms and in special situations chemicals which if not properly handled have a potential to dangerously pollute shallow wells (Adio et al., 2014). Solid waste from the abattoir includes aborted fetuses, undigested bones, condemned meat, horns, hair and feaces. Liquid wastes include blood, gut contents, urine, and water and dissolved solids. Increasing meat production for the world population has some pollution problems attached (Rabah et al., 2008). According to Rabah et al. (2008), adhering to Good Manufacturing Practices (GMP) and Good Hygiene Practices (GMP) is a great challenge in many countries leading to pollution arising from meat production.

2.3. Groundwater vulnerability

The concept of groundwater vulnerability to contamination was introduced in the 1960s in France (Alwathaf, 2011). Groundwater vulnerability was defined by Liggett and Talwar (2009), as an intrinsic property of groundwater that depends on the degree to which the environment systems and humans are likely to cause harm. The study of groundwater vulnerability assessments describes the risk of the water table to contaminants that can reduce the quality of groundwater (e.g. industrial chemicals, nitrates) (Liggett and Talwar, 2009). This implies that groundwater vulnerability may be concluded to involve the introduction of possible contaminants in an underground system (Rahman, 2008). The aspect of groundwater vulnerability comes from the assumption that physical geo-material provides some level of protection to groundwater with regards to pollution entering the ground. This will lead to some land being vulnerable than the other (Iuliana and Mădălina, 2012). There is an ongoing debate whether groundwater vulnerability is “intrinsic” or “specific”(Focazio et al., 2002). Foster et al. (2013), defined “specific vulnerability” as accounting for anthropogenic activities that causes contaminates to reach the subsurface and “intrinsic vulnerability” as natural risk to contamination based on the physical characteristics of the environment. According to Eskom (2014), when natural factors provide little protection to shield groundwater from contaminates groundwater vulnerability becomes high and when natural factors provide good protection, little contamination will occur hence groundwater vulnerability is low. Five vulnerability classes were identified by Piscopo (2001), which shows groundwater assessment for each class. The various sets of classes used in many vulnerability assessments include low, low-moderate, moderate, moderately high and high.

2.4. Methods of assessing groundwater vulnerability

Groundwater vulnerability is based on three methods which are index overlay, statistical and process-based. According to Focazio et al. (2002) index overlay methods assess vulnerability spatially over large regions and can therefore show the vulnerability of the water table or upper most aquifers in a region. Indexing methods are easy to implement, use readily available data, very popular and produce categorical results. Statistical methods involve the calculation of the probability of a particular contaminant exceeding a certain concentration (Liggett and Talwar, 2009). Statistical methods produce spatially distributed probabilities of exceedance, rather than a categorized high, medium and low ranking (Kaur and Rosin, 2012). Process-based are physically based methods for example, SWAT. Process-based methods use deterministic approaches to estimate time of travel, contaminant concentrations and duration of contamination to quantify areas of high and low vulnerability (Focazio et al., 2002). This method shows a representation of the flow system however, it is data intensive and is applicable at a local scale.

2.4.1. Index Overlay Methods

According to Saidi et al. (2011) the assessment of groundwater vulnerability to pollution has been subject to intensive research and a variety of index overlay methods have been developed. Index overlay methods are based on assembling information on the most relevant factors affecting aquifer vulnerability (geological formation type, soil type, recharge, etc.), which is then interpreted by integrating, scoring, or classifying the information to produce an index, rank or class of vulnerability (Harter and Walker, 2001). Several approaches of developing groundwater vulnerability have been developed in the category of index overlay based methods including AVI

(Stempvoort et al., 1993), EPIK (Doerfliger et al., 2007), IRISH (Bexfield et al., 2011) and DRASTIC (Aller et al., 1987). Out of the above list, AVI and DRASTIC methods meets the requirement of most countries globally hence they have been widely accepted. The difference between AVI and DRASTIC is that, DRASTIC requires more data to make a decision on groundwater vulnerability and AVI requires a few to do the same work and can use readily available data (Anornu and Kabo-bah, 2013).

2.4.2. Aquifer Vulnerability Index (AVI) Model

Stempvoort et al. (1993), defined Aquifer Vulnerability Index Model as a method for mapping the vulnerability of groundwater, determining high vulnerability areas in contrast to low areas with respect to potential to pollute groundwater. Stempvoort and others developed AVI method in 1993 in Canada. The method have been used in different areas including Canada, (Stempvoort *et al.*, 2013), California (Harter and Walker, 2001) and Nigeria, (Abdullahi, 2009). AVI model is based on two key parameters, 1) thickness of each sedimentary unit layer (for example sand, till, gravel) and 2) estimated hydraulic conductivity of each of these layers. Using well and borehole records these parameters are combined to obtain a reasonable estimate of the hydraulic resistance of the protective aquitard cover. Stempvoort et al. (2013) and Denny et al. (2007) agree that AVI relies quite comprehensively on groundwater data that includes geology, depth to water levels, land cover. Denny et al. (2007), hinted that studies that were done in British Columbia comparing DRASTIC and AVI methodologies yielded similar results. Further studies on AVI were done in Northeast of Portugal by (Fraga and Fernandes, 2013) and in Sana'a Basin in Yemen by (Alwathaf, 2011). AVI map is determined by assigning point ratings (1-10) and weights (1-5) to the individual data layers and then adding the points together in GIS environment when those layers are combined into a vulnerability map (Hassan and Hallaq, 2011). Parameters needed by AVI Model are readily available which makes it suitable for regional scale assessments. The Model can be applied to a wide geographic region. However, some parameters rely on estimated values e.g. hydraulic conductivity. Weighting of the parameters is somewhere arbitrary and some parameters have a sound theoretical basis (for example geology controls on permeability) (Trent, 1991).

2.4.3. Aquifer Vulnerability Index Conceptual Model

Figure 6 shows Aquifer Vulnerability Index Conceptual Model. According to Bexfield et al. (2011) three main components of the AVI Model are, the upper four layers that represent soil or hydraulic conductivity, density of sinkhole features that is (material overlying the aquifer) and estimated aquifer recharge; yellow extruded lines are training points (monitoring wells) respectively from the top. The lower layer is the model output, or aquifer vulnerability map.

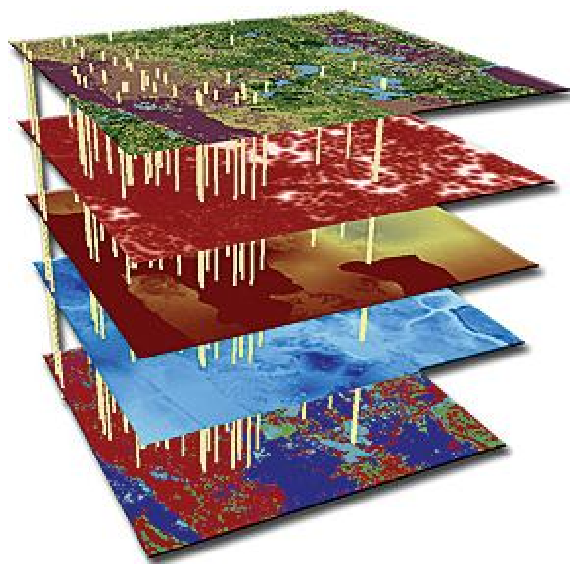

Figure 6: AVI Conceptual Model: Adopted from (Bexfield et al., 2011)

2.4.4. DRASTIC Model

Aller et al. (1987), developed the Drastic Model for the United States Environmental Protection Agency. The Model is a groundwater vulnerability model used to spatially and comparatively display areas of low and high vulnerability with respect to the potential to pollute groundwater (Musa and Katsina, 2009). The Model was used in South Africa (Musekiwa and Majola, 2013), Nigeria (Omosuyi and Oseghale, 2012), Canada (Liggett and Talwar, 2009) among other countries. DRASTIC is an acronym for Depth to water table, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and Conductivity. In order to reflect the relative importance of these parameters, weights in the scale of 1–5 are assigned to each of these parameters (Kumar et al., 2014). In addition, the seven hydrological parameters are also assigned ratings in the range of 1-10. The DRASTIC method is widely used and a powerful tool for assessing groundwater vulnerability. Reliable results have been obtained even for complex areas (Rahman, 2008). However, in some areas availability of data is a challenge. For example a study that was done by Piscopo (2001) used DRASTIC and GIS to create a groundwater vulnerability map for the Castlereagh Catchment in Australia. The author excluded hydraulic conductivity from the final DRASTIC calculation due to lack of data.

2.4.5. Comparison of Index Overlay Methods

Table 2 shows a comparison of different groundwater vulnerability models, the data they require, areas where the model was applied and their key references.

Table 2: Groundwater vulnerability models

Model name	**Data required**	**Areas where Model was applied**	**Key Reference**
AVI	Hydraulic conductivity Thickness of each sedimentary layer (sand, till, gravel)	Canada, Nigeria, Portugal, Yemen, Brazil	(Stempvoort *et al*., 1993)
DRASTIC	Depth to water table, Recharge, Aquifer media Soil media, Topography, Impact of the vadose zone Conductivity	Australia, South Africa, Nigeria, Canada, USA	(Aller *et al*., 1987)
GOD	Groundwater confinement, Overlying layers and Depth	USA, Nigeria, Morocco, Brazil, Italy	(Foster, 1987)
EPIK	Epikarst, Protective cover, Infiltration conditions Karst network development	Nigeria, Portugal, Jordan, Italy	(Doerfliger *et al*., 2007)

Groundwater vulnerability studies enable assessment of how severe the likely consequences of pollutant loading may be. The severity of the consequences is measured in terms of water quality deterioration. In this study, Aquifer Vulnerability Model (AVI) will be used to assess groundwater vulnerability in Norton, Town and to assess groundwater quality deterioration.

CHAPTER 3
STUDY AREA

3.1. Description of Study Area

3.1.1. Location of Study Area

Figure 7 shows the location of Norton Town in Zimbabwe. Norton town is located 40 kilometers to the west of Harare, the capital city of Zimbabwe in Mashonaland West Province (Chigonda, 2011). It is located between Lake Chivero and Lake Manyame (Tendaupenyu, 2012). Norton falls in the agro-ecological region 11. Region 11 is characterised by mean annual rainfall, length of growing season and soil data (Mugandani et al., 2012). The settlement began in 1914 when a railway siding was built. The town was named after the Norton Family who were farming in the area since the 1890s.

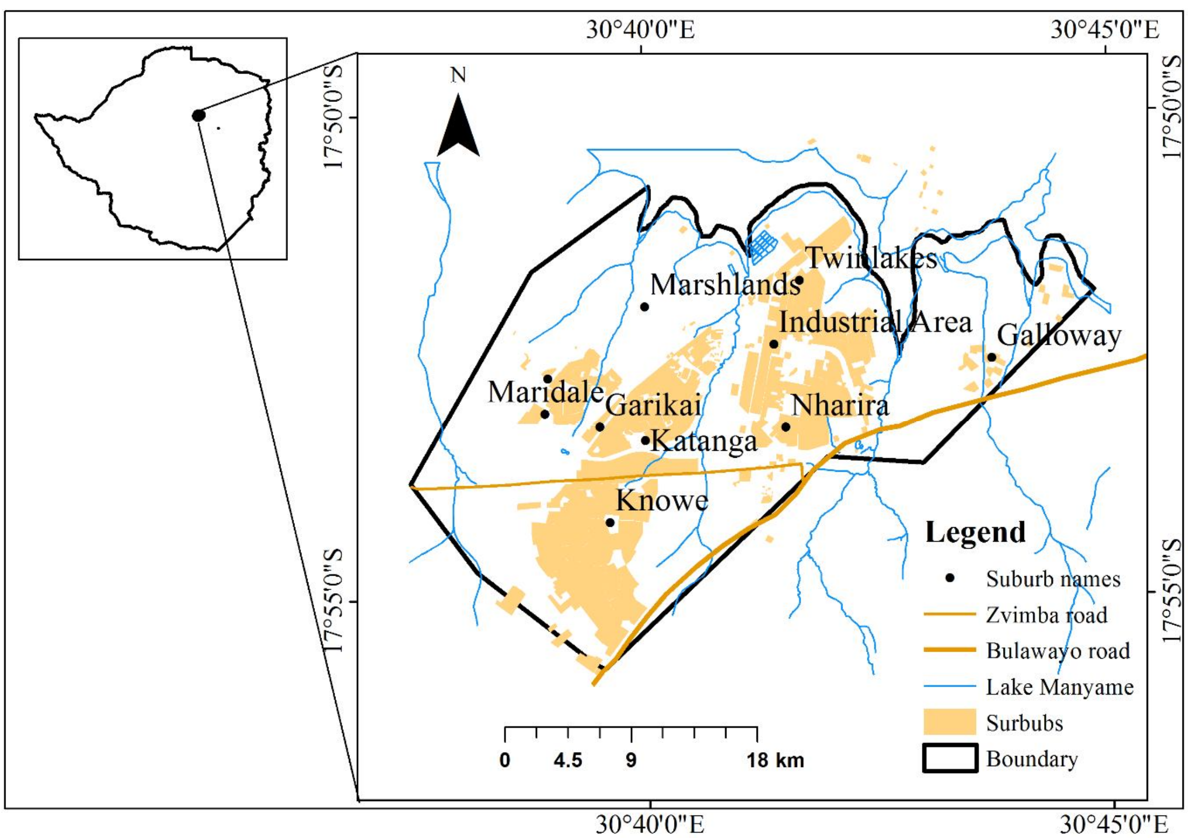

Figure 7: Location of Norton Town in Zimbabwe

3.1.2. Population and settlement

By 2012, Norton had an urban population of approximately 68,000 with growth rate of 3.2 % (ZIMSTAT, 2012). Figure 7 above shows some of the suburbs of Norton. Maridale, Garikai, Marshlands and Johanesburg are high density areas whilst Knowe, Twinlakes and Galloway are medium to low density areas. Maridale, one of the high-density suburbs in Norton, was established in 1999 by a private property developer. In 2003, people started building houses and as of 2010 the suburb had 3,111 (150 m²) housing units (Chigonda, 2010).

