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Department of Geography and Environmental Science

AN ANALYSIS OF GROUNDWATER IN MCHINJI DISTRICT OF CENTRAL MALAWI.

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November, 2010

An Analysis of Groundwater in Mchinji District of Central Malawi

By

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A Dissertation submitted in partial fulfillment

of the requirements of the Master of Science Degree in

Geography at the

University of Fort Hare, Republic of South Africa.

November, 2010

Research Supervisor: Dr Werner Nel

DECLARATION

I, Prince Mleta, hereby declare that the dissertation entitled ‘An Analysis of Groundwater in Mchinji District of Central Malawi is the product of my own original investigation except where otherwise stated, and that it has not been submitted for a degree to any other University.

NAME: Prince W. E. C. Mleta

SIGNATURE: ……………………………

DATE: …………………………….

PLACE: UNIVERSITY OF FORT HARE

DEDICATION

To

My beloved wife Jane, children Wanja (Wanja girl), Martin (Linga boy) and who knows,

Parents, brethren and relatives

I wish you and the people of the whole world easy access to potable water.

May dry throats be soothed with good quality water

In required amounts, ALWAYS

Now Jacob's well was there, Jesus, therefore, being wearied with his journey, sat on the well: and it was about the sixth hour…..Jesus answered and said unto her, whosoever drinketh of this water shall thirst again but whosoever drinketh of the water that I shall give him shall be in him a well of water springing up into everlasting life. (John 4 Vs 6, 13 & 14. KJV)

ACKNOWLEDGEMENTS

Praise and glory be to God Almighty for giving me the wisdom, courage and strength to complete my research work. My sincere gratitude goes to the Malawi Government (My employer) through the Department of Human Resource Management and Development (DHRM&D) for awarding me the scholarship after successful interviews, to pursue the post graduate studies. Many thanks to my research supervisor Dr Werner Nel, for his invaluable input and untiring guidance to my research work. Without his commitment in directing my research, the work could have been jeopardized. Further gratitude is extended to members of staff and students in the Department of Geography and Environmental Science especially during seminar presentations. Prof. Seethal you played a remarkable role in my admission to the programme, enough respect.

My further sincere thanks goes to Mr Hector Kankuwe for your untiring role in the statistical analysis of my work, I salute you. Ms Ivy Gondwe kindly receive my acknowledgements for the role you played in the Remote Sensing and Geographical Information System analysis, God bless you. My fellow workmates and colleagues at the Ministry of Irrigation and Water Development: Mr. S.Y.C Maweru, Mrs. M.B. Kanjaye, Mr. Peaches Phiri, Mr. G. Matiki, Mr. M. Nkhata, The Chintengos, Mr. D. Kambuku, Mr. R. Chiwaula, Mr C. Chivunga, Mr.

Kaswadwa, Mr. Mdima, Mr. Munthali, Ms Ching'oma, too many to mention, I thank you for various roles you played during my research.

I would do a great injustice not to thank my beloved wife Jane for shouldering the family chores alone during my absence. Thanks for your prayers and encouragement. Finally I wish to thank the Mchinji District Assembly and the water users in Mchinji District for the cooperation and assistance rendered to me during data collection through interviews and focused group discussions.

ABSTRACT

Groundwater resources is the major source of potable water in Mchinji District of Central Malawi and globally. Although the total amount of water on and under the earth's surface is generally assumed to have remained constant, the rapid population boom coupled with extension of agricultural farmland and industrial development are putting pressure and stress on the quality and quantity of water resources. In principal therefore, 'use and discard' philosophy in water resources cannot be subscribed (Lloyd, 1999). The situation ultimately calls for rational management of water resources to ensure its sustainability.

Water intended for human consumption must be free from organisms that are the causative agents of diseases and must not contain chemical substances at concentrations that may be hazardous to human health. In addition drinking water should be aesthetically acceptable, free from unpleasant taste, color, odor and turbidity. Drinking water should also be free from bacteria and viruses whose presence would indicate fecal contamination. Some are known to be toxic and their concentrations must be below acceptable value, taking into account that drinking water is but one of the several pathways by which substances enters the body.

Due to perceived concerns of over extraction and rapid water resources depletion, optimal management of groundwater resources are now receiving much attention. Their associated literatures have taken quite different approaches both philosophically and operationally to the analysis of how groundwater should be managed, allocated and cared for spatially and temporally.

This study investigated the spatial and temporal fluctuations of concentrations of chemical and biological substances in groundwater such as pH, electrical conductivity, total dissolved solids, iron, fluoride, manganese, chloride, sulfates, sodium and fecal coliform in Mchinji District of Central Malawi. Through examination and analysis of static water levels as an indicator of water table fluctuations, groundwater availability was also measured. It was found that anthropogenic activities on the landscape can impact the quality and quantity of the water resources in this area and this impact on the various sectors of the inhabitant's livelihoods. Groundwater in Mchinji is composed of a number of chemical and biological elements whose origin is either from the material in which it percolates through, or stored before exploitation. Anthropogenic activities in this area plays a role in the quality and quantity of groundwater through land use and land cover change as evidenced by comparisons of Landsat Thematic

Mapper™ satellite images over different time scales. In Mchinji no regular groundwater monitoring is being done indicating a deficiency in sustainability interventions of the resource.

This study calls for integrated and sustainable water resources management and coordinated efforts amongst water users, local councils, regulatory authorities and environmental policy makers. Of far greater importance in groundwater sustainability analysis is the issue of groundwater monitoring. It is imperative therefore to preserve the resource while preservation is still possible. Groundwater is now turning into 'blue gold' and becoming a highly sought-after commodity. It should, however, be utilized sustainably to meet the needs of the present without compromising the ability of future generations to meet their own needs.

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ACRONYMS

ADMARC	Agricultural Development and Marketing Cooperation
CBM	Community Based Management
DNV	Digital Number Values
ECD	Electron Capture Detector
EC	Electrical Conductivity
EMA	Environment Monitoring Agency
EPA	Environment Protection Agency
ETW	Earth Trade Water
FAO	Food and Agricultural Organization
GC	Gas Chromatography
GDP	Gross Domestic Product
GIS	Geographic Information System
GPS	Global Positioning System
HIV/AIDS	Human Immuno deficiency Virus/ Acquired Immuno Deficiency Syndrome
IBWA	International Bottled Water Association
JICA	Japan International Cooperation Agency
LSP	Local Service Provider
LU/LC	Land Use/Land Cover
LWTS	Lenntech Water Treatment Solutions

MBS	Malawi Bureau of Standards
MGDS	Malawi Growth and Development Strategy
MDGs	Millennium Development Goals
MoAFS	Ministry of Agriculture and Food Security
MPRSP	Malawi Poverty Reduction Strategy Paper
Mg/l	Milligram per litre
MoIWD	Ministry of Irrigation and Water Development
NWDP	National Water Development Project
NGO	Non Governmental Organization
NSO	National Statistics Office
RS	Remote Sensing
SADC	Southern African Development Community
SPADNS	sodium parasulphophenylazzo dihydroxy- naphthalene disulphonate
Sq km	square kilometer
SWL	Static Water Level
TC	Trading Centre
TDS	Total Dissolved Solids
TM	Thematic Mapper
UNEP	United Nations Environment Programme
USA	United States of America
USGS	United States Geological Survey

UTM	Universal Time Mercantile
VLOM	Village Level Operation and Maintenance
WHO	World Health Organization
WGS	World Geodetic Survey
WPC	Water Point Committee
WSIS	Water Stewardship Information Series

CHAPTER I

BACKGROUND TO THE STUDY

Introduction

Lee (2010) defines groundwater as the water that is present below the surface of the ground, within the soil pores and the fissures of the lithosphere. It is stored in and moves slowly through layers of soil, sand and rock formations usually referred to as aquifers. An aquifer is considered as a hydrostratigraphic unit that is saturated, permeable and capable of yielding economic water (Freeze and Cherry 1979). These materials are permeable because they have large connected spaces that allow water to flow through. The speed at which groundwater flows, depends on the size of the spaces in the soil or rock and also how well the spaces are connected (LWTS, 2008).

The composition of groundwater is determined by the geological nature of the soil or rocks where it is contained or passes through. Lloyd (1999) observed that the water is constantly in contact with the ground/medium in which it circulates or stagnates allowing equilibrium to develop between that of the soil/rock and that of the water. The dissolved minerals in groundwater will therefore be controlled by either the types of minerals that make up the aquifer and the length of time that the water is in contact with the minerals. Since different rocks have different minerals, groundwater will have different compositions (Lee, 2010). In principle, therefore, owing to the medium in which groundwater is stored and transmitted, it is bound to have varying chemical, biological and physical elements as it dissolves minerals from the rocks and soils which it comes into contact with, which if they are consumed in excess or very minute amounts causes various problems to human health. Unfortunately, since groundwater is not naturally visible it is a rather difficult and complicated task to evaluate the extent of its degradation until the repercussions become evident after extraction or from scientific testing (Freeze and Cherry, 1979).

Globally the main source of groundwater recharge is through precipitation and it is assumed that about 10% of total rainfall infiltrates to become part of groundwater (Ministry of Water Resources (India), 2002). After a rainfall event, some water runs on the surface as runoff to the rivers and lakes, while some evaporates back to the atmosphere and some water slowly percolates and infiltrates into the ground to become part of the groundwater. Another source of groundwater is fossil or connate water. This is groundwater that is trapped in impermeable structures of the lithosphere which can only become accessible once the structure has been penetrated (Freeze and Cherry., 1979).

Although groundwater is considered as a renewable natural resource it must be used properly. Lack of proper knowledge on how to monitor and manage the utilization of the reserves may create problems such as overexploitation which has a direct consequence to the sustainability of the resource. The rule of environmental justice is to make sure that the resources are utilized in a sustainable manner to benefit the future generations.

Overexploitation of groundwater has been known to cause land subsidence in areas such as California in the United States of America, northern Kanto plane of Japan and eastern coalfields of India (Leake, 2004; Kobayashi, 2005). Furthermore, long term over exploitation of groundwater may cause a decline in the exploitable yield. In addition, over pumpage and environmental degradation reduces water reserves and may raise pollution to higher levels (Collin and Melloul, 2001).

Land use activities on the landscape can also affect the natural environment. It has been scientifically documented that life in the natural environment is to some extent dependent on groundwater (Scanlon et al., 2005). Due to the dependency of life in the natural environment to groundwater it is imperative that anthropogenic activities on the landscape should be regulated to avoid unwarranted vegetation clearing, harmful bush fires, unregulated groundwater extraction and poor agricultural practices (World Bank, 1992). These acts have the ability to affect groundwater quality and quantity.

Freeze and Cherry, (1979) noted that no threats to groundwater supply can be identified without the benefit of sound, scientific evidence demonstrating its impact on its quality and quantity. Likewise, IBWA (2005) noted that comprehensive groundwater resource management must be supported by a foundation of sound science, which should provide for projections of use and determine the limitations of the resource base. Such comprehensive resource management, planning and policy must also incorporate a capability to resolve conflicting interests based on the principle of equitable partition of the resource base.

Groundwater in Mchinji district in central Malawi, same as globally, is governed by the interplay between climatic conditions, geology and human activities on the landscape. Groundwater extraction through boreholes is the main source of domestic water supply I n Mchinji district of central Malawi. However, there has not been contemporary analysis and updated information on the levels of concentration of the chemical and biological parameters in the groundwater as well as indicative information on the amounts being reserved underground.

Mchinji is one of the nine administrative districts in the central region of Malawi in central Africa and has an area of 3356 square kilometers which represents 3.6% of the total land area of Malawi. Topographically it lies between 1200 and 1829 metres above sea level and has two distinct terrains. The hilly western part, consisting of Mchinji Mountain ranges with gentle slopes where almost all rivers found in the district originate from, and the rest of the district within a plain of mostly arable land which is generally drained by dambos and water ways. Mchinji experiences mean temperatures ranging from 17 to 20°C per annum. Lowest temperatures are experienced in June while high temperatures are experienced during the months of October and November. The district receives average rainfall of between 800 and 1230 mm per annum with the wet rainy season running from November to April (Mchinji District Assembly, 2008).

There has not been substantial research done in Mchinji district regarding the current levels of concentration of certain important chemical and biological parameters in the groundwater being consumed by the society. Current concentrations of iron, manganese, total dissolved solids, fluoride, electrical conductivity, pH, fecal coliform and fecal streptococci are largely unknown. There is also no indicative information available on the total groundwater reserves available as well as the amount of water extraction by the local population and the influences of land use and land cover (LU/LC) change on groundwater resources from 1992 to 2008, a time frame where data is available.

Given the foregoing, this thesis aims to investigate firstly, the current levels of certain groundwater chemical and biological concentrations. Secondly groundwater availability and variability from 1992 to 2008 were analysed. Land use and land cover change in Mchinji will also be examined to ascertain the possible impacts on the sustainable and integrated water resource management.

Literature Review

Certain chemical elements in groundwater are essential and beneficial to human health, but only in acceptable amounts or concentrations. These elements play an important role in metabolic processes of human beings. Intake of groundwater with high concentration of mineral elements such as fluoride has detrimental effects to human health. Gupta (1998) noted in a study in India that intake of fluoride exceeding its permissible level is toxic and had many adverse effects on human bone and teeth as it affected general body metabolism. Appelo et al. (2005) also observed that intake of excess fluoride causes painful skeleton deformations leading to a disease termed fluorisis which is common in India, Kenya and Ethiopia. Dental fluorisis is the most common manifestation of chronic use of water with high fluoride content, and has greatest impact in growing teeth, and children under seven years of age are particularly vulnerable. Dental fluorisis gives unsightly marks on the teeth (Murray, 1986). Gastro intestinal discomfort is also associated with consumption of groundwater with higher concentrations of fluoride.

In Madagascar, Rasolofinirina et al. (2004) concluded that high levels of manganese and iron in groundwater caused black and reddish precipitates which formed coatings on kitchen utensils. The manganese was also associated with the staining of clothes and also caused objectionable tastes in the water and beverages. Exposure to high concentrations of manganese is associated with toxicity to the nervous system and produces a syndrome that resembles Parkinsonism to the elderly (EPA, 2002). In the same study, it has also been documented that infants may be affected if baby formulas that contain manganese are prepared with water that also contains more manganese. The infants may get a higher dose since they are known to absorb more manganese and excrete less as opposed to the elderly (EPA, 2002).

In some parts of the globe, the natural arrangement of local ecosystems may depict increased concentration of particular chemicals that are toxic, for instance, the availability of arsenic in groundwater in some parts of Bangladesh and Chile is linked to the geology and environmental condition of the ecosystem. In addition the presence of naturally occurring excess chemical substances in groundwater such as iron and sulphates in Wisconsin, USA meant that groundwater is unusable (Tornes et al., 2007).

Groundwater with high iron content, more than the permissible concentrations, causes reddish stains on plumbing fixtures and clothing. EPA (1992) noted although iron does not pose a health risk at levels normally found in groundwater, its presence indicates deteriorating groundwater quality and may indicate other problems with the water quality which may cause adverse health effects. However, Tornes et al. (2007) concluded that iron and manganese concentrations in a well can fluctuate seasonally and vary with the depth and location of the well. The geology of the area also determines the concentration of manganese in the well.

