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DEPARTMENT OF CIVIL ENGINEERING

AN ASSESSMENT OF GROUNDWATER POTENTIAL AND VULNERABILITY IN THE UPPER MANYAME SUB-CATCHMENT OF ZIMBABWE

BY

ALFRED MISI

MASTER OF SCIENCE IN INTEGRATED WATER RESOURCES MANAGEMENT (MSc IWRM)

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SUPERVISORS: **Mr. W. GUMINDOGA**
Eng. Z. HOKO

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

JULY 2016

DECLARATION

I, **Alfred Misi**, declare that this research is my own work. It is submitted in partial fulfillment of the requirements of the Master of Science Degree in Integrated Water Resources Management (MSc IWRM) at the University of Zimbabwe. This work has not been submitted before for any other degree of examination at any other University.

Signature:..

Date:..

Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

CFU	Colony Forming Units
GIS	Geographic Information Systems
GoZ	Government of Zimbabwe
GWP	Groundwater Potential
ILWIS	Integrated Land and Water Information Systems
MRC	Mineral Resource Centre
PCA	Principal Component Analysis
SAZ	Standards Association of Zimbabwe
SPSS	Statistical Package for Social Sciences
WHO	World Health Organization
WMO	World Meteorological Organization

DEDICATION

This project is dedicated to my parents (Mr. and Mrs. Misi) and the whole family at large.

ACKNOWLEDGEMENTS

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Above all, I would like to thank the Lord for everything.

ABSTRACT

Groundwater plays a pivotal role in meeting potable water needs. However, significant stresses generated from anthropogenic activities have affected its safe use. In-order to enable appropriate risk communication and informed decision making on groundwater use and management, full knowledge of its quality, quantity and vulnerability is fundamental. The main objective of this study was to assess Groundwater Potential (GWP) and vulnerability in the Upper Manyame Sub-catchment (UMSC). GWP was mapped through the use of Geographic Information Systems and remote sensing-based multi-criteria analysis. Spatial thematic layers; viz., geology, slope, land-use, drainage density, recharge, topographic index, altitude and rainfall were developed and weighted using Saaty's Analytical Hierarchy Process (AHP) and the Quantile Method. Layers were subsequently aggregated using the Weighted Linear Combination and Index Overlay methods, respectively, to develop two Groundwater Potential Index (GWPI) maps. Indices from each map were correlated with borehole yield data to select the best method from which GWP zones were then developed. Given the widespread use of groundwater for domestic purposes in the study area, its quality was also analysed. Groundwater samples from 15 sampling sites were analysed for selected physico-chemical and biological parameters as recommended by the World Health Organization. Results were then subjected to descriptive statistical analysis and Principal Component Analysis (to identify key parameters). Repeated Measures ANOVA (RMA) was used to analyse if there were any significant variations in mean groundwater parameter levels. Groundwater vulnerability was determined using the GOD Model with key input parameters being groundwater occurrence, overlaying lithology and depth to water table. The results for GWP mapping showed that AHP-based GWP index map exhibited a stronger correlation with borehole yield data (r=0.65, n=120), indicating the robustness of the AHP as a factor rating method. About 72 % (2725.9 km^2) of the UMSC was noted to be of moderate GWP (10-100m^3/day), while 19 % (719.3 km^2) and 9 % (340.7 km^2) exhibited high and low GWP, respectively. Groundwater quality results indicated that: pH, coliforms, TDS, EC, total hardness, Fe, NH_4^+ and turbidity exceed SAZ/WHO drinking water limits in most cases. However, Fl^-, Zn, Pb, Cu and Cl^- were within acceptable limits. Four Principal Components (PCs) representing 84 % of the cumulative variance were extracted. PC1 was characterized by high dominance of pH, TDS, EC and total hardness. PC2's variance was found to be associated with elevated levels of Cl^-, Zn and Cu. On the other hand, PC3 had high loadings of total and faecal coliforms, Fl^-.and turbidity. PC4 was characterized by high loadings of Pb, Fe, ammonia and turbidity. Overall, PCA showed that most of the variation in the water quality was accounted for by pH, Zn, Cl^-, TDS, ammonia, Fl^-, Cu, turbidity, Fe, Pb and faecal. The results of RMA indicated that there were significant differences in mean parameter levels across sampling sites and within subsequent campaigns ($p<0.05$), for parameters DO, total coliforms and faecal coliforms. The study area was found to be largely of moderate groundwater vulnerability (77.3 % of area). A moderate correlation of 0.47 was exhibited between the measured ammonia levels and groundwater vulnerability indices. The correlation indicate instances of ammonia contamination, hence it can be concluded that groundwater in the UMSC is being polluted by anthropogenic activities. Regular monitoring is therefore recommended to safeguard public health and prevent further deterioration of groundwater.

Keywords: Groundwater Quality, Principal Component Analysis, Vulnerability Assessment, ANOVA, Upper Manyame Sub-catchment.

CHAPTER 1
INTRODUCTION

1.1 Background

Water is vital for human life (UNESCO, 2006; Burnett *et al.*, 2015). Its availability in the right quality and quantity is integral to supporting socio-economic development and vital ecosystems which depend upon it (GWP and INBO, 2009; Pietersen *et al.*, 2009; Arkoprovo *et al.*, 2012; Yazdani and Aryamanesh, 2013). Global statistics indicate that fresh water is limited, constituting only 2.5 % of the global water resources (Shiklomanov, 1993). Despite it being limited, natural and anthropogenic stressors are further threatening its availability and suitability for multiple uses (Pietersen *et al.*, 2009). Thus, human activities have cumulatively induced significant pressure on the available freshwater resources, especially in developing countries across Africa (GWP and INBO, 2009; Kamusoko *et al.*, 2013; Mudyazhezha and Ngoshi, 2014). Surface water resources have suffered most from both anthropogenic and natural forcings, i.e. climate change (Zhang *et al.*, 2010; Dohare *et al.*, 2014). As a result, groundwater has become a more important and dependable alternative of potable water supply (Burke and Villholth, 2007; MacDonald *et al.*, 2012; Waikar and Nilawar, 2014; Sorensen *et al.*, 2015).

Globally, groundwater withdrawal rates have grown exponentially from 100 $km^3 yr^{-1}$ in the 1950s to over 1000 $km^3 yr^{-1}$ by the year 2000 (Burke and Villholth, 2007; Dölla *et al.*, 2012; Wada *et al.*, 2014). An estimated 2 billion people rely on groundwater for their basic water needs (Morris *et al.*, 2003). About 75 % and 62 % of Africa and SADC's population, respectively, depend on groundwater (Malzbender and Earle, 2007; Pietersen *et al.*, 2009; Clough *et al.*, 2010; UN-Water/Africa, 2010). Zimbabwe is no exception with over 68 % of its population depending on groundwater (Dzvairo et al., 2006).

According to Nhapi and Tirivarombo (2004) as well as Manzungu *et al.* (2012), most cities in Zimbabwe, particularly Harare, experienced significant post-independence changes in terms of the population distribution, land-use, industrial activities and pollution control strategies. As such, the changes have seen increased degradation of surface water resources coupled with potable water shortages, in most urbanised catchments such as the Upper Manyame Sub-catchment (Masere *et al.*, 2012). Consequently, groundwater demand has drastically increased in the Upper Manyame Sub-catchment (UMSC). However, the most challenge in the utilization of groundwater in the sub-catchment is that there is limited information pertaining to its spatial and temporal variability due to the inadequacy of groundwater monitoring networks (Chikodzi, 2013). This has contributed to unsustainable development and use of groundwater in the UMSC, hence compromising the need to effectively manage the resource for future generations. Furthermore, the significant increase in the human population in the sub-catchment; from 1.2 million in 1992 (Hranova, 2003) to 2.7 million in 2012 (Zimstat, 2012) has resulted in significant pollution of water resources (Masere *et al.*, 2012). Partially treated effluent, illegal dumpsites, poorly engineered and decommissioned landfills, sewer leakages, industrial discharges, agricultural runoff and mushrooming of unserviced settlements have been identified as the major sources of pollution (Nhapi *et al.*, 2002; Nhapi and Tirivarombo, 2004; GoZ, 2011; Masere *et al.*, 2012; Kibena *et al.*, 2013). Waterborne disease outbreaks experienced in the sub-catchment for the period 2008 to 2009 are a manifestation of water quality problems and potable water shortages (Manzungu *et al.*, 2012; Masere *et al.*, 2012). However, there is still *ad hoc* development and use of groundwater resources in the UMSC (Love *et al.*, 2006).

In-order to make informed decisions on groundwater utilisation in the sub-catchment, proper investigation and characterization of Groundwater Potential (GWP) and groundwater vulnerability is vital, given the prevailing potable water shortages and high pollution levels (Masere *et al.*, 2012; Tsiko and Togarepi, 2012). Rahmati *et al.* (2014) defined GWP as the possibility of groundwater occurrence in an area, whereas, groundwater vulnerability is defined as the tendency or likelihood for contaminants to reach a specified position in the ground water system after introduction at some location above the uppermost aquifer (Morris *et al.*, 2003). Globally, the quantification and protection of groundwater have become major causes for concern. Thus, quantitative and spatially explicit information on groundwater is required to inform strategies of adapting to the growing groundwater demand (MacDonald *et al.*, 2012). On the other hand, vulnerability of groundwater to human impacts is now being recognized as a serious worldwide socio-economic and ecological problem (UNESCO, 2007). For this reason, vulnerability maps have also become more important tools for investigating groundwater vulnerability (Khemiri et al., 2013). Vulnerability maps reveal areas that require protection, hence they are important as valuable decision making tools. As such, Geographic Information System (GIS) and Remote Sensing (RS) based GWP mapping (Chikodzi, 2013; Chuma *et al.*, 2013; Fenta *et al.*, 2015; Nejad *et al.*, 2015) and groundwater vulnerability assessments (Morris *et al.*, 2003; Polemio *et al.*, 2009; Abdelmadjid and Omar, 2013; Khemiri *et al.*, 2013) have become valuable tools in capturing the spatial dynamics of both phenomena (groundwater potential and vulnerability). Such work has not been done extensively on the UMSC's groundwater resources, leaving a wide information gap (UMSCC, 2014). As such, this study sought to address this existing gap so as to inform the management of the resource and safeguard public health.

1.2 Problem statement

The UMSC is facing water and sanitation problems (ZIMSTAT, 2012; WHO/UNICEF, 2014). Human and ecological health is under serious threat from high pollution levels coupled with persistent potable water shortages (Nhapi *et al.*, 2002; Nhapi, 2009; Manzungu *et al.*, 2012; Kibena *et al.*, 2013; Moyo and Rapatsa, 2015). Widespread cases of water borne diseases between the years 2008 and 2009 are clear-cut pointers to deteriorated water quality and sanitation services (Chipare, 2010; Hove and Tirimboi, 2011; Manzungu *et al.*, 2012; Musingafi *et al.*, 2015). In the same context of water borne diseases, the Zimbabwe Humanitarian Situation Report by UNICEF-Zimbabwe (2016) reported 944 cases of typhoid in Harare since January to March 2016, with 55 confirmed cases and 5 deaths. Despite the recurrences of water related diseases (UNICEF-Zimbabwe, 2016); increasing pollution load (Tsiko and Togarepi, 2012) and increasing dependence on groundwater (Broderick, 2012; UMSCC, 2014), groundwater quality and quantity in the UMSC remains largely unknown (Love *et al.*, 2006). A wide array of scientific research carried out to better understand the UMSC's water resources (Nhapi *et al.*, 2002; Hranova, 2003; Nhapi and Tirivarombo, 2004; Nhapi, 2009; Masere *et al.*, 2012; Nyakungu *et al.*, 2013; Nyamangara *et al.*, 2013; Muserere *et al.*, 2014); pertained more to surface water pollution. Thus, there has been comparatively little research conducted to understand groundwater potentiality and vulnerability, despite its significance in mitigating problems of water shortages in the sub-catchment (UMSCC, 2014). Isolated efforts put across to assess groundwater within the sub-catchment lack spatial representation of both the quality and quantity aspects (Chikodzi, 2013). Therefore, efforts to effectively utilise and protect groundwater resources are being hindered due to lack of comprehensive information on the spatial distribution of groundwater and its susceptibility to pollution. There is need for a comprehensive groundwater assessment to spatially determine its potential and vulnerability, so as to make informed decisions on groundwater utilisation and management in the UMSC.

1.3 Justification

As is the case in many regions around the world, groundwater is an important resource in the UMSC (UMSCC, 2014). It is being used year round for industrial, agricultural and, most importantly, domestic purposes. High dependence on groundwater in the UMSC is mainly centered on the need to supplement inadequate potable water supply by city councils (Nhapi, 2009; Hove and Tirimboi, 2011). Broderick (2012) indicated that most of the medium-density and low-density suburbs last received council water supplies in more than a decade. This implies that most of the households in these areas solely depend on groundwater. However, there is insufficient information to show the spatial and temporal variability in groundwater storage in the UMSC due to inadequacy of monitoring stations (Chikodzi, 2013). Consequently, most of the groundwater development projects in the study area, by either individuals or corporate organizations, are being done on *ad hoc* basis (Love *et al.*, 2006). As a result, there is unsustainable utilisation of groundwater in the UMSC (Rwasoka *et al.*, 2007; Broderick, 2012). Also, given the high levels of water pollution in the sub-catchment, groundwater is under serious threat (Masere *et al.*, 2012). Morris *et al.* (2003) and UNEP (2006) indicated that once aquifers are polluted, remediation is very difficult and practically impossible in most developing countries such as Zimbabwe, hence the need for vulnerability assessments to inform groundwater protection strategies. UN (2006) also highlighted that it is important to ascertain the quality of potable water as a fundamental stride to safeguard public health. Therefore, it is clear that a proper scientific diagnosis of the aquifers in the UMSC area is critical. This can significantly contribute to the designing of an effective groundwater management strategy which enables consistent assessment of the extent, rate and progress of groundwater use and aquifer degradation in the study area (UNEP, 2006). Earlier studies conducted in the sub-catchment have assessed groundwater quality and potential in isolation (Dzvairo *et al.*, 2006; Hoko, 2008; Chuma *et al.*, 2013). However, this study has combined both GWP mapping and vulnerability assessment to enable a comprehensive assessment that will enable better management of groundwater resources in the study area.

1.4 Objectives

1.4.1 Main objective

The main objective of this study was to assess groundwater potential and vulnerability in the Upper Manyame Sub-catchment, so as to inform groundwater management and protection programmes.

1.4.2 Specific objectives

The specific objectives of the study were:

i. To determine the groundwater potential of the Upper Manyame Sub-catchment using GIS and remote sensing techniques.

ii. To identify point and non-point sources of groundwater pollution in a micro-catchment of the Upper Manyame Sub-catchment (Marimba) for developing a pollution risk map.

iii. To analyze the physico-chemical and biological quality of groundwater in the Marimba Micro-catchment and assess its conformity to SAZ standards and WHO guidelines for drinking water.

iv. To determine aquifer vulnerability to pollution in the Marimba Micro-catchment using an Index Overlay model (GOD).

CHAPTER 2
LITERATURE REVIEW

2.1 Overview of groundwater; importance, potential and protection

Groundwater plays a pivotal role in the provision of water for multiple cross-sectoral uses world over (GWP and INBO, 2009; Kumar *et al.*, 2015). An estimated 2 billion people rely on groundwater for their basic water needs (Morris *et al.*, 2003). This makes groundwater the world's most extracted raw material, with withdrawal rates exceeding 1000 km^3/yr (Malzbender and Earle, 2007; Wada *et al.*, 2014). Foster (1987) and MacDonald *et al.* (2012) pointed out that groundwater is a strategic reserve which is vital to meeting public water needs. According to Chikodzi (2013), its importance stems from its ability to act as a large freshwater reservoir that provides buffer storage, even in the advent of extreme hydro-meteorological events such as droughts. Gupta (2014) and Kumar *et al.* (2015) highlighted that groundwater is comparatively safe and reliable than surface water. However, groundwater is often misused, poorly understood and rarely well managed despite its importance to human livelihoods and vital ecosystems (Morris *et al.*, 2003). Most importantly, the rapid growth of human civilization has exerted enormous stresses onto the available groundwater resources (Liu *et al.*, 2015). Both increased abstraction and pollution, in most instances, have resulted in groundwater mining and quality deterioration, respectively.

Morris *et al.* (2003) and Gupta (2014) highlighted in their researches in Kenya and Jabalpur District of Madhya Pradesh, respectively that, though groundwater is not easily polluted, it is extremely difficult to remediate once polluted. Thus, prevention and control of groundwater pollution are principally crucial for its effective management (Morris *et al.*, 2003; Kaur and Rosin, 2008; Gupta, 2014; Kumar *et al.*, 2015; Sorensen *et al.*, 2015). Fenta *et al.* (2015) and Gogu and Dassargues (2000) recommend Groundwater Potential (GWP) mapping and vulnerability assessments as a basic requirement for effective management and protection of groundwater systems. The resultant efforts of groundwater vulnerability assessment can give a fundamental overview of the susceptibility of a certain groundwater system to pollution, hence informing decision making and protection plans (Morris *et al.*, 2003). As such, many tools and methods have been developed to analyze groundwater vulnerability. In as much as many researchers have highlighted the need for groundwater vulnerability assessments (Gogu and Dassargues, 2000; Foster *et al.*, 2002; Kaur and Rosin, 2008; Gupta, 2014), it has been argued that there is need to quantify the available groundwater resources to enable informed management programmes (Burke and Villholth, 2007; Bera and Bandyopadhyay, 2012; Magesh *et al.*, 2012; Fenta *et al.*, 2015). According to Chikodzi (2013), many countries with severe groundwater depletion problems have limited information on the spatial and temporal variability in groundwater storage, which is the quantity of water in the saturated zone (Buddemeier *et al.*, 2000). Therefore, careful characterization of the groundwater resources, through GWP mapping, is required to guide investments in water supply and in managing the resource to minimize widespread depletion. Thus, it becomes imperative for groundwater managers to determine whether the quantity of the resource justifies the need for protection. This can allow cost effective measures to be put in place since management efforts can be directed to areas with sustainable groundwater quantities.

2.2 Global groundwater distribution and occurrence/potential

Groundwater constitutes about 95 % of the global freshwater (35 million km^3), discounting 67.8 % of freshwater that is locked in the polar ice caps (Shiklomanov, 1993; Morris *et al.*, 2003). MacDonald *et al.* (2012); through extensive review of available maps, publications and data; estimated the total groundwater storage of Africa to be 0.66 million km^3. Thus Africa has limited groundwater resources (UN-Water/Africa, 2010), which constitute only 2.8 % of the global groundwater resources - 23.4 million km^3 (Shiklomanov, 1993). Given that more than 75 % of Africa's population depends on groundwater as the main source of drinking water, groundwater is under serious pressure (Clough *et al.*, 2010).

In terms of occurrence/potential, groundwater is found almost anywhere in the world and in almost all types of geological formations (Fenta *et al.*, 2015). However, its distribution in terms of quality and quantity varies from one place to another and from one geological formation to another (Liu *et al.*, 2015). UN-Water/Africa (2010) indicated that an interplay of natural and anthropogenic factors determine the distribution and quality of groundwater. Primarily, groundwater potential/occurrence depends on the geology, geomorphology and effective rainfall (MacDonald *et al.*, 2012). These factors determine aquifer transmissivity, effective porosity and groundwater recharge, among others. Kaur and Rosin (2008), outlined that groundwater systems are dynamic and the movement of groundwater is a function of the hydraulic head. The study further indicates that the flow can be dependent on factors such as the fracture network density. However, aquifer yield is highly variable. As such, groundwater potential is highly variable. Thus, supplies located in different aquifers or in different parts of the same aquifer, can tap water of widely different capacity and residence time (Morris *et al.*, 2003). Morris *et al.* (2003) further highlighted that, this characteristic is an important factor for contaminants that degrade over time and for the control of disease-causing microorganisms.

MacDonald *et al.* (2012) indicated that groundwater is limited and highly variable in terms of its spatial distribution. Given the high variability of groundwater, even over small areas, the available global quantitative information from literature should be scaled down to account for the variability groundwater potential that can occur over very small areas. The integration of geophysical techniques (e.g. pumping tests) and modern techniques (GIS and remote sensing) can help address the quantitative and spatial information gaps.

2.2.1 Methods of determining groundwater potential/occurrence

According to Fenta *et al.* (2015), geophysical and geoelectrical techniques have been used in groundwater exploration over the past centuries. The methods have been applied in various groundwater assessments across Zimbabwe (Martinelli and Hubert, 1985). The assessment of Harare's aquifer system by Broderick (2012) and the assessment of recharge in the mid-Zambezi's Karoo system by Larsen *et al.* (2002), successfully employed these methods. However, Roscoe (1990) highlighted that the methods are expensive and time consuming. Groundwater analysis techniques have evolved over time. In recent developments, GIS and remote sensing (RS) techniques have become widely used tools in the assessment of groundwater resources (Fenta *et al.*, 2015; Nejad *et al.*, 2015). Researches done in: the Dulung Watershed in east Bengal, India (Bera and Bandyopadhyay, 2012); the Bulawayo Metropolitan area, Zimbabwe (Chuma *et al.*, 2013); and the Western Cameroon Highlands (Sokeng *et al.*, 2016), successfully employed GIS and RS techniques. The techniques are less time consuming and have quick results turn over (Fenta *et al.*, 2015). According to Liu *et al.* (2015), GIS and RS use geomorphological and geophysical factors to determine groundwater occurrence. In terms of reliability of the results, Fenta *et al.* (2015) pointed out that GIS and RS are less reliable than the traditional techniques, especially if not supported by actual measurement data. However, Liu *et al.* (2015) argued that GIS and RS methods provide spatially representative, multi-temporal and cost-effective results, hence they are the best tools in the assessment of hydrogeological processes. It can however be noted that, both traditional techniques and RS-based techniques need complement each other, than being used isolation. Thus, in as much as traditional techniques can yield accurate results, they lack spatial representation. On the other hand, GIS and RS based techniques lack the quantitative aspect, thus they fail to provide absolute groundwater volumes. Therefore, a combination of both techniques can provide a comprehensive result in terms of spatial distribution and the absolute quantities.

2.3 Groundwater pollution

Groundwater pollution has affected the safe use of the resource worldwide (UN-Water/Africa, 2010). Foster (1987) defines groundwater pollution or contamination as the addition a substance which has the potential to alter groundwater quality, hence lessening its usage value. A study by UNEP (2006) indicated that groundwater degradation has become one of the most serious water resources problems worldwide, especially in most developing countries. In the study, it is further highlighted that groundwater pollution can go undetected for long, since the movement of pollutants is slow, such that contamination is mostly discovered after encountering health problems. Once groundwater related health issues surface, implications are that the aquifers would have been largely affected by contamination (Morris *et al.*, 2003). At such point, remedial action is very costly and in most cases practically impossible (Morris *et al.*, 2003; Dohare *et al.*, 2014). Foster *et al.* (2002) agrees with the assertion by Morris *et al.* (2003) that, solutions to groundwater pollution are relatively few and costly, hence focus must be on prevention of the problem. According to a research by WMO (2013), most undesirable changes in groundwater quality are induced, to a greater extend, by anthropogenic activities and to a lesser extent by geogenic/natural factors. Thus, the main threats to groundwater sustainability arise from the increased groundwater demand and disposal of wastes on the land surface. The changes in groundwater quality impair its suitability for intended purposes. Morris *et al.* (2003) offered a different view with regard to the causes of groundwater pollution. They suggested that contamination of groundwater can occur as a consequence of poor design and construction of the groundwater source (borehole, well or spring supply). In their argument, they sighted that failure to provide a proper sanitary seal between the well casing and the ground can provide a ready and rapid pathway for contaminants. Although this can also contribute to groundwater contamination, the ultimate source of pollution are anthropogenic activities, as indicated by various researchers. As such, it can be concluded that, anthropogenic factors are more responsible for the vast of pollution problems being experienced world over.

2.3.1 Sources of groundwater pollution

Worldwide, aquifers are experiencing an increasing threat of pollution from urbanization, industrial development, agricultural activities and mining activities (Foster *et al.*, 2002; Pietersen *et al.*, 2009). The main sources of groundwater pollution are presented pictorially in *Figure 1*. In most developing countries, contaminants originate from indiscriminate waste disposal practices, proliferation of uncontrolled expansion of housing, sewage and effluent leakages, uncontrolled industrial and commercial activities as well as agriculture (Nhapi and Tirivarombo, 2004; UNEP, 2006). The pollutants can be grouped into point and non-point sources. A point source is a pollution input that can be related to a single outlet (UNESCO/WHO/UNEP, 1996). Examples include sewage disposal points, mines and industrial effluents (Nhapi and Tirivarombo, 2004). On the other hand, diffuse sources can be defined as sources that cannot be ascribed to a single point or a single human activity (Nyamangara et al., 2013). They may be due to many individual point sources, for example agricultural and urban run-off (Adekunle *et al.*, 2007). Point source pollution can be collected, treated or controlled unlike non-point (Chowdary *et al.*, 2001).

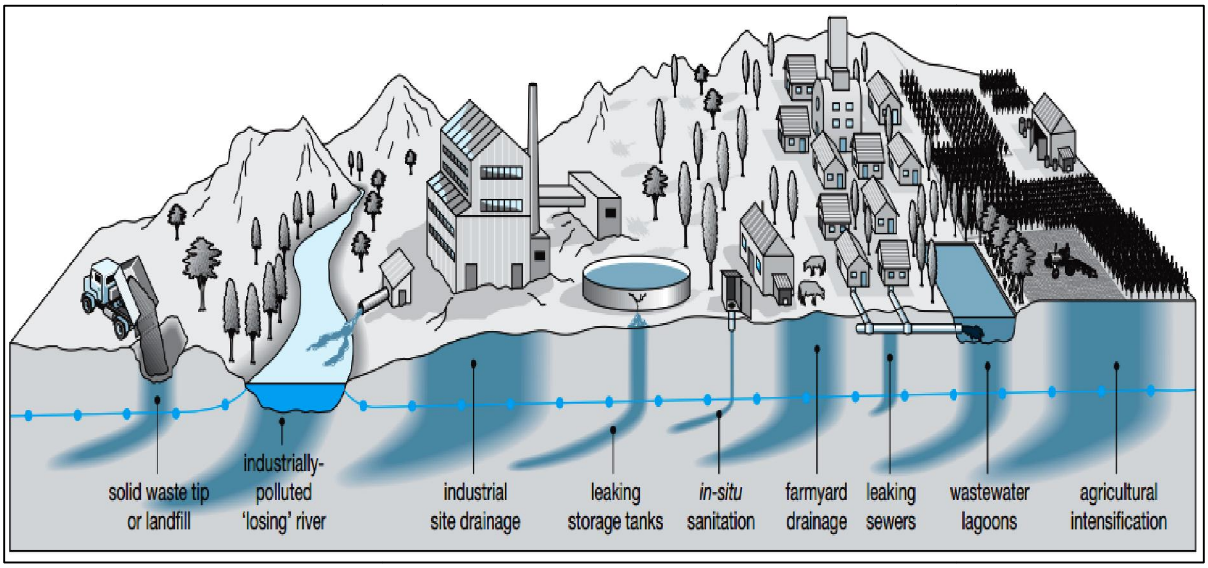

Figure 1: Major sources of groundwater pollution (Foster et al., 2002).