3.1.3. Climate

The climate is that of hot wet summers and cool dry winters, typical of the Savanna (Mugandani et al., 2012). Savanna has three seasons which are; a warm, wet season from November to March/April; a cool, dry season from May to August; and a hot, dry season in September/October. According to ClimaTemps.com, (2016) high average temperatures of 26 °C are experienced in summer and low temperatures of between 22 °C and 16 °C are experienced in winter. The area receives rainfall ranging between 650-800 mm annually (Brown et al., 2012).

3.1.4. Background on water supply in Norton

Norton Town gets its treated water supply from the Morton Jaffray Water Treatment Plant. Harare, Chitungwiza and Epworth also get treated water from Morton Jaffray. This has created a water demand for about 3,5 million people (ZIMSTATS, 2012). Lake Chivero the main source of raw water is heavily polluted (Magadza, 2007). This has led Norton into persistent water supply problems. In spite of this water supply challenge, Norton has continued to grow from 3 suburbs in 1980 to 11 (Chigonda, 2010). Such phenomenal growth has added to the water supply problem. The impact of inadequate water supply in Norton, just as in other towns in the country, is mainly being felt by the residents of newly established suburbs, like Maridale, Marshlands as the water supply infrastructure's capacity is no longer able to effectively accommodate them due to already high demand. Low supply of water by the local authorities has resulted in a high demand for alternative water sources for new residents in the form of boreholes and wells to substitute tap water (Makwara and Tavuyanago, 2012). A study carried out by Chigonda (2010) revealed that Norton residents that were not getting adequate water supply (75 %) had dug wells at their homes, of which 60 % had shallow wells and 15 % fairly deep wells. The remaining 25 % had boreholes and others would outsource from neighbours' wells or from acquaintances residing in areas with a better council water supply service.

3.1.5. Sanitation issues

Norton Town Council sewage treatment plant is not fully functional and operates well below capacity. It is operating at 10 % capacity. Untreated raw sewage is channelled directly into Lake Manyame posing health hazards to the environment. In addition, 65 % of Norton residents are connected to the sewerage reticulation system with 35 % relying on pit latrines and septic tanks. (www.nortontown.com). There is constant choking of sewer pipes due to overcrowding and this poses a threat particularly to shallow and unprotected wells. Boreholes and wells located close to contaminates are vulnerable to contamination and led to the spread of water borne diseases. A study done by Dzwairo et al. (2006) showed that pit latrines are capable of contaminating groundwater within 5m radius.

3.1.6. Economic activities

According to David (2015) Norton Town is relatively small in terms of its geographical coverage. It used to house some big companies like Dandy Zimbabwe, Battery Company, Forge Company Hast, Pulp and Paper, which have downsized their operations. The area houses Lake Chivero a booming fishery business which also gives another lucrative source of livelihood. Norton has several conditions favourable to urban food production. These include a relatively wet climate and large open spaces. The agricultural activity in the study area is mainly crop production. Maize is the main crop produced during the wet season. Vegetables are produced throughout the year. At most, 1 % of households within the residential areas keep small livestock, such as poultry (Mbiba, 2000).

3.1.7 Geology and soil

Geology is the main controlling factor in groundwater hydrology (Hudec, 2005). The nature and the properties of the rock aquifer, specific yield, retention, the chemistry of water are governed by the geology of the environment (Ocheri et al., 2014). Geology in Norton occurs largely in secondary aquifers, dominated by fractured meta-sediment formations, granite and basaltic formations as shown in Figure 8 (Baldock et al., 1991). The geology type is a mixture of consolidated and unconsolidated rock. Soils vary from clay to sandy soils, a mixture of poorly and well drained soils.

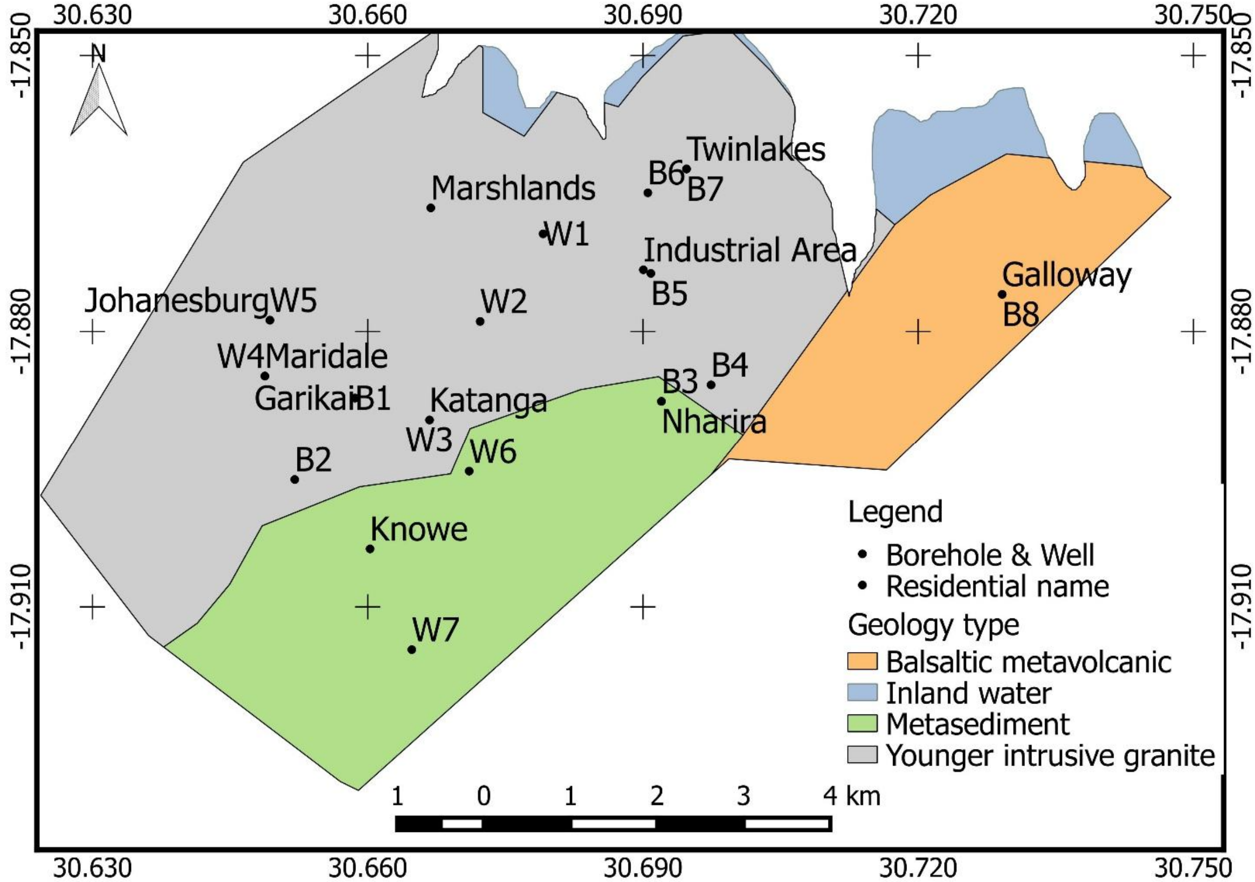

Figure 8: Geology type of Norton*: adapted from (Geological Survey, 1963)*

CHAPTER 4
MATERIALS AND METHODS

4.1. Study design

4.1.1. Selection of study site

Groundwater in Norton is becoming increasingly vulnerable to pollution due to rapid urbanization (Chigonda, 2010). Also, Norton Town is in close proximity with Lake Chivero which is heavily polluted with organic matter, blue-green algae, heavy metals and faecal coliforms (Nyamangara et al., 2013). The study area has water and sanitation problems, with choked sewer, unprotect wells, one tanker and a few boreholes available to the population (Chigonda, 2010). In addition, Norton Town Council has been unable to match water supply demand by its growing population density. People have resorted to the use of shallow wells as a substitute of tap water (Mukuhlani and Nyamupingidza, 2014). According to WHO (2008), the 2008 outbreak of cholera is an example of poor water quality management in Southern Africa. Hence, there is an urgent need to thoroughly investigate the impact of groundwater vulnerability to protect water resources for present and future generational needs. The study was therefore conducted in the town of Norton, situated within the Manyame Catchment of Zimbabwe.

4.1.2. Identification of potential groundwater pollution sources

The following are the methods that were used to identify potential pollution sources. Two categories of potential pollution sources that enter groundwater resources were identified from literature as, point source pollution, and non-point source pollution. Point source pollution comes from a specific place that can be pin-pointed as the source of the pollution contaminating a waterbody. Examples include effluent outflows from waste treatment plants, factories. Non-point source pollution is the pollution of water resources from a wide variety of human activities that take place over a large geographic area that include residue of human agricultural practices and fertilizers (EPA, 2003). A feedback-based methodology of comprehensive interviewing system was later carried out to ascertain the existence and exact location of potential pollution sources. The interview targeted mainly the Norton Town council employees that are well versed with the geography of the town. Choice of adopting the interview approach was based on the fact that verbal and non-verbal cues prompt more complete and better explained responses.

Norton image of 5 January 2016, Landsat 8 was digitized for potential pollution sources that were for high resolution of 30 m x 30 m that include landfill, urban agriculture and irrigation. The digitized polygons were converted to shape files using Q-GIS software, and a potential pollution source map was created. Field surveys were also undertaken to identify potential pollution sources that are of low resolution. A Global Positioning System (GPS) measurement and processing technique was used for the purpose of rectifying medium and high resolution satellite imageries and establishing ground control points (GCP). A GPS has the ability to record precise coordinates of locations that can be identified within an image and the image can be georeferenced. Care was taken to minimize the positional error of any point on these maps.

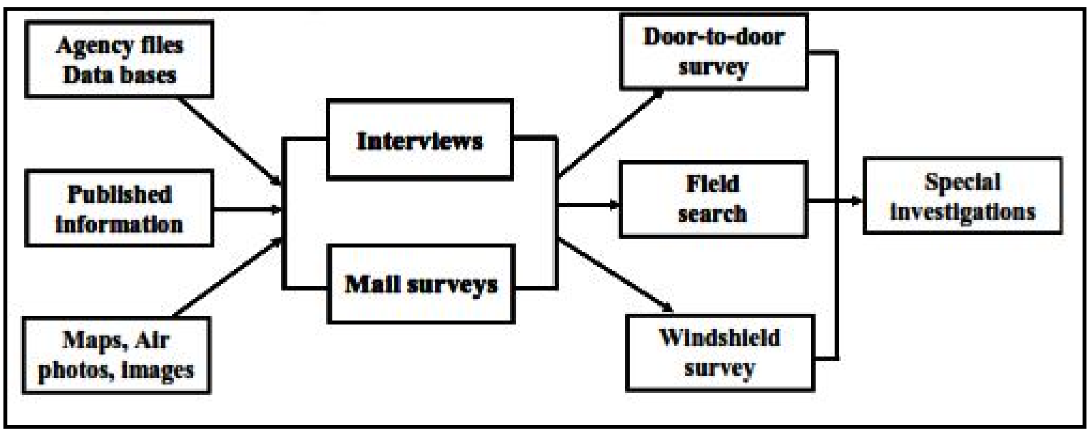

Figure 9: Potential pollution sources identification: ***Adapted from (Ferral et al., 2014)***

4.1.3. Selection of sampling sites

Groundwater sampling was carried out to determine if water quality parameters were falling within the recommended limits to assess drinking suitability and aesthetic value. The sampling points were systematically selected based on their closeness to potential pollution sources. The location of the wells and boreholes was determined using a Geographical Positioning System (GPS) and coordinates georeferenced to the Universal Transverse Mercator Zone 36 south projections based on the WGS84 Datum. Figure 10 shows the location of the selected groundwater sampling sites in Norton. A total of 15 sampling sites were selected and these included 8 boreholes and 7 wells. Table 3 shows attributes of groundwater sampling sites.