Groundwater is less susceptible to bacteria pollution than surface water because soil and rocks through which groundwater flows, screen out most of the bacteria. However, bacteria occasionally find their way into groundwater, sometimes in dangerously high concentrations (Murray, 1986). Freedom from bacteria alone does not mean that the water is fit to drink. Murray (1986) further noted that many unseen dissolved mineral and organic constituents are present in groundwater in various concentrations. Some are beneficial while others may be highly toxic.

Groundwater availability and amounts are judged simply by the water table level (Anuraga, 2006). Water table fluctuations are caused either naturally due to climatic conditions such as drought and geologic setting, or through human activities caused by excessive withdrawals that exceed replenishable recharge (Kumar, 2002; Tornes et al., 2007). When extracting groundwater, it is essential to have some knowledge of the pattern of water table fluctuations if one is to make predictions on sustainability especially in the light of future climatic changes. Information on water table fluctuation is necessary to avoid depletion of groundwater resources and provides important scientific criteria for rational exploitation and regulation of groundwater resources (Mingmin, 1982). Yonghui et al., (2001) suggested that of all the factors influencing fluctuation in water table, rainfall is the major determining factor of groundwater availability and a practical plan must be prepared to maintain the balance of groundwater.

Human activities have been known to impact groundwater. Desertification may occur as a result of unwarranted vegetation clearing. These activities affect rainfall infiltration which in turn may affect groundwater reserves (Carter et al., 1995). Furthermore, agricultural activities are normally linked to be sources of nitrate concentrations in groundwater in some studies in USA, Poland, Canada, Uganda and Tanzania (Burginska, 1994; Kongolo et al. 1998; Taylor, 1998; Robbarts, 2006). The nitrate is believed to originate from inorganic fertilizers and herbicides which are applied to the agricultural fields near to groundwater sources. Chemical fertilizers, herbicides and pesticides that are not properly contained have entered the soil, infiltrated some aquifers and degraded the groundwater quality (Robbarts, 2006).

In aquifers around Lusaka in Zambia, several studies have proved that groundwater is polluted and that about 80% of the wells are contaminated chemically by elements like iron and nitrate from agricultural areas (Tammeaid et al., 1993). They further noted that once a pollutant has reached the water table only a certain amount of dilution can take place while the rest remain. These toxic chemical elements in groundwater pose significant health hazard to people. The most possible sources of these chemicals range from careless human activities to accidental or deliberate spills. Leszczynska et al., (2006) observed that apart from natural causes that result in contamination of groundwater, the main source of pollution is human activities. Generally, spills or leaks on the surface of soil are washed or leached and ultimately cause groundwater contamination.

Guidelines for appropriate measures towards sustainable groundwater management and utilization combines environmental, land use and land cover (LU/LC) change and social components. Collin et al., (2001) in a study in Israel identified the environmental effects as hydrology (water table), physiographic (slope), soils (permeability) and vegetation cover. Land use factors on the other hand include conservation and recreation areas, agricultural fields, residential areas and industrial or commercial areas. It is also necessary to consider social factors such as education level, people's income and political system. According to Collin et al., (2001), the combination of these factors enables the establishment of appropriate measures in the eco- hydrological systems to mitigate and modify presently destructive trends that may affect groundwater.

Groundwater and land use management require integration of plans and operations with needs of the society. Collin et al., (2001), in a related study in Israel noted that the attainment of the ultimate goal of groundwater resource sustainability requires an educated society with public backing for financial support and pollution control. Humans exert large scale changes on the terrestrial biosphere, primarily through agriculture. However, the impacts of such changes on the hydrological cycle are poorly understood. It also impacts the subsurface portion of the cycle by changing recharge and thrashing salts to underlying aquifers (Scanlon et al., 2005). Thick unsaturated zones contain a reservoir of salts that are readily demobilized under increased recharge related to LU/LC changes. Such a process potentially degrades groundwater quality and quantity (Scanlon et al., 2005). In essence sustainable land use requires quantitative knowledge of the linkages between ecosystem change, recharge and groundwater quality. The underlying factor in groundwater sustainability is resource planning (Tindimugaya et al. 1998; Verhagen et al. 1998; Kalua et al., 2006). Sustainable groundwater resources management and planning can be achieved in the long run only when land use is ecologically balanced with the requirements of the population.

Research Aim

The study firstly aims to investigate the levels of concentrations of certain selected chemical and biological parameters in groundwater in Mchinji district of central Malawi. Secondly, it also examines the amount of the groundwater reserves available for extraction through analysis of groundwater water table fluctuations over time. Thirdly, the study presents findings on human activities and their impacts on the groundwater resource and suggests possible rehabilitative measures for groundwater sustainability.

Key Research Objectives

The specific objectives of the study include:

i) Determining levels of concentration of certain chemical and biological elements in groundwater in Mchinji district such as iron, manganese, fluoride, pH, total dissolved solids, electrical conductivity, faecal coliform and feacal streptococci (bacteria).

ii) Assessing fluctuations of groundwater table between 1992 and 2008 and investigating whether there is a correlation with temperature, rainfall and evaporation.

iii) Examining human activities on the landscape and their possible impacts on the groundwater resource.

iv) Formulating guidelines to ensure proper groundwater sustainability and utilization.

v) Suggesting possible rehabilitative measures in order to return or maintain the groundwater acceptable state.

Research Methodology

The research adopted an intensive design as advanced by Sayer, (1992). It used multiple research techniques including secondary empirical data as well as data generated through interviews, questionnaires, focused group discussions and participatory observation. Triangulation (multi method) approach as advanced by Flowerdew et al., (2005) was adopted in order to scrutinize the full multidimensional, dynamic nature of the agency (people) and its interaction with groundwater resources and their interplay. Both quantitative and qualitative techniques are used in data collection.

Water samples from twenty randomly selected wells in the Mchinji District in central Malawi are analyzed to determine levels of concentrations of chemical and biological elements in the groundwater. Levels of iron, manganese, total dissolved solids, fluoride, electrical conductivity, pH, fecal coliform and fecal streptococci are measured. The samples were tested in the laboratory as highlighted below:

Iron Analysis: Colorimetric and Spectrophotometry method using UV/Visible Spectrophotometer is employed. This is a process in which iron is bound into a colour-forming complex with 1 to10 phenanthroline.

Bacteriological Analysis: Membrane filtration method is used. This is a process where a measured/known volume of water is filtered under a vacuum, through a cellulose acetate membrane of uniform pore diameter, usually 0.45 µm. Bacteria are retained on the surface of the membrane which was placed on petri dish containing a suitable selective medium in a sterile container and incubated at an appropriate temperature. For *Fecal coliform* type of bacteria, incubation was done at 44-44.5 ^{0}C for 24 hours and Fecal streptococci at 35-37 ^{0}C for 48 hours.

pH analysis/measurement: This is a measure of concentration or quantity of hydrogen ions in a solution. It is measured using a pH meter. The common features are a sensing electrode and a reference electrode connected to an electronic circuit that amplifies the voltages produced when the electrodes are immersed in a solution or water sample. The sensing electrode then senses the quantity of the hydrogen ions in the solution.

Electrical Conductivity (or specific conductance): This is measured using a conductivity meter. This measures the ability of water/solution to conduct current and depends on the concentration of ions in the solution.

Nitrate Analysis: This is done using the Spectrophotometry method. This is a process where concentration of nitrate is established after the sample develops colour that is measured at specific wavelength.

Chloride Analysis: Titrimetric and Colorimetric method using silver nitrate is employed. In this method, chloride is determined in a neutral or slightly alkaline solution by titration with standard silver nitrate, using potassium chromate as indicator. Silver chloride was then quantitatively precipitated before red silver chromate was formed.

Fluoride Analysis: This used sodium 2- (parasulphophenylazzo-) -1.8-dihydroxy-3.6-nephthlene disulphonate) (SPADNS) colorimetric method. This method is based on the reaction between fluoride and zirconium-dye. Fluoride reacted with the dye, dissociating a portion of it into a colourless complex and the dye. As the amount of fluoride increased, the colour produced becomes progressively lighter.

Analysis of the water samples was done at the Malawi Central Laboratory. Water samples were analysed within 24 hours of collection. This is a scientific requirement as it avoids contamination of the water samples before laboratory analysis. The results from the samples taken in 2008 were compared with those obtained soon after construction of the wells (1992). The analysis also included both bacteriological and physical analysis of the samples. Physical analysis involved observation of water turbidity (due to unavailability of a measuring device such as sighting disk), colour, temperature, taste and odor as these have also a significant bearing of water utilization.

The conditions of the selected parameters will be compared with both World Health Organization (WHO) drinking water guidelines and Malawi Government drinking water standards. These enforceable standards for drinking water contaminants are established to protect the public against consumption of drinking water that present a risk to human health. In short they set maximum allowable levels of contaminants in drinking water.

In determining the groundwater availability, the Water Table Rise Method as advanced by Anuraga et al., (2006) is used to assess the trend of groundwater fluctuations in the randomly selected wells during the period from 1992 to 2008. Temperature, rainfall and evaporation data are used to determine if there was any correlation between groundwater table fluctuations data, temperature, rainfall and evaporation between 1992 and 2008. Statistical regression analysis is used to determine the correlation.

Scanlon et al., (2005) observed that vegetative cover depletion has been known to have tremendous effects on groundwater. As such it is of paramount importance to trace its amount, extent, rate and perhaps its causes if interventions can be done. In recent times, to undertake such Land Use and Land Cover (LU/LC) analyses Geographic Information System and Remote Sensing have been found to be quite important integral tools. It has been proven that these tools are fast in terms of operation and relatively easy and inexpensive to collect data, apart from being relatively accurate and efficient as regards LU/LC cover assessment. In this research therefore, data on human impacts such as through forestry cover degeneration or depletion was collected. A variety of approaches can be used to assess the impact of land use and land cover change (LU/LC) on subsurface hydrology as advanced by Scanlon et al., (2005). It was observed that the most direct approach is to relate LU/LC change to water table fluctuations. In principle, variations in groundwater chemistry over time could provide information on the impact of LU/LC changes on water quality so much so that water table fluctuations and trends in groundwater solutes could provide information on regional spatial and temporal response to LU/LC changes.

Satellite images of different time series were sourced and analyzed to verify land use and land cover change. Furthermore, data of portion of land being used for farming, farming practice, methods and type of fertilizers being applied was collected. Land use and land cover change Landsat Thematic Mapper™ satellite images over time series of 10 years of precisely between 1989, 1999 and 2009, with resolutions of 30m, 30m and 15m respectively, in Mchinji district is used. The rate of deforestation and its driving factors are the primary focus of this objective. Land cover change is defined as the conversion from one land cover category to another (Krishna et al., 1996). This type of phenomena results in a change of reflected Electromagnetic Radiation (EMR) values representative as a surrogate of the Earth's surface which can be remotely sensed.

Within the scope of this research, the concept behind the process of mapping land cover change over time begins with mapping 1989 Landsat TM satellite imagery and it was followed later by mapping of the 1999 Landsat TM imagery and finally 2009 ETM+ imagery. This is to examine the land cover change between 1989, 1999 and 2009. Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times (Alwashe et al., 1993). In interpretation of the images ArcGIS 9.3 was used for the actual analysis while ERDAS 9.1 is used for data processing, georeferencing, image mosaicing, image subsetting, image enhancement/sharpening and classification. These procedures are explained below.

Data processing and analysis involves activities ranging from raw data processing, manipulation and analysis. This included: importing raw data and geometric correction, image enhancement, subset, classification, digitizing and analysis. Analysis was done through comparing the change in area coverage classes. Layer stacking started with importing necessary bands. This was done to bands 4/3/2 in all the images. The band combination was done for the purpose of image visualization. The spectral response of Band 2 is in the visible portion of the electromagnetic spectrum that corresponds with green light. The spectral response of Band 3 is in the visible portion of the electromagnetic spectrum that corresponds with red light. The spectral response of Band 4 is in the Near Infrared (NIR) portion of the electromagnetic spectrum.

Georeferencing was done to rectify any error introduced into an image by geometry of the curved earth's surface and the movement of the satellite. The georefrencing assists to put image elements in their proper planimetric (X and Y) positions. The 2009 Landsat image was georeferenced using points collected by Map60 GPS. The 2009 image was used to georeference the other two sets of images. The datum used was UTM, WGS 1984. Image mosaicing and subsetting on the other hand involved pairing of images for both years. The pairs for each year were mosaic to produce one image. Subsets were done using vector data (boundary) of the study area. The enhancement of images aimed at improving appearance of the images. Sharpening was done to improve resolution especially to 2009 ETM+ image. It was done using panchromatic band 8 to give it a 15m resolution.

Classification of the images used spectral signatures of pixels while unsupervised classification was done to match the spectral classes in the data to the information of classes of interest. The study area was grouped into five classes. False color composite was applied to classify Digital Number Values (DNV) was assigned to specific colors thereby increasing the contrast of particular DN values with the surrounding pixels in an image. After ground truthing supervised classification was done, the five classes were named High density forest, Medium density forest, Low density forest, Degraded forest and Agriculture/settlement.

On screen digitizing of the land cover classes into vector format was applied to all the images where classes were presented in polygon form and areas were calculated for each class. To detect land cover change of Mchinji from 1989, 1999 to 2009, areas of the land cover classes were calculated for each image for comparison. Rate of change per year was calculated as follows.

Percentage Area of Class = AC/AT * 100

ΔC = Area (%) Recent Year – Year (%) Old Year Rate = $\Delta C/\Delta P$

Where:

AC = Area of the Cover Class

AT = Total Area

ΔC = Cover Change

ΔP = Time Difference

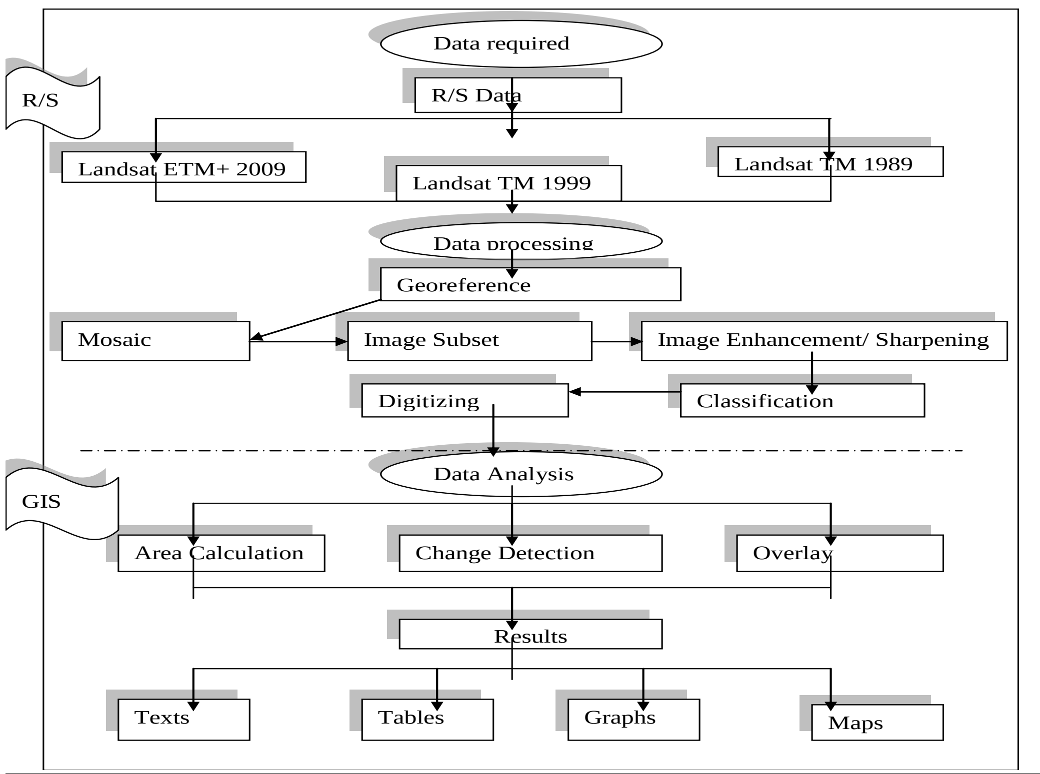

Figure 1: Flowchart for imagery interpretation

Interviews were conducted with personnel from the water affairs department and water users in an effort to collect data on whether monitoring of water quantity and quality was being conducted or not. The importance of groundwater monitoring is that among other issues it assists in tracking changes in groundwater levels to help decision makers better understand long term sustainability of an aquifer as a source of water supply and make informed choices and decisions. William et al., (2007), documented that groundwater monitoring provides an idea on groundwater contamination such as identification of groundwater contaminants, their levels and their sources. Groundwater monitoring is also important in that it assess the effects of climate change on groundwater levels and helps timely warnings, declarations and mitigation measures.