Large scale expansion of irrigated agriculture promotes intensive use of chemical fertilizers and pesticides (Morris *et al.*, 2003). It was revealed by UNEP (2006) and Morris *et al.* (2003) that, the increased use of pesticides and fertilizers, to increase food production, is causing significant groundwater pollution. Thus, fertilizers and pesticides used in agriculture are the major non-point pollutants and have cumulative effects. On the other hand, industrial effluents and municipal wastes are major sources of groundwater pollution in mega cities and industrial clusters. The disposal of partially treated and untreated industrial effluents onto the land potentially pollutes groundwater. It is indicated in a research by Obade *et al.* (2014) that; it is difficult to separate the effects of a non-point or point source of pollution since there is no clear-cut distinction between the two. This is because the non-point sources are related or result from a large number of individual point sources (UNESCO/WHO/UNEP, 1996).

2.3.2 Pollutant pathways

Pollutants can be released into the environment as gases, dissolved substances or in the particulate form and can reach the aquatic environment through a variety of pathways, including the surface flows, atmosphere and the soil (UNESCO/WHO/UNEP, 1996). The pollutants can then be dispersed within the aquifer as the water moves. Kaur and Rosin (2008) indicated that there are different processes which control pollutants behaviour in subsurface depending on the porous media and pollutant properties. Some hydrogeological settings can determine the residence time of a pollutant, in some instances allowing degradation or attenuation of the pollutant (Morris *et al.*, 2003). Therefore, the hydrogeomophology setting plays an important role in the transport and the transformation of groundwater pollutants.

It can be noted that human activities generate a diverse of pollutants which, in most instances are difficulty to link to their origin. Those pollutants are difficult to control, hence the protection of groundwater from any further deterioration is difficult.

2.4 Groundwater quality and major groundwater parameters for drinking water

Apart from the increasing need to quantify groundwater resources, WMO (2013) and UNEP (2006) suggested that; emphasis should also be placed on the quality of groundwater resources as a fundamental stride in safeguarding human health. Thus, groundwater quality is highly important as a determinant of the suitability of groundwater for intended uses, especially under the current situation of increased contaminant load (WHO, 2008).

Water quality is defined as a general descriptor of water properties in terms of its physical, chemical and biological characteristics (Altansukh, 2008). Groundwater quality is affected by materials delivered from either point or nonpoint sources (Pohlert *et al.*, 2005). The quality of groundwater can be determined directly in the laboratory by measuring and analyzing the physico-chemical and biological parameters (Obade *et al.*, 2014). According to WHO (2008), the harmful materials in drinking water should be within permissible limits in order to safeguard human health. Thus, groundwater quality parameters should meet specified standards, in terms of its intended use. According to WHO (2008), water related diseases and deaths have been on the rise. As such, it is critical to ascertain the concentration of water quality parameters, especially when the water is intended for potable use (UNESCO, 2009). Various standards have been set for various uses. With reference to potable water use, international and national guidelines and standards have been set for specified groundwater parameters (WMO, 2013). Such parameters include: pH, Turbidity, total dissolved solids, electrical conductivity, total hardness, sulphates, nitrates, chloride, fluoride, Zinc among others. Due to increased generation of contaminants (Tsiko and Togarepi, 2012), the parameters are mostly found above recommended limits, hence most aquifers have become polluted. Since, groundwater pollution has become more worrisome, despite groundwater being the most reliable source of potable water, there is ultimate need for scientific characterization of the pollutants and the susceptibility of groundwater to pollution (Gogu and Dassargues, 2000).

2.5 Groundwater Vulnerability

According to NRC (1993) as well as Maia and Cruz (2013), all aquifers are vulnerable to contamination; to a greater or lesser extent and in either short or long term. Therefore, the establishment of a surveillance network for monitoring the extent of aquifer pollution, e.g. through aquifer vulnerability assessments, becomes key to effective groundwater protection (Morris *et al.*, 2003). The concept groundwater vulnerability was developed in France in the 1960s to create awareness towards groundwater health (Vrba and Zoporozec, 1994; Alwathaf and Mansouri, 2011). The concept was developed as a risk communication and decision making tool in groundwater use (UNEP, 2006). According to NRC (1993), vulnerability is the tendency or likelihood for contaminants to reach a specified position in the ground water system after introduction at some location above the uppermost aquifer. Vulnerability analyzes and delineates areas which are more susceptible to contamination, hence assisting in the remediation, protection or prevention of further groundwater degradation, thus enabling policy makers to manage the resource in a sustainable manner (Foster, 1987; Foster *et al.*, 2002). Vulnerability can either be intrinsic or specific. NRC (1993) and Khemiri *et al.* (2013) defined intrinsic vulnerability as the vulnerability that is independent of whether or not contaminants are present. It focuses primarily on the description of the natural environmental conditions. It considers only the inherent hydrogeological settings and does not refer to any specific pollutants. On the other hand, specific vulnerability is the vulnerability of groundwater to a particular contaminant or group of contaminants. Thus, specific vulnerability is a pollution type dependent vulnerability which looks at the specific pollutant or landuse. It considers a specific pollutant or land use practice and integrates the corresponding properties in the assessment process (NRC, 1993). Foster *et al.* (2002), Morris *et al.* (2003) and Bera and Bandyopadhyay (2012) agree with the assertion that vulnerability is a function of the hydrological, geological and soil conditions. According to Kaur and Rosin (2008), the basic concept of aquifer vulnerability is the natural inherent ability of hydrogeological systems to provide a certain degree of protection through their characteristics. Thus, the overlying materials are a key factor in determining pollution likelihood of a certain aquifer (Gogu and Dassargues, 2000). Foster (2006), pointed out that, the vulnerability of an aquifer is characterized by means of natural factors such as: (i) accessibility of the saturated zone to penetration of pollutants; (ii) the attenuation capacity resulting from the physical-chemical retention or reaction to the pollutant in unsaturated zone; and (iii) the dilution and remobilization of contaminants. The protection degree provided by certain hydrogeological systems are presented through groundwater vulnerability maps which reflect the relative degree of exposure of a certain aquifers to pollution (Kaur and Rosin, 2008). The identification of the vulnerable areas helps in protecting groundwater from further deterioration (Gogu and Dassargues, 2000). The degree of vulnerability can be classified into classes extreme, high, moderate, low and negligible as defined by Foster *et al.* (2002) and Morris *et al.* (2003), *Table 1*.

Table 1: Groundwater vulnerability classes (Foster et al., 2002).

Vulnerability class	Corresponding definition
Extreme	Vulnerable to most water pollutants with rapid impact in many pollution scenarios
High	Vulnerable to many pollutants (except those strongly absorbed or readily transformed) in many pollution scenarios
Moderate	Vulnerable to some pollutants but only when continuously discharge or leached
Low	Only vulnerable to conservative pollutants in the long-term when continuously and widely discharged or leached
Negligible	Confining beds present with no significant vertical groundwater leakage

2.5.1 Purpose of groundwater vulnerability assessments

Though groundwater is not easily contaminated, once this occurs, it is difficult to remediate (Foster *et al.*, 2002; Morris *et al.*, 2003). Therefore, vulnerability assessment should be included within the traditional efforts of groundwater protection (Foster *et al.*, 2002). According to Morris *et al.* (2003), the purpose of vulnerability assessments is to provide a decision making tool based on available data and good scientific judgment. Morris *et al.*

(2003), further highlighted the importance of vulnerability assessments as a tool to direct groundwater protection efforts such that desired results are met at least cost. In further expanding the objectives of vulnerability assessments, various authors concurred that, vulnerability assessments direct regulatory, monitoring, educational and policy development efforts to those areas where they are most needed for the protection of groundwater quality (NRC, 1993; Vrba and Zoporozec, 1994; Foster *et al.*, 2002). Thus, highly sensitive zones can then be targeted as opposed to applying universal protection measures to the entire aquifer system (Maia and Cruz, 2013).

Vrba and Zoporozec (1994) argued on the usefulness of vulnerability assessments citing that, hydrogeological conditions are too complex to be summarized by the simple vulnerability tools. The authors recommended that it can be more consistent to evaluate vulnerability to contamination by each contaminant or group of contaminants. However Foster *et al.* (2002) argued against the idea citing inadequate data and/or insufficient human resources to achieve the idea. In as much as there are such weaknesses in vulnerability assessments, they still remain a basic requirement for groundwater management. They provide basic knowledge on groundwater susceptibility to any contamination, hence enabling informed decision making. Thus, groundwater vulnerability assessment still remain a basic requirement for groundwater management.

2.5.2 Vulnerability assessment methods

Various approaches have been subsequently developed since the 1960s to assess groundwater vulnerability. Conventional vulnerability models such as: DRASTIC, SI, GOD, AVI and SINTACS were developed over the years (Khemiri *et al.*, 2013). According to Kaur and Rosin (2008), vulnerability assessment approaches are grouped into three major categories which are: the index and overlay indices, statistical approaches and process-based simulation models. The choice of an assessment method is a function of data availability, the purpose of evaluation and the hydrogeological settings of the natural system (NRC, 1993). Of these major approaches, the overlay/index method has been the most widely adopted approach for large scale aquifer sensitivity and ground water vulnerability assessments (Polemio *et al.*, 2009). The method is less costly, less data demanding and has quick results turnover. The vulnerability assessment methods are as explained as below:

a. Process-Based models

Process based methods use simulation models to quantify, predict and validate contaminant migration processes (Kaur and Rosin, 2008). According to NRC (1993), the vulnerability is presented as quantitative assessments of pollution risk, i.e. in terms of travel times, concentrations or critical loads. It is further highlighted that, process-based tools allow testing of management scenarios, predict conclusions of high risk and high cost environmental manipulations, manage remediation measures and protection actions and set priorities. Limiting factors for the effective use of the models in assessing groundwater vulnerability lies in the spatial heterogeneities of the natural environmental systems (Kaur and Rosin, 2008). Under such heterogeneous environmental systems, the models involve usage of large quantities of data. Use of probabilistic models is then inhibited when data is scarce. This method can be less applicable in most developing countries since most developing countries have less data due to the inadequacy of monitoring networks and/or human resources (MacDonald *et al.*, 2012; Chikodzi, 2013). Thus, values of input parameters for sophisticated models are not always available, hence their values have to be estimated e.g. using surrogate parameters or extrapolated from data collected at other locations (NRC, 1993). There are vast errors and uncertainties associated with such estimates or extrapolations hence producing unreliable results.

b. Statistically-Based methods

According to Kaur and Rosin (2008), statistical methods are used to quantify the vulnerability of groundwater contamination through the determination of the statistical dependence or relationship between potential sources of contamination, observed contamination and environmental conditions that characterize an area. NRC (1993) pointed out that statistical methods are rather used to test other methods, hence very few vulnerability assessments are directly based on statistical methods. It is indicated that, the vulnerability obtained using statistical methods is expressed as contamination probability (NRC, 1993). As such, the higher the contamination probability, the higher the vulnerability. The disadvantage of the method is that it is difficult to develop and once established, it can only be applied to regions that have similar environmental conditions to the region for which the statistical model was developed (NRC, 1993; Zhang *et al.*, 1996). Statistical methods are also data intensive, hence they are difficulty to execute in most of the developing continents due to data scarcity (Kaur and Rosin, 2008). Statistical methods, such as principal components analysis, discriminant analysis and cluster analysis are used to analyse groundwater.

c. Index overlay methods

The index overlay method uses location specific vulnerability indices (Zhang *et al.*, 1996). It is based on the factors controlling movement of pollutants from the ground surface to the saturated zone. NRC (1993), highlighted that the method is based on combining thematic layers of various physiographic attributes by assigning an index or score to each attribute. The index overlay ground water vulnerability method integrates attributes of important factors controlling pollutant transport from the surface to an aquifer (Foster, 1987; Morris *et al.*, 2003).

These methods assess groundwater vulnerability qualitatively using a relative scale. They are based on the assumption that a few major parameters largely contribute in groundwater protection or affect groundwater vulnerability (NRC, 1993; Vrba and Zoporozec, 1994). Thus, hydrogeological information and parameters are classified according to a certain scoring or ranking system. All weighted parameters are superimposed in a numerical ranking system to develop a dimensionless vulnerability map (NRC, 1993; Morris *et al.*, 2003). The map will be showing the relative magnitude of vulnerability. The index overlay method is advantageous in that it provides relatively simple algorithms or decision trees to integrate a large amount of spatial information into maps of vulnerability classes or indices (Kaur and Rosin, 2008). The methods are also suitable for data limited areas. Thus, they are less constrained by data shortage and computational difficulties (NRC, 1993). The major drawback is that the results tend to be subjective if not supported by actual measurement data (Gogu and Dassargues, 2000; Foster *et al.*, 2002). However, Gogu and Dassargues (2000) suggested that index overlay methods can be very useful in combination with the process-based models.

Of all the vulnerability methods presented earlier, the Index Overlay methods proves to be more suitable for developing countries such as Zimbabwe since they are less data demanding and a less costly. Other methods are more complex, and cannot be executed due to data and human resource limitations. The GOD model is one of the most used overlay index models. Its functionality is as described in section 2.6.

2.6 Groundwater vulnerability assessment using the GOD model

The GOD method is an empirical method for the assessment of aquifer vulnerability (Foster, 1987). The method was developed by Foster in 1987. It considers three parameters, viz. (i) groundwater occurrence; (ii) overall aquifer class; and (ii) depth to groundwater table (Foster *et al.*, 2002). The parameters for the model are weighted and aggregated to provide a measure of vulnerability on a continuous probabilistic scale of 0 to 1 (Polemio *et al.*, 2009). The model uses a multiplicative approach to integrated influencing parameters (*Equation 1)*.

$$GOD\ Index = G_r * O_r * D_r \qquad \textit{Equation 1}$$

where: G_r = type of aquifer (Overall aquifer class).

O_r = the lithology of the unsaturated zone.

D_r = the depth to the groundwater surface

The GOD method is useful for mapping large areas with high vulnerability contrasts and poor data sets (Polemio *et al.*, 2009; Abdelmadjid and Omar, 2013). The parameters are aggregated as shown in *Figure 2.*

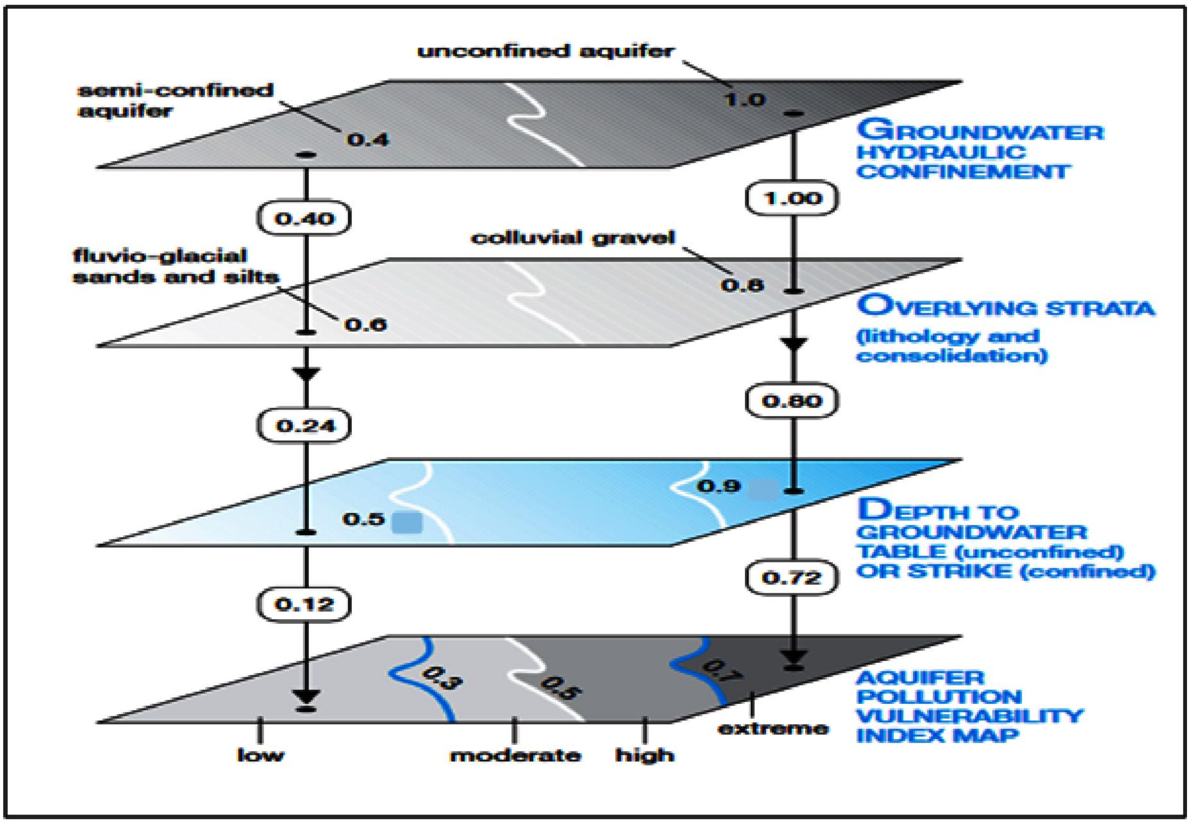

Figure 2: GOD-based aquifer vulnerability map generation (Foster, 2002)

The GOD index model was successfully applied in the assessment of intrinsic groundwater vulnerability in different regions of the world. The model was applied in: (i) the assessment of vulnerability in Karstic aquifers of Apulia, Southern Italy (Polemio *et al.*, 2009); (ii) the evaluation of groundwater vulnerability in an alluvial aquifer of IRAN (Khodapanah *et al.*, 2011); (iii) the assessment of groundwater pollution by nitrates in the Nil valley, Jijel, North-East Algeria (Abdelmadjid and Omar, 2013); and (iv) the assessment of groundwater vulnerability in Abarkooh, southeast of Yazd Province, Iran (Ghazavi and Ebrahimi, 2015). The researches established that the model is more applicable for large basins, and it is less data intensive, hence suitable for data scarce areas. The characteristic of being less data demanding makes the model applicable in the current study area.

CHAPTER 3
STUDY AREA

3.1 Description of Study Area

3.1.1 Study area location

The Upper Manyame Sub-catchment (UMSC), shown in *Figure 3*, is a headwater catchment of the Manyame River which eventually flows into the Zambezi River (Rwasoka *et al.*, 2011). The sub-catchment spans over 3786 km^2 of both rural and urbanized centres, draining through Harare's commercial centres; high and low-density suburbs; as well as agricultural land, collecting surface runoff before eventually discharging into lakes Chivero and Manyame (Nhapi and Tirivarombo, 2004; Nyamangara *et al.*, 2013). Hydrologically, it is bordered by the Upper Mazowe Sub-catchment to the north, the Middle Manyame Sub-catchment to the north west, the Sanyati Catchment to the south west, the Nyagui Sub-catchment to the north and north east and the Save Catchment to the east and south east (Mazvimavi *et al.*, 2005; UMSCC, 2014). Its boundary straddles across four administrative districts namely: the Harare Metropolitan, Goromonzi, Marondera, Manyame and Zvimba (UMSCC, 2014).

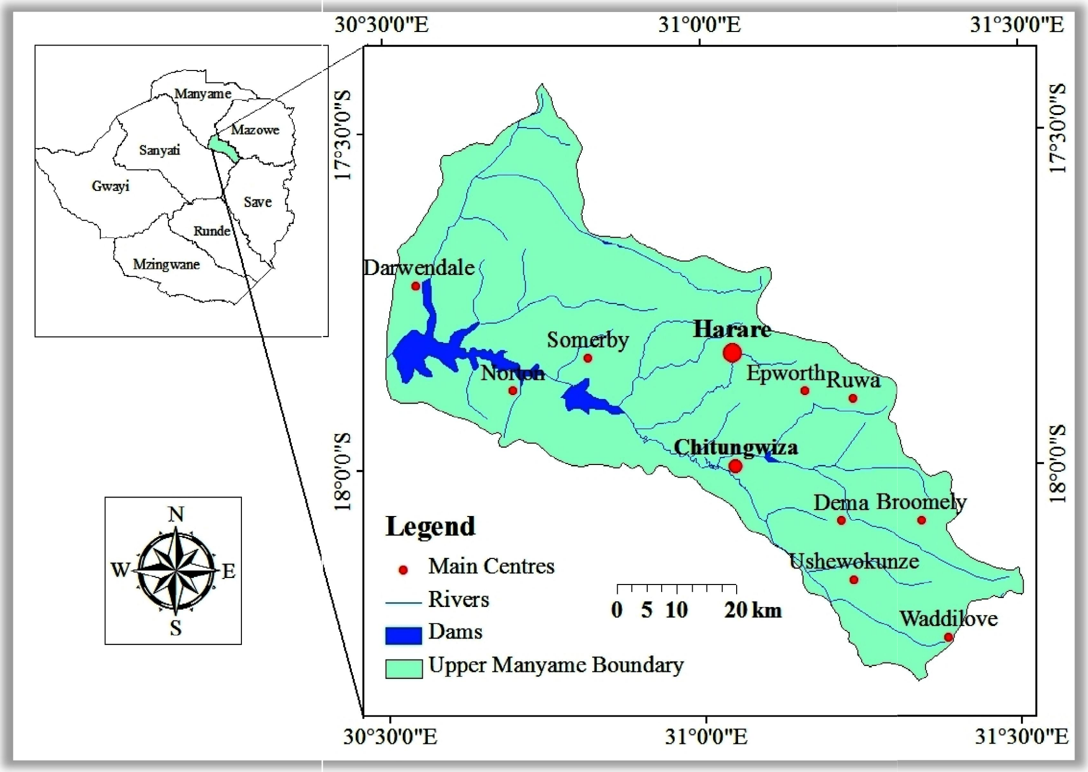

Figure 3:Map showing the Upper Manyame Sub-catchment

3.1.2 Population, landuse and socio-economic activities

The UMSC is the most urbanized sub-catchment in Zimbabwe (Rwasoka *et al.*, 2007; Masere *et al.*, 2012). It houses Harare's (the capital city) main commercial centres/towns and its fast growing dormitory suburbs (UMSCC, 2014). According to the CSO (2012), the sub-catchment constitutes over 16 % of the total population of Zimbabwe (approximately 2.7 million people). The sub-catchment's population growth rate was estimated to be 5 % per annum; a growth rate mainly attributed to the rapid urbanisation since the attainment of independence (Hranova, 2003; Tsiko and Togarepi, 2012).

In terms of landuse, the sub-catchment is characterised by complex and contrasting spatial socio-economic development patterns (Kamusoko *et al.*, 2013). With reference to a study by Kibena *et al*. (2013), in the UMSC, agriculture and built-up areas have expanded by 24.4 % and 41.6 %, respectively since 1984. The major socio-economic activities in the sub-catchment include; industrial manufacturing, mining, agriculture as well as day to day activities by inhabitants of the sub-catchment (Dlamini *et al.*, 2016). Unregulated activities such as, stream bank and wetland cultivation, brick molding and sand mining are also rampant (UMSCC, 2014). These activities have become an alternative to earning a living for many due to the economic recession (Nhapi, 2009). However, the activities have become the epicenter of siltation and pollution problems being faced in the sub-catchment.

3.1.3 Climate and hydrology

The Mean Annual Precipitation (MAP) of the sub-catchment ranges from 750-900 mm/yr (Mazvimavi *et al.*, 2005). A recent study by Kibena *et al.* (2013) found a MAP of 810 mm/yr for the period 2000–2010, with a potential evapotranspiration rate of 1600 mm/yr. The sub-catchment is divided into two hydrological sub-zones, CH4 and CH5, based on the mean annual rainfall (Mazvimavi *et al.*, 2005). In terms of Zimbabwe's agro-ecological regions, the sub-catchment falls under Region II, with hydrological sub-zones CH4 and CH5 falling into agro-ecological sub-regions II (a) and II (b) respectively (Mugandani *et al.*, 2012). Sub-region II (a) is characterized by intensive farming systems with less dry spells during summer while sub-region II (b) is characterized by more severe dry spells during the rainy season or the occurrence of relatively short rainy seasons (Mugandani *et al.*, 2012). Nhapi (2009), pointed out that the spatio-temporal variation in rainfall patterns in the UMSC have increased due to the effects of climate change and/or climate variability.

3.1.5 Water resources situation

The UMSC is faced with piped water shortages (Nhapi, 2009). Urban councils are failing to meet the increasing potable water demand (Manzungu *et al.*, 2012). Rapid urbanization in the sub-catchment, without complimentary improvement of the potable water supply infrastructure, has been the main cause of potable water shortages. On the other hand, high levels of water pollution have induced higher potable water treatment costs, consequently aggravating the plight of potable water shortages (Hove and Tirimboi, 2011; Manzungu *et al.*, 2012; Tendaupenyu, 2012). The main water supply reservoirs and major rivers within the sub-catchment are seriously polluted; i.e. Lake Chivero (Dlamini *et al.*, 2016), Manyame river (Masere *et al.*, 2012; Kibena *et al.*, 2013), Marimba river (Kamusoko and Musasa, 2012), Ruwa river (Nyakungu *et al.*, 2013), Nyatsime and Mukuvisi river (Moyo and Rapatsa, 2015). Industrial areas, agricultural land and dormitory suburbs dotted around the sub-catchment are situated upstream of the water supply reservoirs, Lake Chivero and Lake Manyame. This set-up, coupled with rapid urbanization and poor waste disposal mechanisms highly contributed to the pollution of the water bodies (Moyo and Rapatsa, 2015). Researches by Nhapi and Tirivarombo (2004) , Hranova *et al.* (2001), Magadza (2008), Masere *et al.* (2012) and Nyamangara et al (2013) identified industrial effluent; partially treated sewage from wastewater treatment plants; urban runoff; agricultural runoff and leachate, among others, as the main contaminants of surface water. Consequently, groundwater dependence has increased significantly (UMSCC, 2014). The populace is relying on a combination of hand-dug wells and public/private boreholes for their drinking water, to supplement potable water shortages. However, it is evidenced from research done in the sub-catchment that, groundwater is under threat from increased pollution load (Masere *et al.*, 2012). A research by Love *et al.* (2006) highlighted instances of groundwater pollution from diffuse pollution. This has consequently led to serious health risks.