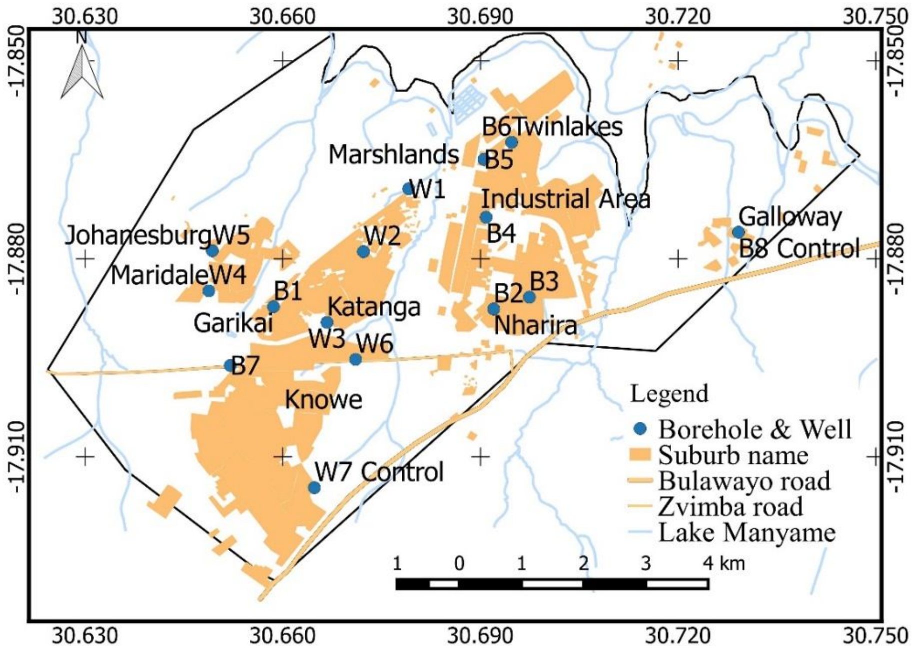

Figure 10: Location of groundwater sampling points in Norton

Table 3: Attributes of groundwater sites

Groundwater site	Distance from potential pollution source (m)	Soil type	Groundwater depth (m)	Geology type
B1	6	clay	40	granite
B2	65	clay	42	granite
B3	21	sandy	40	metasediment
B4	18	sandy	45	granite
B5	8	sandy	40	granite
B6	19	sandy	40	granite
B7	5.5	sandy	45	granite
B8	35	sandy	55	Basaltic metavolcanic
W1	3	sandy	5	granite
W2	7	sandy	7	granite
W3	8	clay	7	granite
W4	6	clay	9	granite
W5	7	clay	8	granite
W6	12	clay	7	metasediment
W7	5	sandy	6	metasediment

4.1.4. Selection of parameters for analysis

In order to assess groundwater quality, the water samples were analyzed for different physico-chemical properties such as temperature, turbidity, pH, Dissolved Oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), total hardness, chlorides, iron, sulphates, faecal coliforms and total coliforms. The above parameters were chosen in line with studies undertaken by Hoko (2005) and Dzwairo et al. (2006) which demonstrated that turbidity; DO, pH and electrical conductivity in groundwater quality are problematic with regards to onsite sanitation.

Chloride has been the most commonly investigated chemical indicator of groundwater contamination from latrines because of its high concentrations in excreta and its relative mobility in the subsurface. Chloride is non-toxic to humans, but elevated levels make water unpotable due to the salty taste. Chloride concentration in excess of about 250 mg/L can give rise to detectable taste (WHO, 2010). According to Afuye et al. (2015), turbidity does not have direct health implication, but there may be other consequences such as interference with water treatment, rejection by the consumers and staining of clothes and household fittings. Hoko (2005), emphasized that, the research of these parameters such as chlorides, turbidity, faecal coliform, sulphates, total coliforms, conductivity and total hardness (magnesium and calcium) is important for development studies.

4.2. Methods of sampling and frequency

Discrete grab water samples were collected from the 15 sampling sites for onsite measurements and laboratory analysis. The spouts of hand-pumps were cleaned and sterilized before sampling with methylated spirit to prevent contamination of samples. Extreme caution was exercised to ensure that samples were not subject to outside interference. To make sure groundwater samples were representative, boreholes were purged to remove stagnant water before groundwater samples were collected (EPA, 2003). Samples for micro-biological analysis were collected using sterilized 500 ml glass bottles whilst samples for physical and chemical analysis were collected using plastic 500 ml containers. Samples were properly sealed, labelled with date, time, and location of the area. They were preserved with ice at lower temperature inside coolers for storage and transport, ready for laboratory analyses. Groundwater samples for laboratory investigations were collected according to the APHA (2012) sampling guidelines on the standard operating procedures for examination of water and wastewater. Water samples were collected from 8 boreholes and 7 wells from different places in the study area. Four sampling campaigns were carried out beginning of January 2016 till end of February 2016, giving a total of sixty (60) groundwater samples.

4.3. Methods of water quality analysis

Methods of water quality analysis included onsite measurements and laboratory measurements. Parameters that were measured onsite included temperature, turbidity, dissolved oxygen (DO) and pH. Electrical conductivity, total dissolved solids (TDS) sulphates, chlorides, iron, total hardness, faecal coliform and total coliform were analysed in the laboratory. Methods of water quality analysis were according to standard methods for examination of water and wastewater specified by American Public Health Association (APHA, 2012). Table 4 shows water quality parameters, method and instruments used for analyses.

Table 4: Equipment and methods used for analysis

Parameter	Method	Instrument /Equipment
pH	Electrometric	pH meter
Temperature	Electrometric	Thermometer
DO	Electrometric	DO meter
Turbidity	Electrometric	Turbidity meter
Electrical Conductivity	Electrometric	Conductivity meter
TDS	Electrometric	Conductivity meter
Total Coliform	Multiple tube fermentation technique	Bacteriological Incubator
Feacal Coliform	Multiple tube fermentation technique	Bacteriological Incubator
Iron	Digestion followed by Atomic spectrometry	Atomic Absorption Spectrometer
Chlorides	Titration by AgNO3	-
Total hardness	Titration by EDTA	-
Sulphate	Barium sulphate Turbidimetric	-

4.3.1. Laboratory analysis of chlorides

Figure 11 shows titration method of chlorides. Titration is a process by which the concentration of an unknown substance in solution is determined by adding measured amounts of a standard solution that reacts with the unknown (APHA, 2012). Silver nitrate was used to estimate the chloride ions in groundwater. Potassium chromate serves as an end point indicator for the determination of chloride with silver ions to form a brick-red silver chromate precipitate as shown below.

Figure 11: Chlorides analysis in the Civil Engineering laboratory at the University of Zimbabwe

4.3.2. Quality assurance and quality control

Table 5 shows quality assurance and quality control measures that were carried out during sampling and analysis periods. Quality assurance refers to a system of documented procedures and plans established to ensure that the water monitoring program produces data of known precision and bias (Francy et al., 1998). This includes calibration processes, staff training programs, written procedures and record keeping. Quality control refers to operational activities that confirm the quality assurance methods are functional and information collected is accurate, precise and properly recorded. Quality assurance and quality control produce data of good quality.

Table 5: Quality assurance and quality control

Step	Quality assurance	Quality control
Use of specialised equipment	Following calibration procedures	Any equipment failing calibration was not used
Sample collection	Following methods outlined in water quality sampling manual (APHA, 2012), keeping records with clear site locations, appropriate samples for each location, sample labelling, defined bottles, replicates on samples	Use of field blanks
Record keeping	Double recording of data manually and electronically	Data validation-data rechecked by an assistant
Storage and transport	Use of ice, foil paper, minimisation of time between collection and storage	Fridges and freezers in good condition
Sample analysis	Methods based on Standards Methods for the Examination of Waste and Wastewater, another set of samples were sent for analysis at the department of Biological Sciences at the University of Zimbabwe	Use of calibration standards and laboratory blanks

4.4. Methods of data analysis and interpretation

Statistical Package for Social Sciences (SPSS) version 23 is a software package that was used for the purpose of statistical analysis of the data. SPSS Software was chosen because it is an integrated family of products that offers a rich set of capabilities for every stage of the statistical data analytical process from planning to data collection to analysis, reporting and deployment. Data from groundwater samples was tabulated in the form of the arithmetic mean, range, and standard deviations. Analysis of Variance (ANOVA) was used to test if there is any significant difference between the measured parameters and different sites.

The Principal Component Analysis (PCA) within the SPSS software was used for data reduction. PCA is a statistical technique for data analysis and processing (Tipping and Bishop, 2010). PCA reduces dimensions of the multi-index data by changing initial random vectors related to its components into new random vectors which are not related to its components. Secondly, the variance is considered to be the measurement of information and dimension of high variant space is lowered making the calculating process much easier (Jing and Yufei, 2011).

4.4.1. Spatial and temporal variation of groundwater parameters

Spatial and temporal variation maps were created using geo-statistical method in ILWIS 3.3 version. The Moving Average Interpolation technique was selected. It was selected on the bases that it works well with point maps, relatively quite easy to use and unlike other methods such as Kriging, IWD (Inverse weighting distance) which have problems of non-stationarity and requires sophisticated programming (EPA, 2004). Spatial variation maps that were created for different campaigns were compared and the aspect of temporal was achieved.

4.5. Choice of groundwater vulnerability method

Choosing the best method for groundwater vulnerability depends on a number of factors that include, the data availability, the purpose of the map, the scale of mapping, spatial data distribution and the hydrogeological setting (Musa and Katsina, 2009). The better the data availability, the more detailed the map. Aquifer Vulnerability Index (AVI) is one of the most commonly used model and it requires less data input. A study that was done in British Columbia by Denny et al. (2007) concluded that DRASTIC and AVI methodologies yielded similar results. Aquifer Vulnerability Index (AVI) model was the suggested method considering the above.

4.5.1. Determination of groundwater vulnerability using (AVI)

Aquifer Vulnerability Index (AVI) method was used for mapping the vulnerability of groundwater. It is based on two key parameters, 1) thickness of each sedimentary unit above the uppermost aquifer, and 2) estimated hydraulic conductivity of each of these layers. Using groundwater records, these parameters are combined to obtain a reasonable estimate of the hydraulic resistance of the protective aquitard cover if present at each site. AVI regions of iso-vulnerability (very low, low, moderate, high and very high) are obtained (Stempvoort et al., 2013). AVI maps are merged with other GIS-referenced information, such as land use. Table 6 shows Model inputs used to compute Aquifer Vulnerability Model.

Table 6: Model inputs used to compute AVI Model

Model inputs	**Method of acquiring inputs**
Hydraulic conductivity	Estimated hydraulic conductivity from literature
Thickness (soil media)	Digitized soil map from Zimbabwe Geology Survey
Depth to water level	Field measurement, interpolation in GIS and create contour maps
Aquifer media (geology map)	Digitized geology map from Zimbabwe Geology Survey
Slope media	Dem hydro-processing
Land cover map	Classified images from USGS Glovis (http://glovis.usgs.gov)

4.5.2. Weighting and rating model inputs

AVI model inputs were processed in GIS using ILWIS software to create Aquifer Vulnerability Index map. The model yielded a numerical index that was derived from ratings and weights assigned to the six model parameters. The significant media types or classes of each parameter represent the ranges, which were rated from 1 to 10 based on their relative effect on the aquifer vulnerability (Table 9). The six parameters were then assigned weights ranging from 1 to 5 reflecting their relative importance (Table 7) (Kallioras et al., 2006). The following equation was used to calculate AVI map.

$$Equation1{:}Index = \text{depth to water level R} * \text{wD} + \text{soil media R} * \text{wS} + \text{geology R} * \text{wG} + \text{slope R} * \text{wSL} + \text{land cover R} * \text{wLC} + \text{hydraulic conductivity R} * \text{wC}$$

Where:

- R -rating; w-weight; D-depth to water level; S-soil media; G-geology; SL-slope; LC-land cover; C-hydraulic conductivity

The numerical ratings and weights for individual parameters were determined from EPA manual and from the application of AVI to other study areas within similar environments (Aller et al., 1987) . This makes the model suitable for producing comparable vulnerability maps on a regional scale. Once the index is calculated, susceptible areas can be classified as very low, low, moderate, high and very high. Table 7 and Table 9 below shows the weights and rating of AVI parameters respectively;

Table 7: Weights of AVI Parameters: ***Adapted from (Aller et al., 1987)***

Parameters	AVI weights
Hydraulic conductivity	3
Thickness (soil media)	2
Depth to water level	5
Aquifer media (geology map)	3
Slope map	1
Land cover map	5

4.5.3. Hydraulic conductivity

Estimated hydraulic conductivity from Aller et al. (1991) was used in the model and a raster map was created from the type of sediment that suited Norton Town. The table below shows the estimates of hydraulic conductivity and overall weight given is 3.