The focused discussions also attempted to find out the knowledge that the water users and the relevant stakeholders have on water quality and quantity issues. The people that were interviewed included users of the wells as well as officials from the government departments. In addition, questionnaires were used to collect data on whether the users perceive groundwater as a renewable or non-renewable resource including their knowledge in groundwater issues. Participatory observation was another major research technique that was used in this research. Questionnaires and guidelines for focused group discussions that were used in this research appear in the Appendix A, Appendix B and Appendix C.

In the quest of formulation of appropriate water policies, an appraisal of existing water policies was done in an attempt to find their strengths, weaknesses and shortfalls. Information from water users' strategies that are in place on groundwater monitoring was sought with the aim of establishing the level of their awareness on dangers of groundwater contamination. Suggestions to manage groundwater effectively will be made to maintain the sustainability of groundwater sources in Mchinji district.

Research Location

The research location is Mchinji administrative district in central Malawi. In Mchinji a groundwater development project was implemented in 1992. It comprises 300 wells which were constructed with assistance from the Japanese Government as part of a grant aid. This location for this study was selected largely because the wells were professionally constructed and that all the necessary procedures were followed during construction. Furthermore, necessary borehole construction and most water quality analyses were done in 1992 and the data were carefully recorded and are still available for use. It, therefore, provides a good basis for comparison of groundwater status during construction time and present (2008). The area is also undergoing intensive maize and tobacco farming by the local communities thus providing a means of assessing what pressure is being put on groundwater resources.

Research Significance

The research will bring awareness about the chemical and biological concentrations in the groundwater being consumed. Current concentration levels of certain important elements like iron, fluoride, manganese, total dissolved solids, pH, faecal coliform and fecal streptococci which have detrimental effects if consumed in excess will be known. The trend of groundwater reserves during the observation period as well as the impact of human activities on the landscape will be investigated. This will ensure integrated groundwater resource management, sustainability and proper utilization of the resource in Mchinji district as the findings will generate recommendations and remedial measures.

Structure of the Thesis

The thesis is structured as follows: chapter one comprises the introduction to the study, literature review, research aim and objectives, research methodology, study location and significance of the study. Chapter two includes a detailed analysis of the study area and an outline of its geography in terms of physical and human characteristics, and also governance and legislation of water resources in Mchinji and Malawi as a whole. The data from the research is presented and analyzed in chapter three. Chapter four covers discussion and suggestions of research findings while chapter five highlights conclusions and recommendations of the research.

CHAPTER II

THE STUDY AREA

Introduction

This chapter gives a contextual description of Mchinji district. The description includes the location, climate, soils, vegetation, topography, population, economy, land use and environment of the study area. These selected sectors are strongly linked to the factors that influence the availability and status of groundwater resources. The chapter also presents an overview of water resources in Malawi as regards its availability, governance and policy framework in the course of attempting to attain an integrated water resources management. This ensures availability, sustainability and quality of the water resources.

Description of the study area

This study is based in Mchinji district of central Malawi. Mchinji is one of the nine administrative districts in the central region of Malawi. It is 335,600 hectares in size. Mchinji shares borders with Kasungu district to the north, Lilongwe district to the east, and Zambia to the West and Mozambique to the south (Fig. 2). The district headquarters is located along the main road that connects Lilongwe and Zambia.

Mchinji district is 110 kilometres away from Lilongwe City and 10 kilometres away from the Zambia border.

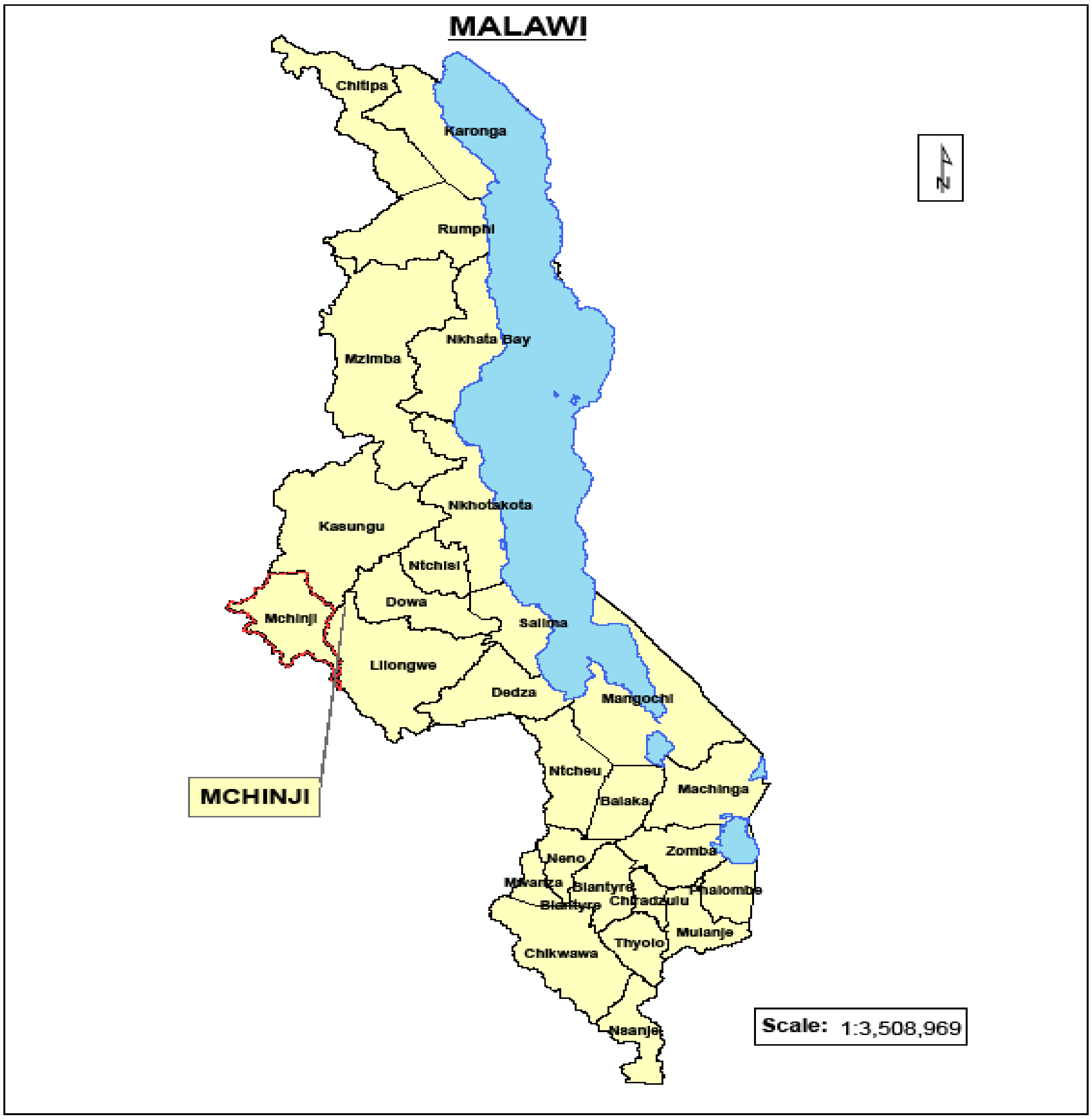

Figure 2: Map of Malawi showing Mchinji District

Physical Characteristics

Mchinji district lies between 1,200 and 1,829 m above sea level. Geomorphologically, Mchinji district has two distinct terrains. The hilly western part, consisting of Mchinji mountain ranges, has gentle slopes that are 1,600 to 1,830 m above sea level. Almost all rivers found in the district originate from these hills (Fig. 3). The remaining part, which forms the biggest part of the district, lies within a plain of mostly arable land. Dambos and waterways drain the plains into Bua and Rusa rivers (Mchinji District Assembly, 2002).

Geologically Mchinji lies in the basement complex which is composed of the Precambrian metamorphic and igneous rocks. This Precambrian rocks consists of various lithologies and structures such as gneisses, quartzites and marbles (Geological Survey, 1968). The stratigraphy of the area consists of reddish latosols at the top then unconsolidated clays that are characterized by heavy collapsing when being penetrated. The unconsolidated generates into weathered granitic rock formations where most of the reliable aquifers are located, and then fresh granite that forms the bed rock.

According to Mchinji District Assembly (2002), the climate of Mchinji is characterized as having the hilly areas which are generally cool and wet. Mean annual temperatures range from 17^0C to 19^0 C. Lowest temperatures are experienced in June while highest temperatures are experienced in the months of

October and November every year. In contrast the plains are generally warm and dry. Mean annual temperatures vary from $19^{0}C$ to $21^{o}C$.

Like many areas in Malawi, Mchinji has two distinct seasons. The dry season runs from May to October while the wet/rainy season is from November to April. The hilly areas receive average rainfalls of between 1000 mm and 1230 mm per annum. The plains receive rainfall ranging from 800mm to 1030mm per annum (Ministry of Natural Resources, 1996).

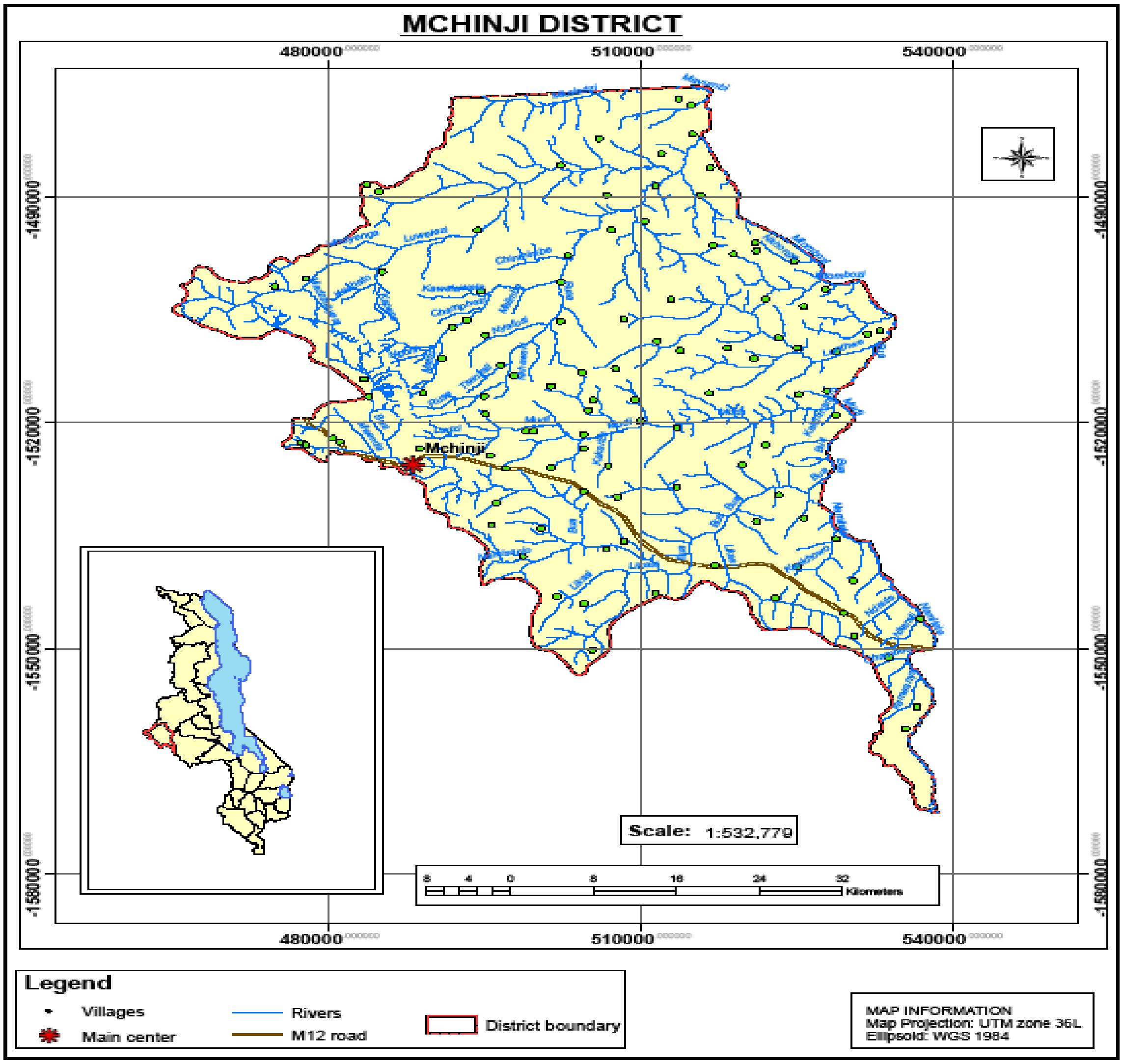

Figure 3: Map of Mchinji District showing selected features

Analytical synopsis of the soils in the study area shows that there are four main soil groups as described by Moyo et al. (1993). The latosols are red to yellow, leached acid soils in which water movement within the profile is predominantly downwards. They occupy freely-drained areas, mainly on the gently-sloping plains but also in some steeply dissected hills. The calcimorphic soils are grey to greyish brown. They occur on depositional plains with imperfect drainage. The hydromorphic soils are black, grey or mottled and waterlogged for all or part of the year (Moyo et al., 1993). The fourth group comprises lithosols that are shallow or stony soils and regosols that are immature soils developed from sand.

In terms of biogeography Mchinji district lies in the tropics. The vegetation is typical savanna woodland with *Brachystegia* as the dominant species (Mkanda, 1995) alongside natural growing grass. The different vegetation communities are a habitat to diverse wildlife. Crops such as maize, tobacco, groundnuts and beans form part of vegetation during the growing farming season.