3.1.4 Hydrogeological setting

The UMSC is composed of the Bulawayan, the Dolerites/Gabbros, the Granitoids and the Shamvaian geological formations, with the granitic formation occupying the greatest (76 %) proportion of the study area (2877 km^2) as shown in *Figure 4* (Martinelli and Hubert, 1985; UMSCC, 2014). The formations are of variable groundwater potential depending on the depth and spatial extent of both fracturing and secondary weathering (Mazvimavi *et al.*, 2005). Mazvimavi *et al.* (2005) and Broderick (2012) further highlighted that the study area is characterized by generally shallow, water tables (less than 20 m) with borehole yields varying from 10 to 100 m^3/day. Specific groundwater yields of individual formations, are defined by Martinelli and Hubert (1985) as follows:

(i) The Shamvaian formation is of low groundwater prospect with borehole yields ranging from 10-25m^3/day, only suitable for single point primary supply;

(ii) The Granitic formation has borehole yields ranging from 10-100 m^3/day (50-100 m^3/day in African surface and 10-50 m^3/day in post African surface). The formation is of moderate to low groundwater potential

(iii) The Dolerite/Gabbros group is of moderate to high groundwater potential with borehole yields ranging from 50-100 m^3/day (yields are suitable for primary supply and small. piped schemes), and;

(iv) The Bulawayan group has a good aquifer, supporting yields ranging from 100-250 m^3/day. Suitable for small scale irrigation schemes and piped water supplies for larger growth points.

According to the MRC (2009), the Shamvaian rocks are characterized by shallow water tables averaging 10 m below the surface and are rarely deeper than 20 m. On the other hand, the granitic formation has very poor primary porosity and permeability, hence groundwater in this unit is irregularly developed and is scattered typically occurring in the weathered and fractured regolith (Martinelli and Hubert, 1985). The Bulawayan formation is an excellent aquifer with abundant water supplies (Martinelli and Hubert, 1985; MRC, 2009).

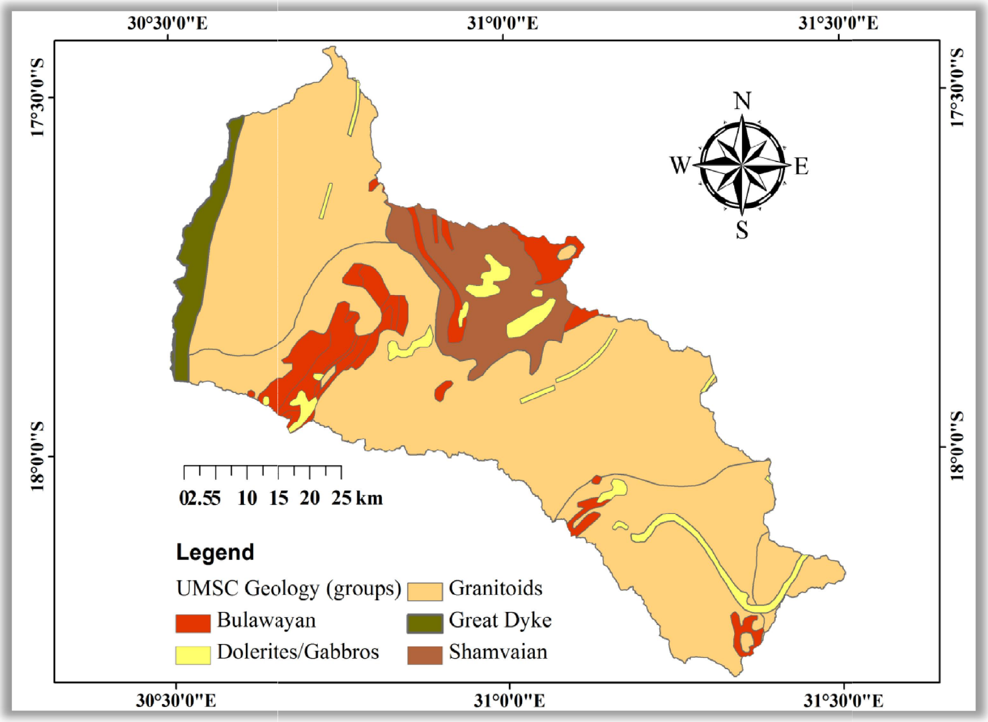

Figure 4: Geology map of the Upper Manyame Sub-catchment

Source: Extracted from the Zimbabwe Geology Map, 1985, Zimbabwe Geological Survey.

3.1.6 Groundwater Storage

Groundwater is stored in aquifers. Aquifers are defined as groundwater reservoirs composed of geologic units that are saturated with water and sufficiently permeable, to yield water in a usable quantity (Buddemeier *et al.*, 2000). Aquifers provide two important functions: (i) they transmit ground water from areas of recharge to areas of discharge, and (ii) they provide a storage medium for useable quantities of groundwater (Meijerink *et al.*, 2007). According to Broderick (2012), the UMSC is composed of an unconfined aquifer. Unconfined aquifers are characterized by perched water bodies, separated from the main groundwater by a impermeable stratum (Meijerink *et al.*, 2007). Broderick (2012) highlighted that, most parts of Harare are underlain by a massive granite which extends from Amby, covering areas like Masasa, Hatfield, Waterfalls, and the western suburbs. These areas are said to be of poor groundwater prospect due to the massive and resistant nature of the bedrock, hence poor storage. Therefore the available groundwater tends to be perched at shallow depths and is often only exploitable by means of hand-dug wells. It is highlighted that the available groundwater is superficially stored in secondary porosity and its storage is dependent on the degree of fracturing and weathering (Broderick, 2012). Therefore the type of an aquifer determines the storage capacity, hence specific groundwater yields. According to Meijerink *et al.* (2007), specific yield is defined as the ratio of the volume of water that drains from a saturated rock owing to the attraction of gravity (or by pumping from wells) to the total volume of the saturated aquifer. The yield is dependent on the storage capacity of the aquifer.

3.1.7 Groundwater use in the Upper Manyame Sub-catchment

The demand for groundwater in the Sub-catchment remains high with the inhabitants relying on a combination of hand-dug wells and boreholes for their drinking water (UMSCC, 2013). This has placed groundwater under serious pressure. A hydrocensus carried out to determine groundwater use in the UMSC identified 15830 boreholes and wells in 2014 (UMSCC, 2014). The hydrocensus established high borehole densities in most of the high income residential suburbs such as Alexandra Park and Belgravia.

According to the Water Act of Zimbabwe, Chapter 20:24 of 1998 and Statutory Instrument 206 of 2001, it is a pre-requisite that no borehole or well should be sunk within a radius of 200 meters from an existing one. Groundwater development in the sub-catchment is however contrary to this legal requirement as almost every household has a groundwater source, particularly the low and medium-density suburbs which have gone to over a decade without municipal water supply (Broderick, 2012). Boreholes are mostly found in the middle and high income suburbs as well as industrial areas who can afford high development costs associated with the establishing boreholes (Manzungu *et al.*, 2012). On the other hand, low income earners and informal settlements are depending mainly on community boreholes and/or shallow wells.

According to UMSCC (2014), sustainable utilisation of groundwater should strike balance between groundwater fluxes; that is groundwater recharge and discharge (which include withdrawal for human consumption). Efforts to perform allocation based groundwater balance assessment for two micro-catchments in the UMSC (Marimba and Mukuvisi), using first order approximations show that the current permit allocation regime of 2.5 Mega Litres (ML) per annum per household will result in groundwater mining, *Table 2* (UMSCC, 2014). A total of 5026 and 9335 households in Marimba and Mukuvisi micro-catchments, respectively, were used for the groundwater balance assessment. The assessment adopted the 2 percentum rule (2 % of the Mean Annual Precipitation); which is laid out in the Government of Zimbabwe Statutory Instrument 206 of 2001, Section 16 (3), for the estimation of recharge. Permit allocations of less than 0.5 ML/yr were found to be sustainable from the study. However, the assessment failed to take into consideration the variations in the withdrawal volumes across various sectoral uses as well as unknown groundwater utilisation in the sub-catchment. Therefore, the recommended withdrawal rates per household may not be sustainable for other uses.

Table 2: Groundwater balance for Marimba and Mukuvisi micro-catchments (UMSCC, 2014)

Micro-catchment	Area (km^2)	MAP (mm)	Annual Recharge (ML)	Allocation (@ 2.5 ML/yr)	Balance (ML)	Allocation (@ 0.5475 ML/yr)	Balance (ML)	Allocation (@ 0.1825 ML/yr)	Balance (ML)
Marimba	215	799	3436	12565	-9128	1626	1811	542	12023
Mukuvisi	221	821	3629	23337	-19708	3635	-6	1212	2417

CHAPTER 4
MATERIALS AND METHODS

4.1 Study design

The study employed quantitative data collection and analysis methods. Geographic Information Systems (GIS) and Remote Sensing (RS) techniques were employed for Groundwater Potential (GWP) mapping and groundwater vulnerability assessment. Groundwater quality parameters were analysed onsite and at the University of Zimbabwe Civil Engineering Laboratory.

4.1.1 Selection of the study site

The study was conducted in the Upper Manyame Sub-catchment (UMSC): one of the most urbanised sub-catchments in Zimbabwe (Masere *et al.*, 2012). The sub-catchment is characterized by an intertwined assortment of socio-economic activities and development patterns which have exposed the sub-catchment's water resources to significant pressure and pollution (Masere *et al.*, 2012; Kamusoko *et al.*, 2013). The health consequences of such socio-economic activities and development patterns in the sub-catchment have been severe, thereby rendering the sub-catchment the most negatively impacted and most vulnerable in Zimbabwe. NAC (2012) singled out high levels of pollution in the sub-catchment as a health threat. Despite the looming and the already encountered health risks, the general public has no option but to depend on the much polluted surface water (Nhapi, 2009; Masere *et al.*, 2012); and even more on the less investigated groundwater (Love *et al.*, 2006; Malzbender and Earle, 2007; Chikodzi, 2013). Ultimately, there is need for more research to assess the availability and suitability of groundwater as an alternative to potable water shortages in order to safeguard the health of millions depending on the resource.

4.2 Ground water potential mapping

RS and GIS-based multi-criteria approaches were used to map GWP zones as recommended by various researchers (Bera and Bandyopadhyay, 2012; Magesh *et al.*, 2012; Awawdeh *et al.*, 2013; Fenta *et al.*, 2015; Nejad *et al.*, 2015). Thematic layers of: geology, slope, land-use, drainage density, recharge, topographic index, altitude and rainfall, were prepared from RS data in a GIS environment. The selection of thematic layers for GWP mapping was based on similar studies by; Magesh *et al.* (2012), Yazdani and Aryamanesh (2013), Fenta *et al.* (2015) and Mondal (2012). Thematic layers and individual classes within thematic layers were independently weighted/rated using Saaty's Analytical Hierarchy Process (AHP) and the Quantile method (QM) as described by Fenta *et al.* (2015) and Nejad *et al.* (2015). The weighting methods have been used by; Bera and Bandyopadhyay (2012); Magesh *et al.* (2012), Jasrotia *et al.* (2013), Waikar and Nilawar (2014) and Fenta *et al.* (2015) who concurred on the robustness of the AHP method in factor rating as compared to the QM. Thematic layers were then aggregated using the Weighted Linear Combination (WLC) (Saaty, 2008) and the Index Overlay (IO) methods respectively (Foster *et al.*, 2002), to develop two Groundwater Potential Index (GWPI) maps. The GWPI maps were correlated with borehole yield data from 120 boreholes to check the validity of the results. The R-based Spearman's correlation coefficient was used for correlation analysis. Correlation coefficients were used to describe the correlations.

4.2.1 Data sources

RS data and secondary data, obtained from different platforms, were used in GWP mapping. The Digital Elevation Model (DEM) of the study area was obtained from Shuttle Radar Topography Mission (SRTM DEM). The slope, topographic index, elevation and drainage density maps were then developed from the DEM using the DEM hydroprocessing tool in ILWIS. Cloud free images from Landsat 8 Operational Land Imager (OLI), for the dry month of August 2015 were downloaded from the United States Geological Survey website (http://glovis.usgs.gov). Landsat images are of high resolution (30 m), hence they are suitable for landuse classification (Kibena *et al.*, 2013). The Landsat OLI images were then used to develop the landuse map of the study area through supervised classification using the maximum likelihood algorithm. According to Kibena *et al.* (2013), the maximum likelihood classification assumes that the statistics for each class in each band are normally distributed and calculates the probability that a given pixel belongs to a specific class. Monthly spatial precipitation data was obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) platform using the ISOD toolbox in ILWIS. The satellite-based rainfall was used to develop the mean annual rainfall and recharge maps for the study area. In addition to the RS data, ancillary data was also used. The mean annual rainfall data for two rainfall stations, Belvedere and Harare Airport, obtained from the Meteorological Services of Zimbabwe, were used to validate the spatial rainfall data from CHIRPS, at an annual time scale. Borehole yield data from 120 boreholes, obtained from the UMSCC and ZINWA, was used for the validation of the GWPI maps.

4.2.2 Generation of groundwater conditioning factors/thematic layers

GWP conditioning factors; slope, drainage density, rainfall, land use/land cover, geology, Topographic Wetness Index, elevation and recharge, were prepared in a GIS environment. ILWIS software version 3.0 and QGIS Desktop 2.8.1 were used for spatial analysis as described below:

a. Slope

Slope is one of the important factors that determine GWP (Magesh *et al.*, 2012). It controls infiltration of water into the subsurface (Fenta *et al.*, 2015). Flat and gentle slope areas increase the residence time of runoff, hence promote infiltration. Steep slopes facilitate surface runoff generation, hence comparatively less infiltration (Nejad *et al.*, 2015). The gentle the slope, the high infiltration, hence high GWP. In this study, the slope map was developed from SRTM DEM of 30 m resolution using the DEM Hydroprocessing Tool in ILWIS. The slope map was developed as shown in *Equation 2.*

$$SLOPEDEG = RADDEG\left(ATAN\left(\frac{SLOPEPCT}{100}\right)\right) \qquad \textit{Equation 2}$$

where: SLOPEDEG = slope in degrees

ATAN and RADDEG = internal Map Calculation/Table Calculation functions

SLOPEPCT = slope in percentage

Five slope classes: nearly level, very gentle, gentle, moderately steep to steep and very steep, corresponding to ranges: 0-1, 1-5, 5-10, 10-15 and > 15, were prepared based on the slope classification by Waikar and Nilawar (2014). The slope of > 15^o was classified as very steep.

b. Drainage Density

Drainage density is a measure of the total length of the stream segment of all orders per unit area (Magesh *et al.*, 2012). It is determined by the nature and structure of the bedrock, kind of vegetation, rainfall absorption capacity of soils, infiltration, geomorphology and slope gradient (Rahmati *et al.*, 2014). Low drainage density regions are characterized by decreased surface runoff, hence more infiltration is likely. These areas are suitable for groundwater development (Magesh *et al.*, 2012). Areas of high drainage density represent areas of greater runoff generation, hence low recharge potential. The drainage density for the UMSC was derived from SRTM DEM (30*30 m). The drainage density was classified into classes very low (< 0.1 km/km^2), low (0.1-0.4 km/km^2), moderate (0.4-0.6 km/km^2), high (0.6-0.8 km/km^2) and very high (> 0.8 km/km^2) using the drainage density ranges developed by Awawdeh et al. (2013).

c. Rainfall

Rainfall distribution is considered to be of greater influence to GWP (Rahmati *et al.*, 2014; Fenta *et al.*, 2015). It is one of the important variables that affect groundwater recharge, hence potentiality. Satellite based rainfall data was obtained from CHIRPS database through the ILWIS ISOD Toolbox. The dataset is a 30+ year quasi-global rainfall dataset starting from the year 1981 to near-present. It incorporates 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series. The 33 year long (1981 to 2014) monthly rainfall was averaged to develop an annual average rainfall map for the study area. Rainfall data from the Belvedere and the Harare Airport meteorological stations, were used for the validation of the spatial rainfall data obtained from CHIRPS at an annual time span.

d. Land use/land cover

According to Mondal (2012), Land use/land cover (LULC) plays a major role in determining the occurrence and development of groundwater. It affects evapotranspiration, surface run-off and groundwater recharge among others. In this study, the LULC map was generated using supervised classification. The maximum likelihood classifier algorithm was chosen due to its robustness (Gumindoga *et al.*, 2014). Seven major landuse classes were developed, viz., bareland, cultivation, forest & shrub, grassland, irrigation agriculture, settlements as well as water & marshy. Accuracy assessment for the classified LULC map was done through the use of the Confusion matrix in ILWIS software as recommended by Zhang *et al.* (2010). A total of 50 Ground Control Points; obtained from Google Earth images and field surveys (using a handheld Global Positioning System receiver) were used for accuracy assessment

e. Geology

Geology significantly influence groundwater fluxes, both on the surface and subsurface (Nejad *et al.*, 2015). It is recommend that geology should be taken into account in studies related to GWP mapping (Chuma *et al.*, 2013; Rahmati *et al.*, 2014; Nejad *et al.*, 2015). Areas with high resistant rocks inhibit infiltration, hence low GWP. On the other hand, highly permeable subsoil material encourage infiltration hence promoting recharge (Nejad *et al.*, 2015). In the present study five geology groups, namely, the Bulawayan, the Dolerites/Gabbros, the Granitoids, the Great Dyke formation and the Shamvaian are found in the UMSC, *Figure 4* (Martinelli and Hubert, 1985). The geological classes were weighted based on their groundwater yield potential as outlined by Martinelli and Hubert (1985). The Bulawayan group was allocated the highest weights as it is characterized by high specific yields greater than 100 m^3/day. The lowest rating was assigned to the Shamvaian group which is characterized by low groundwater yields ranging from 10-25m^3/day.

f. Topographic Wetness Index

The Topographic Wetness Index (TWI) plays an important role in determining GWP (Nejad *et al.*, 2015). The index was developed by Beven and Kirkby (1979). It presents the spatial distribution of wetness conditions or areas with a tendency of water accumulation in the catchment (Gumindoga *et al.*, 2014; Nejad *et al.*, 2015). Thus, the index serves to predict local variations in the water table (Gumindoga *et al.*, 2014). The higher the values of the TWI, the higher the GWP (Nejad *et al.*, 2015). The TWI of the study area was developed from the UMSC DEM as a logarithmic ratio between the specific catchment area/specific runoff contributing area (A_s) and the average outflow gradient/slope ($\tan\beta$), *Equation 3:*

$$TWI = ln\frac{A_s}{tan\beta} \qquad \textit{Equation } 3$$

In this study, the TWI was classified into 4 classes; 3-6; 6-8; 8-18 and >18. A classification by Nejad *et al.* (2015) was applied in this study since the TWI values for the UMSC exhibited a similar value ranges.

g. Elevation/Relief

Elevation plays a significant role in determining GWP. The local and regional relief setting determines the general direction of groundwater flow, groundwater recharge and discharge (Sokeng *et al.*, 2016). Thus, elevation determines the infiltration rates, flow accumulation, transit and dissipation zones (Liu *et al.*, 2015). Areas of low elevation/relief are associated with groundwater accumulation. Thus, low elevation areas experience slow surface runoff; allowing more residence time for rainwater to percolate, whereas, high elevation areas facilitate high runoff, hence comparatively less infiltration. High infiltration can lead to high GWP and vise-versa. The elevation map for the study area was developed from the DEM of the study area after elimination of artificial depressions (sinks) using the *Fill Sink* operation in ILWIS. Elevation ranges: > 1560 m, 1480-1560 m, 1400-1480 m and 1320-1400 m, were developed.

h. Recharge

Groundwater recharge is a hydrologic process where water moves downward from the surface to the subsurface (Rusinga and Taigbenu, 2005). This process usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. The higher the recharge the high the GWP. A study by Houston (1990) in a basement aquifer of Masvingo (areas around the town) gave recharge estimates 2-5 % of the Mean Annual Precipitation (MAP). The aquifer setting of Masvingo (basement complex) is similar to that of the UMSC. In a similar study by Macdonald *et al.* (1995), the average recharge for Zimbabwe's basement aquifers, an aquifer set-up similar to that of the UMSC, were found to range from 2-5 % of the MAP. In the studies, recharge was measured using baseflow analysis, chloride balance and soil moisture budgeting methods. In another study carried out in the Nyamandlovu aquifer to estimate recharge, the recharge rates between 1.6 % to 4.2 % of the MAP were observed using C14 groundwater ages (Rusinga and Taigbenu, 2005). A model developed by Rusinga and Taigbenu (2005) calculated recharge as a function of precipitation (P), runoff (R), evapotranspiration (ET) and the fluxes. Their study estimated the recharge as 6.8 % of the MAP. However there was no validation of their model. Additionally, the water law of Zimbabwe, Statutory Instrument 206 of 2001, proposed 2 % of the MAP as the recharge rate. However, this study uses the 2-5 % recharge rate as highlighted in a study carried out in the UMSC by Broderick (2012). The recharge map was developed as a function of the MAP of the study area. The recharge rate of 3.5 % (the mean for the 2-5 % recharge range) of the MAP for the period 1981-2014 was used to develop the recharge map for the UMSC. According to Broderick (2012) and Davies and Burgess (2014), the groundwater cycle in the sub-catchment is dependent more on rainfall, hence the use of a proportion to the MAP to estimate recharge

4.2.3 Computation of weights using the AHP and the Quantile methods

GIS-based spatial multi-criteria evaluation approaches, the AHP and QM, were used to compute weights of thematic layers and their individual attributes. Fenta *et al.* (2015) indicated that these methods are the most widely used for scaling the rates/weights of factors, with the AHP Method being more robust. Both methods were used in this study for comparison purposes, hence for selection of the best method for GWP mapping.

a) The Analytical Hierarchy Process

In this study, thematic layers and individual attributes of thematic layers were compared to each other and weighted by means of the Pair-Wise Comparison Matrix (Waikar and Nilawar, 2014). Saaty (1980) suggested a rating scale of 1 to 9 for the Pair-Wise Comparison Matrix (PCM) elements as summarised in *Table 3*.

Table 3: AHP preference scale (Saaty, 2008)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favor one activity over another is of the highest possible order of affirmation
Reciprocals of the above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	
1.1-1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities, the size of small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities

The PCM allows consistency checking and identification of judgment errors by means of the Consistency Ratio (CR). According to Saaty (2008) and Fenta *et al.* (2015), it is critical to determine the CR as a measure of accuracy. In this study, the CR were calculated for each thematic layer. Saaty (1980) recommended that the CR should be less than 0.10, otherwise any values greater than 0.10 should be re-evaluated. The CR was determined as shown in *Equation 4* (Fenta *et al.*, 2015).

$$CR = \frac{CI}{RI} \qquad \textit{Equation 4}$$

Where CI is the Consistency index which is the deviation or degree of consistency, calculated as shown in *Equation 5*.

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad \textit{Equation 5}$$

λ_{max} is the largest eigenvalue of the PCM *(Equation 6),* while *n* is the number of criteria to be considered.

$$\boldsymbol{\lambda_{max}} = \sum_{i=1}^{n} \left(W_i * \frac{P_i}{\sum_{i-1}^{n} P_i} \right) \qquad \textit{Equation 6}$$

Where W_i = weight for each thematic layer

P_i = priority of the alternative *i*

RI is Saaty's ratio index or the randomized consistency index for a matrix of order n. The values of the index given in *Table 4.*

Table 4: Saaty's Ratio Index (RI) for different values of n

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

The AHP has been successfully applied in other GWP mapping studies (Mondal, 2012; Chuma *et al.*, 2013; Olutoyin *et al.*, 2014; Nejad *et al.*, 2015). In a different study, the AHP method was successfully applied for landslide susceptibility mapping at in the Haraz Watershed of Iran (Pourghasemi *et al.*, 2012c). The researches confirm the robustness of the AHP method.

b) The Quantile Method

The Quantile classification approach is based on expert judgments. Factor maps or thematic layers are placed in classes of equal intervals (Rahmati *et al.*, 2014; Nejad *et al.*, 2015). In this study, individual themes and their attributes were rated on a scale of 1-10, with 1 representing extremely low contribution to GWP. Rahmati *et al.* (2014) indicated that the method is highly subjective. Existing literature was used to assess the relative importance of each factor over the other for the allocation of weights. The method fails to account for consistence of the ratings, hence it is considered highly subjective.

4.2.4 Aggregation of thematic layers using the WLC and the IO methods.

After the computation of weights of eight thematic layers and their attributes; two Groundwater Potential Index (GWPI) maps were developed by aggregating the thematic layers using the WLC method (Saaty, 2008) and the IO method (Foster *et al.*, 2002). According to Rahmati *et al.* (2014), a GWPI is a dimensionless quantity that helps to predict the groundwater potential zones in an area.

(i) The Weighted Linear Combination Method

According to Saaty (2008), the WLC technique is a modification of the Index Overlay Technique. It involves standardization of ratings of thematic layers and their individual attributes. Saaty (2008), further highlights that standardization of factor maps is necessary so that all maps are positively correlated with the suitability. The WLC technique then combines the standardized suitability maps to obtain an overall GPWI index map, as shown in *Equation 7*.

$$GWPI\ 1 = \sum_{w=1}^{m} \sum_{i=1}^{n} \left(W_j \times X_i\right) \qquad \textit{Equation 7}$$

where W_j = normalized weight of the j thematic layer

X_i = rank value of each class with respect to the *i* layer

m = the total number of thematic layers

n = the total number of classes in a thematic layer.

In this study the WLC based GWPI map (GWPI 1) was calculated as shown in *Equation 8*.

$$GWPI\ 1 = G_W G_{WF} + S_w S_{wf} + LU_w LU_{wf} + TWI_w TWI_{wf} + DD_w DD_{wf} + R_w R_{wf} + R/F_w R/F_{wf} + A_w A_{wf}$$

Equation 8

where G Geology, S=Slope, DD=Drainage Density, R/F=Rainfall, TWI=Topographic Wetness Index, A=Altitude/Elevation, R=Recharge, LU=Landuse

"w" = normalized weight of a theme

"*wf*" = normalized weight of the individual features/classes of a theme

(ii) *The Index Overlay method*

The index overlay method is differentiated from the WLC method by the fact that, factor maps and their attributes are not standardized relative to each other. The IO method was used to develop GWPI 2 as shown in *Equation 9*.

$$GWPI2 = \frac{\sum_{i=1}^{n} W_i X_i}{\sum_{i=1}^{n} W_i} \qquad \textit{Equation 9}$$

where W_i= weight for each thematic layer

X_i = rated thematic layer.

4.2.5 Validation of the GWPI maps

Borehole yield data was used to validate the identified GWP zones in the study (Olutoyin *et al.*, 2014; Rahmati *et al.*, 2014; Fenta *et al.*, 2015). A total of 120 boreholes dotted across the sub-catchment were used. A test for normality was first performed on the borehole yield data using the Kolmogorov Smirnov test. The data was found not to follow a normal distribution, hence the Spearman's Correlation Coefficient was used for correlation analysis. Borehole yield data were correlated with GWP Indices from the maps. The GWPI map that exhibited the best correlation coefficient with borehole yield data was then used to develop the final GWP map for the study area. The GWPI values were re-classified into three GWP zones; low, moderate and high. The zones were classified according to a classification of groundwater yields in Zimbabwe by Martinelli and Hubert (1985).