Table 8: Conductivity (K) estimates for various sediments: ***Adapted from (Aller et al., 1991)***

Sediment type	Standard code	Hydraulic conductivity
Gravel	A	1000 m/d
Sand	B	10 m/d
Silt sand	C	1 m/d
Silt	D	10^{-1} m/d
Fractured till, clay or shale (0-5m) from ground surface	E	10^{-4} m/d
Fractured till, clay or shale (5-10m) from ground surface	F	10^{-3} m/d
Fractured till, clay or shale (10m) from ground surface but weathered based on colour: brown or yellow	F	10^{-4} m/d
Massive till or mixed sand-silt-clay	G	10^{-5} m/d
massive clay or shale	H	10^{-6} m/d

Table 9: AVI Model parameter rating: ***Adapted from (Aller et al., 1987)***

Parameter	Range	Rating
Depth to water level (m)	0-2.5	10
	2.5-5	9
	5-10	7
	10-15	5
	15-25	3
	25-35	2
	55+	1
Slope (%)	0-2	10
	2-62	9
	6-12	5
	12-18	3
	18+	1
Land cover	Animal husbandry, horticulture, urban and agricultural area	8
	Palm tree and other permanent crops	5
	Water body	3
	Swamps and marsh land, grass and wetland	2
	Forest land	1
Hydraulic conductivity	1000 m/d	10
	10 m/d	9
	1 m/d	8
	10^{-1} m/d	7
	10^{-2} m/d	5
	10^{-3} m/d	4
	10^{-4} m/d	3
	10^{-5} m/d	2
	10^{-6} m/d	1
Soil media	Gravel	10
	Sand	9
	Shrinking and/or aggregated clay	7
	Sandy loam	6
	Loam	5
	Silty loam	4
	Clay loam	3
	Non-shrinking and non-aggregated	1
Aquifer media (geology)	Granite	7
	Basalt	6
	Meta-sediments	3

4.5.4. Geology and soil media

The dominant soils in Norton are chromic Luvisols (clay soils) and Ferralic Cambisols (sandy loam) (Mugandani et al., 2012). Geology and soil map for Norton was obtained from Zimbabwe Geological Survey. Maps were digitized and raster maps were created using ILWIS software. The created raster maps were given weights and ratings as already explained in Figure 7 and Table 9.

4.5.5. Depth to water level

Figure 12 shows the measurement of depth to water level. This was done using an analogue multimeter. An analogue multimeter is a direct current ammeter used to measure an electric current (Jay, 2007). However, an electric current can be compared to water current. Depth to water level is a significant parameter because of its ability to control contaminates to reach groundwater. Groundwater depth to water level was assigned weights and ratings as shown in Table 7 and Table 9 respectively. High range of depth to water levels for example 55 m is given the least rating of 1 whilst low range (0-2.5) m is given the highest rating of 10.

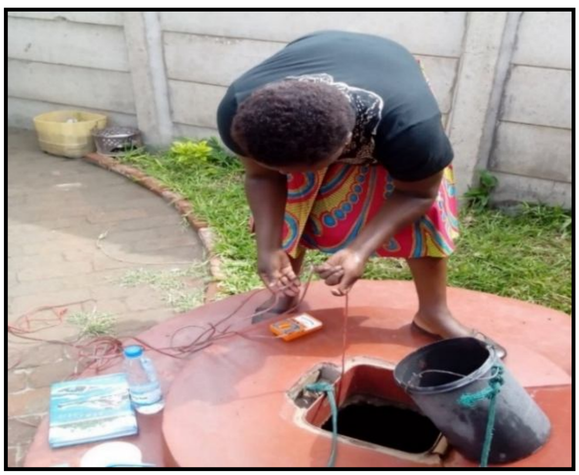

Figure 12: Water depth measurement using analogue multimeter

4.5.6. Slope from DEM Hydro-processing

The development of DEM processing algorithms as well as relevant software to extract hydrologic information from DEM is increasing and makes it widely applied (Singh, 1995). A full topologically based hydrologic network was extracted from DEM hydro-processing. Advanced Space born Thermal Emission Radiometer (ASTER) 30m DEM covering Norton Town was selected as this dataset has a near global coverage at a resolution suitable for hydrological analysis of larger areas. GIS software Integrated Land and Water Information System (ILWIS) and remote sensing were used from the DEM hydro processing. The software delivers a wide range of features including import/export, digitizing, editing, analysis and display of data, as well as production of quality data (Maathuis et al., 2006). Slope map was extracted from DEM hydro-processing. The slope map was assigned an overall weight of 1 and ratings as shown in Table 7 and 9 respectively.

4.5.7. Land cover

Land cover assessment was done using supervised classification in ILWIS Software. A map showing built –up, bareland and irrigated crops was created. Landsat 8 was obtained from the US Geological Survey website for the year 2015. Table 10 shows the land cover classification technique that was used. Table 9 illustrates the land cover rating that was also used in coming up with a slope rating map. The false color composites were used in the classification process because of their ability to enhance image interpretation that are critical in assessing changes in land cover as a result of urbanization (Gumindoga et al., 2014).

Table 10: Land cover

Land cover	**Description**
Built-up	Residential, industrial, commercial and services, solid waste landfills and construction sites
Bareland	Fallow land, bareland
Irrigated crops	cultivated land or land being prepared for raising crops, irrigated crops

Sensor	**Date of acquisition**	**Spatial Resolution (m)**	**Bands used**	**Cloud cover (%)**
Landsat 8 OLM	2015-09-30	30	5,4,3	0

This chapter was showing the methods that were used to carry out this study, to map potential pollution sources, to determine spatial and temporal variation of groundwater quality and to determine groundwater vulnerability. The next chapter will illustrate the results of the study and discussions.

CHAPTER 5
RESULTS AND DISCUSSION

5.1 Mapping potential pollution source

Figure 13 shows potential pollution sources from Norton Town area. Potential pollution sources were identified from Google Earth map and Ground Control Points. The growth of suburbs for example Maridale, Marshlands, Galloway in Norton is relative to the growth of population. Pollution increases parallel to population growth (Oktem et al., 2014). On average, human sewage production is 0.12 kg per adult per day, with an average composition of 71 % water and 29 % dry matter (Zevit et al., 2008). Potential amount of human waste produced per day in Norton can be predicted. The population residing within Norton is estimated to be more than 68,000 (ZIMSTATS, 2012), therefore the potential total sewage produced is 8,160 kg per day. Onsite sewage disposal system that include pit latrines, septic tanks, treatment plants as shown in Figure 13 contribute to groundwater pollution in Norton.

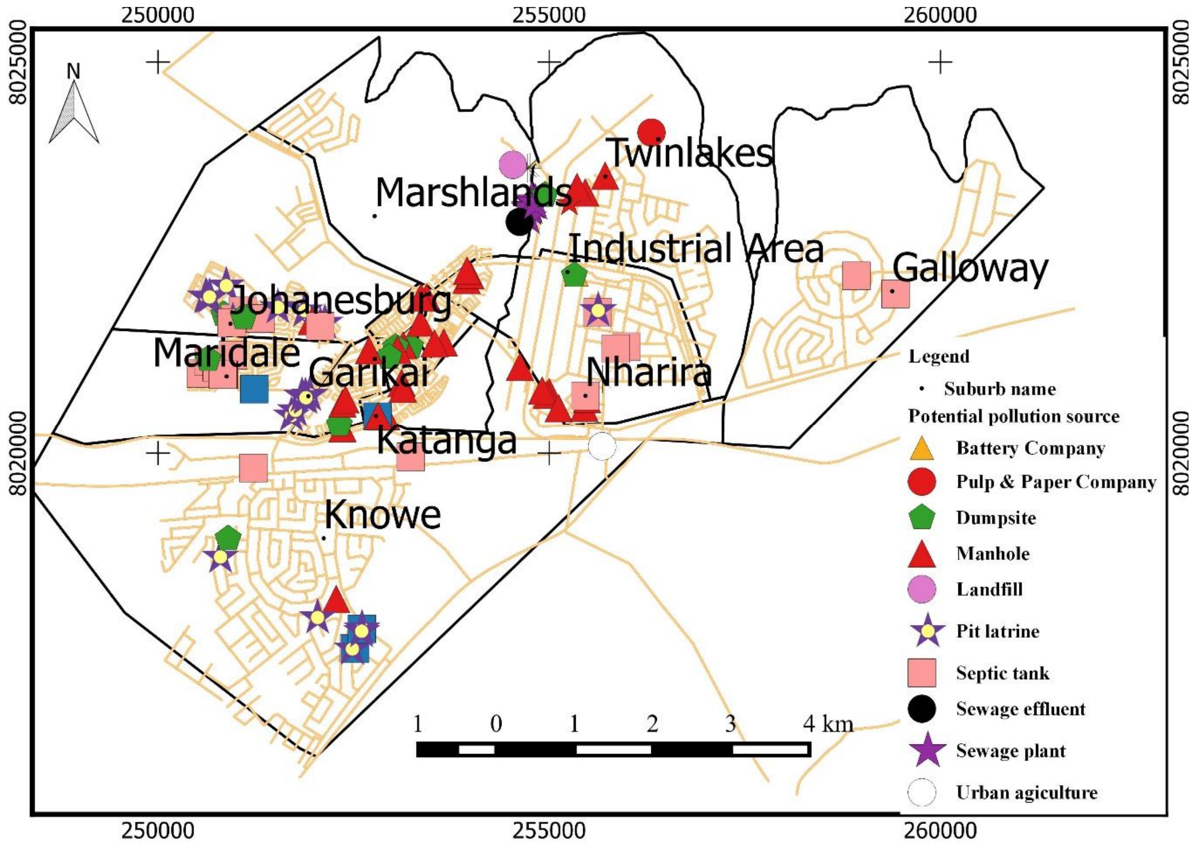

Figure 13: Potential pollution sources in Norton

Information obtained from the interviews carried out showed that onsite sanitation is a major challenge in the high residential areas in Norton. While it has been estimated that there are over 1000 on-site sewage disposal system, there is little information on how many of these are properly functioning, how many are still in service or how often they are serviced. Literature confirms that urban groundwater quality is influenced by onsite sanitation, landfills, illegal dumpsites and the rate of urbanization in a study done in Nigeria (Ocheri et al., 2014). Agricultural practices for example the use of pesticides, fertilizers and herbicides, industrial activities and improper disposal of solid wastes and wastewater are the main causes of groundwater pollution in Norton. This notion is supported by UNEP (2003). This study concludes that potential pollution sources are affecting groundwater sources.

5.2 Groundwater quality

The water quality standards for drinking water have been specified by the Standards Association of Zimbabwe and World Health Organization, SAZ (1997) and WHO (2010). Table 11 shows the results of water quality suitability of Norton Town. Parameters that exceeded the 50 % for WHO include the following total hardness, sulphates, chlorides, faecal coliform and total coliform exceeded the WHO limit by 53 %, 53 %, 53 %, 73 % and 87 % respectively. Electrical conductivity, total hardness, sulphates, faecal coliform and total coliform exceeded the SAZ limit by 67 %, 53 %, 53 %, 73 % and 87 % respectively. Parameters that were observed to be below 50 % limit for both SAZ and WHO include, turbidity, pH, dissolved oxygen, total dissolved solids and iron. The descriptive statistics of the water quality parameters are presented in Table 12. Table 12 shows the amount of groundwater variables in comparison with SAZ (1997) and WHO (2010) recommended maximum permissible limits for drinking purpose. Groundwater parameters are presented in the form of mean, minimum, maximum, kurtosis, standard deviation and skewness.

Table 11 : Water quality suitability for Norton Town

Sampling sites	Temp	Turbidity	pH	DO	EC	TDS	Hardness	Iron	Sulphates	Chlorides	FC	TC
B1	25.2	7.6	7	4.1	363	182	512	0.48	388	112	0.5	27.5
B2	25.3	0.7	7.5	5.2	405	202	474	0	63	98	0	2.5
B3	25.3	0.9	7.1	5.5	303	153	388	0.01	163	62	0	0
B4	25.8	1.3	7	5.2	238	106	333	0.05	113	292	0	495
B5	26	1.2	7	0.3	1217	551	1662	0.05	1125	461	11.25	0
B6	25.2	1.4	6.7	1.1	1051	526	2007	0.07	1738	491	1.25	92.5
B7	25.4	1.2	6.7	1.6	560	277	755	0.01	300	91	0.4	5
B8	27.2	1.1	7.6	4.6	274	129	349	0.04	125	99	0	145
W1	25.1	3.3	7.1	5.6	274	178	320	0	775	358	2246	2007
W2	26.2	1.4	6.9	2.3	1472	615	1062	0	563	714	2448	2470
W3	25.9	33.5	7.3	6.2	620	348	883	0	500	319	2480	2427
W4	25.6	7.9	7.3	3.6	1000	497	733	0.02	113	53	2715	2712
W5	25.6	21.4	8.1	5	368	185	513	0.02	150	98	1860	2012
W6	26.2	13.1	6.9	3.7	299	150	301	0.07	88	842	1351	427
W7	25.3	5.5	7.5	1.3	225	99	179	0	625	142	2108	2040
Standard WHO (2010)	**	<5	6.5-8.5	**	1380	250	500	0.3	250	300	0	0
% sample > WHO limit	**	40	0	**	6.7	40	53	6.7	53	53	73	87
SAZ 560: (1997)	**	<5	6.5-8.5	>5	300	250	500	0.3	250	250	0	0
% sample > SAZ limit	**	40	0	40	67	40	53	6.7	53	47	73	87

Table 12: Summary of descriptive analysis for water quality parameters

	pH	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Feacal coliform (cfu/100mL)	Total hardness (mg/L)	EC (µS/cm	Sulphates (mg/L)	Chlorides (mg/L)	Temper ature	TDS (mg/L)	Total Coliform (cfu/100mL)	Iron (mg/L)
Minimum	6.5	0.48	0.01	0	132	180	50	35.5	23.8	62.4	0	0
Mean	7.17	6.78	3.66	1015	698	580	455	282	25.67	280	991	0.05
Maximum	9.1	105	8.25	7200	2796	175	2750	1560	29	875	6500	0.80
Std. error	0.68	2.13	0.32	245	77.61	590	72.60	38.74	0.12	26.27	216	0.02
Kurtosis	3.1	24.78	-1.26	4.42	3.54	750	5.93	7.08	1.99	0.57	3.96	19.32
Skewness	1.46	4.76	0.14	2.31	1.88	1360	2.32	2.39	0.46	1.22	2.19	4.26
CV	0.52	16.47	2.45	1895	601.13	460	562.3	300	0.97	203	1673	0.14
WHO (2010)	6.5-8.5	1- 5	**	0	500	< 1380	250	< 300	**	<250	0	0.3
SAZ 560: (1997)	6.5-8.5	<5	>5	0	500	< 300	250	< 250	**	<250	0	0.3

5.2.1. Selection of principal parameters in Principal Component Analysis

Principal component analysis was performed on water quality parameters for Norton Town. Table 13 shows the principal component results along with percentage of variance, percentage of cumulative and factor loads values as well as Appendix 1.