On fluvial drainage, Mchinji district has dambos and waterways that drain the plains into Bua, Namitete and Rusa rivers. These are the most important sources of perennial streams. Most of the smaller river channels are seasonal. Mchinji Agriculture Department (2009), noted that Dams and irrigation are not highly pronounce in Mchinji. However small scale irrigation is done along the banks of perennial river streams during the dry season.

Human Characteristics

Mchinji has a population of approximately 325,000 (National Statistical Office, 2002). The district population density of 97 persons per square kilometer is lower than the national average of 105 persons per square kilometer. The population is fast growing at an average growth rate of 2, 5% per annum. This trend is attributed to a number of factors which include high total fertility rate of 7,6 compared to national average of 6,5. The average number of persons per household is 4, 5 (Mchinji District Assembly, 2002).

Contrary to the national averages, distribution of the district population by gender reveals that there are more males than females (Malawi National Statistical Office, 2002). The sex ratio, defined as the number of males per 100 females is 102 compared to national average of 96,1 (Malawi National Statistical Office, 2002). This implies that either more males are born or more males than females migrating into the district to work especially in the estates or as businessmen. It appears that Mchinji is experiencing more immigration than emigration (Mchinji District Assembly, 2002). The district has plenty of tobacco estates where people from other districts come to work as casual workers or tenants. In addition, other ethnic groups move to the district to conduct business (Mchinji District Assembly, 2002). More importantly, the district shares borders with Zambia and Mozambique so cross border migration can be expected.

Mchinji Agriculture Department (2009), gives total land size of Mchinji district to be 335,600 hectares. There are three major land tenure systems, namely customary, public and leasehold land. About 50% of the total land in Mchinji is held under customary tenure, of which 6% is under community managed forests (Mchinji Agriculture Department, 2009). Traditional leaders who include chiefs and village heads are the custodians of the customary land. They control and distribute land to household members and relatives inherit the land through matrilineal or patriarchy lineage. Mchinji land holding size per household varies from area to area but on average, a household owns about 1 ha (District Assembly, 2002). It is also common to find household owning pieces of land in different locations. This land fragmentation is the result of growing family sizes. The community forest reserves are currently under threat of deforestation. There is increased expansion of estates, increased small holder cultivation due to the growing populations and increased utilization of fuel wood and charcoal as income generating activities (Mchinji Forestry Department, 2002).

Public land constitutes about 6% of the total land in Mchinji district (Mchinji District Assembly, 2002). The Malawi Government designated this land for construction of public utilities such as roads, hospitals, schools, government offices and forest reserves (Mchinji District Assembly, 2002). Private leasehold land accounts for about 15% of the land in Mchinji district. Individuals or companies own land under leasehold arrangement with the Malawi Government. About 45% of the land which translates to about 27,796 ha of leased land comprises tobacco estates. The rest of the land is built up area and used for residences and business premises (Mchinji District Assembly, 2002).

It should be noted that according to the agricultural land classification by the Ministry of Agriculture and Food Security (2002), Mchinji district has 222,455 ha of arable land out of the 335,600 ha and that only 208,500 ha is currently under cultivation. Forests and woodlands cover some 42,551 ha. Out of this 21,385 ha are community forests and customary land while 21,166 ha are under Malawi Government managed forest reserves (Mchinji Forestry Department, 2002). Mchinji district has government forests, community forests and tree plantations mainly owned by big private estates (Ministry of Natural Resources, 1996). The natural forests have different indigenous tree species and some *brachystegia* species. However, the natural forests have been diminishing since 1960s and conspicuously in the 1970s (Ministry of Natural Resources, 1996) when the district hosted Mozambican refugees following internal strife in Mozambique. At that time many forests were cleared for the construction of houses and cultivation of fields (Mchinji District Assembly, 2002).

Mchinji district has two major forest reserves under government control. The Mchinji forest reserve, covering some 19,166 ha, is in the western part of the district (Mchinji Forestry Department, 2002). It is within the Mchinji hills and forms the border between Malawi and Zambia. Bua, Ludzi, Luweredzi and Rusa rivers originate from this forest reserve. The other is the Thyolasanu forest reserve that is an extension of Dzalanyama forest reserve from Lilongwe district. It covers approximately 2000 ha (Mchinji Forestry Department, 2002). The forest reserve forms the boundary between Malawi and Mozambique, along the southern part of Mchinji district. Namitete River which forms the boundary between Lilongwe and Mchinji districts originates from this forest reserve. This forest reserve suffered greatly with the influx of the Mozambican refugees (Mchinji Forestry Department, 2002).

Most of the community forests under the customary land have been depleted (Ministry of Natural Resources, 1996). Today there are few and are associated with graveyards. However, there are still some well managed village community forests in Mchinji district (Mchinji District Assembly, 2002). The National Policy on forestry (Ministry of Natural Resources, 1996) aims at sustainable utilization of forestry resources and in addition, it emphasizes to the enhanced role of communities in the management of natural resources. A concept of village natural resource management committees has been introduced in the district and is being adopted (Ministry of Natural Resources, 1996).

Some of the major activities leading to deforestation are charcoal burning, tobacco curing, opening of new estates, brick burning for house construction, uncontrolled bush fires during hunting and increased use of fuel wood (Mchinji District Assembly, 2002). In particular, the increasing dependence on forestry products as a source of income generating activities is currently contributing significantly to the problem of deforestation. World Bank (1992) documented that the negative impact of the deforestation has been tremendous and reflected through increased sedimentation in rivers, increased localized flooding, soil erosion and loss of fertility, lack of fuel wood and difficult access to construction materials (Mchinji District Assembly, 2002).

The tobacco estates are major users of trees in the district and have contributed significantly to deforestation of natural forests (Mchinji Forestry Department, 2002). Estate demands for fuel wood reached its peak in the 1990s thereby necessitating the Malawi Government to introduce measures to address the problem. The measures included a fee levied on the use of indigenous trees (Ministry of Natural Resources, 1996). Tree plantations mainly appear in estates which are privately owned. They are mostly planted with *eucalyptus* and *gmelina* species. This is to replace the indigenous trees which have been depleted in the estates and farms.

The tourism sector aims at optimizing usage of Malawi's tourist assets and attractions to increase market share wherever possible and to create favorable and positive image of Malawi within and outside the country (Ministry of Tourism, 2002). To support this Mchinji district offers a number of activities and services such as provision of tourism information, promotion of tourism businesses, conducting health and safety inspections on tourism facilities and promotion of community participation in tourism activities (Mchinji District Assembly, 2002). There are a number of tourist attractions in Mchinji district such as old buildings, cultural attractions, panoramic view of mountains and wood carvings. On parks and wildlife, Mchinji district has a good number of wild animals that include antelopes, hyenas, hares, hippos, snakes etc. However, settlements, cultivation, indiscriminately hunting and uncontrolled bush fires threaten wildlife and game. Some of the tourist attraction centers such as mountains are covered by vegetation adding to the scenic view of the sites (Ministry of Tourism, 2002). Clearing the vegetation affects both the tourism and the water sectors hence harmonization of the sectors has direct effect on the quality and quantity of the water (Ministry of Irrigation and Water Development, 2005).

The Ministry of Agriculture and Food Security (2002) describes Mchinji as reliant on rain fed agricultural main cropping system (maize and tobacco), and accounts for most of the crop production. It is practiced from October to March since this is the period that Mchinji receives most of its rainfall every year. Small irrigated agriculture is practiced from April to October along the banks of some streams and dambo areas. Crops grown in the irrigated farming include maize, beans, potatoes, peas, cabbage, tomatoes and onions (Ministry of Agriculture and Food Security, 2002). Most farmers practice monocropping in which crops are grown on separate pieces of land (Ministry of Agriculture and Food Security, 2002). This system of farming occurs especially where there is plenty of land. Inter-cropping on the other hand is common where land is scarce. Some farmers are now practicing agro forestry in order to enhance and improve soil fertility (Ministry of Agriculture and Food Security, 2002). Major tree species used for the improvement of soil fertility include *Sesbania Sesban, Tepphrosia Vogelli* and *Senna Siamea* (Mchinji Department of Agriculture, 2002).

Agriculture is the main economic activity for Mchinji district. Word Bank (1992) observed that over 90% of the population depends on agriculture for livelihoods, incomes and employment. The agricultural target as advanced by Ministry of Agriculture and Food Security (2002) aims to promote economic growth by raising farm incomes, employment and household food security. These, while focusing on increased agricultural productivity, commercialization, diversification and sustainable use of natural resources, are achieved through the development of partnerships with and promotion of private sector investment. However, currently, the district faces a number of challenges such as food shortages during some parts of the year (Mchinji Department of Agriculture, 2002).

By January each year, about 50% of the farmers will have run short of maize which is the staple food from their own production and as a result they lack food security. This is because most households have no stable incomes (World Bank, 2002). Major causes of the food insecurity include low food production, low livestock production and poor nutrition planning among farmers. According to Mchinji Department of Agriculture (2002) crop yields are generally low for many subsistence farmers due to limited access and limited use of expensive modern farm inputs such as fertilizers, seed and pesticides. There is potential for dambo production and irrigated agriculture but such opportunities have not been fully explored since production is not on a larger scale. High livestock mortality, poor feeding, poor housing, poor breeding practices all affect livestock productivity in Mchinji district (Mchinji District Assembly, 2002).

Mchinji Department of Agriculture (2002) observed that land degradation and soil erosion are common due to bad farming practices such as mono- cropping and over cultivation. Fewer farmers have access to agricultural extension services due to staffing constraints. The agricultural extension worker ratio to farmers is very high in which case one agricultural extension worker is responsible for a larger group of farmers. Consequently, there is little adoption of modern agricultural technologies and practices.

Agricultural production is undertaken at smallholder and estate levels. According to Mchinji District Assembly (2002) smallholder production, which is basically subsistence, accounts for 167,731 ha. There are over 100,000 farm families in the smallholder sector. Land holding sizes are small, generally less than 2 ha. Estate farming on the other hand is highly commercial. Commercial farming is characterized by larger land holding sizes and better management practices than the smallholder farming (Mchinji Agriculture Department, 2002). There are over

2,000 estates which together account for 91,329 ha (Ministry of Agriculture and Food Security, 2002). Major smallholder crops produced in Mchinji include maize, groundnuts, burley, tobacco, cassava, sweet potatoes and beans (Mchinji Agriculture Department, 2002) and these crops cover over 90% of the cropped land. It should be noted that crop production in Mchinji district has varied greatly over the years (Ministry of Agriculture and Food Security, 2002). In particular, there has been great variation in cropped area. Some crops have enjoyed remarkable growth while others have experienced significant decline. Major factors have included poor rainfall, inability to access better varieties and other inputs and lack of markets (Ministry of Agriculture and Food Security, 2002).

Groundwater Resources

Groundwater resource occurrence in Malawi is associated with three major aquifer types; basement complex, alluvial and escarpment (fault zones) (Ministry of Water Development of Malawi, 2001). According to Geological Survey of Malawi (1968), Mchinji district falls under the Precambrian weathered basement type of aquifers. The extensive but lower yielding weathered basement aquifer of the plateau area is where most of Mchinji district lies. The weathered zone is commonly 15 to 30 m thick and the average yield in the weathered zone of the basement complex lies in the range of 1 to 3 litres per second (Geological Survey, 1968).

Alluvial aquifers are fluvial and lacustrine in nature; and are highly variable in character both in vertical sequence and lateral extent. According to Geological Survey (1968) these occur in several basins which, apart from Lake Chilwa areas, are all located along the rift valley floor of Karonga Lake Shore, Salima - Nkhotakota Lake Shore, Upper Shire Valley and the Lower Shire Valley. Most lithological records from boreholes give little detailed information about the geological successions (Geological Survey, 1968).

In Mchinji just like many areas in Malawi the overall impression is that clays and laterites usually dominate the sequence although in many localities there is significant thickness of poorly sorted sands. According to Ministry of Water Development (2001) the sedimentary environments likely to produce the highest groundwater yields are buried river channels and littoral zones of the lake shore where the deposits are usually coarse grained and well sorted. Yields of up to 20 litres per second in the alluvial aquifers have been obtained (Ministry of Water Development, 2001).

Estimates of groundwater recharge in Malawi have been made through the analysis of flow hydrographs, groundwater level fluctuations, flow nets and catchment water balances (Ministry of Water Development, 2001). On the basis of the river hydrographs, the annual recharge is estimated at 15 to 80 mm to weathered basement aquifers where Mchinji lies, and at 3 to 80 mm to alluvial aquifers. In the alluvial aquifers, the recharge will also occur by seepage from the river beds where these are significantly permeable. On the basis of 15mm to 80 mm, Kalua et al., (2006) calculated the average recharge over Malawi to be about $1414x10^6 m^3$ per year.

On a national scale, groundwater quality is generally acceptable for human consumption though variations do appear in localized areas. The Geological Survey of Malawi (1968) observed that the basement aquifers are characterized by water which is dominated by alkaline earth in the cation group and by the carbonates in the anion group. Total dissolved solids content values are generally less than 1000 mg/l and typically around 350 mg/l. On the other hand groundwater in the alluvial aquifers is more mineralised than in the basement aquifers (Geological Survey, 1968) but in general water from deeper boreholes is of much better quality than water from shallow wells.

The inferior quality of water drawn from shallow wells according to Kalua et al. (2006) is a direct result of the following factors:

i) shallow groundwater tables usually less than 2m due to seasonal fluctuations bring them close to the ground surface where water can easily get polluted;

ii) fecal contamination since dambos are extensively used for grazing and watering of livestock all year round, and;

iii) poor siting of water points since some dug wells are sometimes located very close to traditional water polluting sources such as pit latrines which are always open and invariably grossly polluted.

Ministry of Water Development of Malawi (2006) describes the existing and potential environmental problems that the groundwater resources faces are in the following three areas:

i) Local contamination of groundwater by arsenic compounds from for example cattle dip tanks, agro-chemicals and earth latrines;
ii) Overexploitation of the groundwater resources
iii) Presence of saline ground water intrusions

Even though groundwater resources appear abundant; the economically exploitable resources are limited. The existing aquifers are not extensive, but disjointed with characteristic relatively low yields and in most cases these aquifers are highly localized (Kalua et al., 2006). Water resources availability, exploitation and utilization are governed by an enabling policy and legislative framework in Malawi.

<u>Policy and Legislative Framework</u>

A number of policies and respective laws have and are being revised and updated in Malawi to ensure that they reflect the central policy of national economic development. The latest is the National Water Policy of Malawi of 2005 with its subsequent second edition of 2007. The review is also targeted at consolidating Malawi's position and commitment in regional and international organizations including Southern Africa Development Community (SADC).

The sectoral policies and legislation are being updated and developed in different sectors of the economy including agriculture and irrigation, energy and mining, environmental management, water resources management, trade and industry, fisheries, forestry, parks and wildlife and transport and communication. A co-ordination and harmonization of policies approach has been undertaken to ensure sustainable and equitable water resources management (Ministry of Irrigation and Water Development, 2005).