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4.3 Identifying and mapping potential groundwater pollutants

A pollution risk map was developed for Marimba, a micro-catchment in the UMSC. The micro-catchment was chosen since it exhibits similar characteristics as the UMSC, in terms of socio-economic activities and development patterns (UMSCC, 2014). The micro-catchment spans over 220.5 km^2 (Gumindoga *et al.*, 2016). It originates from the University of Zimbabwe grounds, draining the northern and western parts of Harare's commercial centers, dormitory suburbs (i.e. Tynwald, Westgate, Greencroft, Kuwadzana, Dzivarasekwa, Budiriro 5 and Kambuzuma among others) and the industrial areas (i.e. Bluffhill, Workington, Tynwald, Aspindale and Southerton), before eventually draining into Lake Chivero (Nhapi and Tirivarombo, 2004). Downscaling to a micro-catchment was done to reduce over generalization, as compared to using the whole of the UMSC. Major landuses (potential groundwater pollution sources) of the study area were delineated using the classified landuse/landcover map of the UMSC (*Figure 13*). The classified landuses were superimposed with Google Earth imagery in-order to identify the detailed landuses contributing to groundwater pollution such as industrial and agricultural areas (Gumindoga *et al.*, 2016). As such, Google Earth images were used to digitize the identified landuse classes that were deemed pollution risk areas. Landuse classes: Irrigated Agriculture, Cultivation and Settlement were considered potential pollution sources as summarised in *Table 5.* The choice of potential groundwater pollution sources was made with reference to findings by several researchers in the study area (Hranova *et al.*, 2001; Foster *et al.*, 2002; Hranova, 2003; Dzvairo *et al.*, 2006; Love *et al.*, 2006; UN-Water/Africa, 2010; Masere *et al.*, 2012; Kamusoko *et al.*, 2013; Kibena *et al.*, 2013; Nyakungu *et al.*, 2013; Sorensen *et al.*, 2015). The authors identified agriculture, industries and household wastes as the main sources of point and non-point pollution in the UMSC. Municipal wastes were also identified as major potential groundwater pollutants e.g. dumpsites such as the Golden Quarry and cemeteries (Love *et al.*, 2006), as well as Wastewater Treatment Plants (WWTTP) such as the Crowborough WWTTP (Nhapi *et al.*, 2002).

Table 5: Classification of potential pollution sources using landuse/landcover classes

Landuse	Pollutant Class	Description
Cultivation	Agricultural	Included clusters of small subsistence plots
Irrigated Agriculture	Agricultural	Included commercial farms and waste water irrigation farms (e.g. Crowborough farm)
Settlement	Industrial and domestic	Include industrial sites and dormitory-suburbs

One hundred and sixty (160) ground control points from field surveys and Google earth were used for the validation of the pollution risk map. The pollution risk map was used to develop a groundwater sampling frame for the Marimba Micro-catchment.

4.4 Groundwater quality assessment

4.4.1 Selection of sampling sites

Fifteen sampling sites, 6 open wells and 9 boreholes, were established in the Marimba Micro-catchment. The pollution risk map of the micro-catchment, obtained after mapping the point and non-point groundwater pollution sources, guided the setting up of sampling points in the Micro-catchment. A Stratified Random Sampling technique was employed on the identified potential pollution source, to eliminate bias. Selection of sampling sites was based on fundamental requirements such as the knowledge of: (a) the actual and potential sources of pollution; (b) the actual and potential groundwater uses; (c) the groundwater system; (d) the sampling objectives and, (e) the type of the water body to be sampled, as recommended by the WMO (2013). According to the WMO (2013), these requirements should be made in order to obtain representative samples. Field surveys were conducted to capture the location of sampling sites using a GPS receiver. Figure 5 shows the spatial location of the selected groundwater sampling sites in the Marimba Micro-catchment. Of the 15 established sampling sites, a borehole in the University of Zimbabwe, BH1, was set as the baseline/control site. According to WHO (2008) and the WMO (2013), a baseline site should be typically located in aquifers where direct diffuse or point-sources of pollutants are unlikely to be found. The baseline site is used to: (i) establish the natural water-quality conditions; (ii) provide a basis for comparison with other sampling sites having significant direct human impacts and also; (iii) provide a basis for the identification of causes or influences on measured water quality conditions.

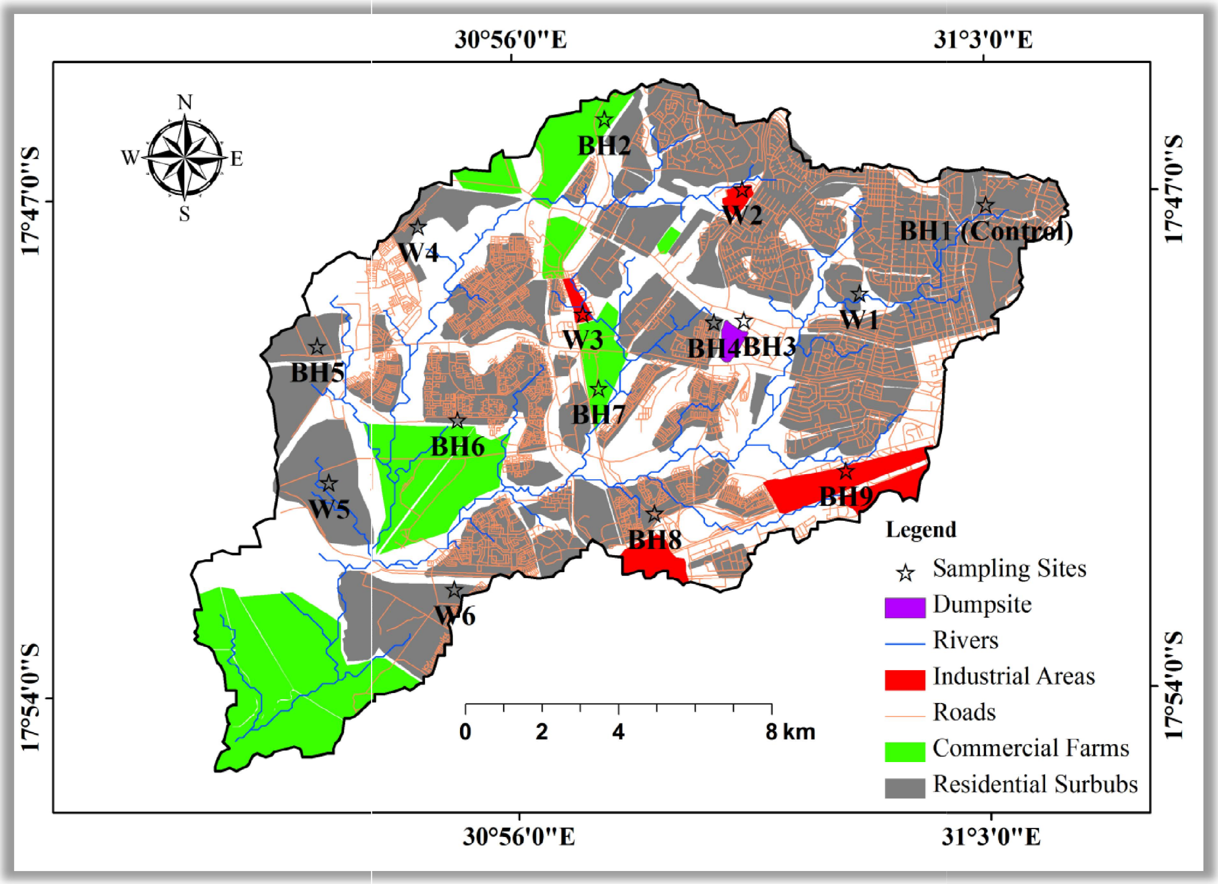


Figure 5: Groundwater sampling sites

4.4.2 Selection of parameters to be analyzed

Groundwater quality parameters selected in this study included: temperature, pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Dissolved Oxygen (DO), Turbidity, Ammonia (NH_4^+), Total and faecal coliforms, Chloride (Cl^-), Total Hardness (TH), Fluoride (Fl^-), Iron (Fe), Zinc (Zn) and Lead (Pb). The parameters are very important, especially when the water is intended for drinking purposes (WHO, 2008). This is in agreement with the recommendation by WMO (2013) that the selection of parameters should take into consideration the intended uses. Use-oriented assessments indicate whether the water quality is satisfactory for a specific purpose. For this study, considerations were made to the potability of groundwater since it is largely used for the provision of potable water. Thus, the selected parameters are required to meet permissible limits set in the WHO drinking water guidelines and SAZ standards (Love *et al.*, 2006). As such, the concentrations of biological and physico-chemical parameters were compared with the WHO/SAZ drinking water requirements.

The study also applied the contaminant based parameter selection. Thus, key parameters were selected based on the identified potential contaminants. This agrees with the recommendation by WMO (2013) that, water quality assessments should often examine the effects of specific activities on a receiving water body. As such, the selection of variables itself should be governed by knowledge of the pollution sources and the expected impacts on the receiving water body. Various researches indicated that water quality parameters are closely associated with onsite sanitation systems (Dzvairo *et al.*, 2006; Pujari *et al.*, 2012). As an example, chlorides and ammonia are highly linked to groundwater contamination from latrines because of their high concentrations in excreta. As such, these parameters were selected since the study area consists of high density and unserviced suburbs that use the latrine system. In addition, a study by Hoko (2008) indicated correlations between some water quality parameters. For example, chloride concentrations can be related to EC. On the other hand EC can be used to infer the concentration of TDS. Therefore, this study took into account the intended use of groundwater and the potential contaminants, to select the parameters for analysis.

4.4.3 Methods of water quality analysis

Standard methods for assessment of drinking water were employed in the assessment of groundwater quality parameters (WHO, 2008). On-site water quality testing was performed on physical parameters such as pH, temperature, turbidity, TDS, EC and DO using available field-test kits. Samples for chemical and microbiological analysis were preserved in a cooler box at 4^oC (Muserere *et al.*, 2014) and taken to the University of Zimbabwe laboratory for analysis. Heavy metals: Pb, Zn and Cu, were analyzed using the Atomic Absorption

Spectrophotometer. Table 6 summarizes the groundwater parameter assessment methods used in this study.

Table 6: Parameter analysis methods/tools

Parameter	Measurement method/tool
Electrical Conductivity (EC) and TDS	Conductivity meter/TDS meter
pH	pH meter
Dissolved Oxygen (DO)	Dissolved Oxygen meter
Ammonia	Palintest
Chlorides	Titration
Fluoride	Palintest
Iron	Palintest
Lead	Atomic Absorption Spectrophotometer (AAS)
Zinc	Atomic Absorption Spectrophotometer (AAS)
Copper	Atomic Absorption Spectrophotometer (AAS)
Total Hardness	Titration
Turbidity	Turbidity meter
Coliforms	Membrane filtration technique

4.4.4 Methods of sampling and frequency

A total of 3 sampling campaigns were made from 15 sampling sites for the period, February to March 2016. The grab sampling method was used to collect groundwater samples for both onsite and laboratory measurements as prescribed by APHA *et al.* (2005). Sterilized 500ml glass bottles were used to collect samples for microbiological analysis. Samples for heavy metals (Zn, Cu and Pb) were collected in 500 ml polyethylene bottles, where concentrated nitric acid was added to prevent precipitation of metallic elements. Samples for chemical parameters such as, chloride, fluoride, ammonia, iron and total hardness were collected separately using 500 ml sterile polyethylene bottles. The samples were immediately stored in ice boxes at 4^{o}C to prevent any further chemical reactions.

4.4.5 Quality assurance procedures

Data quality assurance is an important aspect in water quality analysis (UNESCO/WHO/UNEP, 1996). According to WMO (2013), quality-control procedures should be taken during sampling and analyses to help eliminate sources of error. Thus, a series of data checks and precautions should be applied at all stages of data gathering and subsequent handling to identify any problems that might lead to mistakes, hence incorrect conclusions. In this study, quality control measures were taken. To avoid erroneous values in parameter concentrations, sampling bottles were pre-washed with detergent water and then rinsed thoroughly with distilled water as recommended by Adekunle *et al.* (2007). Sampling bottles for bacteriological analysis were also sterilized in an autoclave at 121 ^oC for 15 minutes. During onsite and laboratory measurements, outlier parameter values were monitored and in cases where abnormal values were detected, further checks and analysis were conducted as recommended by WMO (2013). On the other hand, all necessary information was collected and recorded during the field work to be able to relate the outcome of the water quality analysis to the observed field conditions (UNESCO/WHO/UNEP, 1996). Split samples were also taken for analysis of selected parameters (Fe, Pb, Cl^- Fl^- total hardness and ammonia), at the Government analyst laboratory. According to UNESCO/WHO/UNEP (1996), split samples are used to determine the reproducibility of analysis results and field operations.

4.5 Groundwater quality analysis

Groundwater quality data was used to asses groundwater suitability for potable use as well as to understand the spatio-temporal variations in parameter values as described below.

4.5.1 Groundwater suitability for potable use

Groundwater quality data was analysed using the descriptive statistics tool in Statistical Package for Social Sciences (SPSS), version 23. Groundwater parameter results were then presented in the form of ranges (minimum and maximum), means and standard deviations (Dzvairo *et al.*, 2006). The results were compared with WHO guidelines for drinking water (WHO, 2008) and SAZ drinking water standards (SAZ, 1997). The comparisons of mean groundwater quality results and SAZ/WHO limits were presented graphically.

4.5.2 Analysis of spatio and temporal variations in groundwater quality

The Repeated Measures Analysis of Variance (RMA) was performed on groundwater quality data to test for significant variations and inter-element relationships using SPSS version 23. In the RMA, the independent variable has categories called levels or related groups where measurements are repeated overtime. In this case, the sampling sites were taken as the independent variable from which different sampling campaigns were undertaken and various parameters were analysed. The RMA performs multiple comparisons of means based on the Levene's test for equality of variances (Levene, 1960). The test is used to test if k samples have equal variances. According to Levene (1960), this allows examination of which means are different and magnitude of their differences. In this study the multiple comparison of means was performed using the General Linear model's repeated measures sub-dialog box in SPSS version 23. The variations in mean parameter levels were analysed across sampling sites (treatment variability) and between sampling campaigns (within subjects variability).The null and alternative hypotheses for the analysis were defined as follows:

H_0: The population means are equal for all levels of a factor ($\mu_1=\mu_2=\mu_3\ldots$)
H_1: At least one treatment or observation mean is different from the others
where μ is the measured mean parameter value

Mauchly's Test of Sphericity was used to test the null hypothesis that the population means are equal. Thus, if Mauchly's Test of Sphericity is statistically significant ($p< 05$), we can reject the null hypothesis and accept the alternative hypothesis that the variances of the differences are not equal. If the null hypothesis is rejected, then a post-hoc test should be done to determine which of the conditions differed and by how much.

4.5.3 Extraction of key parameters affecting groundwater quality

The Principal Component Analysis (PCA) was used to identify key parameters responsible for the overall variability of the groundwater quality; a method applied by Moyo and Rapatsa (2015) in the assessment of the spatial and temporal variations in water quality in the Mukuvisi and Gwebi Rivers. SPSS software version 23 was used to perform PCA on the groundwater quality data. According to Jolliffe (2002), PCA simplifies a data set by reducing the dimensionality of multi-variate data whilst preserving all the relevant information on the variables. Jolliffe (2002) further highlighted that PCA performs linear transformation on the data to a new coordinate system such that the new set of variables, which are the principal components, are linear functions of the original variables. Thus, it changes initial random vectors related to its components into new random vectors which are not correlated (orthogonal) to its components. In this study, the decision on the number of principal components determining groundwater quality variation was based on the total eigenvalue and the percentage contribution of each parameter. Components/factors with a total eigenvalue greater than one were selected (Smith, 2002).

4.6 Determination of groundwater vulnerability

In this study, the GOD method was used to assess aquifer vulnerability in Marimba Micro-catchment. The model was selected due its applicability for the assessment of large areas and areas with high vulnerability contrasts (Gogu and Dassargues, 2000; Polemio *et al.*, 2009; Ghazavi and Ebrahimi, 2015). The method is also less data intensive (UNESCO, 2007), hence applicable in areas with poor data sets such as the Marimba Micro-catchment. The model is composed of three variables: groundwater occurrence (G_r), overlying lithology of the aquifer (O_r) and depth to groundwater table (D_r). The advantages of the model include quick results turnover and the attainment of convincing results especially when applied in large scale assessments (Alwathaf and Mansouri, 2011; Ghazavi and Ebrahimi, 2015; Kumar *et al.*, 2015). Figure 6 illustrates the concept of developing a GOD based vulnerability map as applied by Kumar *et al.* (2015). This study applied the same concept to develop the vulnerability index map for the Marimba Micro-catchment.

4.6.1 Derivation of the groundwater vulnerability map

The GOD model (Foster, 1987), was used to develop a groundwater vulnerability map of Marimba Micro-catchment. The model considers three parameters: the groundwater occurrence, the overlying lithology, and the depth to groundwater. Its framework is as presented in *Figure 6*.

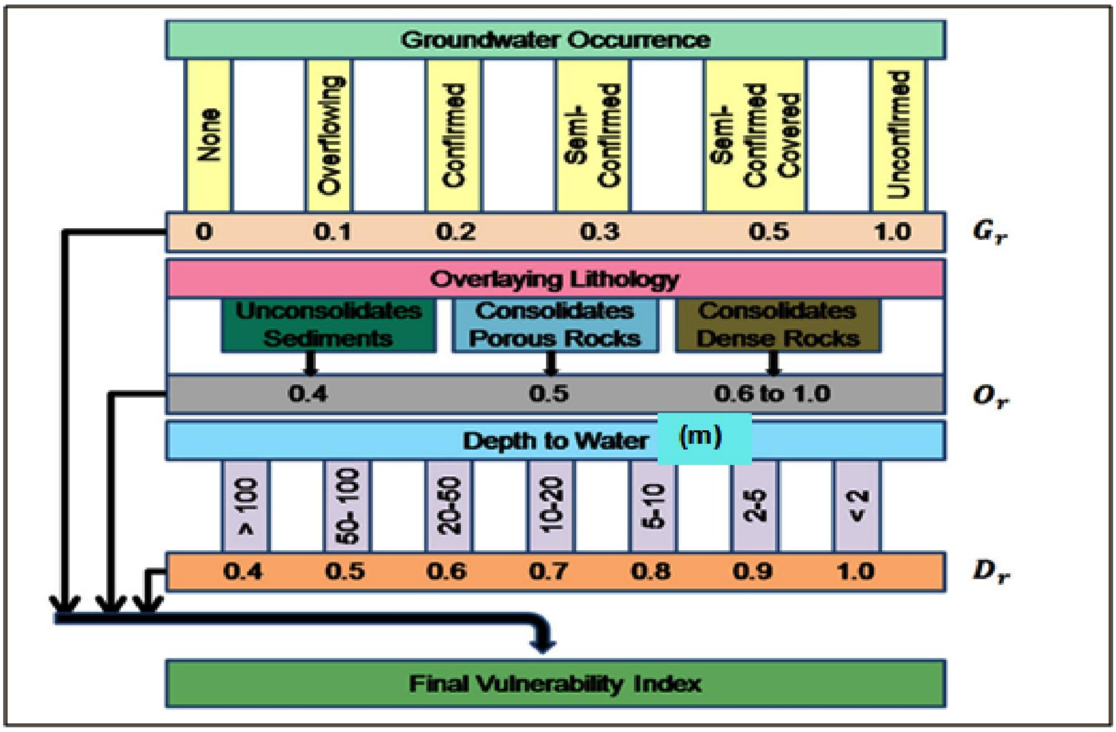


Figure 6: The GOD model framework (Foster, 1987)

The governing equation for the calculation of the vulnerability index using the GOD model is as shown in *Equation 10.*

$$GOD\ Index = G_r * O_r * D_r \qquad \textit{Equation 10}$$

where: G_r = type of aquifer (Overall aquifer class).

O_r = the lithology of the unsaturated zone.

D_r = the depth to the groundwater surface.

The three parameters were aggregated to develop a vulnerability index map. The slicing tool in ILWIS was then used to re-classify the resultant vulnerability index map into classes: negligible, low, moderate, high, and extreme. The index ranges used for re-classification are summarized in *Table 7*.

Table 7: Aquifer vulnerability classes (Gogu and Dassargues, 2000)

Vulnerability class	Negligible	Low	moderate	High	extreme
Index range	0-0.1	0.1-0.3	0.3-0.5	0.5-0.7	0.7-1

4.6.2 GOD parameter derivation

The parameters for the GOD model were developed as described below:

(i) Depth to Groundwater surface

The parameter Depth to Groundwater (Dr) was developed from groundwater levels data obtained from direct field measurements (using a water level meter) and static water levels from borehole logs and pumping tests. A total of 24 groundwater level observation points were used in this process. Of the 24 sites used, 6 were wells from which direct measurements were taken simultaneously during sampling campaigns while the rest were static water levels for the period, January 2014 to December 2015. Grid interpolation was performed using the inverse distance to a power algorithm in QGIS Desktop 2.8.1 to extract contours depicting groundwater depth zones. The resultant layer was then converted into raster format and reclassified into 7 classes ranging from < 2 m to > 100 m (Gogu and Dassargues, 2000). Variable depths were then weighted on a rating scale of 0 to 1 (Foster, 1987). High ratings were assigned to lower depth-to-water table. Lower rates were allocated to areas of deeper water table since they offer the best protection against contamination largely due to longer travel time of the contaminant to the water table (Gogu and Dassargues, 2000; Foster *et al.*, 2002). Thus, ranges: <2 m, 2-5 m, 5-10 m, 10-20 m, 20-50 m, 50-100 m and > 100 m, were allocated rates: 1, 0.9, 0.8, 0.7, 0.6, 0.5 and 0.4, respectively.

(ii) Lithology of the unsaturated zone

The lithology data was obtained from the Zimbabwe Geological Survey. The data shows that Marimba Micro-catchment mainly is composed of four lithological classes namely: the Basaltic Metavolcanics with Intercalated Metasediments (Bulawayan group); Dolerites and Gabbros (Dolerites/Gabbros group); Metasediments & Felsic Metavolcanics (Shamvaian group) and the Younger Intrusive Granite/Granodiorite-adamellite of the Granitoids group (Martinelli and Hubert, 1985). The Basaltic Metavolcanics with Intercalated Metasediments were given a higher rating since they belong to the bulawayan group. According to Martinelli and Hubert (1985) and Owen and Madari (2009), the Bulawayan unit is characterised by moderate to deep weathering, hence can have high permeability. On the other hand, the Metasediments & Felsic Metavolcanics of the Shamvaian formation were given the lowest rating since they consist of clayey material and are characterised by shallow weathering hence reduced permeability (Martinelli and Hubert, 1985). The Dolerites often form cappings to hills and as such, they are highly permeable and well drained. The Granitoids group are composed of clay with residual mica and quartz, hence they are moderately permeable (Martinelli and Hubert, 1985). The lithological classes were rated on a scale of 0-1, where 0 was depicted low vulnerability. Rates, 0.8, 0.6, 0.5 and 0.4 were given to the Bulawayan, Dolerite/Gabbros, Granitoids and Shamvaian lithology respectively (Gogu and Dassargues, 2000).

(iii) Type of aquifer or Overall aquifer class

A number of studies of Harare aquifers confirmed unconfined conditions (Rwasoka *et al.*, 2007; Broderick, 2012). As such, the Marimba Micro-catchment being, part of the Harare's large aquifer system, is characterized by unconfined aquifer conditions. Therefore an overall rating of 1 was assigned to the whole study area. Since the aquifer is open to surface element, a score of 1 represents maximum vulnerability to pollution.

4.6.3 Validation of the groundwater vulnerability map

Validation refers to some independent procedure that is used to verify the results of a vulnerability analysis (Ghazavi and Ebrahimi, 2015). In this context, the most common validation approach in vulnerability assessments is the comparison of the vulnerability map with the actual occurrence of some common pollutant in groundwater. Studies by Kaur and

Rosin (2008), Ghazavi and Ebrahimi (2015) and Abdelmadjid and Omar (2013) utilised nitrates for the validation process. In this study ammonia was selected as the primary parameter amongst the ones analysed. Mean values of ammonia from 15 sampling sites were used in this study. A correlation coefficient was established as a measure of association for the vulnerability indices and the values of the selected parameter.

CHAPTER 5
RESULTS AND DISCUSSION

5.1 Groundwater potential mapping

The spatial variations of groundwater conditioning factors used for GWP mapping are presented in *Figures 7-10*. The resultant Groundwater Potential Index (GWPI) maps obtained after aggregating groundwater conditioning factors using the Weighted Linear Combination (WLC) and Index Overlay (IO) methods are presented in *Figure 11*. After correlating borehole yields with GWPI maps, the WLC based GWPI map (*Figure 11a*) exhibited a fairly strong positive correlation (r=0.65) with borehole yields data, hence it was used to develop the final GWP map, *Figure 12*. The re-classification indices and corresponding GWP zones are presented *in Table 9.*

5.1.1 Spatial variation of attributes within groundwater conditioning factors

Figures 7-10 summarize the resultant groundwater conditioning factors developed for groundwater potential (GWP) mapping, using spatial analysis tools.