Table 13: Eigen value showing principal parameters

Component	Eigen value	Variability (%)	Cumulative (%)
F1	4.322	36.013	36.013
F2	2.846	23.718	59.732
F3	1.296	10.804	70.536
F4	1.047	8.729	79.265
F5	0.840	6.996	86.261
F6	0.641	5.339	91.600
F7	0.518	4.320	95.920
F8	0.285	2.374	98.294
F9	0.179	1.494	99.789
F10	0.017	0.145	99.934
F11	0.007	0.062	99.996
F12	0.000	0.004	100.000

Eigen Values of 1.0 or greater are considered significant as they give a measure of the significance of the factor (Pathak and Limaye, 2011). Factor loading is classified as strong, moderate and weak corresponding to absolute loading values of >0.75, 0.75 - 0.50 and 0.50 - 0.30 respectively. F1, F2, F3 and F4 had Eigen values greater than 1.0 and they are considered significant. F1, F2, F3, F4 and F5 had factor loads of >0.75 and are regarded as being strong. F5 and F6 had moderate loading values of 0.64, 0.52 respectively whilst F8 to F12 had weak loads of 0.29 to 0. Eigen values greater than 1 were considered to be the significant parameters contributing to water quality variations in Norton. These parameters are chlorides, dissolved oxygen, electrical conductivity and faecal coliforms.

5.3 Spatial and temporal variation of turbidity, faecal coliform, EC, chlorides and total hardness

To estimate the spatial and temporal variation of the parameters, the geostatistical method Moving Average interpolation in ILWIS version 3.3 was used. The colours that were used, were adopted from Environmental Management Agency (EMA) of Zimbabwe which state that blue colour is environmentally friendly, green is low environmental hazard, yellow is medium environmental hazard and red is high environmental hazard.

5.3.1. Spatial and temporal variation of turbidity

Figure 14 shows the spatial and temporal variation of turbidity. The minimum and maximum values were 0.48 NTU and 105 NTU with a mean value of 6.78 NTU. Maximum turbidity value of 105 NTU was recorded for W3, whereas minimum value of turbidity 0.48 NTU was for B6. All the boreholes had turbidity less than 0.48 NTU. During the four sampling campaigns W1 to W8 (all the wells) were found turbid and exceeded the WHO guidelines of 5 NTU as compared to the boreholes. This could be attributed to the fact that wells are shallow, open and are situated in close proximity with potential pollution sources (Table 3). Turbidity was mainly caused by contamination from surface water during rain period of January and February. The results from ANOVA showed significant variation between W1 to W8 ($p<0.05$) measured from different sampling sites. The values reported in this study are much lower than those reported for Bindura in Zimbabwe which ranged from 0.78 to 428 for boreholes (Hoko, 2008). This study concludes that groundwater was highly turbid in all the wells and cannot be considered safe for drinking purposes.

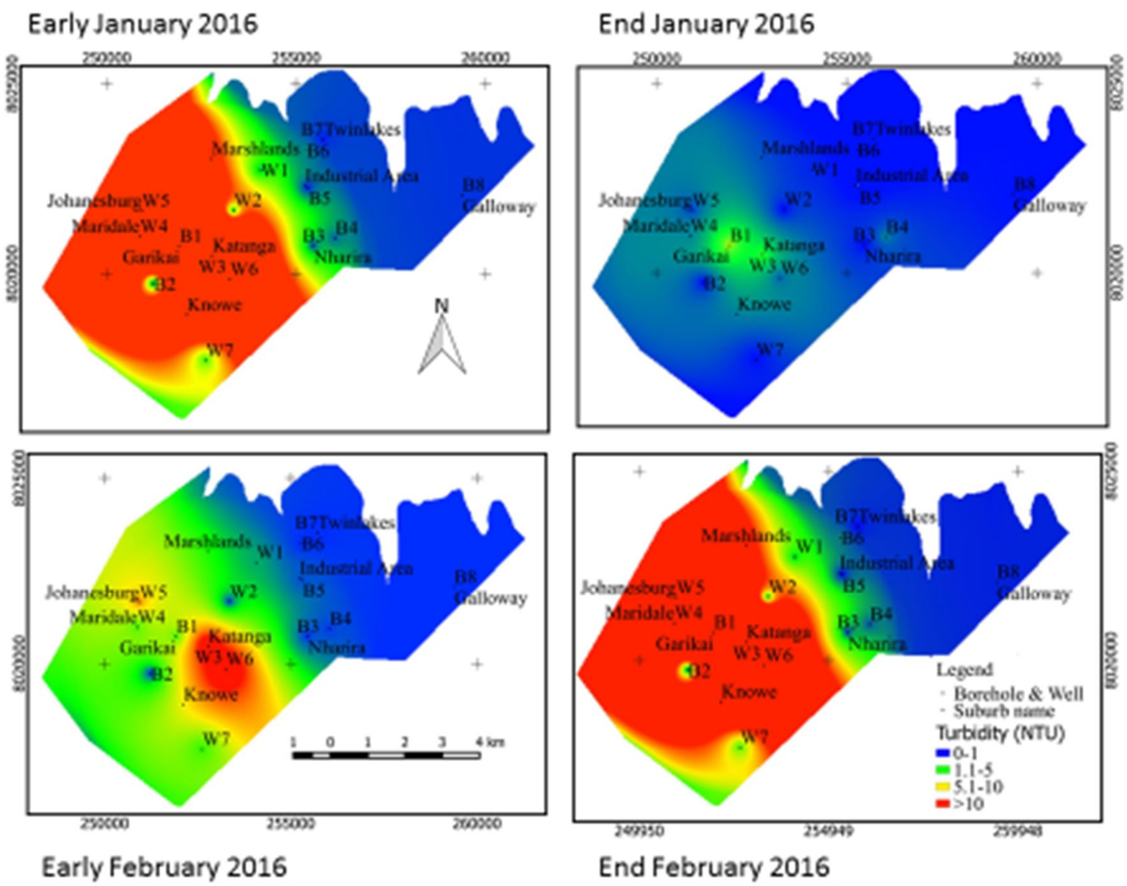

Figure 14: Spatial and temporal variation of turbidity

5.3.2. Spatial and temporal variation of faecal coliform

Figure 15 shows the spatial and temporal variation of faecal coliform. Feacal coliform ranged from 0 cfu/100mLto 7200 cfu/100mL, with a mean value of 1015 cfu/100mL. During the period early January, low levels of faecal coliforms were measured in all sampling sites. There was an increase in the faecal coliforms during the second period of sampling campaign. During the third and fourth sampling campaign of early February to end February, all well sites generally showed higher values of faecal coliforms with the exception of all the boreholes. This could be attributed to the fact that most of the wells are shallow, uncovered and they are at risk of contamination from onsite sanitation. Also, this could be attributed to the fact that wells are in close proximity to pollution sources (Table 3) and the impact of rains during this period. The results by ANOVA showed no significant variation between the faecal coliforms ($p<0.05$) measured from different sampling sites. Studies done by Hassou et al. (2014) in Morocco showed that faecal coliform is good indicator for faecal water pollution. This study concludes that all the wells had faecal water pollution and the water cannot be safe for drinking.

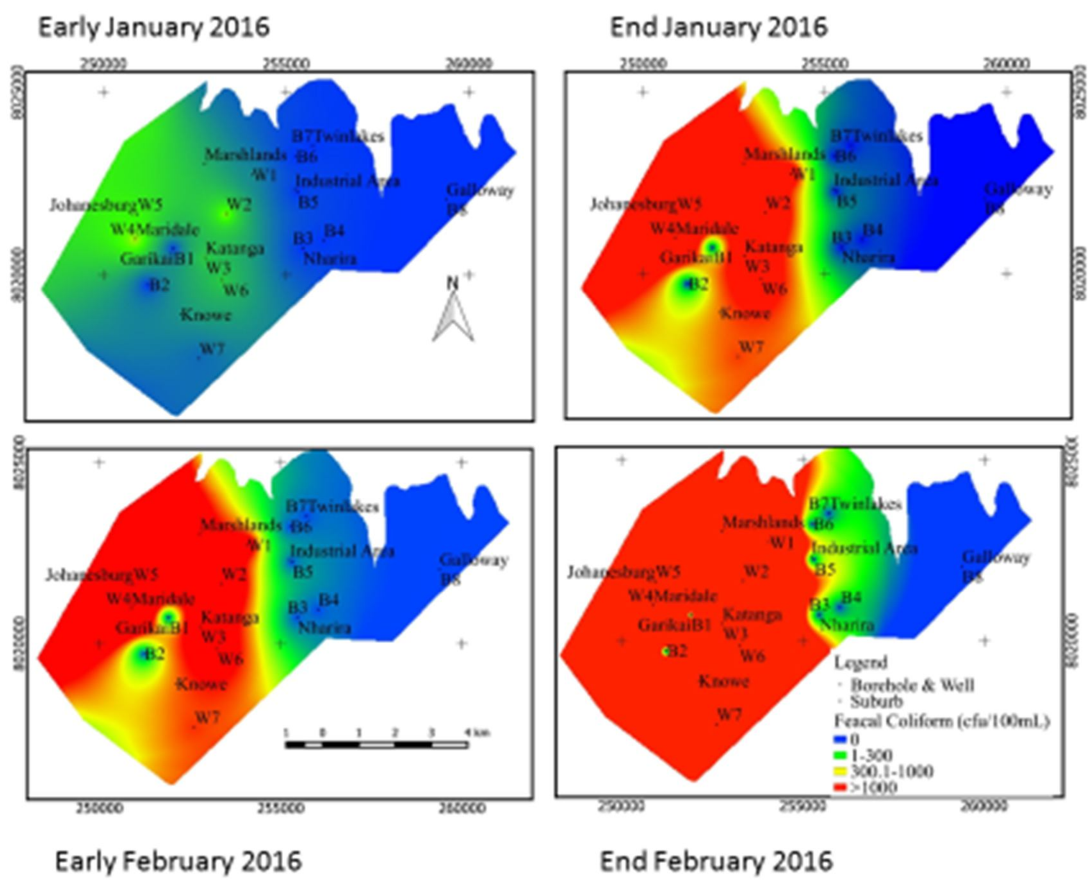

Figure 15: Spatial and temporal variation of faecal coliforms

5.3.3. Spatial and temporal variation of total hardness

Figure 166 shows the spatial and temporal variation of total hardness in the selected sampling sites of Norton Town. During the sampling period, total hardness values ranged from a minimum of 132 mg/L to a maximum of 2796 mg/L and a significant average of 698 mg/L. Total hardness concentration values in W2, W4, B6 and B7 had higher values. Sites B6 and B7 located in Twinlakes had high values throughout the four sampling campaigns. This could be attributed to sewage and runoff from the sandy soils particularly from potential pollution sources like building materials. Rain effect to the underground geology might be contributing to high values of total hardness throughout the sampling campaigns. Sites W2 and W4 had higher values during the first and fourth sampling campaigns respectively. This might be due to surface runoff of sewage into the shallow, uncovered wells. ANOVA results showed a significant variation between total hardness ($p<0.05$) in sites B6, B7, W2, W3 and W4 and sampling sites. Studies done by Fathi et al. (2014) in Libya showed lower values of total hardness which ranged from 103 mg/L to 740 mg/L as compared to this study. This study concludes that groundwater sites with high levels of total hardness might not be used for washing purposes as it form curds with the use of soap.