The Government of Malawi is currently implementing its National Water Policy of 2005 whose overall goal is sustainable management and utilization of water resources. The Policy also shapes the direction to provide water services of acceptable quality and in sufficient quantities that satisfy requirements of every Malawian and enhance the country's natural ecosystems. The goal of this policy for rural water supply is to achieve sustainable provision of community owned and managed water services that are equitable, easily accessible and affordable to individuals in rural communities for socio-economic development. The policy advocates community-based, gender sensitive and demand driven approaches that take into consideration cross-cutting issues of gender, HIV/AIDS, human rights and environmental management among others. It also encourages active participation of Non Governmental Organizations (NGOs) and Local Service Providers (LSPs) (Ministry of Irrigation and Water Development, 2005).

The Malawi Government has also produced a Sanitation Policy (Ministry of Irrigation and Water Development, 2007) whose overall objective is to compliment the National Water Policy and achieve universal access to improved sanitation, improved health and hygiene. The specific objective for rural areas is to promote hygiene practices, increase access to improved sanitation and promote recycling of wastes for environmental protection and wealth creation.

The Sanitation Policy (Ministry of Irrigation and Water Development, 2007) has suggested proactive strategies for promoting hygiene and providing improved sanitation facilities in Malawi. The main roles suggested for Non Governmental Organizations (NGOs) include ensuring integration of water supply, improved sanitation and hygiene education in all water supply and sanitation programmes; assisting in mobilization and securing funding for rural and low income urban and peri-urban communities for water and sanitation projects; and assisting in community sensitization on water, sanitation, and catchment management and conservation among others (Ministry of Irrigation and Water Development, 2007).

The Government of Malawi also adopted a Decentralization Policy (Ministry of Local Government, 1996) and enacted its enabling legislation, the Local Government Act of 1998, which empower District Assemblies to plan and manage their socio-economic development activities, including water resources management issues at local assembly level, to increase efficiency and effectiveness in service provision and delivery. The policy (Ministry of Local Government, 1996) has integrated government agencies at the district and local levels into one administrative unit through the process of institutional integration, manpower absorption, composite budgeting and provision of funds for decentralized services. It has also diverted the centre of implementation responsibilities and transferred these to the local assemblies. The Policy has also assigned functions and responsibilities to the various levels of government and aims at empowering local communities to take full responsibility of their development agenda including water resources management issues (Ministry of Local Government, 1996).

In tandem with the National Water Policy of Malawi, the Malawi National Sanitation Policy and the Malawi Decentralization Policy legislative framework, government of Malawi has recently launched the Malawi Growth and Development Strategy (MGDS), (Ministry of Economic Planning and Development (2007) whose overarching objective is to enhance rapid economic growth while at the same time improving service delivery. Water and sanitation are among the key sectoral measures and crosscutting issues to be addressed. The MGDS targets for the medium and long-term are consistent with the Millennium Development Goals (MDGs). For water supply, the MDGs target is to halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation. Full coverage is to be achieved by 2025 (Ministry of Economic Planning and Development, 2007).

In the water sector, policy and legislation review is expected to set a favorable environment to fulfill the vision of the country and international organizations in particular the SADC. The overall vision of the Ministry responsible for water affairs is to ensure that there are always adequate water resources for all Malawians (individuals or entrepreneurs) to use and contribute towards economic prosperity and human development, on a sustainable and equitable basis for present and future generations. According to the Ministry of Irrigation and Water Development (2005), the strategies for achieving this include formulating and implementing programmes on:

(a) Water resources conservation and infrastructure development that create sustainable and equitable utilization of water resources by all sectors of production and services with emphasis on poverty alleviation and protection of investments.

(b) Strengthening and extension of rural water supply services to the country's population with access to potable water;

(c) Sustaining and improving urban water supply and sanitation through creation of favorable environment for financial investments and water resources utilization; and,

(d) Institutional and capacity building for integrated water resources management.

The major constraint in the Policy and legal framework is the lack of a comprehensive updated water resources management strategy. These are necessary for reviewing and amendment of the existing relevant laws and make them supportive of integrated water resources monitoring, assessment, planning, development, conservation and protection strategies. Once these have been updated and adopted and necessary institutional arrangements made, a favorable environment for multi-purpose and multi-sectoral water resources developments should be created. This will further promote sustainable and equitable utilization of water resources for the advancement of economic recovery and prosperity in water supply and sanitation, agriculture and irrigation, energy and hydro-power, transport and navigation.

A review of the opportunities, constraints and future direction of sectors, gives a guide to the establishment of integrated water resources approaches in Malawi (Food and Agricultural Organization, 2006). The establishment of an integrated water resources management approach is a major breakthrough to the sustainable exploitation, utilization, monitoring of the water resources in Malawi and Mchinji in particular. The integrated approach will entail that all the necessary key players in the multi- dimensional water sector are aware of their required roles and responsibilities in managing the water resources.

Water Supply and Sanitation

Although the Government of Malawi has made tremendous efforts in the provision of water supply to the community; the indication according to the Ministry of Irrigation and Water Development (2005) about 65% of the whole population has access to potable water. The situation is affected by the non-functionality of some of the water points where it is believed that at any one time about 30% are broken or not working. There is still an opportunity that regardless of the existing water and sanitation situation the government of Malawi can achieve the 84% target (Ministry of Economic Planning and Development, 2002) as well as Millennium Development Goals (MDGs) by embarking on a country wide water supply and sanitation program. The establishment of an integrated water resources management will imply that groundwater exploitation, utilization and monitoring for both water quality and functionality of the wells will be guaranteed.

Rural Water Supply

The country has more than 33,000 boreholes, 5,600 shallow wells and 66 gravity piped water supply schemes (Kalua et al., 2006). These rural water supply systems cover about 65% of the population with access to potable water. It is the Government's intention to improve this percentage and achieve 84% coverage and halve population without access to potable water supply by 2015 as a milestone for the achievements of the water related MDGs (Ministry of Irrigation and Water Development, 2005). The problems of operation and maintenance and depletion of water resources has been noted as a major concern in achieving a higher percentage of coverage in rural water supply in Malawi and Mchinji district in particular (Ministry of Water Development, 1999). The government is implementing a number of strategies to address this. One of these is the community based management approach for rural water supplies that empowers the community to operate, maintain and repair their own water supply systems. Once the facility is constructed it is handed over to a well-trained community with the belief that the trained community can on their own maintain, repair and operate the water facility to the best of its capacity (Ministry of Water Development, 1999).

The government is in the process of developing feasible programmes of integrated groundwater development project proposals for all areas that could not be supplied from gravity piped schemes. The strategy is to prepare readymade project proposals that cover the entire country and can be funded and implemented whenever funds are available. New approaches and technologies are going to be considered. These include development of deep and high yielding boreholes that can be pumped and reticulated to various neighboring villages. The approach is also expected to reduce water being contaminated from villages as reticulation would allow boreholes to be drilled away from the settlements and other polluting sources (Watipatsa Consulting, 2006).

In Malawi it is illegal just to utilize water resources of considerable amount for whatsoever purposes without obtaining permission in the form of a water right from the Water Resources Board which is an arm of the Ministry responsible for water affairs. Water resources are considered a national property and asset (Malawi Parliament, 1999). This ensures that only water of designated amount, whether surface or groundwater, is extracted. In addition failure to comply with the extraction of the designated amount of water resources is tantamount to strict penalties inflicted upon the offenders. However, from discussions with technicians from Water Resources Board, enforcement has always been a major challenge especially as compounded with poor monitoring on how the water resources are utilized country wide. This is compounded by shortage of staff to monitor activities on the ground and inexistence of legally binding laws (to support the Water Works Act, Malawi Parliament, 1999) to extend punitive measures to the offenders coupled by lack of civic education on the principles of integrated water resources management to the people. The water sector is attempting to address this problem through the sector's implementation plan (Ministry of Irrigation and Water Development, 2006).

In Mchinji district just like other areas, especially in the peri-urban town centres, the strategy that has been adopted is to supply water through adequate groundwater sources so that water can be reticulated and be supplied to all the residents in the peri- urban centres. This is being done through National Water Development Project (NWDP) that is being supported by the World Bank. The major achievement under the NWDP is the establishment and reorganization of Water Boards in Malawi. The Malawi Parliament (2010) has established Northern, Central, Eastern and Southern Region Water Boards as parastatals which have taken over the delivery of water supply and water borne sanitation services from central government.

CHAPTER III

DATA PRESENTATION AND ANALYSIS

Introduction

This chapter presents quantitative findings with regards to water quality parameters in the sampled wells, such as electrical conductivity, pH variations, manganese, iron, fluoride, chloride, sulfate, sodium, total dissolved solids, fecal coliform and fecal streptococci. The findings are presented graphically and are compared with World Health Organization (WHO) drinking water standards and Malawi national water drinking standards. The chapter further evaluates the trend of groundwater reserves for the observation period from 1992 to 2008. Data on Static Water Levels (SWLs) in the sampled wells were collected and will be compared with data on rainfall and evaporation. This gives an indication of groundwater availability for the entire observation period. Furthermore, the chapter presents data on human impacts on the ecology through Land Use and Land Cover change detection as computed on satellite imagery through the use of Geographical Information System. Data as regards the portion of land being used for agriculture or settlement and other land use categories over the years will be calculated. Degraded forest land area have been calculated to verify the trend change. Spatial variations in groundwater chemical composition and groundwater availability will be compared with the category of land use in which the wells exists. In addition, the chapter attempts to highlight spatial variations in the chemical compositions of the groundwater in the sampled wells. Spatial variations for the groundwater availability will be exposed through analysis of static water levels for the sampled wells during the observation period.

Lastly the chapter gives qualitative information on field observations on peoples' perception on their knowledge of importance of groundwater monitoring and groundwater sustainability through use of the completed questionnaires, participant observation and focused group discussions.

Water Quality Analysis

National primary drinking water regulations and national water drinking standards set mandatory water quality standards for drinking water contaminants for any country. EPA (1992) noted that these are enforceable standards established to protect the public against consumption of drinking water contaminants that present a risk to human health. In essence the standards are simply maximum allowable amounts of contaminants in drinking water (Table 1). Laboratory data for chemical and biological analysis is in Appendix D.

Table 1: WHO and Malawi national drinking water standards

CONSTITU ENT(S)	UNIT	WHO Guideline Standards	MBS (Mineral water) MS560:2004	MBS (Drinking water) MS214:2005	MBS (BOREHOLE & SHALLOW WELLS) MS733:2005	MoIWD (Interim)
Arsenic as As	mg/l	0.05	0.01	50 µg/l	0.50	0.50
Cadmium as Cd	mg/l	0.01	0.003	5 µg/l	0.01	0.01
Cyanide as Cn	mg/l	0.05	0.07	50 µg/l	0.07	0.05
Fluoride as F	mg/l	1.5	2.0	1.0	6.0	3.0
Lead as Pb	mg/l	0.05	0.01	50 µg/l	0.05	0.05
Nitrate as NO_3	mg/l	45	10 as N	10 as N	45	100
Selenium as Se	mg/l	0.01		20 µg/l	0.01	0.01
Faecal coliform i. Treated Water ii. Untreated Water	Number/ 100ml	 0 0	 0 0	 0 0	 0 50	 0 50
Faecal streptococci i. Treated Water ii. Untreated Water	Number/ 100ml	 0 0	 0 0	 0 0	 0 0	 0 50
Calcium as Ca	mg/l	200	100	150	250	250
Magnesium as Mg	mg/l	150	50	70	200	200
Chloride as Cl	mg/l	600	150	200	750	750
Aluminium as Al	mg/l	0.20	0.15	300 µg/l	0.50	0.50
Copper as Cu	mg/l	15	1.0	1000 µg/l	2.0	2.0
Hardness as $CaCO_3$	mg/l	500	-	-	800	800
Colour	TCU	15	15	10	50	50
Sodium as Na	mg/l	200	150	200	500	500
Potassium as K	mg/l	-	12	50	-	-
Iron as Fe	mg/l	1.0	2.0	200 µg/l	3.0	3.0
Manganese as Mn	mg/l	0.50	0.50	100 µg/l	1.5	1.5
Conductivity at 25 ^{0}C	ms/m	-	400	150	3500 µs/cm	-
Total Dissolved Solids	mg/l	1000	1000	1000	2000	2000
Sulphate as SO_4^{2-}	mg/l	400	250	400	800	800
Zinc as Zn	µg/l	15 mg/l	2.0	5 mg/l	15 mg/l	15 mg/l
pH Minimum	pH units	6.5	6.5	5.0	6.0	6.0
pH Maximum	pH units	8.5	8.5	9.5	9.5	9.5
Turbidity	NTU	5	5.0	1.0	25	25

pH Analysis

With reference to Malawi National Drinking Water Standards (2005) (Table 1), pH values for drinking water are required to be between the range of 6.5 to 9.5 while the values for World Health Organization (WHO) recommend the pH range of values to be between 6.5 to 8.5. pH is simply the amount of hydrogen ions mixed with water and is measured on a scale of 0 to 14 with pH value of 7 regarded as neutral water while 0 to 7 is regarded as acidic water while 7 to 14 is regarded as alkaline water (ETW, 2009). Analysis of the sampled wells has revealed that water from one well was found to be slightly acidic and that is Manthalu with pH of 6.4. Its initial value of pH was 6.6 soon after construction. The pH of the other sampled wells was found to be within the acceptable range. A complete pH variation chart for the sampled wells in 1992 and 2008 is presented in figure 4 below. However, all wells show a marked decrease in pH from 1992 to 2008.

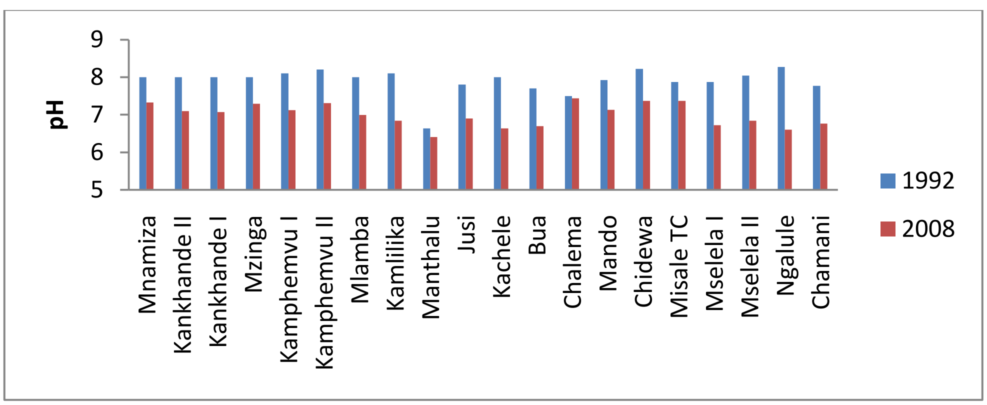

Figure 4: pH variation for sampled wells

Electrical Conductivity and Total Dissolved Solids Analysis

EPA (1992) defines electrical conductivity of water as a measure of the conductivity of an electric current of a solution. It gives an indication of the level of dissolved salts in a water sample. EPA (1992) further noted that electrical conductivity and total dissolved solids within a water sample usually exhibit a strong relationship, since electrical conductivity is a measure of the concentration of dissolved solids. These are predominantly salts, but other particles such as algae or non conductive ions, may also affect the electrical conductivity reading. Total dissolved solids of less than 1000 mg/l indicate that water is generally free from many salts. EPA (1992) observed that the most common chemical constituents of total dissolved solids are phosphates, calcium, nitrates, sodium, potassium, and chloride mainly from agricultural runoff, leaching of soil contamination and point source water pollution discharge from industrial and sewage treatment plants. Figure 5 and 6 below shows the trend of electrical conductivity and the total dissolved solids between 1992 and 2008.