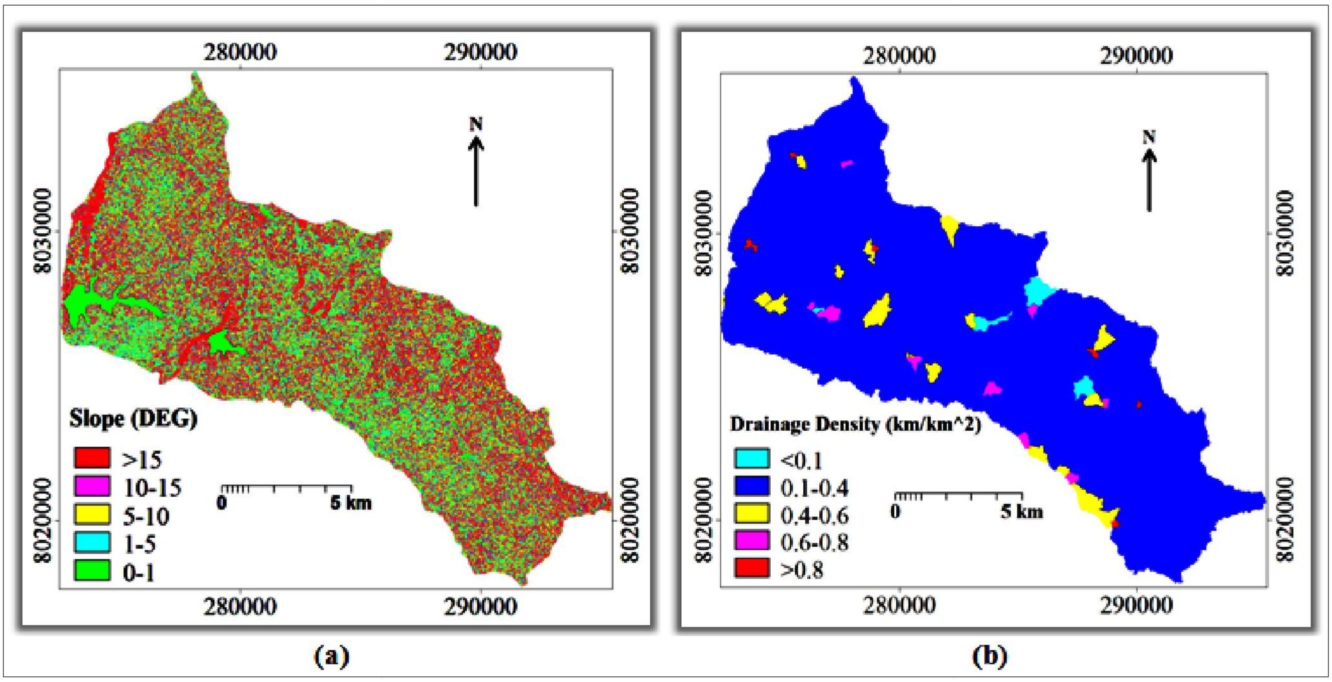


Figure 7: Spatial variation of Slope and Drainage Density in the UMSC

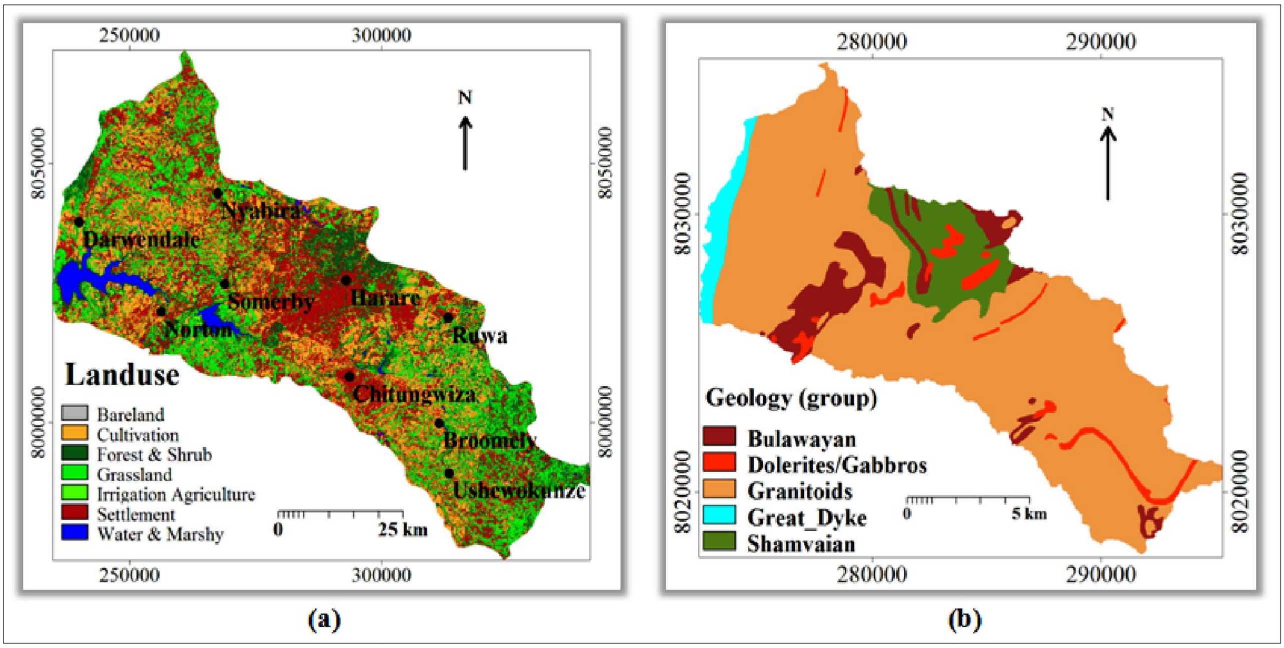


Figure 8: Spatial variation of Landuse and Geology in the UMSC

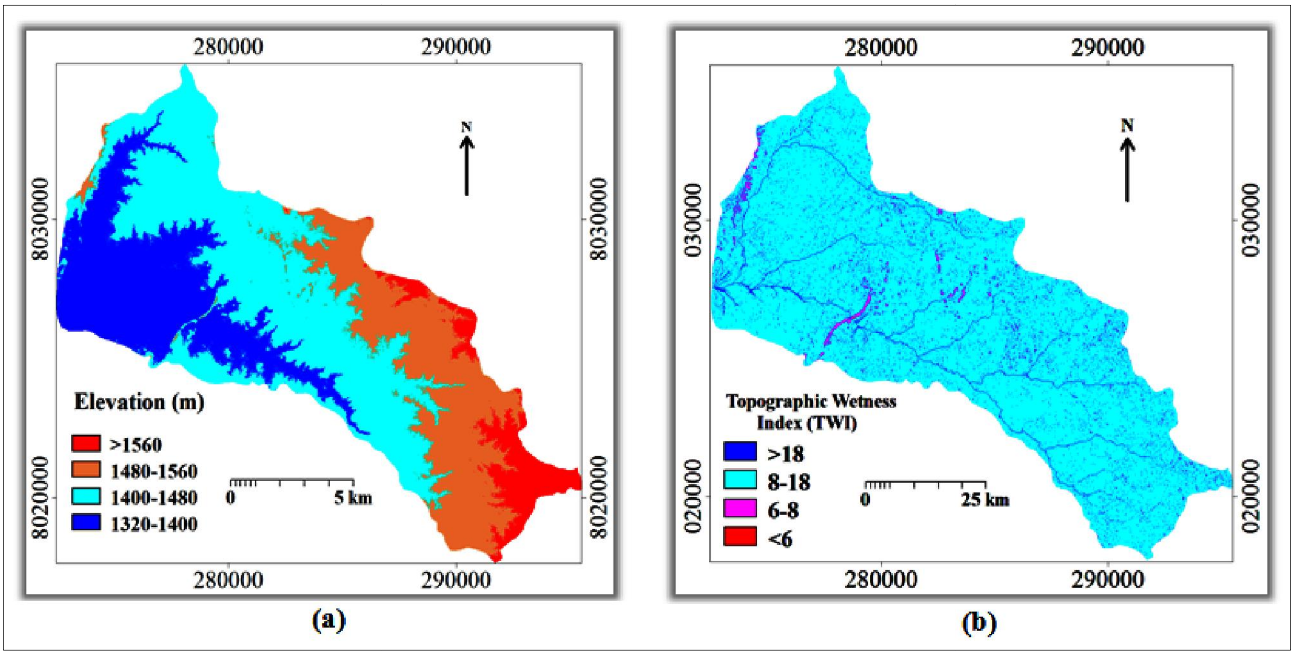


Figure 9: Spatial variation of Elevation and Topographic Wetness Index in the UMSC

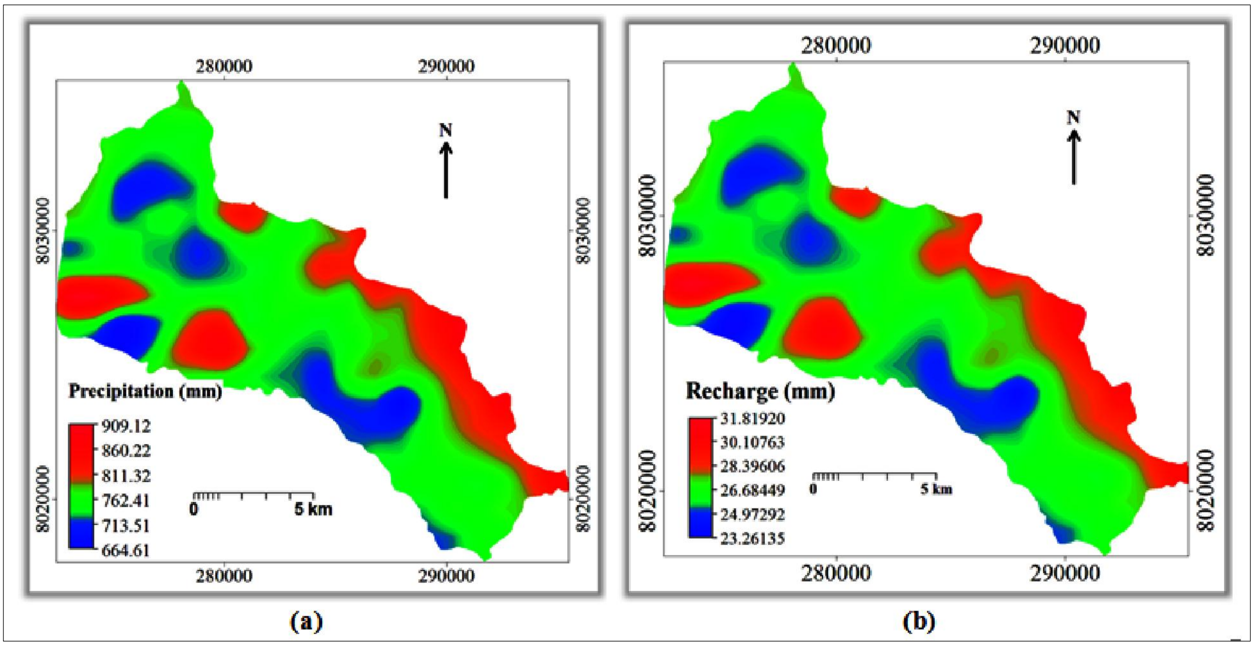


Figure 10: Spatial variation Precipitation and Recharge in the UMSC

Figure 7a shows the classified slope map of the study area. A slope range of 5-10^o was dominant, accounting for 37 % of the study area. Slope ranges; 0-1^o, 1-5^o, 10-15^o, and >15^o accounted for 4 %, 25 %, 22 % and 12 % of the study area, respectively. Overall, classes from nearly flat to moderately sloping (0-15^o) accounted for 88 % of the study area. According to Fenta *et al.* (2015), the slope range of 0-15^o has better groundwater prospect as it is characterized by low runoff generation. On the other hand, the strongly sloping class is characterized by a few isolated patches of high terrain in areas such as the Great Dyke and the Lake Chivero range. In terms of the drainage density (*Figure 7b*), 94 % of the study area exhibited low drainage density (0.1-0.4 km/km^2). Studies by Awawdeh *et al.* (2013) and Nejad et al. (2015) classified densities of 0.1-0.4 km/km^2 as low, hence favorable for groundwater development. This result agrees with the dominance of an overally gentle terrain in the study area. Gentle slopes are associated with low runoff velocities, hence resulting in reduced erosive power of run-off to cause rill, gully or river channel formation. This implies high infiltration and high recharge potential for the study area. The Landuse map, *Figure 8a*, shows the dominance of settlements within the study area, occupying 1285.58 km^2 (33 % of area). Settlements increase runoff generation, hence low infiltration resulting in low GWP. On the other hand, cultivation occupied 1017.27 km^2 (26 % of the study area). Cultivated areas contribute to increased infiltration, hence high groundwater potentiality. The overall classification accuracy for the landuse/landcover map was 74.3 % which is acceptable. It is highlighted by (van Vliet *et al.*, 2011) that, accuracy values above 50 % are considered while values above 70 % are said to be good. In terms of geological conditions, the Granitoids formation occupy 76 % (2877.4 km^2) of the study area (*Figure 8b*). Martinelli and Hubert (1985) indicated that the granitic formation is characterized by moderate to low groundwater yields (50-100 m^3/day), hence a high probability that study area has limited groundwater prospect. On the other hand, the Bulawayan, Dolerites/Gabbros, Shamvaian and the Great Dyke occupy 8 %, 3 %, 3 % and 9 % respectively. The Topographic Wetness Index (TWI) for the study area (*Figure 9a)* was classified into four classes; < 6, 6-8, 8-18 and > 18, a classification used by Nejad *et al.* (2015). The study area is dominantly of the 8-18 range, hence indicating moderate wetness conditions. The groundwater prospect associated with such conditions is moderate. Low TWI areas are coinciding with high altitude areas (*Figure 7g),* while low lying areas with high TWI such as river channels are closely associated with the accumulation of soil moisture (Gumindoga, 2011). In terms of rainfall, the study area exhibited relatively high rainfall with low spatial variability. About 79 % of the study area has a Mean Annual Precipitation (MAP) ranging between 700 and 800 mm (*Figure 10a*). The high MAP contribute to high GWP (Fenta *et al.*, 2015). Figure 10b shows the recharge of the study area. The recharge ranged from 23 mm to 31.8 mm per annum for the study area. Spatially, the annual recharge is showing the same trend with the mean annual precipitation. Low recharge values are found in high altitude areas which form the upstream part of the sub-catchment. Such areas have low GWP.

5.1.2 Spatial distribution of groundwater potential indices in the UMSC

Figure 11 shows the resultant GWPI maps obtained after aggregating groundwater conditioning factors. The indices were classified into five distinct classes with upper bounds; 2.22, 3.42. 4.62, 5.82 and 7.02. According to Rahmati *et al.* (2014), the indices are dimensionless quantities that help predict the GWP zones in an area. Figures 11a and 11b show the WLC and IO based GWPI maps, respectively.

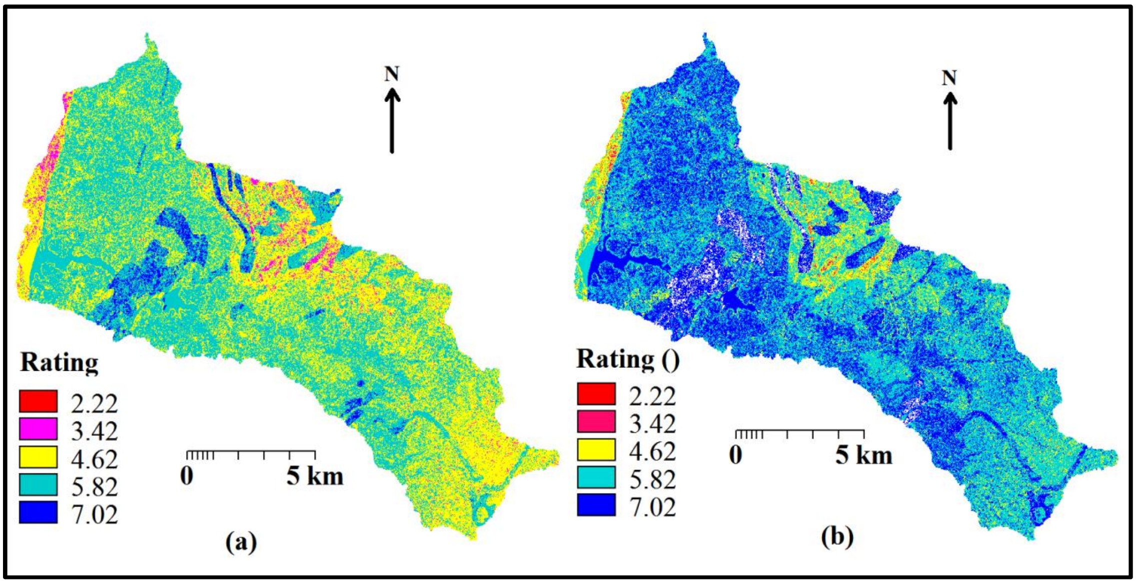


Figure 11: GWPI maps of the UMSC

The IO based index map (*Figure 11b*) exhibited the dominance of high index values, with 88.8 % (3362 km^2) of its area having values greater than 4.62. On the other hand, the WLC based index map (*Figure 11a*), showed 94.2 % (3566.4 km^2) of its area having moderate to high index values ranging 3.42-5.82.

Table 8 summarizes the percentage distribution of index values between the index maps.

Table 8: Percentage distribution of GWPI values

Index	WLC based GWPI map	IO based GWPI map
2.22	0 %	0 %
3.42	3 %	0.6 %
4.62	43.5 %	10.6 %
5.82	50.7 %	53.8 %
7.02	2.84 %	35.0 %

5.1.3 Validation of the Groundwater Potential Index maps

Validation of the GWPI maps was done by performing correlation analysis with borehole yields data. A strong correlation would indicate high validity in mapping GWP as highlighted in a study by Olutoyin *et al.* (2014). Borehole yields varied from 0 to 25,000 l/h (0-600 m^3/day). The WLC based index map (*Figure 11a)* exhibited a fairly strong positive correlation with the borehole data (r=0.65), indicating the method's fairly high accurate in mapping GWP. On the other hand, the IO based index map (*Figure 11b)* yielded a positive but weak correlation (r=0.53) as compared to the WLC based index map, showing a low accuracy. In similar studies by Fenta *et al.* (2015) and Sokeng *et al.* (2016) borehole/well yield data was used to validate the GWP results. Their respective studies yielded correlation coefficients of 74 % and 83.2 %. In this study, the WLC correlation result was regarded being of high accuracy, hence it was used to develop the final GWP zones. The results indicate that the AHP method is a better and less subjective approach in factor rating as compared to the QM.

5.1.4 Development of groundwater potential zones

Figure 12 shows GWP zones of the UMSC developed from the WLC based index map (*Figure 11a)*. The index map was reclassified into GWP classes: low, moderate and high, using the slicing tool in ILWIS. The groundwater yield classification by Martinelli and Hubert (1985) was used to assign potentiality class ranges. According to the authors, the high, moderate and low potential zones corresponded to ranges: > 100 m^3/day, 10-100 m^3/day and 1-10 m^3/day, respectively.

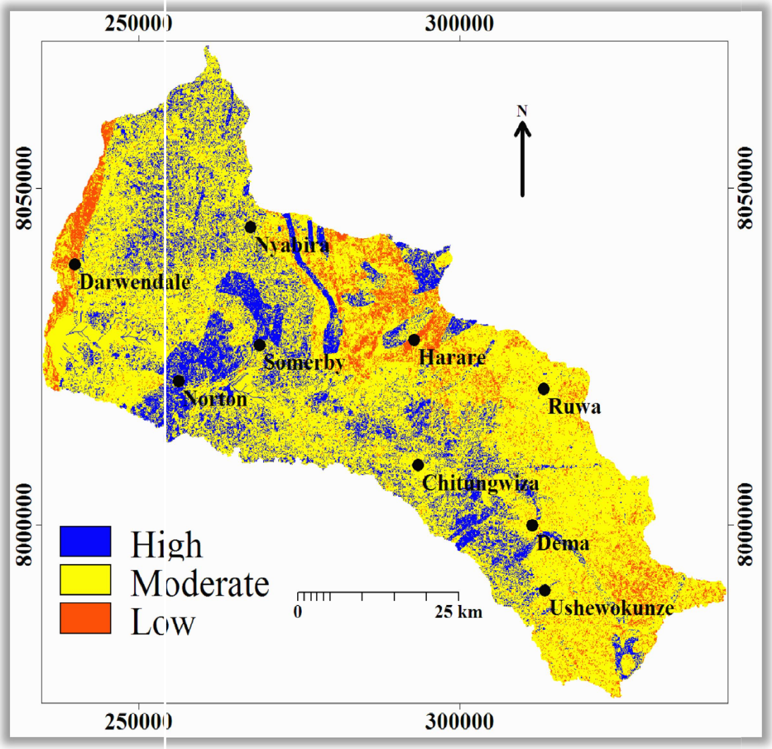
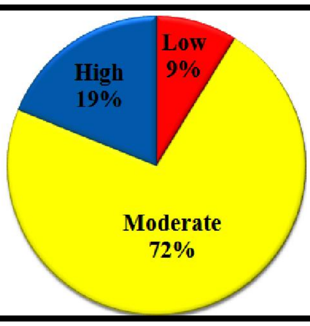


Figure 12: Upper Manyame groundwater potential zones

As shown in *Figure 12*, areas around Norton, Somerby and the southern parts of Dema communal areas were identified as high GWP zones. The areal extent of high potential zones was found to be 19 % (719 km^2) of the total area, with moderate and low zones accounting for 72 % (2726 km^2) and 9 % (341 km^2), respectively. This indicates that the groundwater prospect for the study area is dominantly moderate. Most of the upper parts of the sub-catchment, specifically areas around Ruwa, the south eastern parts of Dema and areas around Ushewokunze communal land show moderate potential. The areas fall within the granitic formation which Martinelli and Hubert (1985) found to be of moderate to low yields (50-100 m^3/day). In a similar study to assess the hydrogeology of the sub-catchment, Broderick (2012) indicated that the area is underlain by massive granite which is characterized by poor and highly variable groundwater development potential for boreholes. Results from a hydrocensus in the study area showed high success rates in groundwater development in the Bulawayan and Dolerites/Gabbros (UMSCC, 2014). This is consistent with the high groundwater potential zones in the same units e.g. areas around Ruwa and parts of Norton. Table 9 summarizes the results of the GWP mapping, mainly the proportional yield for each potential class and the areal coverage.

Table 9: Classification of groundwater potential zones

Percentage Area Coverage	**Area (km^2)**	**Groundwater Potential**	**Index map Values**	**Corresponding Yield (m^3/day)**
	719	High	2.22 - 3.79	> 100 m^3/day
	2726	Moderate	3.79 - 5.2	10 - 100 m^3/day
	341	Low	> 5.2	1 - 10 m^3/day

NB: The actual yield ranges were adopted from Martinelli and Hubert (1985).

5.2 Identifying and mapping potential groundwater pollutants

Figure 13 shows the resultant Landuse/landcover (LULC) map that was developed for mapping potential pollution sources. The map was developed using supervised classification in ILWIS. LULC classes: bareland, cultivation, forest and shrub, grassland, irrigated agriculture, settlement and water & marshy were developed. The overall accuracy for the classification was found to be 74.3 %, a result which shows high accuracy in the LULC classification. According to van Vliet *et al.* (2011), a result above 70 % is regarded as high accuracy, hence highly acceptable. Settlements were found to occupy the greatest proportion of the UMSC, accounting for 32.7 % (1238 km^2). This result agrees with the assertion that the UMSC has experienced significantly rapid urban expansion (Masere *et al.*, 2012; Kibena *et al.*, 2013; Moyo and Rapatsa, 2015). Areas such as Chitungwiza, Ruwa, Norton and Harare itself are experiencing rapid developments, in terms of dormitory suburbs expansion, hence causing an increase in settlements. Cultivation accounted for 24.8 % (938.9 km^2) of the total area. This agrees with the findings by Masere *et al.* (2012) that there was an increase in urban and peri-urban agriculture over the years. The low areal coverage for forest and shrub agree with the findings of Kibena *et al.* (2014) that, the increase in built-up areas and cultivation resulted in massive deforestation in the UMSC.

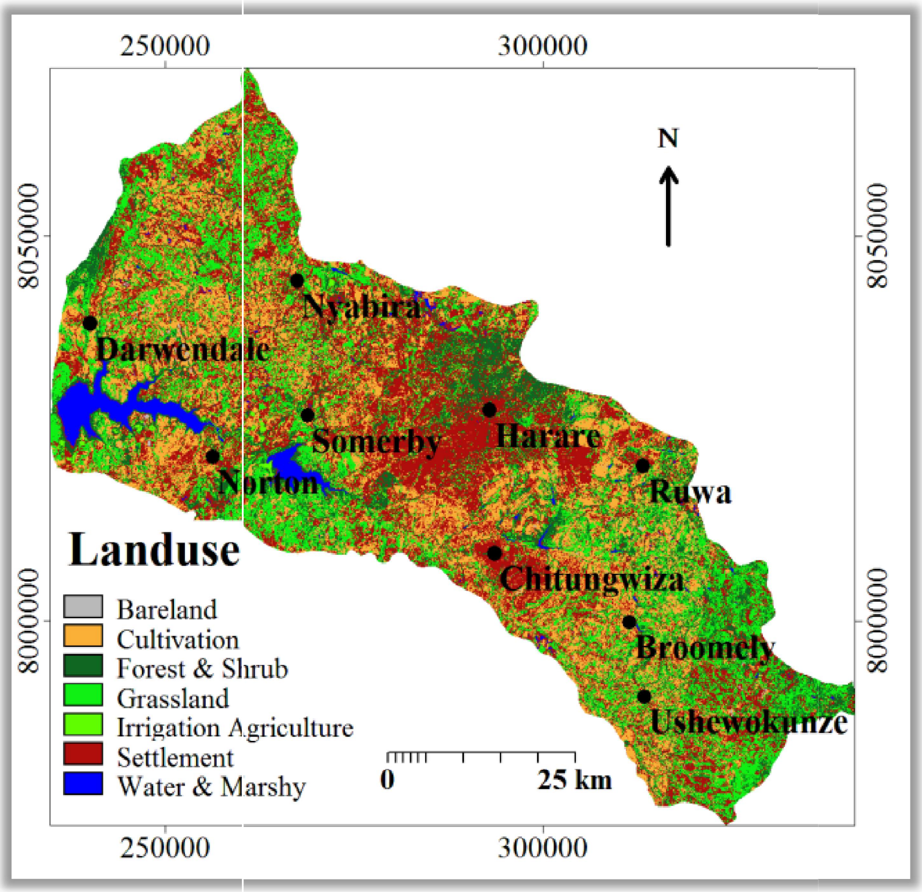


Figure 13: Upper Manyame Sub-catchment Landuse map

Table 10 summarizes the proportional areal coverage of various landuses in the UMSC.

Table 10: Areal coverage of the UMSC landuses for the year 2015.

Landuse/landcover	Area (%)	Area (km^2)
Bareland	0.2	7.6
Cultivation	24.8	938.9
Forest and shrub	13.5	511.1
Grassland	25.9	980.6
Irrigated Agriculture	0.5	19.9
Settlement	32.7	1238
Water and marshy	2.4	90.8

The main identified landuses such as settlement and agriculture were then digitized on Google images to show their spatial distribution. Figure 14 shows the digitized potential pollution sources in the Marimba Micro-catchment. It was observed that the main potential point and non-point sources of pollution in the study area are: agriculture, industrial actives, municipal dumpsites, household wastes, urban refuse/garbage and cemeteries, among others. The afore-mentioned were identified in previous researches as the main sources of pollution in the study area (Hranova *et al.*, 2001; Nhapi *et al.*, 2002; Hranova, 2003; Love *et al.*, 2006; Masere *et al.*, 2012; Tsiko and Togarepi, 2012; Kamusoko *et al.*, 2013). Agriculture was identified as the major non-point source.