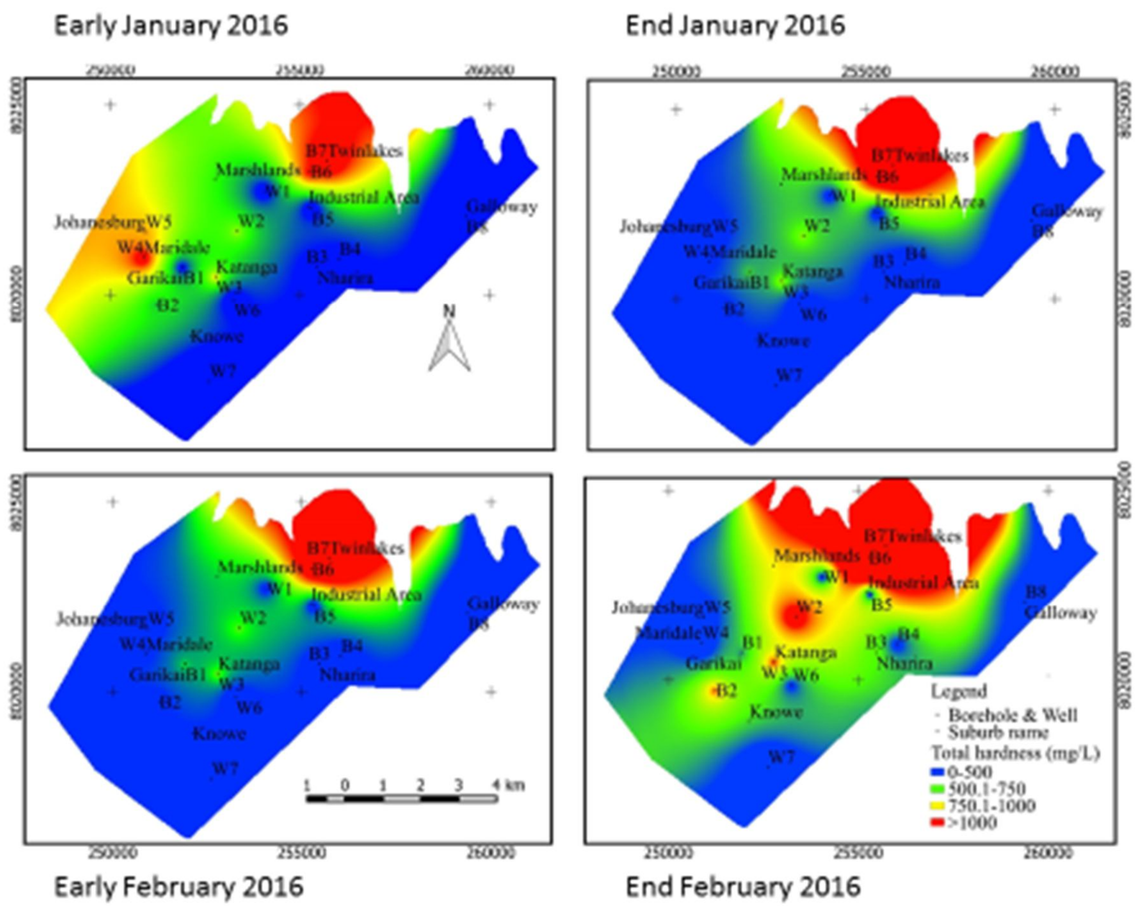

Figure 16: Spatial and temporal variation of total hardness

5.3.4. Spatial and temporal variation of chlorides

Figure 17 shows the spatial and temporal variation of chlorides among the sampled groundwater sites during the four sampling campaigns from early January to end of February. A maximum value of 1560 mg/L was recorded at W6 located in Katanga suburb while a minimum value of 36 mg/L was recorded at B3 in the industrial area. The mean value for chloride was 282 mg/L. Chloride concentration values in W2, W3 and W6 were much higher during the first and second sampling campaigns. This is can be attributed to underground flow contamination from pit latrines and wells. There was a decrease during the third and fourth sampling campaings due to dilution by the rains. The high level of chlorides at site W2 and B7 resulted in the sour taste that was reported by consumers of the water. Chlorides concentrations in B7 could be attributed to rain effect on granite geological formation. Site W2 which is located close to Marshlands surburb had higher chloride values throughout the four sampling campaigns compared to other sites. Excess concentration of chlorides in drinking water gives an unpleasant salty taste. According to Walton *et al*. (2012) chloride has been the most commonly investigated chemical indicator of groundwater contamination from pit latrines because of its high concentrations in excreta and its relative mobility in the surface. WHO (2010) recommends a guideline value of 250 mg/L and any higher value than 1000 mg/L is an indication of polluted water with chloride.

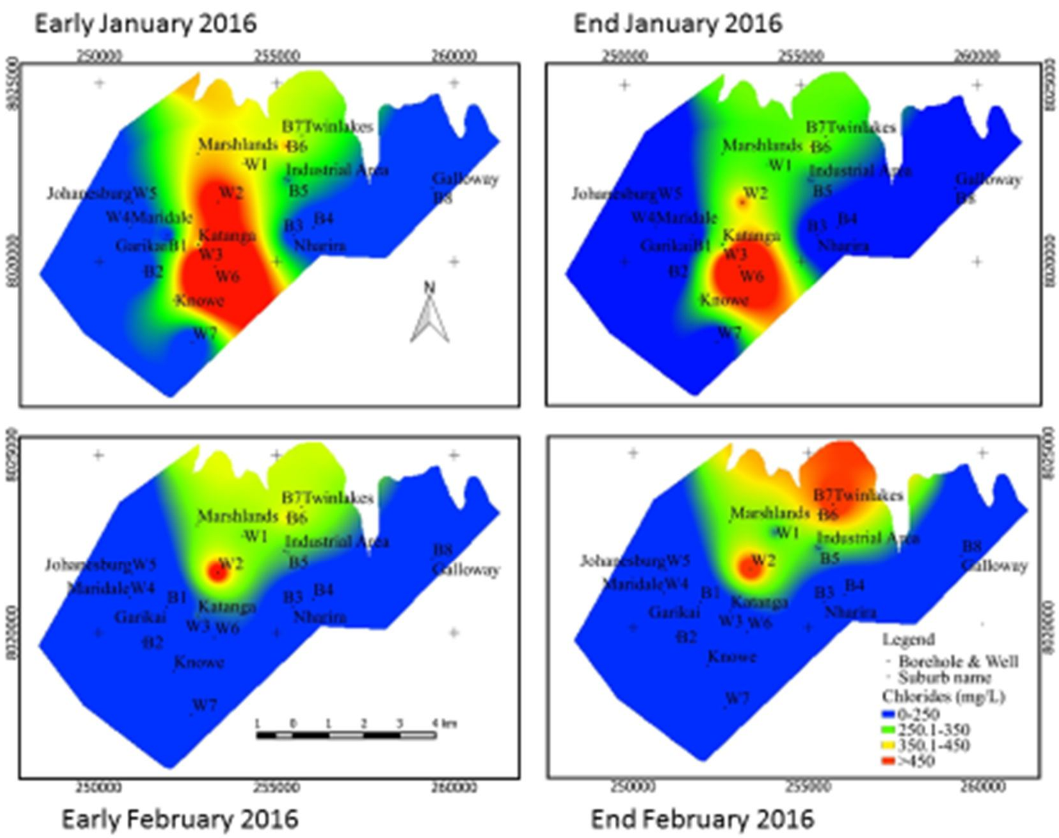

Figure 17: Spatial and temporal variation of chlorides

5.3.5. Spatial and temporal variation of electrical conductivity

Figure 18 shows the spatial and temporal variation of EC from water samples collected in Norton Town. Electrical conductivity values ranged from 180 µS/cm to 1750 µS/cm with a mean value of 580 µS/cm for all the sampling sites. The lowest EC value was recorded at W5 in Johanesburg while the highest EC value was observed at W4 in Maridale Suburb. Maridale Suburb is a high density area that relies on onsite sanitation and during the rain period there might have been well contamination. Sampling points W2 had higher values throughout the sampling campaign and this could have been attributed to potential pollution sources that are in close proximity and the sandy soil type that quickly seeps water through. Sites B5, B6 and B7 had higher EC values throughout the sampling campaign. High EC values for the boreholes could be attributed to the intensive urban farming practiced in the area and the rain effect on the geology. The application of fertilizers contributes to higher concentration of ions into the groundwater (Sajjad et al., 1998). Studies done by Sajjad et al. (1998) in Pakistan observed that EC increased due to wastewater treatment plants, industrial areas, and urban agriculture as they contain soluble salts leading to groundwater contamination.

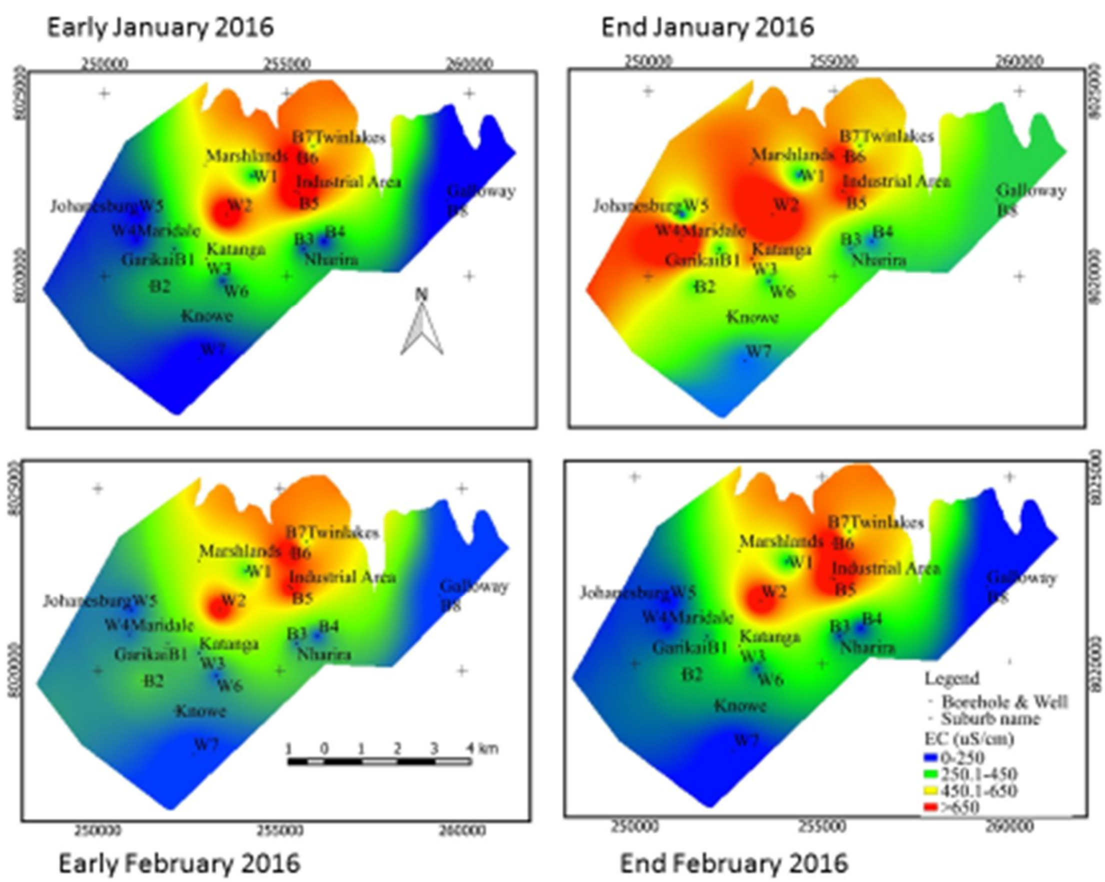

Figure 18: Spatial and temporal variation of EC

5.4. Assessing groundwater vulnerability using AVI Model

The AVI Model was used in this study to perform a vulnerability assessment in the Norton Town area. Six parameters were used namely, depth to water level, slope, soil media, aquifer media, land cover and hydraulic conductivity as discussed below.

5.4.1. Depth to water level

Figure 19 shows the AVI results for depth to water level and water depth rating maps respectively. Depth to water level was derived from field measurements, an analogue multimeter was used to measure the wells and a dip meter was used to measure the boreholes. Inverse Distance Weighting (IDW) interpolation technique was used to create contour map using Q-GIS software. Areas like Marshlands and Katanga fall in the very high range of 0-8 m. These areas were assigned the highest rating because they are nearer to the surface and are prone to contamination (Table 9). Whilst areas >24 m were assiged the least rating because the water table is away from contamination. Depth to water level is a significant parameter of AVI because of its ability to control contaminates to reach groundwater.