Figure 5 and Table 2 below depicts many spatial variations from 1992 to 2008. A marked decrease of electrical conductivity at Mnamizana (-205 ms/m), Mlamba (-77 ms/m), Kamlilika (-126 ms/m), Bua (-84 ms/m), Chalema (-98 ms/m), Misale (-77 ms/m) and Ngalule (-69 ms/m) can be seen. On the other hand, there were no significant variations of electrical conductivity from wells such as Kankhande II (-18 ms/m) and Mselela II (-6 ms/m). The most notable increase of electrical conductivity occurred at

Jusi (11 ms/m), Mzinga (31 ms/m) while Mando registered the biggest increase of 72 (Table 2).

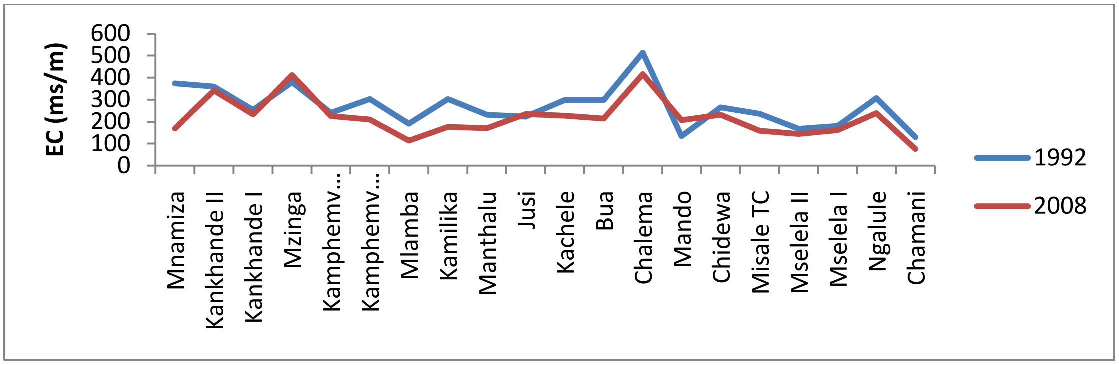

Figure 5: Electrical conductivity variations in wells (ms/m)

Table 2: Differences in EC from 1992 to 2008 per well

Sampled well	Differences (ms/m)
Mnamiza	-205
Kankhande II	-18
Kankhande I	-70
Mzinga	31
Kamphemvu I	-14
Kamphemvu II	-43
Mlamba	-77
Kamlilika	-126
Manthalu	-61
Jusi	11
Kachele	-71
Bua	-84
Chalema	-98
Mando	72
Chidewa	-34
Misale TC	-77
Mselela I	-36
Mselela II	-6
Ngalule	-69
Chamani	-54

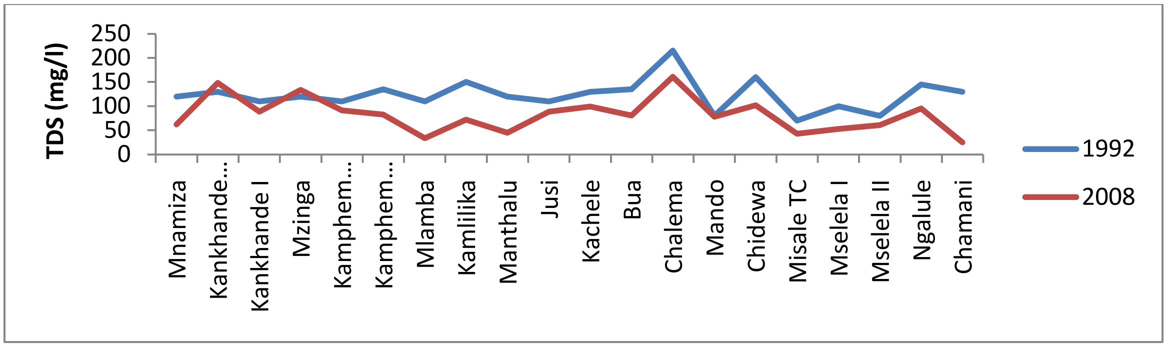

Figure 6: Total Dissolved Solids variations in wells from 1992 to 2008 (mg/l)

Table 3: Differences in TDS in wells from 1992 to 2008

Sampled well	Differences (mg/l)
Mnamiza	-58
Kankhande II	18
Kankhande I	-21
Mzinga	14
Kamphemvu I	-19
Kamphemvu II	-52
Mlamba	-76
Kamlilika	-78
Manthalu	-75
Jusi	-21
Kachele	-31
Bua	-54
Chalema	-54
Mando	-2
Chidewa	-58
Misale TC	-27
Mselela I	-47
Mselela II	-19
Ngalule	-50
Chamani	-105

With reference to Table 1, on maximum allowable concentrations of total dissolved solids to be less than 1000 mg/l, it is evident that water from all the sampled wells is within acceptable range. Examination of total dissolved solids in spatial variation as depicted in Table 3 and Figure 6 show that the two point time trend of total dissolved solids has been decreasing from 1992 to 2008. Chamani (-105 mg/l), Ngalule (-50 mg/l), Chalema (-54 mg/l), Bua (-54 mg/l), Kamlilika (-78 mg/l), Mlamba (-76 mg/l), Kamphemvu (-52 mg/l) and Mnamizana (-58 mg/l) all registered significant decreases in total dissolved solids. No significant changes occurred at Mando (-2 mg/l), Jusi (-21 mg/l) and Kankhande I also (-21 mg/l). Two wells have their total dissolved solids increased slightly and these are Kankhande II (+18 mg/l) and Mzingo (+14 mg/l).

Iron Analysis

EPA (1992) observes that iron is considered as one of the aesthetic parameters in groundwater. Iron may impair the taste, smell or color of the water. Although iron does not pose a health risk at levels normally found in drinking water, its presence can indicate deteriorating groundwater quality and could indicate other problems with the well which may cause adverse health effects. EPA (1992) further notes that that the concentration of iron in well water can fluctuate within a season and vary with the depth and location of the well including the geology of the area. Figure 7 and Table 4 gives the trend of iron concentrations in the sampled wells between 1992 and 2008. The trend of iron variations in general indicates that the concentrations have remained constant in most of the wells. It is anomolous that all wells show concentrations of 0.2mg/l during 1992, but this is just a consequence of the way in which the figure was rounded off. All wells had, therefore, concentratons of iron of between 0.2 mg/l and 0.25 mg/l in 1992.

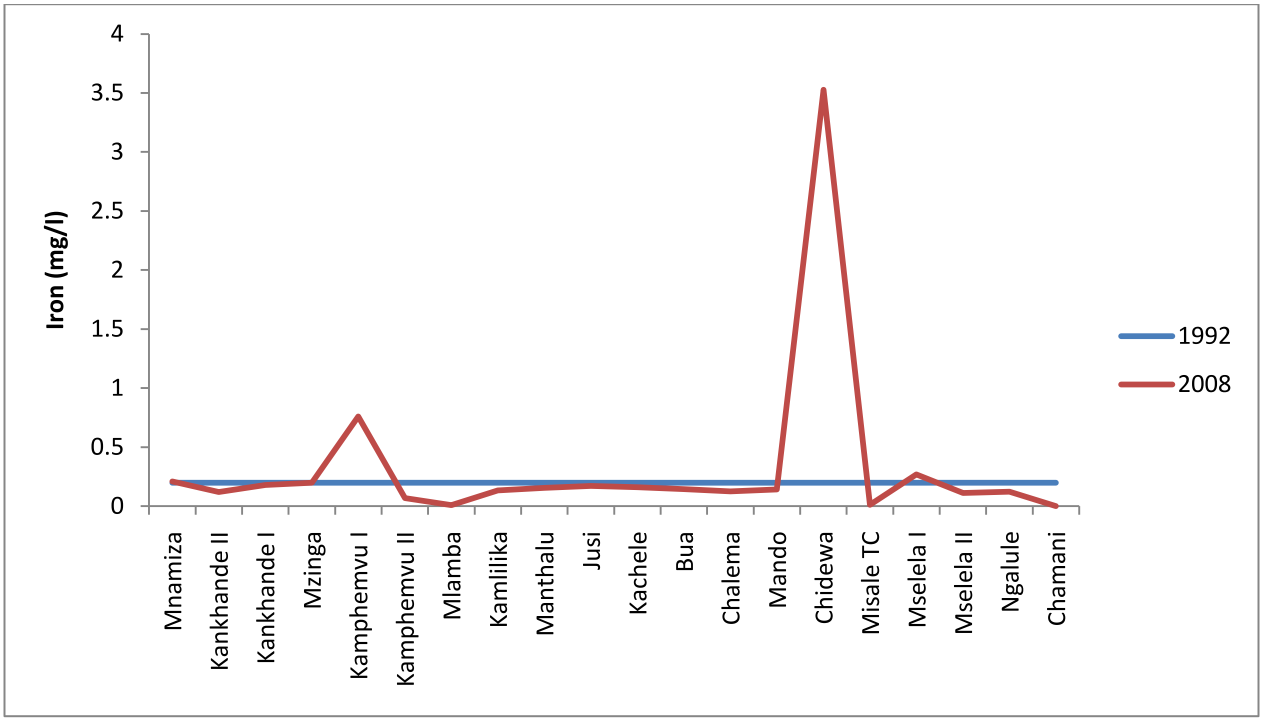

Figure 7: Comparison of iron concentrations in sampled wells (mg/l)

Considering that the recommended concentration of iron according to Malawi drinking water standards (2005) is 1.5 mg/l and that of WHO of 1.0 mg/l, then water from one well (Chidewa) has shown extreme concentration of iron which has increased to 3.5 mg/l from 0.2 mg/l. The iron concentration of the water from Kamphemvu, although still within acceptable range, has increased to almost 1 mg/l. Soon after construction the concentration of iron in these wells were well within acceptable range. These findings could imply that the increase in iron content at these well could indicate a decrease in water quality. Slight decreases in iron concentrations have occurred at Kankhande II, Kamphemvu II, Mlamba and Chamani.

Table 4: Concentrations and temporal differences of iron in the wells (mg/l)

	Iron (mg/ l)		
Sampled well	1992 (Approximate)	2008	Differences (Approximate)
Mnamiza	0.2	0.2	0.1
Kankhande II	0.2	0.1	-0.1
Kankhande I	0.2	0.2	0.0
Mzinga	0.2	0.2	0.0
Kamphemvu I	0.2	0.8	0.6
Kamphemvu II	0.2	0.1	-0.1
Mlamba	0.2	0.0	-0.2
Kamlilika	0.2	0.1	-0.1
Manthalu	0.2	0.2	0.0
Jusi	0.2	0.2	0.0
Kachele	0.2	0.1	-0.1
Bua	0.2	0.1	-0.1
Chalema	0.2	0.1	-0.1
Mando	0.2	0.1	-0.1
Chidewa	0.2	3.5	3.3
Misale TC	0.2	0.0	-0.2
Mselela I	0.2	0.3	0.1
Mselela II	0.2	0.1	-0.1
Ngalule	0.2	0.1	-0.1
Chamani	0.2	0.0	-0.2

Manganese Analysis

Sources of manganese can be part of the natural groundwater aquifer or through underground pollution. Studies by EPA (1992) have shown that exposure to high manganese for a long time can be associated with toxicity to the nervous system. Just like iron, manganese is also an aesthetic parameter that can impair the taste, smell and color of the water. Its presence therefore indicates deteriorating groundwater quality and that its concentrations can fluctuate in the water from a well with season and depth plus the geology of the area (EPA, 1992).

The recommended concentration for manganese according to Malawi drinking water standards is 1.5 mg/l while that of WHO is 1.0 mg/l. Considering the results from the analysis in the sampled wells, it has been found that all the water from the sampled wells were within the acceptable range as they all depicted concentrations of manganese of less than 0.001 mg/l. It should be noted that analysis for manganese was not done soon after construction of the wells hence there is no good basis for tabular comparison but due to its high importance in groundwater it was analyzed during this research to appreciate its current status in the groundwater quality.

Fluoride Analysis

The main natural source of fluoride in groundwater could be the geology of the aquifer, but anthropogenic sources of fluoride also exist. The aquifer may be composed of fluoritic rocks such as carbonates whose slow dissolution may infiltrate into the groundwater (Sajidu et al., 2007).

EMA (2002) noted that high fluoride concentrations in groundwater is mainly associated with sodium bicarbonate and is relatively low in calcium and magnesium concentrations. The WHO guideline value for fluoride in drinking water is 1.5 mg/l. Above that limit mottling of teeth may occur while continuation of consumption of groundwater with high fluoride content may result in fluorisis. EMA (2002) further notes that in many arid and semi arid regions such as Malawi potable drinking water is a scarce resource with an attached cost so that national governments have been forced to set the standard for fluoride at higher levels. The Malawi national drinking water standards recommend the maximum allowable limit for fluoride concentration to be 3 mg/l, double that of the WHO guideline.

Analysis of the sampled wells has revealed that the values for fluoride have been found to be within the acceptable range of both the Malawi standards and those of the WHO (Fig. 8). From the data, it is clear that there is no recognizable general trend in concentrations of fluoride. Although most of the sampled wells have their water in the recommended range, it is evident from the analysis that there are significant spatial variations in the concentrations of fluoride in the sampled wells. For instance some wells such as Kankhande II, Manthalu, Jusi, Kachele, Mando, Chidewa, Mselela, and Ngalule show higher variations than wells like Mnamizana, Mlamba, Bua, Misale Trading Centre and Chamani. Two wells depicting extreme variation are Kachele (high) and Bua Trading Centre (very low).

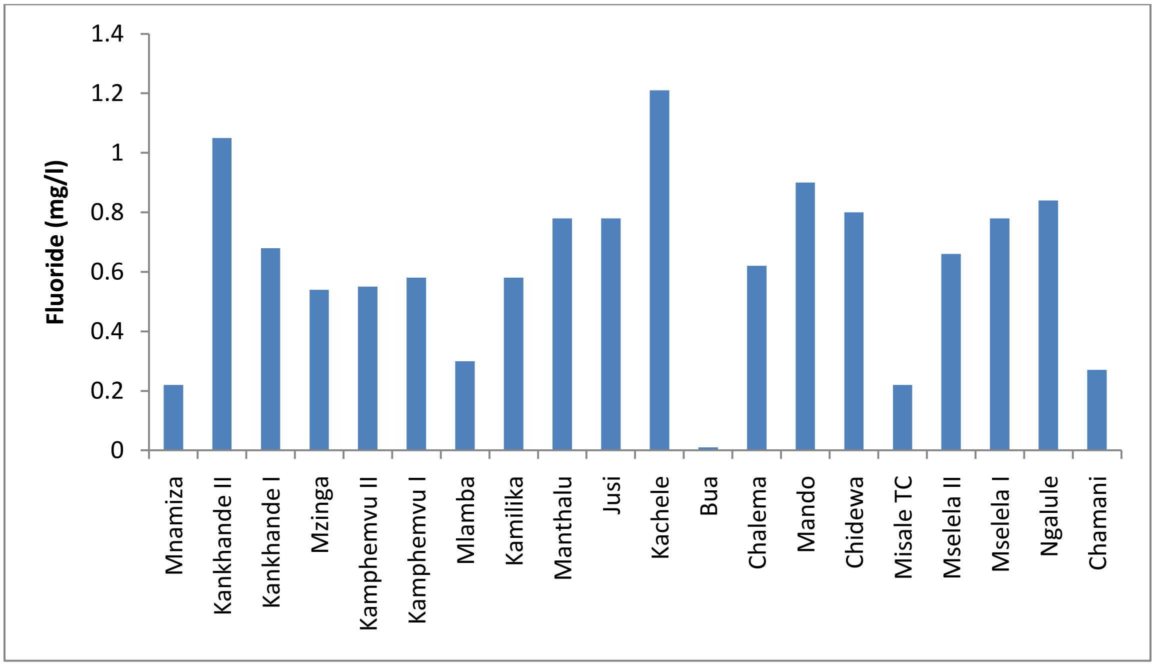

Figure 8: Spatial variation of fluoride in sampled wells in 2008

<u>Chloride, Sulfate and Sodium Analysis</u>

Chloride, sulfate and sodium are other important groundwater chemical parameters whose concentrations should be known before groundwater is consumed. Unfortunately these elements were not analyzed in 1992. However, due to their importance these were analyzed during the research in 2008.