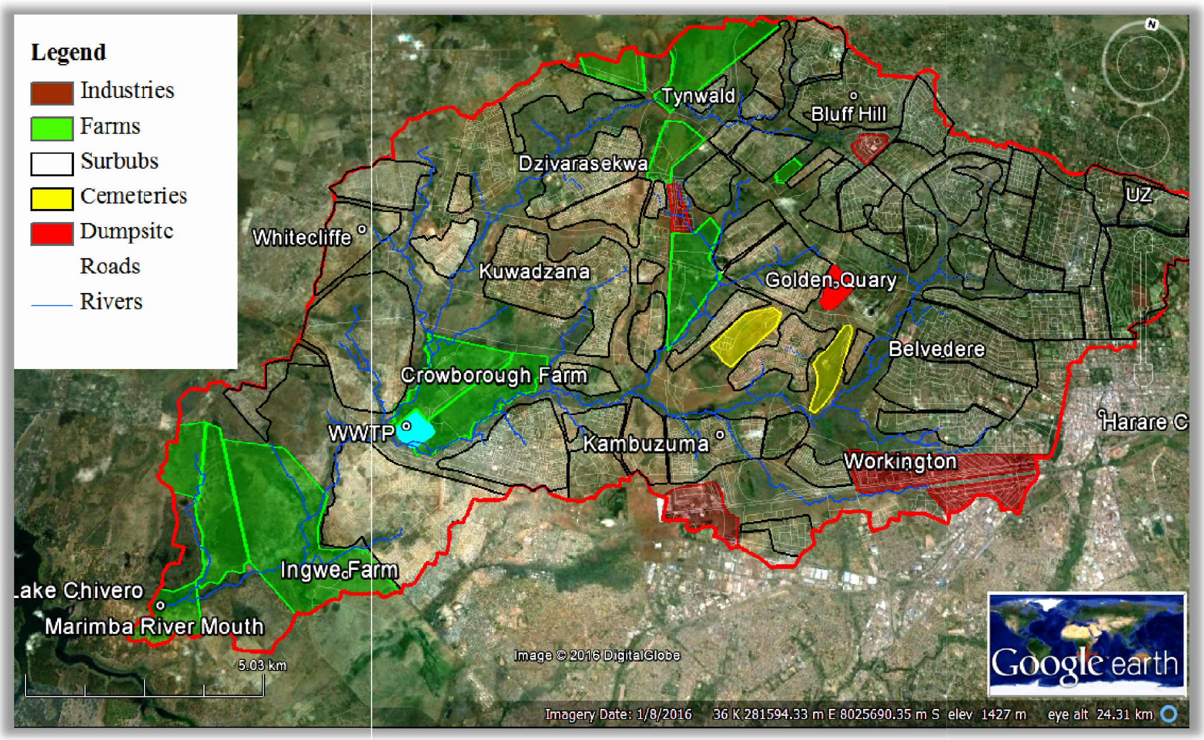


Figure 14: Map showing the digitized landuses of Marimba Micro-catchment

Figure 15 shows the pollution risk map of Marimba Micro-catchment. The map used the physical and geographical features in the study area to map the potential contaminants (Lahr and Kooistra, 2010). The overall accuracy of the pollution risk map was found to be 81 %, which is regarded high accuracy in validation, hence acceptable. Dumpsites, agriculture, industrial areas, dormitory areas and cemeteries were identified as the as the major potential point and non-point sources of groundwater pollution. Commercial agriculture, and industries within the Marimba Micro-catchment were found to occupy approximately 29 km^2 and 5 km^2, respectively. Residential suburbs accounted for 76.8 % (169 km^2) of the study area.

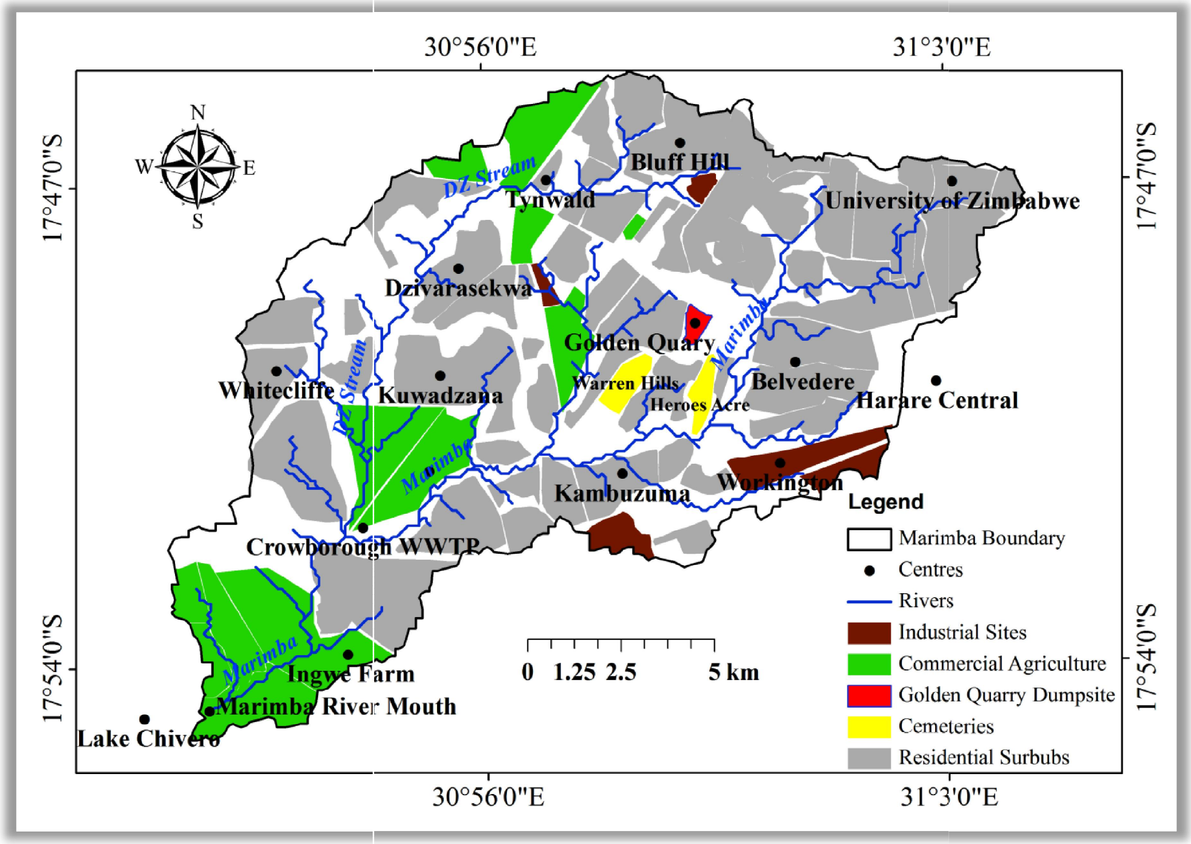


Figure 15: Marimba micro-catchment pollution risk map

A study by Love *et al.* (2006) indicated that the identified socio-economic activities and landuses are threatening groundwater water quality. In support to the findings, Kibena *et al.* (2013) concluded that settlements and agricultural areas are the ones mainly affecting water quality in the study area. It can therefore be concluded from the pollution potential mapping that, anthropogenic forcings are mainly responsible for polluting surface and groundwater in the micro-catchment.

5.3 Groundwater quality analysis

Statistical measures of dispersion and central tendency: the mean, minimum, maximum and standard deviation *(Table 11)* were determined for the groundwater quality data using the descriptive statistics tool in SPSS version 23. Measured parameters were subsequently compared to the either WHO guidelines or SAZ standards for drinking water. Analysis of the spatio-temporal variation in groundwater parameters was determined using Repeated measures ANOVA. The principal Component Analysis was used to determine key parameters responsible for groundwater quality variation. The mean values for the groundwater quality parameters are presented in Table 11 and *Figures 16-25.*

5.3.1 Groundwater suitability for potable use

Mean parameter values of the physico-chemical and micro-biological parameters are presented in *Table 11*. The results were compared with SAZ/WHO standards and guidelines for drinking water. The study revealed that pH, total coliforms, faecal coliforms and Cl exceeded, in most cases, the drinking water guidelines and standards established by WHO and SAZ, respectively (the bold digits indicate mean parameter levels above the permissible limits). Mean values for the parameters were: 6.4, 252 cfu/100 ml, 133 cfu/100 ml, 8.03 mg/L and 304.02 NTU, respectively. DO, TDS, EC, total hardness, Cl^-, Fl^-,ammonia, iron, zinc, lead and copper were within the acceptable limits. Concentration ranges for: TDS (103-3590 mg/L); EC (103-720 μScm^{-1}), total hardness (56-832 mg/L); ammonia (0-0.47 mg/L), Fe (0-0.53 mg/L) and turbidity (0.80-53.40 NTU) indicated instances of the occurrence of outlier parameter values.

Although the overall mean concentrations of DO, TDS, EC, total hardness, Cl^-, Fl^-,ammonia, iron, zinc, lead and copper were found to be below the recommended limits, individual sampling sites exhibited parameter values above the permissible limits. Comparing the mean parameter values of individual sampling sites with permissible limits was recommended by Sabrina *et al.* (2013) after observing that the use of overall means for different sites over-generalizes results and removes outliers. Appendix 1 summarizes the results of suitability assessment of groundwater for individual sampling sites.

Table 11: Descriptive statistics for groundwater samples

Parameter	N	Mean ± Std. Dev	SAZ/WHO Standards/Guidelines	Minimum	Maximum
pH	45	**6.41 ± 0.93**	6.5-8.5	3.60	8
Turbidity	45	**8.03 ± 10.90**	5	0.80	53.4
DO	45	4.98 ± 1.46	> 2	1.47	9
TDS	45	603 ± 819.42	1000	103.7	3590
EC	45	146 ± 193.76	400	21	720
Total Coliform	45	**252 ± 396**	0	0	1352
Faecal Coliform	45	**133 ± 229**	0	0	984
Total Hardness	45	192.51 ± 177.49	250	56.0	832
Chloride	45	**304.02 ± 790.22**	250	21.27	3545
Fluoride	45	0.86 ± 0.24	1.5	0.43	1.43
Ammonia	45	0.13 ± 0.13	0.2	0	0.47
Iron	45	0.11 ± 0.17	0.3	0	0.530
Zinc	45	0.45 ± 1.22	5	0	6.7
Lead	45	0.01 ± 0.01	0.01	0	0.05
Copper	45	0.08 ± 0.28	0.08	0	15

Although the overall mean concentrations of DO, TDS, EC, total hardness, Cl^-, Fl^-,ammonia, iron, zinc, lead and copper were found to be below the recommended limits, individual sampling sites exhibited parameter values above the permissible limits. Comparing the mean parameter values of individual sampling sites with permissible limits was recommended by Sabrina *et al.* (2013) after observing that the use of overall means for different sites over-generalizes results and removes outliers. Appendix 1 summarizes the results of suitability assessment of groundwater for individual sampling sites.

5.3.2 Groundwater quality parameter variations

pH*:* Figure 16 shows the variation of pH across sampling sites. pH values from a total of 15 sampling sites ranged from 3.6 to 8.0, with a mean of 6.43 ± 0.93. Comparative analysis of the pH results with permissible drinking water limits indicated that 73 % of the sampling sites complied with SAZ/WHO permissible drinking water limits. However, 27 % of the sites, mainly within industrial areas (BH9 & W2) and those within the vicinity of the Golden Quarry dumpsite (BH3 & BH4), exhibited acidic pH values (pH < 6.5). Overall, pH values recorded for most of the boreholes were relatively similar to those obtained for the control site (BH1). The pH variation indicates that the groundwater of the study area is slightly acidic in nature.

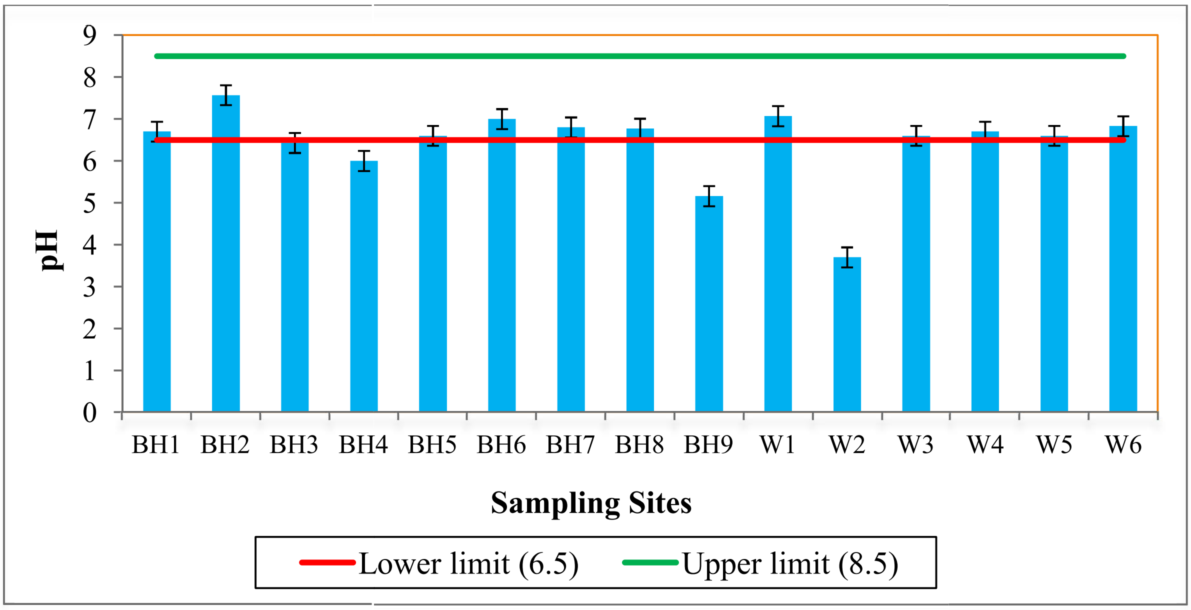


Figure 16: pH variation

Reduced pH values (acidic) obtained for BH3 and BH4 (located close to the Golden Quarry dumpsite) as well as W2 and BH9 (located in industrial areas) are attributed to the dumpsite leachate and acidic contamination from industrial waste, respectively. The pH results obtained for the boreholes, BH3 and BH4 are comparable to those of a similar study by Love *et al.* (2006), which yielded mean pH values of 5.79 and 5.97. Thus, the low pH values for sampling sites within the vicinity of the Golden Quarry dumpsite (BH3 & BH4) suggest acid contamination from leachate. According to Love *et al.* (2006), landfills release the widest suite of acid forming contaminants such as sulphates, nitrates and phosphates. These might have been responsible for the lowering of the pH. On the other hand, the lower values of pH in industrial areas could be due to the release of acid-forming substances such as sulphates and nitrates (Adekunle *et al.*, 2007). Sabrina *et al.* (2013) demonstrated that, at low pH, water can be corrosive and can damage equipment. WHO (2008), indicated that low pH has no direct effect on human health, but can have indirectly affect human health since it causes leaching of metal ions such as: iron, manganese, copper, lead, and zinc, into the water. This may result in elevated levels of toxic metals which are harmful to human health. From the current study, it can be concluded that the Golden Quarry dumpsite and industrial areas are degrading groundwater quality.

***Coliforms**:* The variations of coliform counts from the 15 sampling sites are presented in *Figure 17*. The SAZ/WHO standards and guidelines of 0 CFU/100 ml were not met in 53 % of the sampling sites. Results from descriptive statistics showed mean total and faecal coliform counts of 252 ± 396 cfu/100 ml and 133 ± 228 cfu/100 ml respectively. As shown in *Figure 17*, about 80 % of the wells (5 out of 6), found in areas using the pit latrine system, gave high fecal and total coliform counts. Boreholes found in unserviced settlements (BH5 and BH6) were contaminated. BH4, which is situated less than 100 m downslope the Golden Quarry dumpsite showed positive results of coliform contamination.

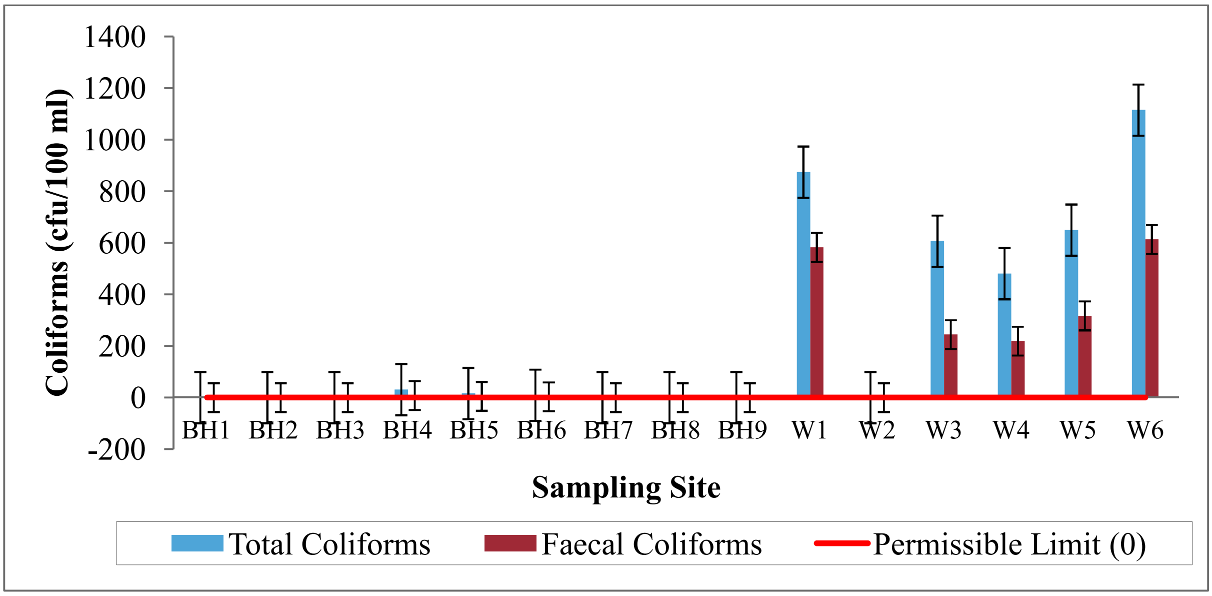


Figure 17: Total Coliform and Faecal Coliform variation

Coliform populations are indicators of pathogenic contamination by faecal matter (WHO, 2008). High faecal coliform populations in well water samples are an indication of poor sanitary conditions in the community (Adekunle *et al.*, 2007). A study by Dzvairo *et al.* (2006) indicated that the pit latrine system is the main source of faecal contamination, especially in areas were onsite sanitation systems are present. A similar study by Love *et al.* (2006), in a semi-formal settlement in Epworth, Zimbabwe, indicated that the pit latrine system contributes to faecal contamination of groundwater. In the study, results of samples from the Golden Quarry dumpsite were positive to faecal contamination. In agreement with the findings, BH4, which is situated < 100 m downslope the dumpsite, showed positive results of faecal contamination. Therefore, the dumpsite is contributing to faecal contamination of groundwater. On BH5 and BH6, the effect of distance from pollution sources was much more defined for faecal and total coliform counts. The counts decreased with increasing distance from the pit latrines. The results for BH5 and BH6 support the findings of (Dzvairo *et al.*, 2006), who suggested that beyond 5 m from a pit latrine or any source of faecal matter, faecal coliforms will be greatly reduced. The results show that, wells are highly susceptible to faecal contamination than boreholes.

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Ammonia (NH_4^+): Figure 18 shows ammonia variations across sampling sites. Ammonia concentrations ranged from 0-0.47 mg/L for all groundwater sampling sites, with a mean concentration of 0.13 ± 0.13 mg/L. About 27 % of the sampling sites exceeded the WHO recommended limit of < 0.2 mg/L. Sampling sites: BH3, BH5, W1 and W2 had mean concentrations of 0.41 mg/L, 0.26 mg/L, 0.39 mg/L and 0.21 mg/L respectively. These concentrations were found to be above the permissible limits for drinking water.

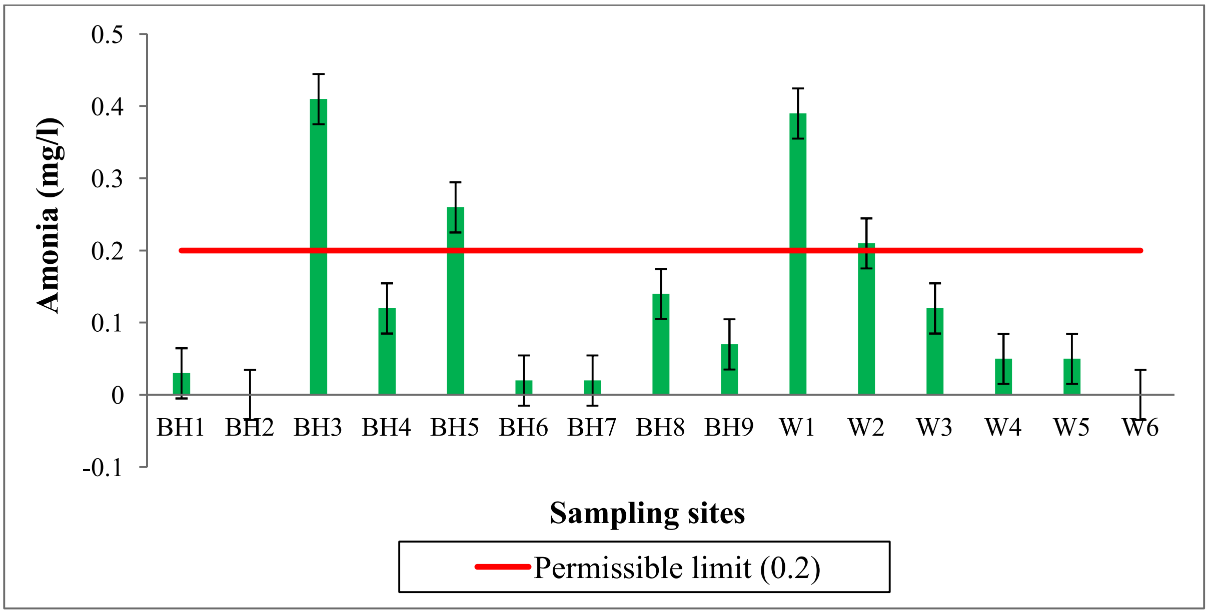

Figure 18: Ammonia variation

Elevated ammonia concentrations in this study were attributed to anthropogenic influence such as: leachate, industrial effluent and the pit latrine system. Since BH5 and W1 are located within an unserviced settlement, ammonia contamination can be attributed to the pit latrines. Dzvairo *et al.* (2006), highlighted in their study that ammonia contamination can be associated with areas that use the pit latrines systems. In the current study, diffusion of ammonia from the faecal matter to the water table could have occurred, hence contributing to ammonia contamination. Ammonia contamination at BH3 and W2 can be attribute to the dumpsite leachate and industrial pollutants, respectively. According to Love *et al.* (2006), landfills and industrial areas release the widest suite of contaminants such as ammonia, hence they can be attributed to ammonia contamination. However, Dzvairo *et al.* (2006) indicated that ammonia usually occurs in drinking water at concentrations well below those at which toxic effects may occur. This agrees with the results found in the present study which exhibited a low range of 0-0.47 mg/L.

Electrical Conductivity (EC)and Total Dissolved Solids (TDS): The results for EC and TDS are as presented in *Figure 19.* EC ranged from 103 µS/cm to 720 µS/cm with TDS ranging from 103.7 mg/L to 3590 mg/L. Sampling sites BH9 (within Lyton industrial area) and W2 (within Bluffhill industrial area) exhibited high EC concentrations of 422.33 µS/cm and 677 µS/cm, respectively (greater than the WHO recommended limit of <400 µS/cm). The high mean EC values for BH9 and W2 coincided with high TDS values of 1486.3 mg/L and 3071 mg/L, respectively. With reference to sites BH3 and BH4, which are within the vicinity of the Golden Quarry dumpsite, fairly high levels of EC were detected. However, the mean values were slightly lower (255 µS/cm and 376.3 µS/cm respectively) than the permissible limit, of 400 µS/cm.

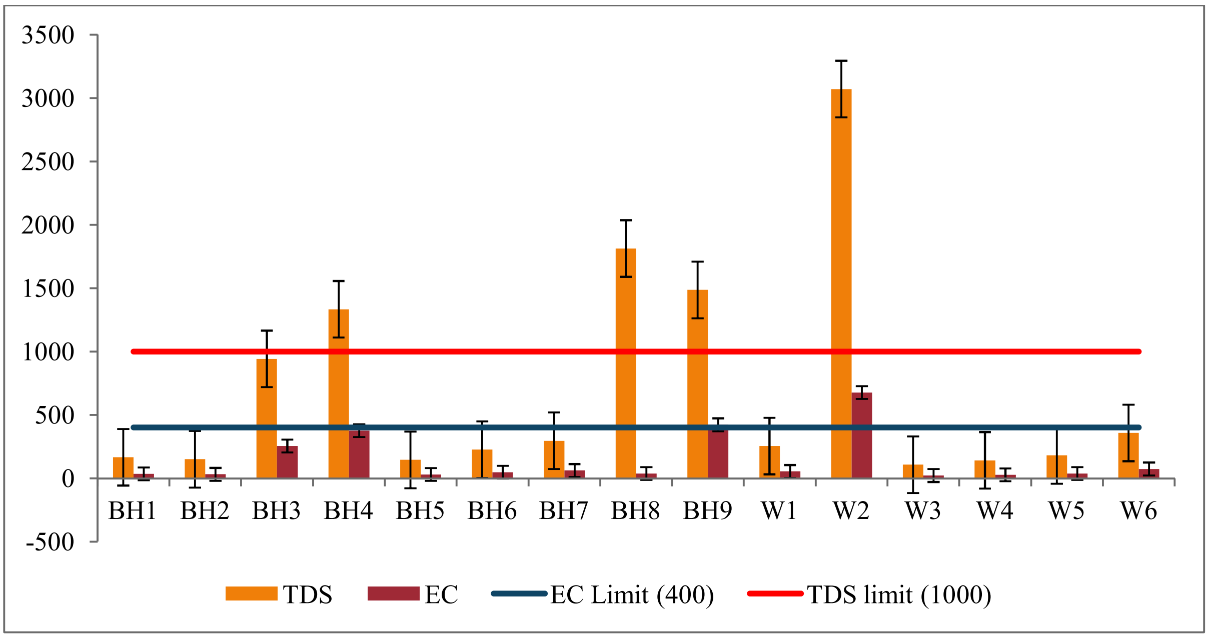

Figure 19: Electrical Conductivity variation

Conductivity indicates the presence of dissolved solids, especially electrolytes (Adekunle *et al.*, 2007). The relatively high EC levels can be attributed to the existence of dissolved salts in groundwater as shown by elevated levels of TDS for sampling sites, BH9 and W2. It was highlighted by Hoko (2008) the there is a direct relationship between EC and TDS. The results indicate that there is a direct association between conductivity and TDS as established in a study by Adekunle *et al.* (2007). The EC results for BH3 and BH4 are highly comparable with those obtained from a study by Love *et al.* (2006) for the Golden Quarry dumpsite. Conductivity values ranging from 100-1920 µS/cm were found in their study. Dissolved salts from the Golden Quarry dumpsite were identified as the potential source of dissolved ions in ground water. The results are also in agreement with the findings by Adekunle *et al.* (2007) that, TDS and conductivity levels of groundwater samples from sources in the vicinities of the dumpsites and industrial sites are high. The researchers highlighted the presence of electrolytes of the cations such as Pb and Cu, hence contributing to high TDS and EC. On the other hand, low values exhibited for shallow-wells maybe be due to insignificant contributions of ions from the main activities within the vicinity of the shallow-wells.