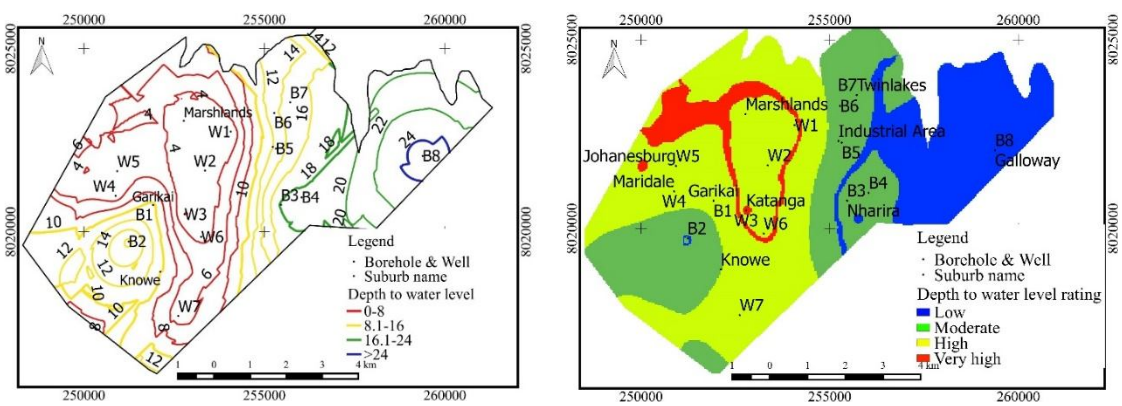

Figure 19 (a): Depth to water level **(b): Water depth rating**

5.4.2. Slope map

Figure 20 shows Norton slope and slope rating maps respectively. Slope map was extracted from Digital Elevation Model (DEM) using ILWIS Software. The slope map was assigned slope rating (Table 9). Slope variation in the study area ranges from 0.75 % to 27.43 %. Knowe and Galloway are classified as areas with low slopes whilst Johanesburg and Marshlands are classified as areas with steep slope. Slope is an important parameter that indicates whether a contaminant will run off or remain on the surface to infiltrate into the ground (Hassan and Hallaq, 2011). Steeper slopes are less vulnerable to contamination because of high run off. Areas with low slope are more vulnerable to contamination because they retain water for a longer period of time (Focazio et al., 2002).

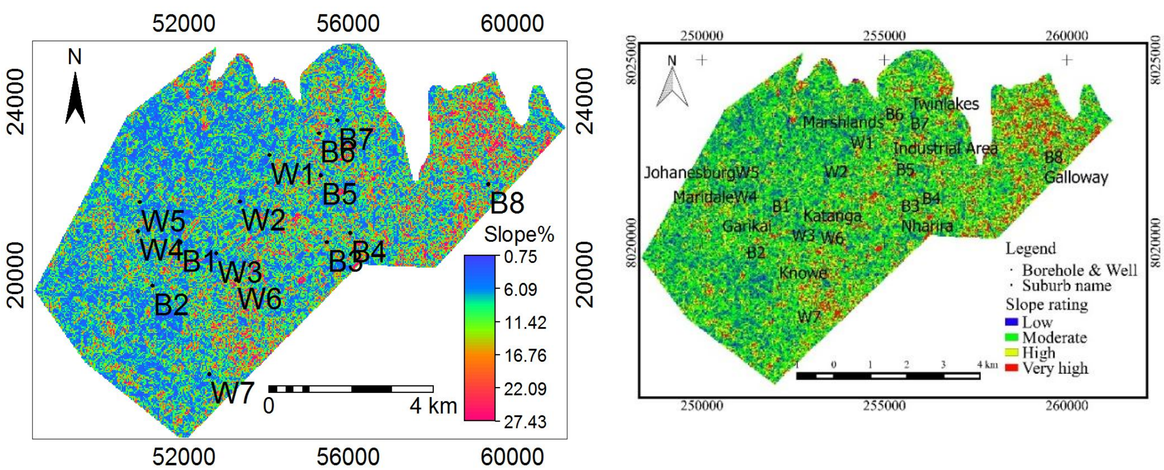

Figure 20 (a): Slope map **(b): Slope rating**

5.4.3. Soil media

Figure 21 shows the soil media types of the study area which area Ferralic Cambisols (sandy soils) and Chromic Luvisols (clay). The soil map was assigned ratings as shown in Table 9. Areas having sandy soils that include Nharira, Galloway, and Knowe are located in high vulnerable range whilst areas having clay soils e.g. Katanga, Garikai fall in the low vulnerable range. Hassan and Hallaq (2011) defined soil media as the soil horizon composed of weathered materials. Soil characteristics influences the amount of pollutant dispersion, the amount of recharge infiltrating into the ground and the purifying process of contaminant. Soil texture and thickness are the two characteristics of the soil that controls the capacity of the contaminates to reach the ground. Soil texture influences the rate at which water percolates into the soil whilst soil thickness determines the length of time contaminates are stored. The soil map of Norton was derived from the Zimbabwe Geological Survey.

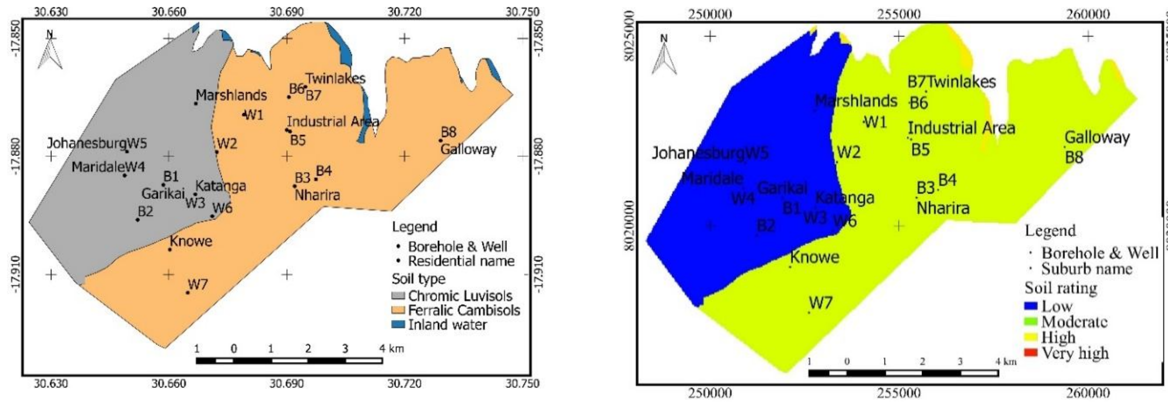

Figure 21 (a): Soil map **(b): Soil rating map**

5.4.4. Aquifer media

Figure 23 shows the digitized and rated geology map respectively. Aquifer media was prepared using a geology map from the Geological Survey Department. The geological map was digitized and created into a raster format. The geology map was then assigned ratings from Table 9. Areas including Garikai, Maridale, Marshlands were assigned the least rating because they comprise of granite rock which is a consolidated material. Knowe falls in the high vulnerability range because it comprises of metasediment which is unconsolidated. Aquifer with large grain sizes has high porosity and high permeability which leads to high vulnerability.

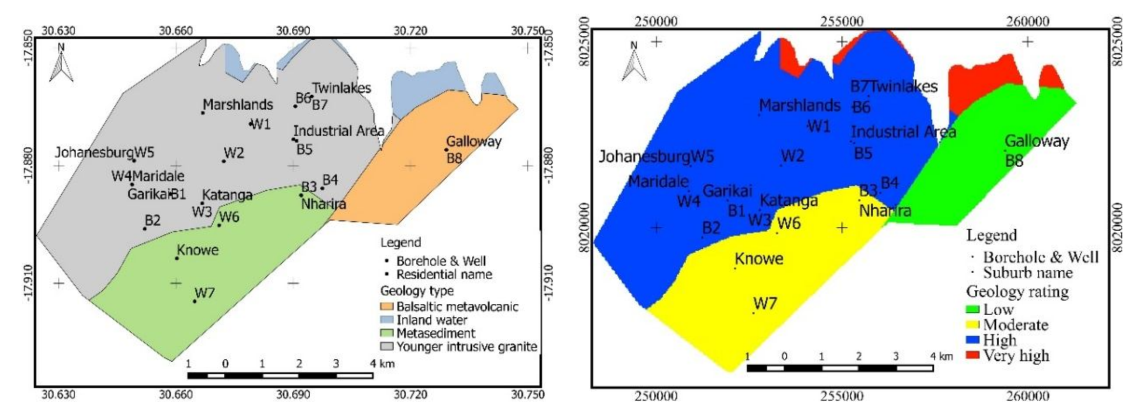

Figure 22 (a): Digitized geology map **(b): Geology rating map**

5.4.5. Land cover

Figure 25 shows the AVI results for the land cover and land cover rating as shown in Table 9. Land cover assessment was done using supervised classification in ILWIS Software. Land cover changes and anthropogenic activities have a significant impact on the groundwater vulnerability of most of the area. Due to land use pattern such as agricultural, industrial, commercial and urban, the pollution potential intensity also varies. Hydrogeological parameters can be greatly hampered by land use pattern for example agricultural activities, drilling well, septic system, mining operation and dumping. Land cover is an important parameter that controlls the ability of contaminants to reach the groundwater through anthropogenic activities.

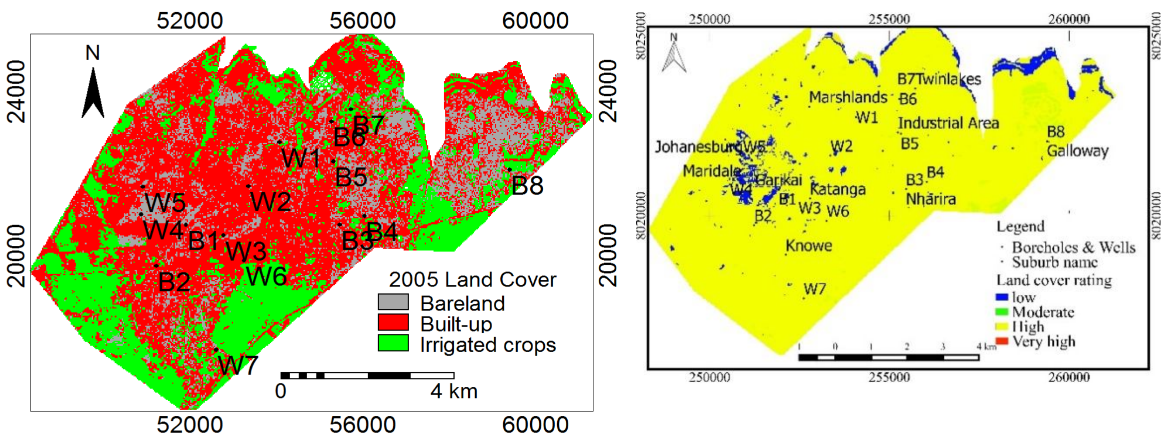

Figure 23 (a): Land cover **(b): Land cover rating**

Statistical data showed that areas coved by the land classes,bareland, irrigated crops and build-up has 17 %, 28 % and 55 % respectively. Areas assigned the highest rating are more vulnerable to contamination. Norton Town area fall in the high rating zone meaning the area is more vulnerable to contamination..

5.4.6. Hydraulic conductivity

Figure 27 shows hydraulic conductivity and hydraulic conductiviy rating maps for Norton Town respectively. Based on estimated hydraulic conductivity adapted from Aller *et al.* (1991). Hydraulic conductivity in the study area varies between 0.001 m/day to 12 m/day for clay and sandy soils. The ability of an aquifer to transmit water for a given hydraulic gradient is called hydraulic conductivity (Khan *et al.*, 2014). The rate of groundwater flow within the aquifer media also controls the rate of contaminant movement.

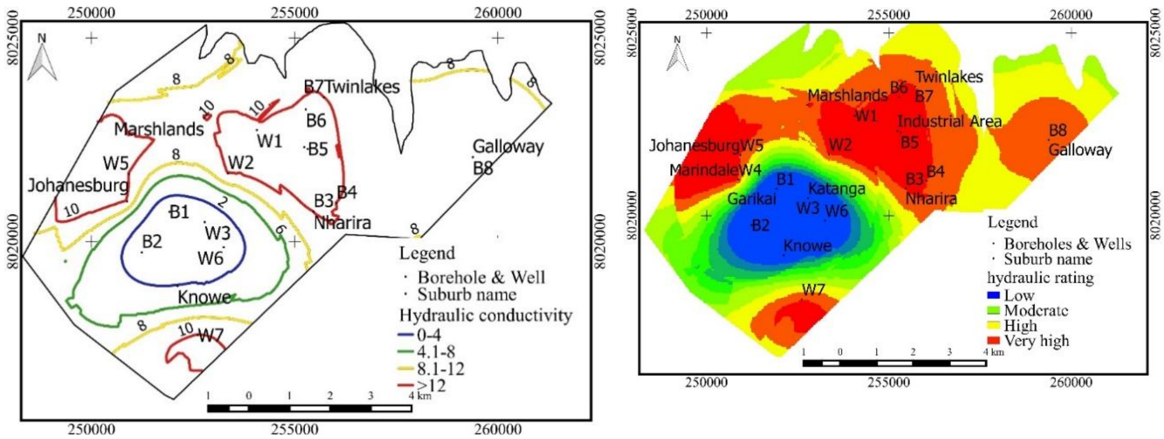

Figure 24 (a): Hydraulic conductivity (b): Hydraulic conductivity rating

The average hydraulic conductivity in the study area is 7.8 m/day and standard deviation is 2.9 m/day. According to the AVI Model, high hydraulic conductivity is associated with high contamination potential (Stempvoort et al., 2013). Different areas have different hydraulic conductivity. Katanga falls in the low range whilst Galloway has the highest rating hence possibility of contamination is very high.