O'connor et al., (2010) documented that in nature, chlorine is only found combined with other elements, mainly sodium (sodium chloride). Because of its reactivity, chlorine is not likely to enter groundwater in large amounts. Sodium's powdered form is highly explosive in water and a poison when combined with many other elements.

Analysis has revealed that the concentrations of sodium (Fig. 9) are very insignificant as the sampled wells depicted very minute concentrations far below the maximum allowable limits. However, spatial variations do exist with regards to sodium concentrations. LWTS (2008) documented that sodium is not mobile in solid form, although it is known to absorb moisture very easily, which could imply that it is found only in minute amounts in groundwater.

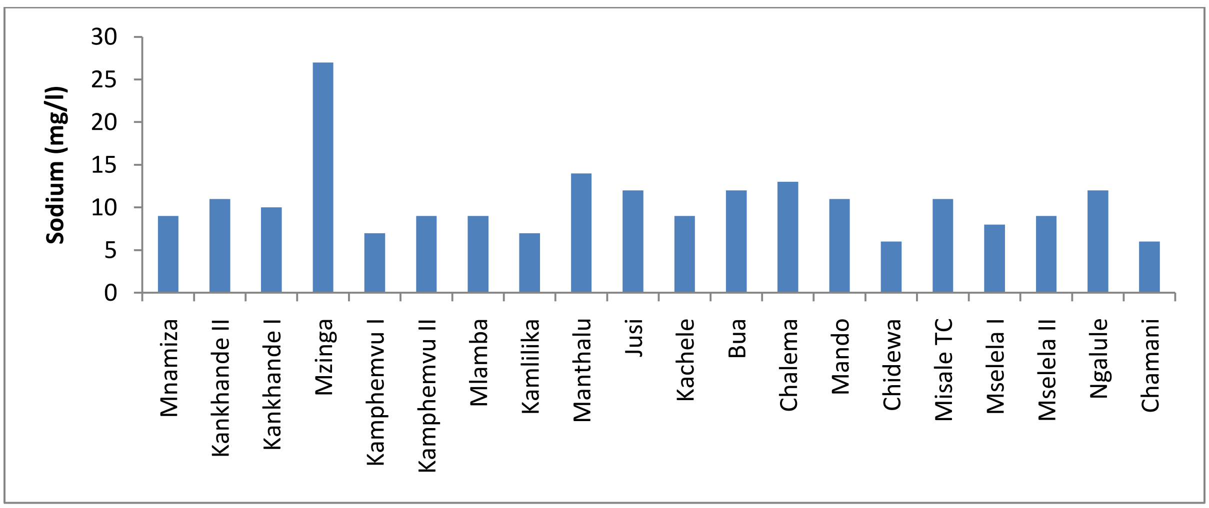

Figure 9: Variations of sodium in sampled wells (mg/l)

The concentration of chloride (Fig. 10) is also very insignificant as the sampled wells depict very minute concentrations.

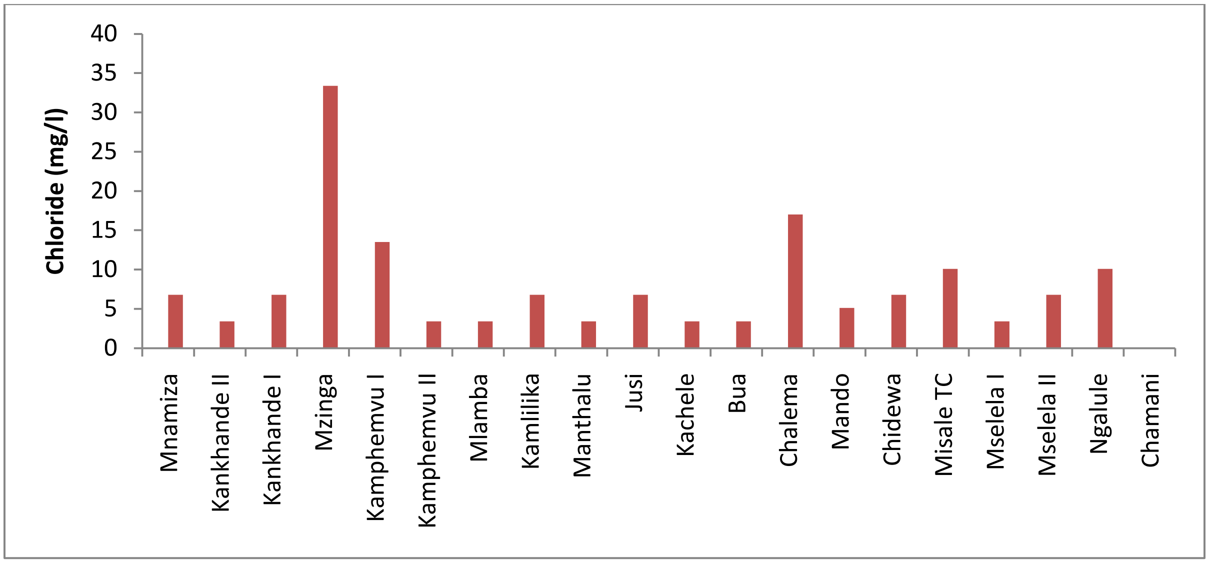

Figure 10: Concentration and variations in chloride in sampled wells (mg/l)

The recommended concentration for chloride according to Malawi national drinking water standards is 750mg/l while that for World Health Organization is 200 mg/l. All the water from the sampled wells showed that the concentrations for chloride were within the recommended limits. The recommended concentration for sodium according to Malawi national drinking water standards is 500 mg/l while that for WHO is 200 mg/l. Again all the water from the sampled wells fell within the acceptable range, but spatial variations do exist.

Sulfates are important parameters to be considered in groundwater because if they are consumed in excess they cause many problems to animals and human health. According to LWTS (2008) the damaging effects of sulfates to animals and human are related to the nervous system and can lead to brain damage through malfunctioning of the hypothalamus. In animals sulfur is known to cause vascular damage in veins of the brain, the heart, liver and kidneys. Some forms of sulfur cause fetal damage and congenital effects. EPA (1992) noted that breast feeding mothers who consume groundwater with high sulfate concentration may have the risk of infecting their babies. Sulfates are also known to cause disorders to internal enzyme systems of animals, stomach and gastro- intestinal problems. The recommended concentration of sulfates according to Malawi national drinking water standards is 800 mg/l while that for WHO is 400 mg/l. Water samples from the wells have revealed that the concentration of sulfates is very insignificant (Fig. 11) and within the acceptable limit.

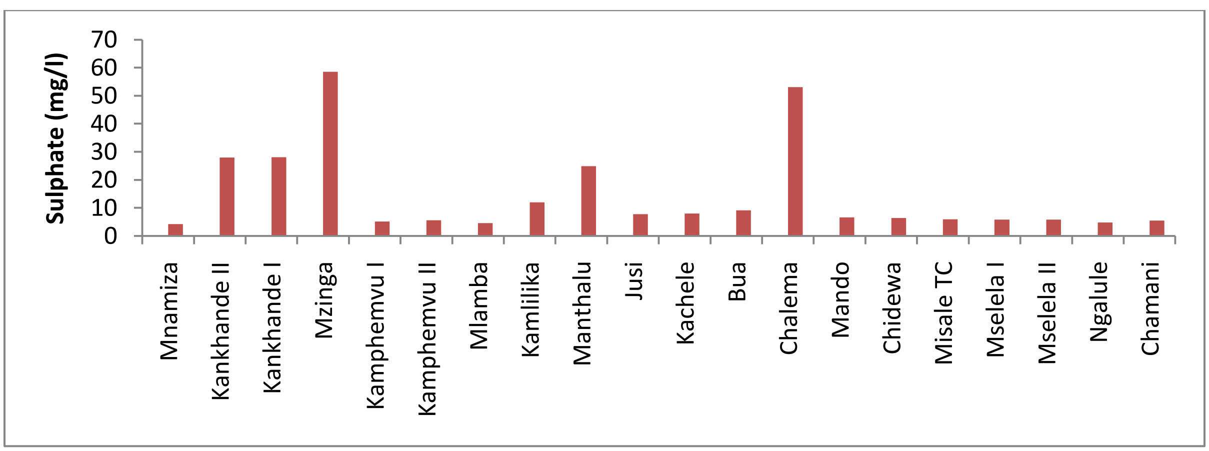

Figure 11: Concentrations and variation of sulphate in sampled wells (mg/l)

Analysis of Pathogens

WSIS, 2007 observed that analysis of pathogens in groundwater involves the determination of bacteria, viruses, protozoa and other disease causing organisms which simply alert a need for precautionary measures or actions. For the purposes of this study only fecal coliform bacteria was analysed. According to WSIS (2007) fecal coliform bacteria are associated with human and animal wastes and they exist in the intestines of warm blooded animals and humans. They enter the soil system through human excrement and animal droppings. Fecal coliform in well water may therefore indicate recent contamination of the groundwater by human sewage or animal droppings. WSIS (2007) further noted that the known sources of fecal coliform in groundwater include agricultural runoff, effluent from septic or sewage discharges and infiltration of domestic or wild animal fecal matter. Fecal coliform are usually given as the number of colony forming units per 100 milliliters of sampled water (WSIS, 2007).

The concentrations of fecal coliform (Fig. 12) is very small. The recommended concentration of fecal coliform according to Malawi Standards is 50 per 100ml while that for World Health Organization is zero per 100ml. All the water were found within acceptable levels according to Malawi standards, but eight wells show traces of coliform which is unacceptable from WHO standards. These are Kankhande, Mzingo, Kamphemvu, Mlamba, Misale Trading Centre, Mselera I, Mselera II, and Ngalule. The water within the boreholes at Mselera I and Mselera II were found with fecal coliform of

43 per 100ml and 39 per 100ml respectively, which is close to the minimum requirements of Malawi.

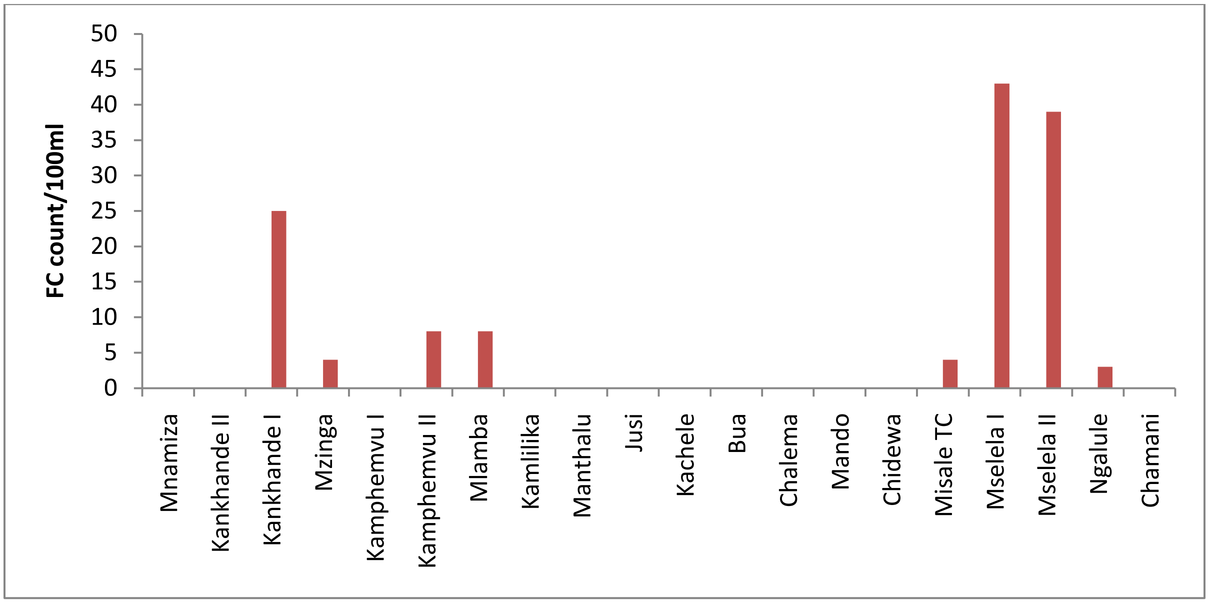

Figure 12: Concentrations of fecal coliform in sampled wells (count/100ml)

The implication for the consumption of such water is that the water users risk suffering from diseases like dysentery, diarrhea and nausea which sometimes may lead to death. Effects may be severe to babies, children and elderly or people with immune deficiencies or other illnesses (EPA, 1992).

Groundwater Availability Analysis

Groundwater availability is believed to be strongly linked to the amount of precipitation that an area receives as it is regarded as the main source of recharge minus the effect of evaporation (Ministry of Water Resources of India, 2002). Furthermore, due to the fact that groundwater is not naturally visible, it is a rather difficult and complicated task to evaluate the amount of groundwater reserves.

Scientists have among other methods used the water rise method (Anuraga, 2002) where water table fluctuations are considered the best indicator of groundwater reserves. The fluctuations of water table can be determined by the periodic measurements of the depth to water in wells. However, if specific yield of an aquifer is known, changes in storage within the aquifer can also be estimated. Static water levels (SWLs) data for some of the sampled wells which had complete data sets was obtained. Additionally, meteorological data such as rainfall and evaporation from weather stations in Mchinji District was also collected for the observation period to use as a basis to test for correlations with water table fluctuations. Correlation matrix analysis between rainfall, temperature and evaporation has been done, but has not been included into main text. (Please refer to Appendix E). Regression data for rainfall and temperature with and without interaction appears in Appendix F and Appendix G.

Figure 13 below shows the variations of rainfall and evaporation from 1992 to 2008 in Mchinji District which will be used in the visual comparison of rainfall and static water levels. Raw data of rainfall and evaporation appears in Appendix H.