Turbidity: As shown in *Figure 20*, mean turbidity values ranged from a minimum of 0.83 NTU to a maximum of 53.4 NTU, with 53 % of results failing to meet the 5 NTU WHO permissible limit. About 80 % of the shallow wells had turbidity values above the permissible limit throughout all sampling campaigns with BH3, BH4 and BH5 showing the same trend. Of interest to note was BH3 which had the highest mean turbidity value of 40.1 ± 10.9 NTU.

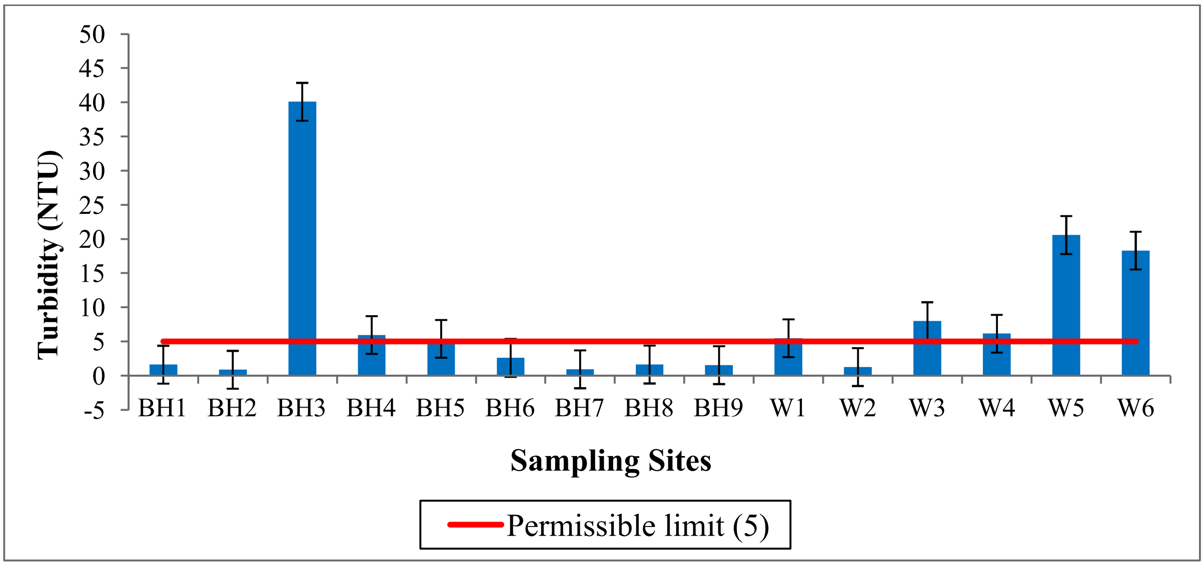

Figure 20: Turbidity variation

Turbidity stems from the reduction of transparency due to the presence of particulate matter in water. High turbidity levels are associated with poor water quality (Adekunle *et al.*, 2007). The high turbidity on BH3 can be attributed to contaminants which include, leachate from the Golden Quarry dumpsite, which is 100m upslope the site, or high levels of iron that are causing rusting in the steel piping connected to the borehole. Fairly high turbidity values detected for shallow-wells W1, W3, W4, W5 and W6 could attributed to: (i) the nature of the soil particles that make up the base of the well, (ii) water disturbances due to rainfall events and withdrawal. A study by Dzvairo *et al.* (2006) established turbidity ranges of 1 NTU to 45 NTU, with turbidity values above the limit mostly being found in shallow-wells. The high levels of turbidity in the study were attributed to soil disturbance and re-suspension within the well during water withdrawal; pit latrine excavations and loosening of the soil. High turbidity in potable water is aesthetically un-acceptable. WHO (2008) highlighted that, high turbidity can provide nuclei on which gastrointestinal disease causing pathogens can attach. Consumption of such water can consequently cause serious health risks. Therefore sites with high turbidity above the recommended limits should be disinfected before use.

Total Hardness(TH)*:* Figure 21 presents the variation of TH across sampling sites. TH for the samples varied from 56 to 832 mg/L, with a mean concentration of 192.5 ± 177 mg/L. WHO recommended 250 mg/L as the permissible limit for TH. High levels of TH were observed from sampling sites BH3, BH4, BH9 and W2 with 73 % of the sampling sites falling below the optimum limit.

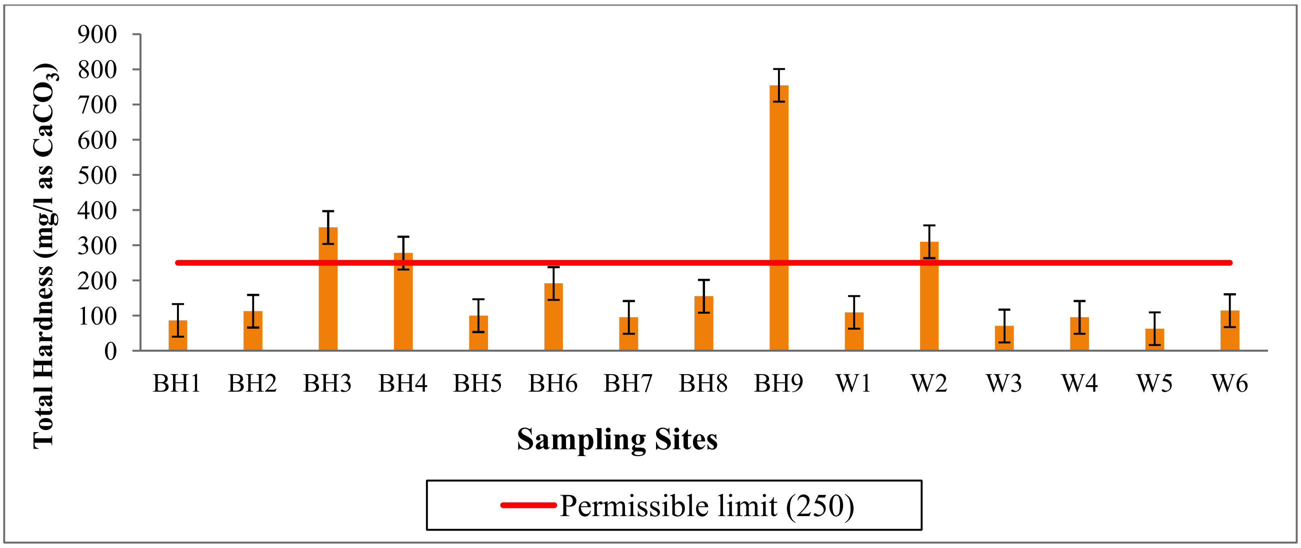

Figure 21: Total Hardness variation

Sampling sites BH9 and W2 are typically in industrial sites while BH3 and BH4 are within the vicinity (< 100 m) of the Golden Quarry dumpsite. High levels of TH in BH9 and W2 can therefore be attributed to the leaching of salts to groundwater from industrial wastes. On the other hand, sites BH3 and BH4 are showing groundwater pollution from leachate of the Golden Quarry dumpsite. According to findings by WMO (2013) and Adekunle *et al.* (2007), industrial areas and dumpsites are known to be associated with hard water. WHO (2008), highlighted that TH in drinking water is not known to pose a health risk to users. However, it prevents lather formation with soap and increases the boiling point of water, producing scales in boilers.

Fluoride:The variation of fluoride concentrations in Marimba Micro-catchment are shown in *Figure 22*. Groundwater samples indicate fluoride concentration ranging from 0.43 to 1.43 mg/L. The mean concentration was found to be 0.86 ± 0.24 mg/L. The results indicate that the levels of fluoride are within the WHO permissible limit of 1.5 mg/L. Fairly high levels of fluoride were however detected in 27 % of the sampling sites, although they were below the permissible limit.

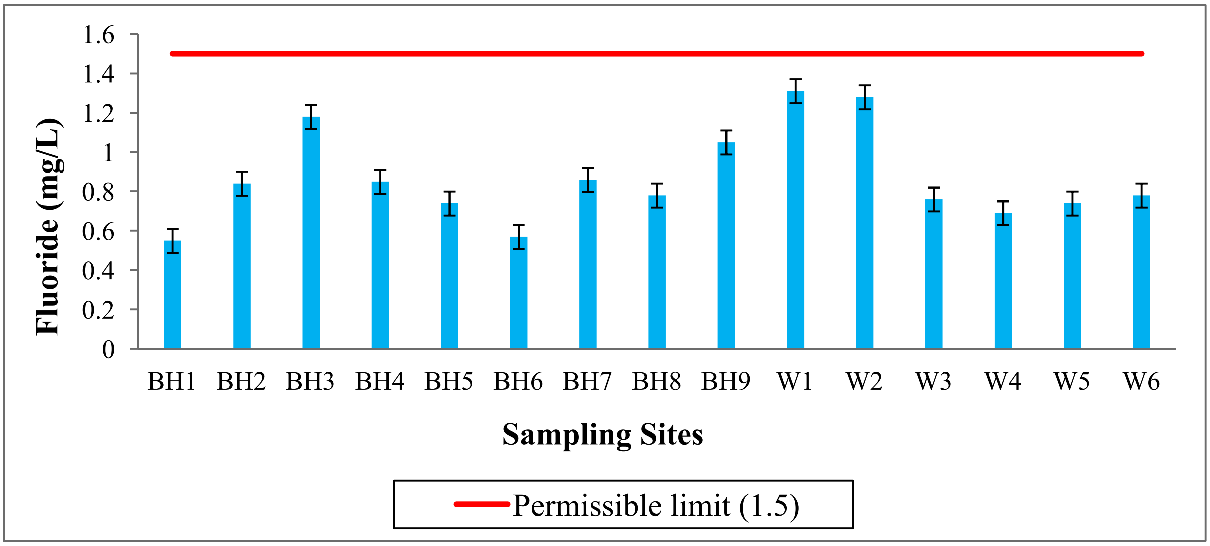

Figure 22: Fluoride variation

The probable source of fairly high levels of fluoride on sampling site BH3 is the dumpsite leachate. However for the rest of the sites, the low levels can be attributed to geogenic/natural sources (WMO, 2013). According to the WHO drinking water guidelines of 2002, the concentration of fluoride below 1.5 mg/L is helpful in boosting human health (e.g. preventing tooth decay and the development of perfect bone structure). However, doses of fluoride above 1.5 mg/L increases the severity of tooth mottling and induces the prevalence of osteoporosis and collapsed vertebrae.

Iron (Fe)*: Figure 23* shows Fe variation within the Marimba Micro-catchment. High iron concentration values above the permissible WHO limit of 0.3 mg/L were detected for BH3, BH4, BH9. Mean Fe values of 0.40 mg/L, 0.48mg/L and 0.39 mg/L, were detected for the sites, respectively. BH3 and BH4 had the highest iron concentrations than the rest of the sampling sites. BH3 and BH4 are with the vicinity of the Golden quarry dumpsite.

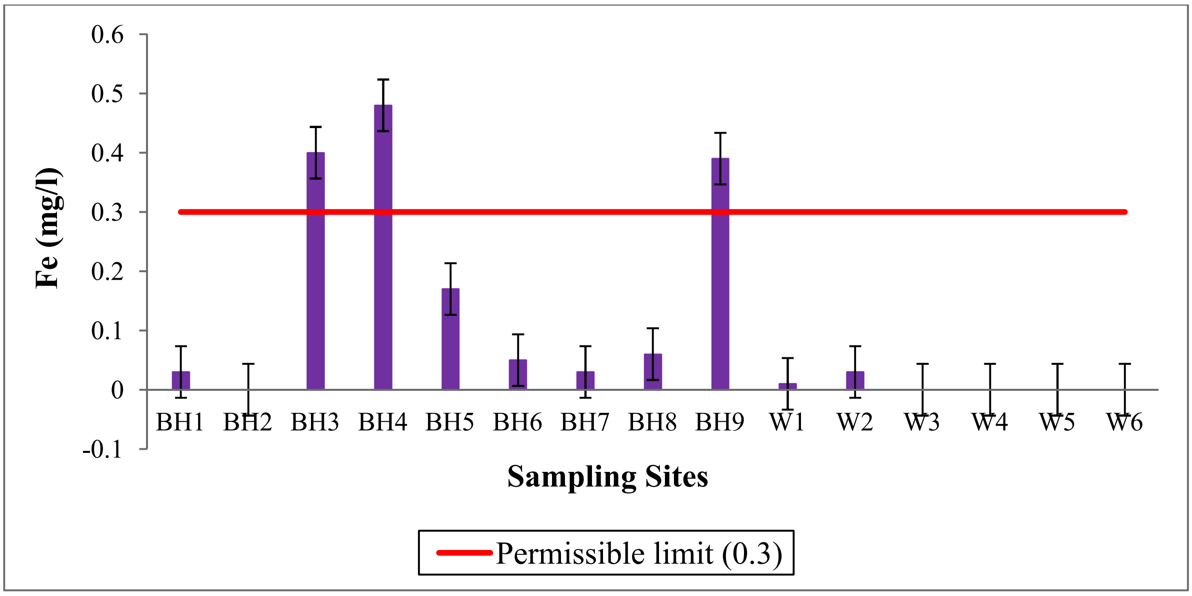

Figure 23: Iron variation

Love *et al.* (2006) found concentrations of 1.21-11.05 mg/L for the Golden Quarry dumpsite. Adekunle *et al.* (2007) highlighted that the concentration of iron in water is dependent on the pH, redox potential, turbidity, suspended matter and the occurrence of several heavy metals. Thus, elevated levels of Fe at BH3, BH4 and BH9 are attributed to pollution from the dumpsite and industrial activities. Therefore, the results of the current study are in agreement with these findings by Love *et al.* (2006) and Adekunle *et al.* (2007). It can therefore be concluded that, the dumpsite and industrial areas are actively releasing ironic compounds into the aquifers. Sampling sites with traces of Fe can be linked to geogenic or natural sources such as rock formations.

Lead (Pb)*:* Figure 24 illustrates the variation of Pb concentrations across sampling sites. All samples complied with the WHO Pb guideline for drinking water of < 0.05 mg/L. Although all the samples were within permissible limits, BH3, BH4, BH6 and W3 had fairly high levels of Pb.

Since, BH3 and BH4 are within the vicinity of the Golden Quarry dumpsite, chances might be that the decommissioned dumpsite is still actively releasing contaminants into aquifers within its vicinity. According to the WHO guidelines of 2008, Pb can bioaccumulate in the body consequently causing damage to the brain, kidneys and red blood cells. Therefore, the slightest concentrations are critical enough to result in consequential human health damage, hence sites with relatively high Pb concentration should be frequently monitored.

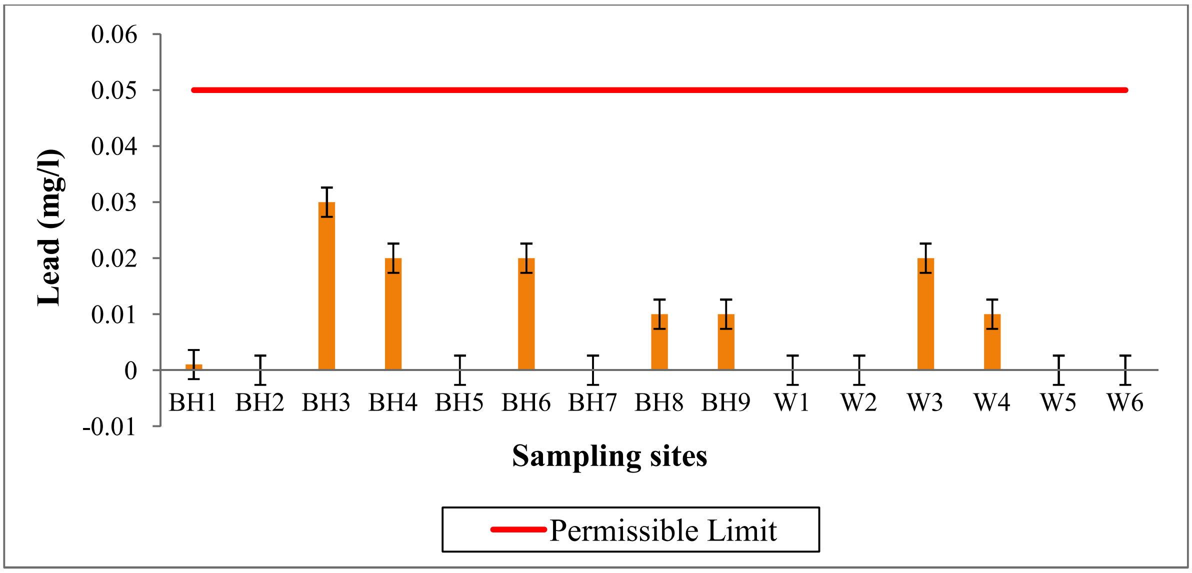

Figure 24: Lead variation

Chlorides (Cl^-): Figure 25 shows Cl^- variations in Marimba Micro-catchment. Out of the 15 groundwater sampling sites, BH3 and W2 showed higher Chloride concentrations which exceeded the SAZ drinking water standard value of <250 mg/L. The sites had mean chloride concentrations of 547.33 mg/L and 3133.3 mg/L respectively. Overally, the mean chloride concentration was 304.02 ± 790.22 mg/L. The rest of the sampling sites had significantly low concentrations of chlorides.

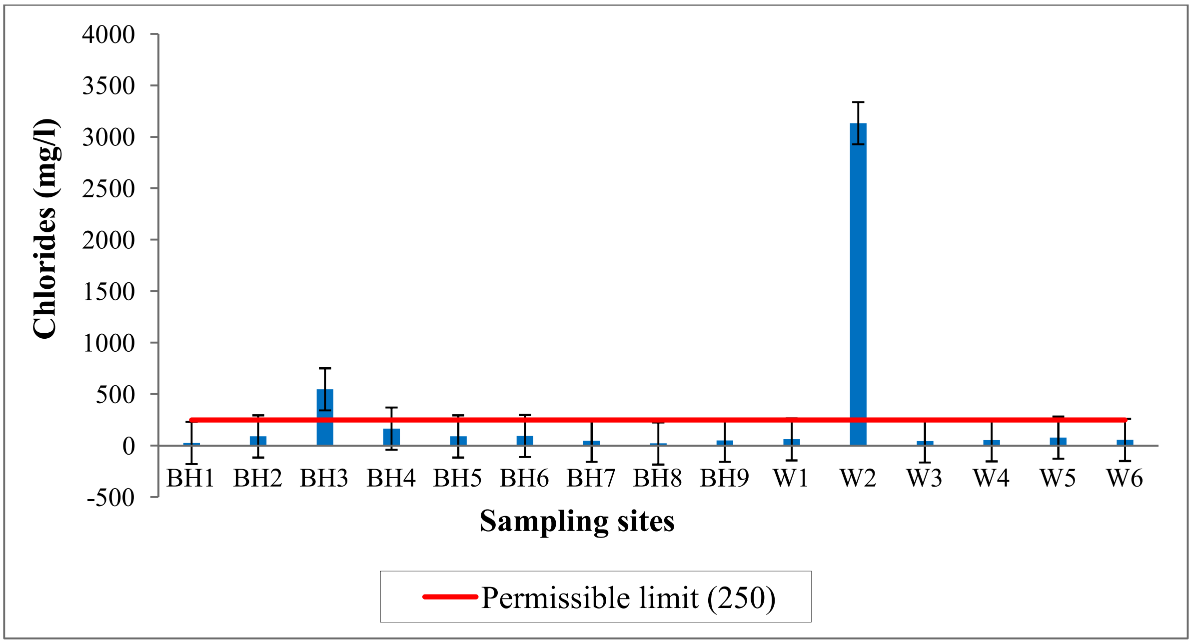

Figure 25: Chlorides variation

For sampling site BH3, the probable source of chloride is the Golden Quarry dumpsite. According to the findings by Mullaney *et al.* (2009), salt from human consumption or activities is commonly deposited in municipal landfills. These salts are typically from food wastes and other products containing salt, including rubber, metals and paper products. The results of this study also agree with the findings by Adekunle *et al.* (2007) that, landfills and industrial sites (BH3 and W2, respectively) contribute to chloride contamination. The salts gradually end up in aquifers in cases of non-engineered dumpsites such as the Golden Quarry. Adekunle *et al.* (2007) further highlighted that agricultural activities, industrial activities and rocks are other sources of chloride. Thus, several minerals in common rocks release chloride ions slowly, hence chloride contamination from rocks is commonly in low concentrations. High chloride concentration imparts a saline taste to water thereby rendering the water unfit for portable uses (WHO, 2008).

5.3.3 Analysis of variations in mean parameter levels

Results from Mauchly's test of Sphericity are shown in *Table 12*. The results indicate that the assumption of sphericity had not been violated ($\chi^2(2) = 4514$, $p = 0.0$). thus, showing that there were significant differences between mean parameter levels across sampling sites and between subsequent sampling campaigns. Since the null hypothesis was rejected (p=0.00), a post-hoc test was run and the ANOVA results are presented in *Table 13*.

Table 12: Mauchly's test of sphericity

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
	0.00	4514	104	**0.00**	0.11	0.12	0.07

Table 13 summarises the results from multivariate tests performed on groundwater quality data using Repeated Measures ANOVA. There were no significant differences ($p>0.05$) in mean parameter levels across sampling sites and within sampling campaigns for parameters: pH, turbidity, TDS, EC, TH, Cl^{-},Fl^{-},Fe, Zn, Pb and Cu. Lack of significant variations in mean parameter levels can be attributed the fact that, all sampling campaigns were conducted during the same season (the rainy season), hence less variation could be expected due to the dilution effect from the rain. However significant differences across sampling sites and between subsequent sampling campaigns were observed for parameters: DO, total coliform and faecal coliforms. Total and faecal coliforms yielded p-values of 0.3 and 0.12 respectively. Thus, indicating that mean parameter levels differed significantly across sampling sites and between subsequent sampling campaigns. The DO results showed a p-value of 0.32, indicating significant differences between the sampling campaigns and across sampling sites. Since DO is temperature dependent, the alternating of temperatures during the rainy season contributed to significant DO variations.

Table 13: ANOVA results for groundwater parameters

Parameter	F	df1 (within subjects variability)	df2 (treatment variability)	Sig.
pH	0.11	2	42	0.90
Turbidity	0.46	2	42	0.63
DO	1.17	2	42	**0.32**
TDS	0.40	2	42	0.68
EC	0.12	2	42	0.89
Total Coliform	1.25	2	42	**0.30**
Faecal Coliform	2.20	2	42	**0.12**
Total Hardness	0.24	2	42	0.79
Chloride	0.23	2	42	0.80
Fluoride	0.67	2	42	0.52
Ammonia	0.18	2	42	0.84
Iron	0.14	2	42	0.87
Zinc	0.61	2	42	0.55
Lead	0.30	2	42	0.75
Copper	0.17	2	42	0.85

5.3.4 Extraction of key parameters affecting groundwater quality

Principal Component Analysis (PCA) was used to determine key parameters that contribute to groundwater quality variation in Marimba Micro-catchment. According to Jolliffe (2002), PCA develops Principal Components (PCs) which can be used as predictor variables in subsequent assessments. Table 14 summarizes the eigenvalues of the covariance matrix for groundwater quality parameters of the study area.

Table 14: Eigenvalues of the covariance matrix for the groundwater quality parameters

	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**	**PC9**	**PC10**	**PC11**	**PC12**	**PC13**	**F14**
Eigen-value	**5.7**	**2.9**	**2.1**	**1.9**	0.9	0.6	0.4	0.2	0.1	0.04	0.02	0.01	0	0
Variability (%)	38.0	19.1	14.3	12.85	6.1	4.1	2.9	1.25	0.9	0.26	0.13	0.03	0.01	0
Cumulative %	38.0	57.1	71.4	84.3	90.4	94.5	97.4	98.7	99.6	99.8	99.9	99.9	100	100

PC1 showed the highest variability of 38 % as compared to other components. PC2 to PC4 exhibited percentage variabilities of 19.1 %, 14.3 % and 6.1 %, respectively. Cumulatively, PC1 to PC4 accounted for 84.3 % of the total variability in groundwater quality in the study area. Therefore, the components can be relied on as the main sources of variation within the dataset. To find the exact number of PCs, the magnitude of the eigenvalue was considered. Thus, the relative contribution of each PC was qualified by the eigenvalue. Components with a total eigenvalue > 1 were chosen as shown in *Figure 26*, as recommended by Jollife *et al.* (2002).

In this case four PCs, 1 to 4, were selected based on the Eigenvalue threshold of 1. Thus, the dimensionality of the multi-variate groundwater data was reduced to 4 principal components. The relative contribution to the overall variability from the principal components 1 to 4 was 38 % , 19.1 %, 14.3 % and 12.85 % respectively, with a cumulative contribution 84.25 % *(Table 14*). The result show that the components can be relied on as the main sources of variation within the dataset. To deduce the actual groundwater parameters for the chosen PCs, the percentage contribution of each variable was used. The contributions represent the extent to which each variable contributed to building the corresponding component (

Table **15**).

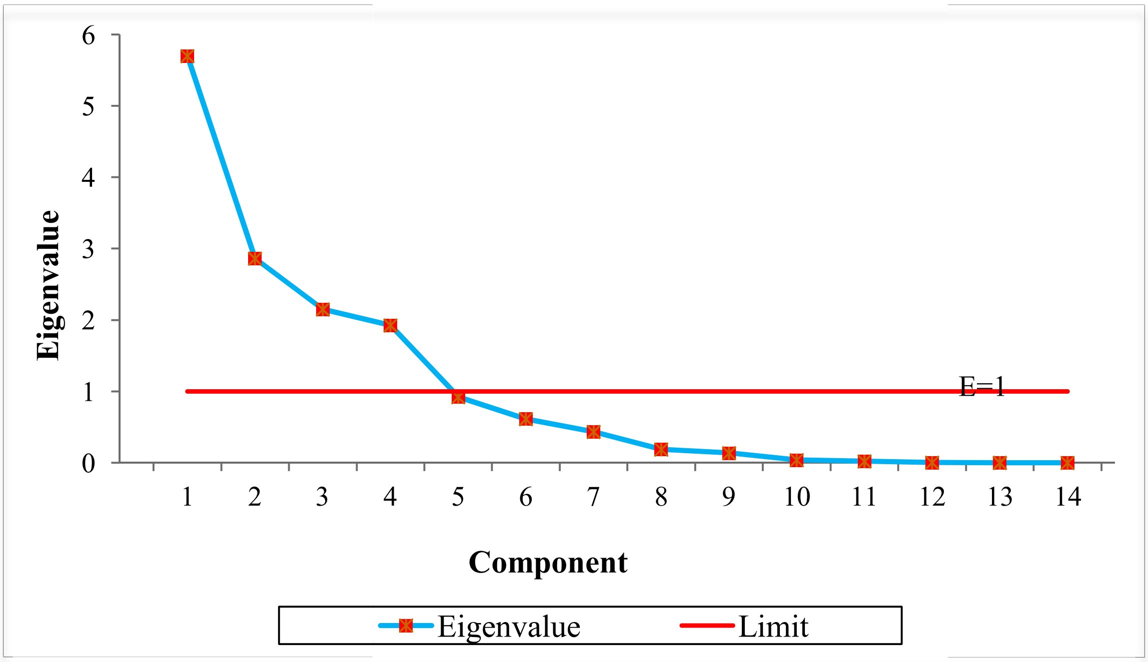

Figure 26: Eigenvalue limit based component selection

Principal parameters were chosen from the four PCs based on the highest percentage contribution into the variability of each component. PC1, which accounted for 38 % of the total variation, was characterized by high dominance of pH, TDS, EC and total hardness. Since EC can be used to infer TDS concentration (Hoko, 2008), it was deliberately eliminated from the key parameters for PC1. PC2's variance was found to be associated with elevated levels of Cl^-, Zn and Cu. On the other hand, PC3 presented high loadings of total and faecal coliforms, Fl^-.and turbidity. PC4 was characterized by high loadings of Pb, Fe, ammonia and turbidity.