5.4.7. Aquifer Vulnerability Index map

An Aquifer Vulnerability Index map was derived by combining the six parameters which include depth to water level, slope, hydraulic conductivity, land cover, geology, and soil media. A raster calculater in ILWIS version 3.3 was used to calculate the index values and an AVI map was created. Statistical data grouping was implemented in order to differentiate five categorical index ranges based on the AVI Model. Index values ranged from 63 to 126 (Table 14). Index values were categorized into five classes as shown by Table 14 and Figure 29 below. They are very low (63-73), low (74-84), moderate (75-85), high (86-106), very high (107-126) groundwater vulnerability. From Figure 29, the area with very high vulnerability of 2.5 % is at the edge of the boundary (part of Twinlakes and Galloway). Vulnerability from this area could be atributed to land cover changes, geology and pollution from industrial discharge, raw sewage among other. The area with high vulnerability of 12.5 % falls in the industrial area of Norton. Low vulnerability of 37,2 % and very low of 17,8 % falls in Maridale, Johanesburg, part of Katanga and Marshlands. This could be attributed to onsite sanitation which is a major challenge in these areas, pitlatrines, septic tanks, dumpsites, sandy soils and land cover changes.

Table 14: Total area covered by each of the class

Aquifer Vulnerability Index Value	Area %	Vulnerability zone
63-73	17.8	Very Low
74-84	37.2	Low
85-94	30	Moderate
95-106	12.5	High
107-126	2.5	Very High

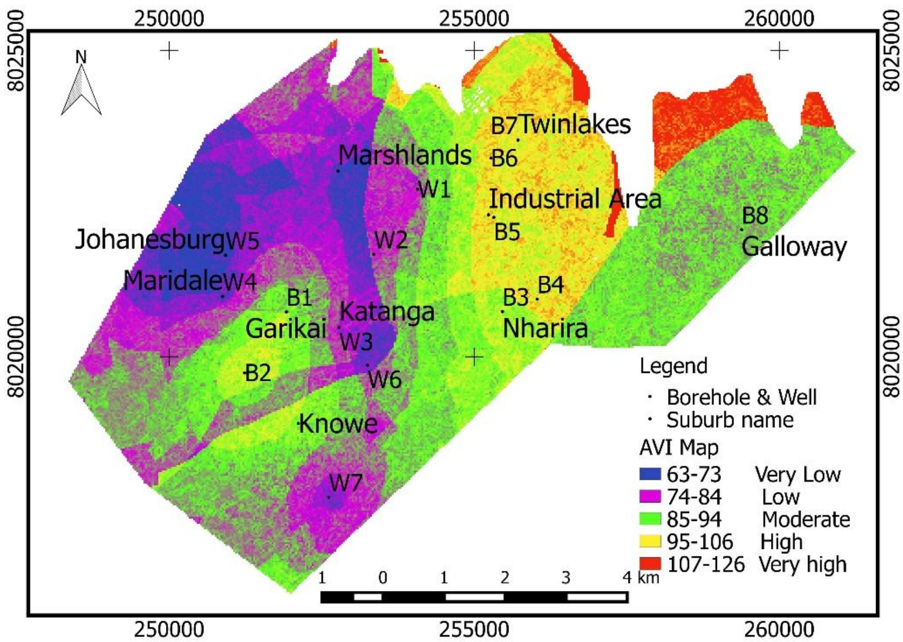

Figure 25: Vulnerability zones according to AVI model

The area with moderate vulnerability of 30 % falls in Galloway, part of Knowe, Garikai amoung other areas. Depth to water level, land cover changes, geology and potential pollution sources digitized on google earth which includes, sewage plant irrigated fields, industries, wastewater ponds, dumpsites, urban agriculture are the major causes of groundwater vulnerability in Norton. Of the six parameters, land cover changes, depth to water level and geology have the highest impact on groundwate vulnerability. Similar studies done by Stempvoort et al. (1993) in Canada showed that groundwater was highly vulnerable due to anthropogenic activities and geographical conditions. This concludes that groundwater vulnerability in this study is as a result of human activity and hydrogeological setting.

5.4.8. Model Validation

Table 15 shows the results from the Spearman's correlation analysis. Model validation with sulphates data showed a significant positive relationship of 0,590. The results of validation support the precision of the AVI vulnerability map. Similar results were obtained by Khan et al. (2014) in India were validation of groundwater vulnerability map with sulphates showed a significant positive relationship. Stempvoort et al. (2013) carried out model validation for DRASTIC using sulphates in Canada and yielded similar results.

Table 15: Model validation using sulphates

Correlations			sulph1	sulph2
Spearman's	sulph1	Correlation Coefficient	1.000	.590*
		Sig. (2-tailed)		.021
		N	15	15
	sulph2	Correlation Coefficient	.590*	1.000
		Sig. (2-tailed)	.021	
		N	15	15

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

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The following conclusions were derived based on the results obtained in this study:

1. The study identified the main pollution sources which are treatment plant, agriculture, landfill, onsite sanitation and industrial discharge. The study also revealed that potential pollution sources are the main causes of groundwater contamination.
2. The results showed that groundwater sources situated in high density areas had faecal coliform counts greater than 100 cfu/100 mL which could be harmful to human health. The presence of FC >100 mg/L in water according to WHO should be treated as it poses health effects on human.
3. Most of the area 55 % is very low to low vulnerability and a significant portion of 45 % being moderate vulnerability.

6.2. Recommendations

Basing on the conclusions noted above and results obtained from this study, the following recommendations are made;

1. The study recommends that boreholes that are situated in close proximity with potential pollution sources be monitored regularly.
2. The use of household water treatment techniques such as the use of chlorine are recommended where groundwater sources are exposed to faecal coliform contamination.
3. The study suggests that this AVI model could be used to determine the most likely areas where groundwater contamination may be a problem today or could occur in the near future

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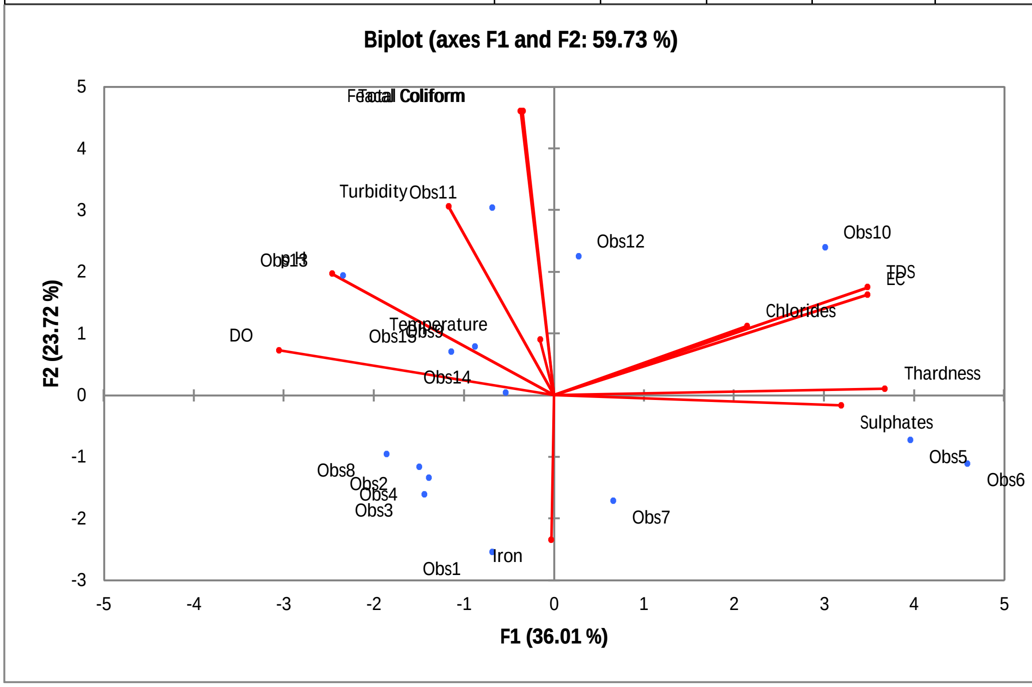
Appendices

Appendix 1: Principal Component Analysis results

Eigen value and contribution of every component

Component	Eigen value	% of variability	Cumulative %
F1	4.322	36.01	36.013
F2	2.846	23.718	59.732
F3	1.296	10.804	70.536
F4	1.047	8.729	79.265

Factor loads Contribution of the variables (%):					
	F1	F2	F3	F4	F5
Chlorides	6.609	1.808	13.334	25.777	15.172
DO	13.417	0.761	0.001	5.240	0.302
EC	17.424	3.834	0.415	0.867	3.760
Feacal Coliform	0.174	30.461	1.722	0.719	5.629
Iron	0.001	7.904	8.166	33.244	15.239
p H	8.721	5.585	0.007	14.012	18.459
Sulphates	14.600	0.039	7.595	0.005	0.187
TDS	17.433	4.408	0.004	0.522	4.508
Temperature	0.035	1.166	62.363	0.427	11.356
Total Coliform	0.199	30.524	3.105	0.099	1.766
Total hardness	19.412	0.016	0.755	0.186	9.835
Turbidity	1.975	13.492	2.534	18.903	13.789



Appendix 2: Statistical analysis results (SPSS outputs)

Chlorides

Parameter	B	Std. Error	t	Sig.
W7	142.000	100.842	1.408	.166
[Parameter=Chlorides]	0[a]	.	.	.
[Site=B1]	-29.625	142.613	-.208	.836
[Site=B2]	-44.375	142.613	-.311	.757
[Site=B3]	-79.750	142.613	-.559	.579
[Site=B4]	150.375	142.613	1.054	.297
[Site=B5]	319.250	142.613	2.239	.030
[Site=B6]	348.625	142.613	2.445	.018
[Site=B7]	-51.500	142.613	-.361	.720
[Site=B8]	-42.625	142.613	-.299	.766
[Site=W1]	216.250	142.613	1.516	.136
[Site=W2]	572.125	142.613	4.012	.000
[Site=W3]	177.000	142.613	1.241	.221
[Site=W4]	-88.750	142.613	-.622	.537
[Site=W5]	-44.500	142.613	-.312	.756
[Site=W6]	700.000	142.613	4.908	.000

EC

Parameter	B	Std. Error	t	Sig.
W7	.225	.130	1.730	.090
[Parameter=(conductivity]	0[a]	.	.	.
[Site=B1]	.138	.184	.750	.457
[Site=B2]	.180	.184	.979	.333
[Site=B3]	.079	.184	.430	.669
[Site=B4]	.013	.184	.069	.945
[Site=B5]	.992	.184	5.400	.000
[Site=B6]	.826	.184	4.500	.000
[Site=B7]	.335	.184	1.825	.075
[Site=B8]	.049	.184	.270	.789
[Site=W1]	.049	.184	.265	.792
[Site=W2]	1.247	.184	6.791	.000
[Site=W3]	.395	.184	2.151	.037
[Site=W4]	.774	.184	4.215	.000
[Site=W5]	.143	.184	.777	.441
[Site=W6]	.074	.184	.404	.688

Feacal Coliform

Parameter	B	Std. Error	t	Sig.
W7	2108.000	870.688	2.421	.020
[Parameter=Feacal Coliform]	0[a]	.	.	.
[Site=B1]	-2107.500	1231.339	-1.712	.094
[Site=B2]	-2108.000	1231.339	-1.712	.094
[Site=B3]	-2108.000	1231.339	-1.712	.094
[Site=B4]	-2108.000	1231.339	-1.712	.094
[Site=B5]	-2096.750	1231.339	-1.703	.096
[Site=B6]	-2106.750	1231.339	-1.711	.094
[Site=B7]	-2107.500	1231.339	-1.712	.094
[Site=B8]	-2108.000	1231.339	-1.712	.094
[Site=W1]	138.250	1231.339	.112	.911
[Site=W2]	340.750	1231.339	.277	.783
[Site=W3]	372.250	1231.339	.302	.764
[Site=W4]	607.000	1231.339	.493	.624
[Site=W5]	-248.000	1231.339	-.201	.841
[Site=W6]	-756.750	1231.339	-.615	.542

Total hardness

Parameter	B	Std. Error	t	Sig.
W7	179.000	181.170	.988	.328
[Parameter=Hardness]	0[a]	.	.	.
[Site=B1]	333.000	256.214	1.300	.200
[Site=B2]	295.000	256.214	1.151	.256
[Site=B3]	209.000	256.214	.816	.419
[Site=B4]	154.000	256.214	.601	.551
[Site=B5]	1482.500	256.214	5.786	.000
[Site=B6]	1828.000	256.214	7.135	.000
[Site=B7]	576.000	256.214	2.248	.030
[Site=B8]	170.000	256.214	.664	.510
[Site=W1]	141.000	256.214	.550	.585
[Site=W2]	883.000	256.214	3.446	.001
[Site=W3]	704.000	256.214	2.748	.009
[Site=W4]	554.000	256.214	2.162	.036
[Site=W5]	334.000	256.214	1.304	.199
[Site=W6]	122.000	256.214	.476	.636