Overall, PCA showed that most of the variation in the water quality was accounted for by pH, Zn, Cl^-, TDS, ammonia, Fl^-, Cu, turbidity, Fe, Pb and faecal coliforms. These groundwater water quality variables were present in most samples that were analysed. The variation in the nature of the parameters across PCs explains the complexity of pollutants within the micro-catchment. As indicated by Kamusoko *et al.* (2013), the study area consist of an intertwined assortment of socio-economic activities and landuse patterns. As such, each activity generates different pollutants. Thus, the industries, agriculture, dumpsites and domestic effluent, to mention a few, vary in the nature of pollutants they generate. PC2 and PC4 are largely characterized by metallic compounds, which suggests pollution from mineral dissolution into the aquifers from industrial areas or dumpsites (Love *et al.*, 2006). PC3 reflecting elevated levels of faecal coliform counts, indicate the susceptibility of groundwater to pathogenic contamination, especially in areas that use the pit latrine system.

Table 15: Percentage contribution parameters to groundwater quality variation

Parameter	**PC1**	PC2	PC3	PC4
pH	**13.5**	3.1	0.6	2.4
Turbidity	0.01	1.9	**12.3**	**19.9**
DO	0.8	10.2	7.7	0.1
TDS	**14.3**	4.2	0.3	0.9
EC	**15.5**	1.9	0	0.3
Total Coliform	4.4	3.9	19.5	3.6
Faecal Coliform	3.8	4.4	**22.2**	3.9
Total Hardness	**13.0**	5.5	3.0	0.2
Chloride	6.9	**16.1**	2.9	1.6
Fluoride	6.3	6.8	**11.7**	0
Ammonia	1.6	6.2	8.4	**11.9**
Iron	7.3	5.3	2.2	**14.8**
Zinc	5.8	**14.9**	3.3	5.1
Lead	1.0	1.8	1.1	**29.1**
Copper	5.9	**13.9**	4.8	6.1

5.4 Determination of vulnerability zones

The GOD model was used in this study for vulnerability assessment. Three input parameters/thematic layers were developed in a GIS environment (ILWIS). A multiplicative analysis technique was used to aggregate the parameters to develop a vulnerability index map which was reclassified into 5 different vulnerability zones.

5.4.1 Spatial variation of groundwater depths

Figure 27 shows the spatial variation of groundwater depths in Marimba Micro-catchment developed from 24 groundwater abstraction sites. The depths averaged 10.9 ± 12.1 m, with a range of 0.45-43 m. In terms of areal coverage, the depths ranges: < 2 m, 2-5 m, 5-10 m, 10-20 m, 20-50 m, 50-100 m and > 100 m accounted for 2.9 %, 21.2 %, 41.5 %, 3.4 % and 0 % for the rest, respectively.

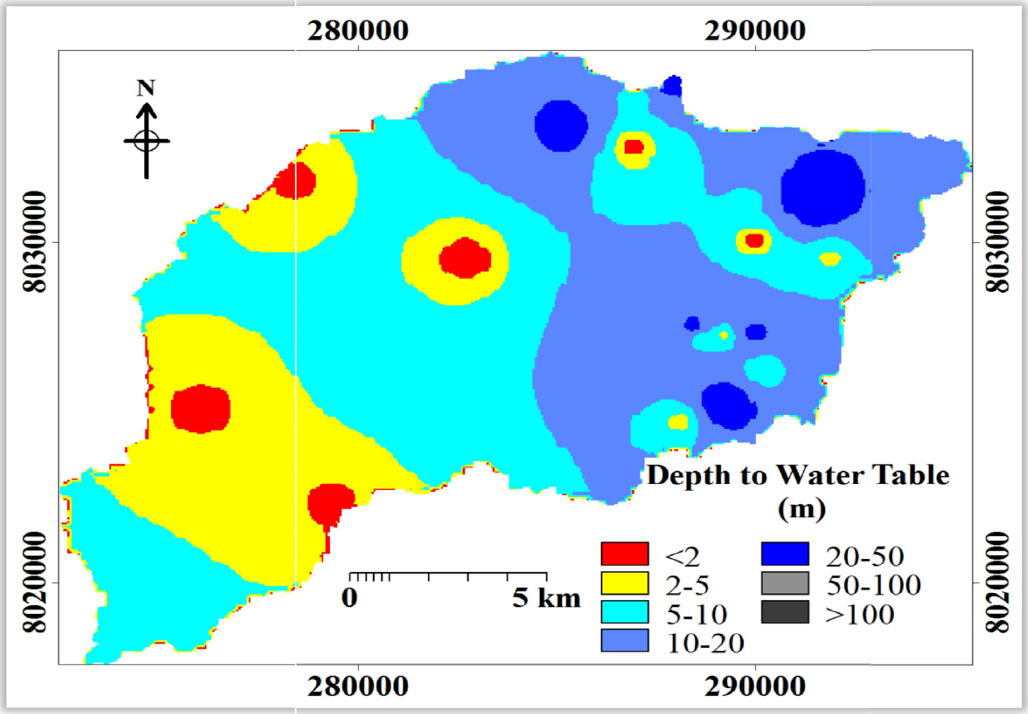

Figure 27: Depth to groundwater table map of Marimba

Table 16 summarises the areal coverages for the groundwater depth ranges in the study area.

Table 16: Groundwater depth variations of Marimba Micro-catchment

Depth range (m)	< 2	2-5	5-10	10-20	20-50	50-100	> 100
Areal coverage (%)	2.9	21.2	41.5	31.1	3.4	0	0

The mean depth to water table of 10.9 ± 12.1 m shows the occurrence of shallow water tables in the study area. Shallow water tables are more vulnerable to contamination than deeper aquifers (Owen and Madari, 2009). Shallow depths contribute to reduced contaminant residence time, hence the contaminant takes a short time to reach the water table of shallow aquifers. Given that the aquifer system of Marimba Micro-catchment is unconfined (Broderick, 2012), its susceptibility to contamination is also high (holding other factors constant, e.g. transmissivity properties of the aquifer). The dominance of shallow water depths agree with the findings of Broderick (2012) that groundwater in the micro-catchment, which is part of the Greater Harare aquifer system, tends to be perched at high levels and is often only exploitable by means of hand-dug wells. Therefore, with such aquifer conditions in the study area, groundwater becomes highly susceptible to pollution.

5.4.2 Overlying lithology

Figure 28 shows the lithological formations of Marimba Micro-catchment. The main formations identified were: the Basaltic Metavolcanics with Intercalated metasediments; the Dolerites and Gabbros; the Metasediments & Felsic Metavolcanics and the Younger Intrusive Granites (Martinelli and Hubert, 1985). In terms of area, the formations occupy 13.53 km^2, 34.45 km^2, 122.47 km^2 and 43.58 km^2 respectively.

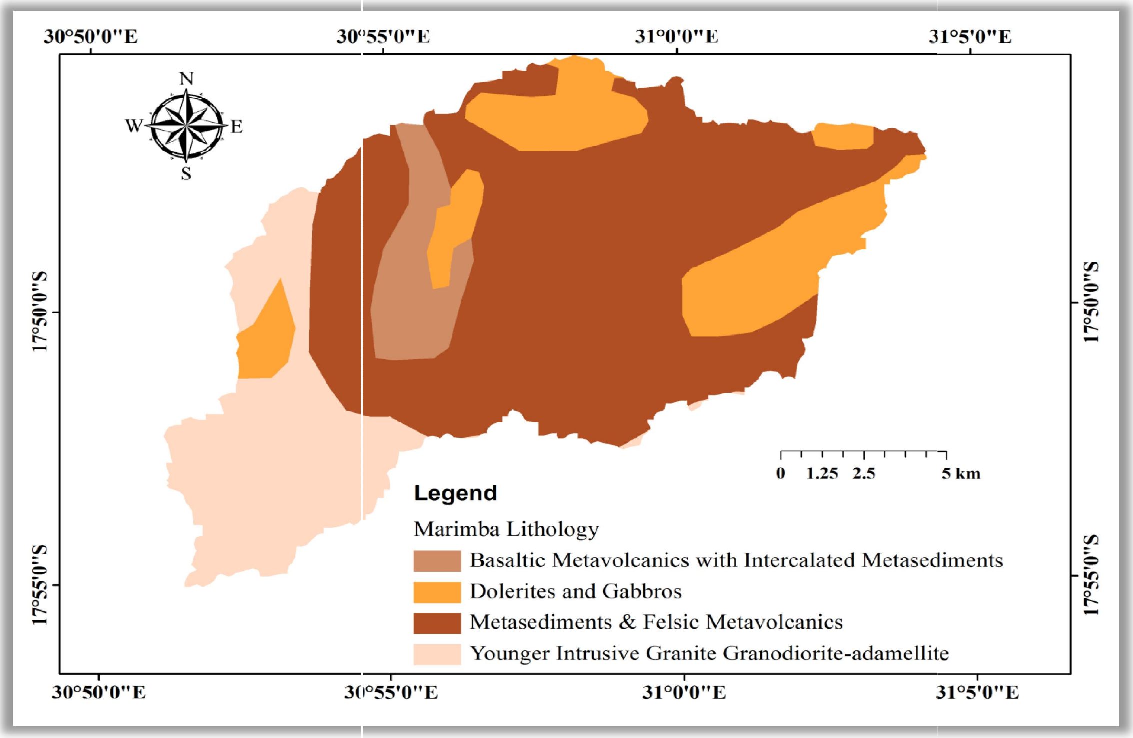

Figure 28: Lithology map of Marimba

The results are showing that the area is largely composed of Metasediments and Felsic Metavolcanics of the Shamvaian group. According to Martinelli and Hubert (1985) and Owen and Madari (2009), such formation is clayey, hence it is characterised by low permeability. As such, aquifers falling under such lithological formation are less vulnerable to contamination than the Basaltic Metavolcanics which were found to be highly permeable. Therefore basing on the lithology of the area, the overall groundwater contamination is likely to be fairly low.

5.4.3 Groundwater occurrence/aquifer type

The groundwater occurrence of the study area was found to be homogeneous, being characterised by an unconfined aquifer system. Broderick (2012) indicated that hydrogeological investigations done on the Greater Harare aquifer, using pumping tests, revealed the existence of an unconfined aquifer. Therefore, the study area is largely unconfined since it falls within the confines of Greater Harare. As such, the aquifer is capable of receiving direct recharge flux from precipitation. Therefore, such unconfined conditions also expose the aquifer to direct contaminant elements, hence the Marimba aquifers are generally more susceptible to contamination.

Although the GOD parameters are overally showing a potentially high degree of susceptibility of groundwater to contamination, it is equally important to note that the micro-catchment is highly urbanised. Urbanisation leads to the increase of impervious surfaces hence changing hydrological regimes (Gumindoga *et al.*, 2014). As such, urbanized surfaces generate more runoff and reduce the area over which infiltration can take place. This can also reduce the leaching of contaminants into aquifers, hence vulnerability can also be reduced. Since the GOD model does not take into consideration of this characteristic, it is recommended that further studies should adjust the model to fit the local conditions.

5.4.4 Marimba groundwater vulnerability

Figure 29 shows the spatial distribution of vulnerability zones in the Marimba Micro-catchment. The vulnerability zones, developed through a multiplicative aggregation of the thematic layers, was classified into five vulnerability classes: negligible, low, moderate, high and extreme. The highest degree of vulnerability (extreme) was found parts of Kuwadzana and Dzivarasekwa suburbs. The extreme vulnerability class constituted 6.3 % (13.9 km^2) of the total area. Moderate vulnerability zones constituted 77.3 % (170.4 km^2) of the study area. Areas such as Belvedere, Bluffhill, Whitecliff and parts of Dzivarasekwa fell under high vulnerability zones. The cumulative surface area under the high vulnerability class was found to be 16.5 % (36.4 km^2). It was also noted from the results that vulnerability classes negligible and low were not found in the study area. Given instances of high pollution load from anthropogenic activities in the study area, groundwater resources area under serious threat and need sustainable protection strategies to or event further degradation.

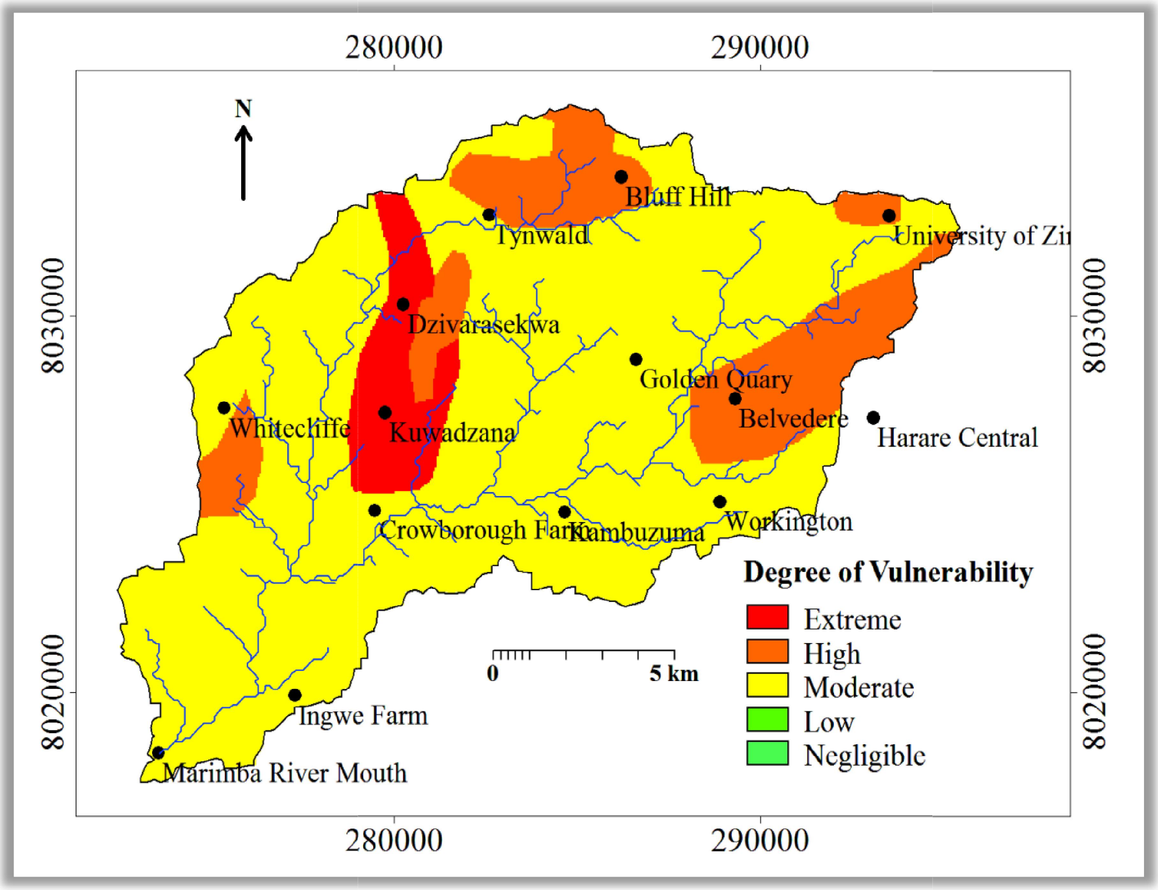

Figure 29: Map of Marimba groundwater vulnerability zones

5.4.5 Validation of Marimba vulnerability map

A correlation analysis was performed between the vulnerability indices and mean values of ammonia from 15 sampling sites. GOD index values were extracted using the MAPVALUE function in ILWIS. A correlation value of 0.47 was found. Although the correlation coefficient was relatively weak, it pointed out to the coincidental occurrence of higher vulnerabilities and groundwater contamination from ammonia. Thus, human activities are polluting groundwater resources. As indicated in the findings of Dzvairo *et al.* (2006), ammonia is associated with areas that are impacted with human waste, in particular, faecal matter. As such, pit latrines in some of the high density suburbs and the dumpsite leachate can be contributing to ammonia contamination. Thus, the results are providing evidence that ammonia, from human related activities, is polluting groundwater resources. Therefore, there is need to develop protection strategies to prevent further deterioration of groundwater quality.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions were drawn from the results obtained

1. Upper Manyame Sub-catchment has limited groundwater potential as indicated by the dominance of moderate groundwater prospect (72.3 % of area covering 2732.3 km^2).
2. Anthropogenic activities and/or landuses such as; agriculture, indiscriminate wastes disposal and industrial area manufacturing are significantly contributing to groundwater quality degradation in Marimba Micro-catchment.
3. Groundwater in the study area is polluted as indicated by parameter values of: pH, TDS, EC, total hardness, turbidity, total and faecal coliforms, ammonia and chlorides, above SAZ and WHO permissible limits.
4. It was established that groundwater in the Marimba Micro-catchment is under moderate vulnerability (70 %-154.35 km^2). The GOD model the GOD model was applicable in mapping vulnerability in the study area.

6.2 Recommendations

It is therefore recommended that:

1. Reliable drilling logs data and geophysical data (used to measure the physical properties of the subsurface), obtained from: electrical resistivity surveys, 'active' electromagnetic methods, refraction seismic methods or ground penetration radar methods, should be provided to enable the actual quantification of groundwater resources within the study area rather than having arbitrary values which are hard to use in terms of demand management.
2. Authorities should consistently monitor human development patterns to ensure that direct interaction of the water table and the sanitation facilities is limited e.g. monitoring the construction of pit latrines to prevent faecal matter from interacting with the water table.
3. Groundwater monitoring networks be set up to ensure rigorous monitoring as a measure to avoid indiscriminate use of groundwater and to prevent further degradation of groundwater quality.

4. Although the GOD model is suitable for large basins, it is recommended that modifications be done on the model to suit local conditions of the study area since each study area has its own characteristics.

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APENDICES

Appendix 1: Comparative summary of individual parameters and WHO/SAZ permissible limits

Parameter	WHO/SAZ Limit	BH1	BH2	BH3	BH4	BH5	BH6	BH7	BH8	BH9	W1	W2	W3	W4	W5	W6
pH	6.5-8.5	6.70	7.57	6.43	6.00	6.60	7.00	6.80	6.77	5.16	7.07	3.70	6.60	6.70	6.60	6.83
Turbidity	5	1.62	0.87	40.1	5.96	5.40	2.62	0.94	1.64	1.55	5.49	1.27	7.98	6.15	20.59	18.31
DO	>2	4.69	7.46	4.99	5.03	5.80	3.95	4.61	3.57	6.05	5.12	3.07	5.12	5.47	4.17	5.64
TDS	1000	166.07	150.90	942.3	1333.3	145.57	226	296	1813	1486.3	254.7	3071.0	107.4	141.73	180.43	358.00
EC	400	35.33	31.33	255.0	376.3	30.00	47.67	61.3	37.7	422.33	53.7	677.0	21.90	28.00	38.00	73.86
Total Coliform	0	0	0	0	31	16	9	0	0	0	875	0	607	481	650	1115
Faecal Coliform	0	0	0	0	8	5	3	0	0	0	583	0	244	219	317	613
Total Hardness	250	86.67	112.67	350.67	278.00	100.00	191.67	95.3	155.3	754.33	109.3	310.00	70.67	95.33	63.33	114.33
Chloride	250	26.15	90.53	547.33	165.90	90.37	94.22	47.9	22.03	49.20	62.31	3133.3	42.78	53.25	78.66	56.25
Fluoride	1.5	0.55	0.84	1.18	0.85	0.74	0.57	0.86	0.78	1.05	1.31	1.28	0.76	0.69	0.74	0.78
Ammonia	<0.2	0.03	0.00	0.41	0.12	0.26	0.02	0.02	0.14	0.07	0.39	0.21	0.12	0.05	0.05	0.00
Iron	0.3	0.03	0.00	0.40	0.48	0.17	0.05	0.03	0.06	0.39	0.01	0.03	0.00	0.00	0.00	0.00
Zinc	5	0.05	0.04	0.09	0.34	0.11	0.05	0.04	1.12	4.59	0.01	0.02	0.04	0.17	0.04	0.03
Lead	0.05	0.001	0.00	0.03	0.02	0.00	0.02	0.00	0.01	0.01	0.00	0.00	0.02	0.01	0.00	0.00
Copper	15	0.00	0.01	0.00	0.02	0.03	0.02	0.02	0.01	1.09	0.01	0.01	0.01	0.01	0.01	0.01

Above the permissible limit (red) — Relatively close to the permissible (blue)

Appendix 2: Description of sampling sites

SITE Name	SITE CODE	LOCATION	COORDINATES	DESCRIPTION	PURPOSE
UZ	BH1	Mt Pleasant	293308; 8032359	Control site	Potable water supply
Ocean Estate	BH2	Westgate	283314; 8034583	On-farm borehole	Irrigation and potable water supply
Warren Hills Golf Club	BH3	Marbelreign	286968; 8029351	Located < 1 km N of the Golden Quarry dumpsite	Potable water supply
Kirkman City	BH4	Tynwald	286180; 8029303	Located < 100m NW of Golden Quarry dumpsite	Construction & potable water supply
Whitecliff North	BH5	Whitecliff North	275783; 8028680	Community borehole in a unserviced settlement	Potable water supply
Kuwadzana	BH6	Kuwadzana	279467; 8026760	Community borehole in a serviced high density suburb	Potable water supply
18 Pleasant Valley Rd	BH7	Tynwald	283161;8027586	On-farm borehole	Irrigation & potable water supply
Kambuzuma High	BH8	Kambuzuma	284625; 8024331	Community borehole in a serviced high density suburb	Potable water supply
Sabie motors	BH9	Workington	289636; 8025449	Borehole in an industrial site	Industrial & potable water supply
Monavalle	W1	Monavalle	289991; 8030053	Well in a medium density suburb	Potable water supply
Bluffhill Catering	W2	Bluffhill	286923; 8032766	Well in an industrial site	Industrial & potable water supply
Stand No. 1259	W3	Tynwald Industries	282751; 8029518	Well in an industrial site	Potable water supply
12354 Tayambuka	W4	Dzivarasekwa Extension	278437; 8031791	Well in a high density suburb	Potable water supply
Granary Suburb	W5	Granary	276093; 8025127	Well in an unserviced settlement	Potable water supply
Budiriro	W6	Budiriro	279390; 8022354	Well in an unserviced settlement	Potable water supply

Appendix 3: SAZ and WHO drinking water standards and guidelines

Parameter	UNITS	SAZ Recommended Standard Limit	WHO Drinking Water Guidelines
pH	-	6.5-8.5	6.5-8.5
Temperature	(°C)	**	**
Turbidity	(NTU)		<5
DO	mg/L	>2.0	
TDS	mg/L	<1000	
Electrical Conductivity	$uScm^{-1}$	400	
Faecal Coliforms	cfu/100mL	0	
magnesium	mg/L	50	
Calcium	mg/L	100	
Chloride	mg/L	150	
Fluoride	mg/L	1.5	
Ammonia	mg/L	**	<0.2
Iron	mg/L	0.3	
Zinc	mg/L	5	
Lead	mg/L	0.05	
Copper	mg/L	15	

Appendix 4: Correlation matrix (Pearson (n) for groundwater variables

Variables	pH	Turbidity	DO	TDS	EC	Total Coliform	Faecal Coliform	Total Hardness	Chloride	Fluoride	Ammonia	Iron	Zinc	Lead	Cu
pH	**1**	0.098	0.423	**-0.943**	**-0.927**	0.266	0.272	**-0.606**	**-0.821**	-0.498	-0.179	-0.315	-0.360	-0.089	-0.383
Turbidity	0.098	**1**	0.004	-0.040	-0.011	0.282	0.255	0.032	-0.042	0.215	0.422	0.298	-0.201	0.275	-0.174
DO	0.423	0.004	**1**	-0.337	-0.273	0.111	0.112	0.076	-0.481	-0.064	-0.137	0.149	0.196	-0.107	0.273
TDS	**-0.943**	-0.040	-0.337	**1**	**0.989**	-0.309	-0.284	**0.622**	**0.861**	**0.622**	0.232	0.391	0.272	0.099	0.299
EC	**-0.927**	-0.011	-0.273	**0.989**	**1**	-0.337	-0.313	**0.709**	**0.778**	**0.618**	0.236	0.514	0.363	0.179	0.388
Total Coliform	0.266	0.282	0.111	-0.309	-0.337	**1**	**0.983**	-0.375	-0.216	0.046	-0.002	-0.423	-0.237	-0.315	-0.184
Faecal Coliform	0.272	0.255	0.112	-0.284	-0.313	**0.983**	**1**	-0.345	-0.202	0.142	0.080	-0.401	-0.225	-0.363	-0.172
Total Hardness	**-0.606**	0.032	0.076	**0.622**	**0.709**	-0.375	-0.345	**1**	0.222	0.447	0.140	**0.712**	**0.853**	0.218	**0.863**
Chloride	**-0.821**	-0.042	-0.481	**0.861**	**0.778**	-0.216	-0.202	0.222	**1**	**0.542**	0.259	-0.037	-0.121	-0.104	-0.089
Fluoride	-0.498	0.215	-0.064	**0.622**	**0.618**	0.046	0.142	0.447	**0.542**	**1**	**0.706**	0.284	0.176	-0.151	0.213
Ammonia	-0.179	0.422	-0.137	0.232	0.236	-0.002	0.080	0.140	0.259	**0.706**	**1**	0.344	-0.099	0.136	-0.107
Iron	-0.315	0.298	0.149	0.391	0.514	-0.423	-0.401	**0.712**	-0.037	0.284	0.344	**1**	0.485	**0.587**	0.465
Zinc	-0.360	-0.201	0.196	0.272	0.363	-0.237	-0.225	**0.853**	-0.121	0.176	-0.099	0.485	**1**	0.015	**0.971**
Lead	-0.089	0.275	-0.107	0.099	0.179	-0.315	-0.363	0.218	-0.104	-0.151	0.136	**0.587**	0.015	**1**	0.004
Cu	-0.383	-0.174	0.273	0.299	0.388	-0.184	-0.172	**0.863**	-0.089	0.213	-0.107	0.465	**0.971**	0.004	**1**

Values in bold are different from 0 with a significance level alpha=0.05