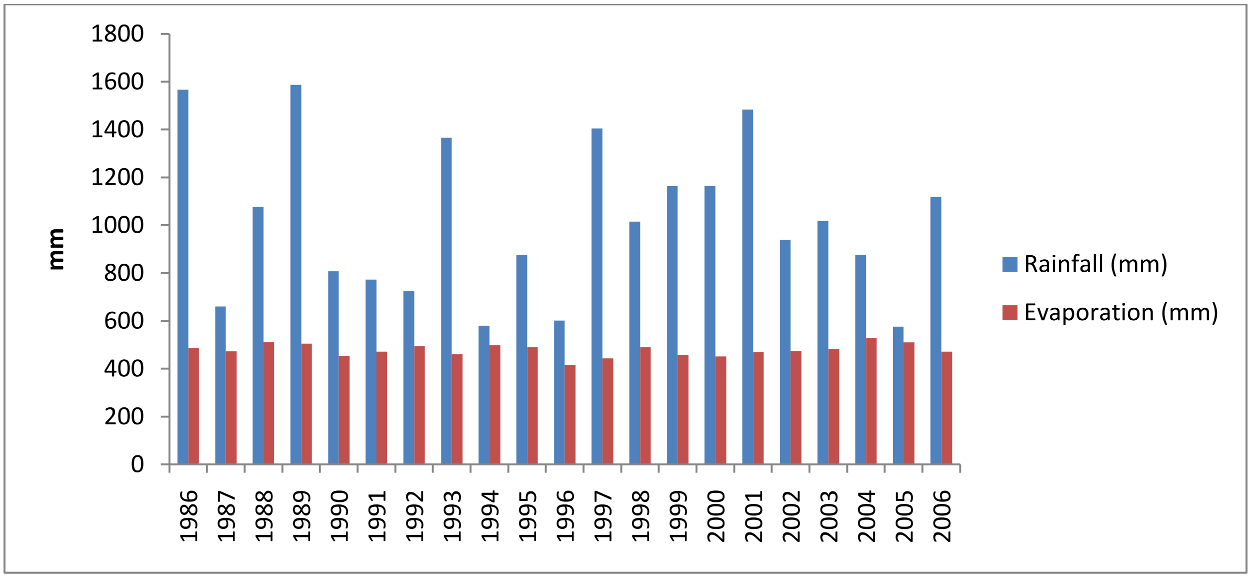

Figure 13: Temporal trend of rainfall and evaporation in Mchinji District

It is evident that during the observation period, Mchinji District received on average significantly more rainfall than what is being evaporated back into the lower atmosphere, except during 1994 and 2005 when the rainfall almost equaled the amount of evaporation. Below average rainfall (800mm) were received in the years 1992, 1994, 1995, 1996, 2002, 2004 and 2005, while above average rainfall amounts were received in the years 1993, 1997, 1999, 2000, 2001 and 2006. Data for the collected static water levels (SWLs) for the sampled wells during the observation period appears in Appendix I.

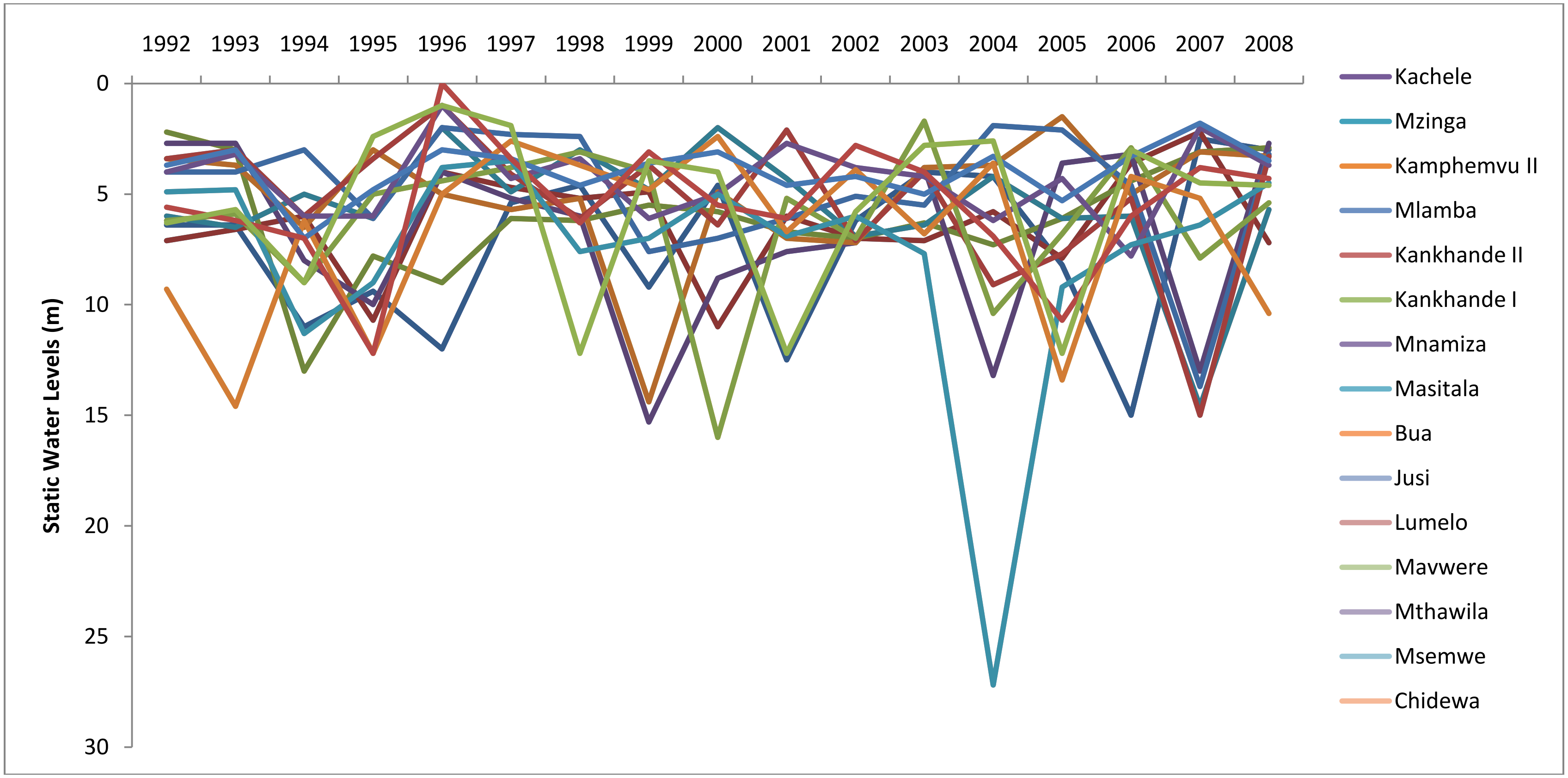

Figure 14: Yearly series plots for static water levels for the sampled wells

According to Bhuiyani et al. (2009) time series analysis of water table fluctuations provides an idea about temporal and spatial variation of aquifer recharge, discharge and availability of groundwater resources. Spatial-temporal variations of rainfall and potential evapo-transpiration both affect water table fluctuations to some extent. It should be noted that the variations can be either regular or irregular due to seasonal rainfall distribution and overexploitation of the limited groundwater resource.

The time series analysis infers that natural recharge varies in Mchinji terrain both spatially and temporally due to variations of infiltration capacity and rainfall dynamics. The obvious description of the spatial variations in groundwater levels for Mchinji is that significant decreases in groundwater levels were experienced at most wells in the years 1994, 1995, 1999, 2001, 2004, 2005 and 2007 as compared to the years 1996, 1997, 2003, 2006 and 2008 when Mchinji experienced increases in the groundwater table (Fig. 14).

To test if a correlation exist between rainfall and evaporation and static water levels in the wells in Mchinji, linear regression analyses were performed on the mean static water levels for the sampled wells and the mean district rainfall and evaporation measurements (Fig. 15 and 16).

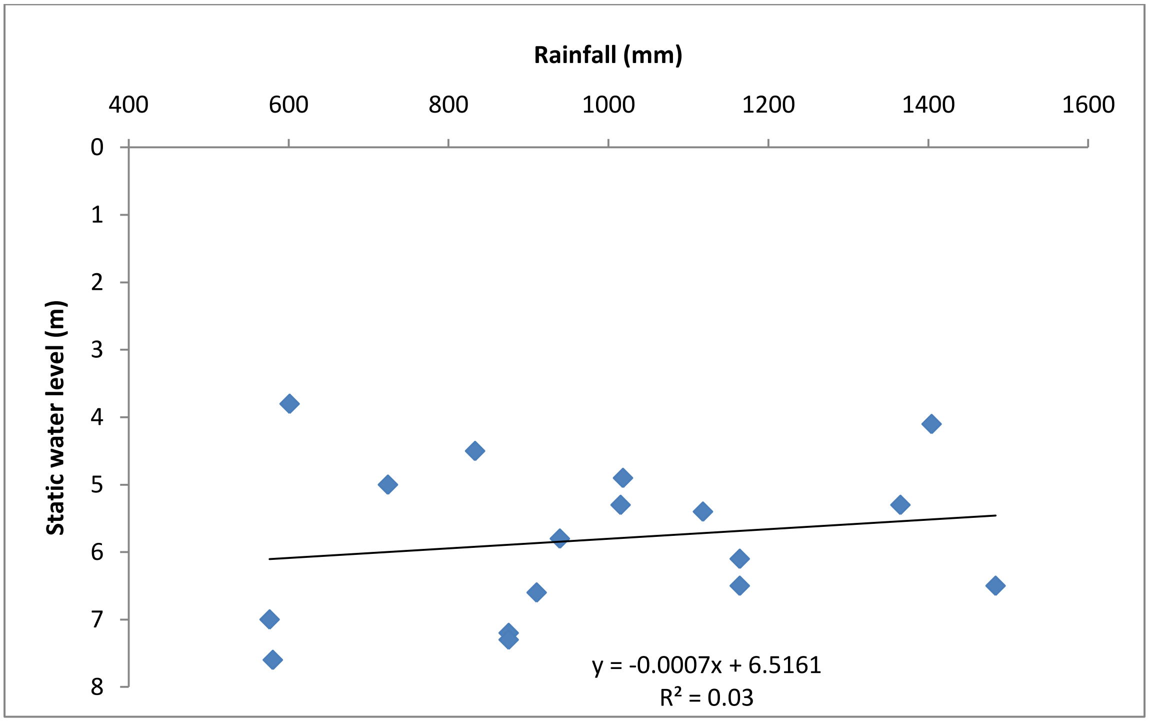

Figure 15: Linear Regression for Rainfall and Static Water Levels

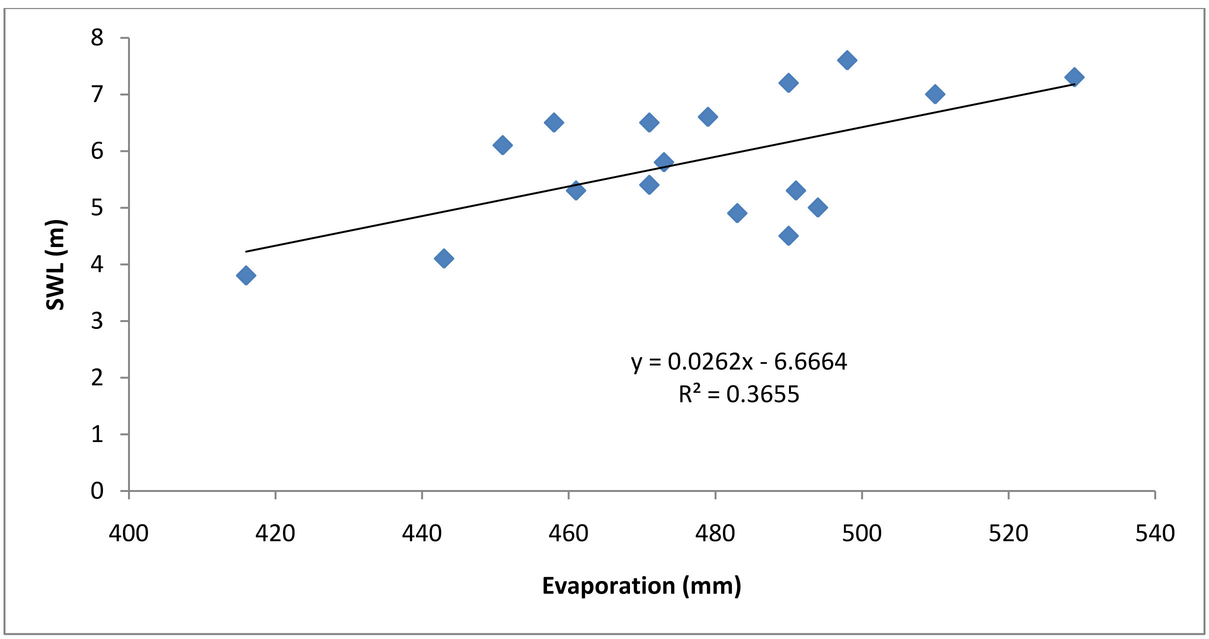

Figure 16: Linear regression for Evaporation and Static Water Levels

The linear regression of rainfall and static water levels (Fig. 15) show that there is no correlation between rainfall and static water levels in Mchinji as evidenced by the weak R^2 of 0.03. Rainfall does not seem to influence static water levels on its own. It should be noted that static water levels are computed using the ground surface as the base and the SWL is the distance from the ground surface to the water table. Linear regression data for rainfall and static water level appears in Appendix J.

The linear regression of evaporation and static water level (Fig. 16) shows that an increase in evaporation is associated with a decrease in water table depicting a reduction in groundwater reserves. The linear regression of static water levels and evaporation show that there is some correlation between static water levels and evaporation (R^2 of about 0.4). This implies that evaporation can possibly influence static water levels in Mchinji District. Linear regression data for evaporation and static water levels appear in Appendix K.

Even though groundwater table fluctuated to lower levels in 1994, 1995, 1999, 2001, 2004, 2005 and 2007, there is no obvious correspondence with low rainfall and the years with low groundwater table levels. Exceptions are the years 1994 and 2005. These years correspond with lower rainfall amounts and corresponding decline of groundwater. It seems that these are the years that Mchinji experienced some widespread droughts and personal communication from technicians indicate that it was difficult to access groundwater in most of the wells in Mchinji. However, analysis has shown that not many years are corresponding between years with high or low amounts with years that had high or low groundwater levels and this is evident from the linear regression between rainfall and static water levels (R^2 = 0.03).

Analysis of Human activities

Scanlon et al., (2005) documented that life in the ecosystem is to some extent dependent on groundwater and coupled with varying human activities on the landscape the impacts of these activities on groundwater can be remarkable. Unwarranted de-vegetation, through aimless clearing or harmful bush fires, unregulated groundwater extraction, poor agricultural practices without deliberate soil and water conservation measures all ultimately affect groundwater quality and quantity (Scanlon et al., 2005).

In this study land use and land cover (LU/LC) change were analyzed using simple Geographical Information System (GIS) and Remote Sensing. Land use and land cover change satellite images over time series of 10 years of precisely 1989, 1999 and 2009 with resolutions of 30m, 30m and 15m respectively in Mchinji were used. Figure 17 below are land cover maps from satellite images for Mchinji while Table 5 is a summary of calculated land use categories during the observation period.

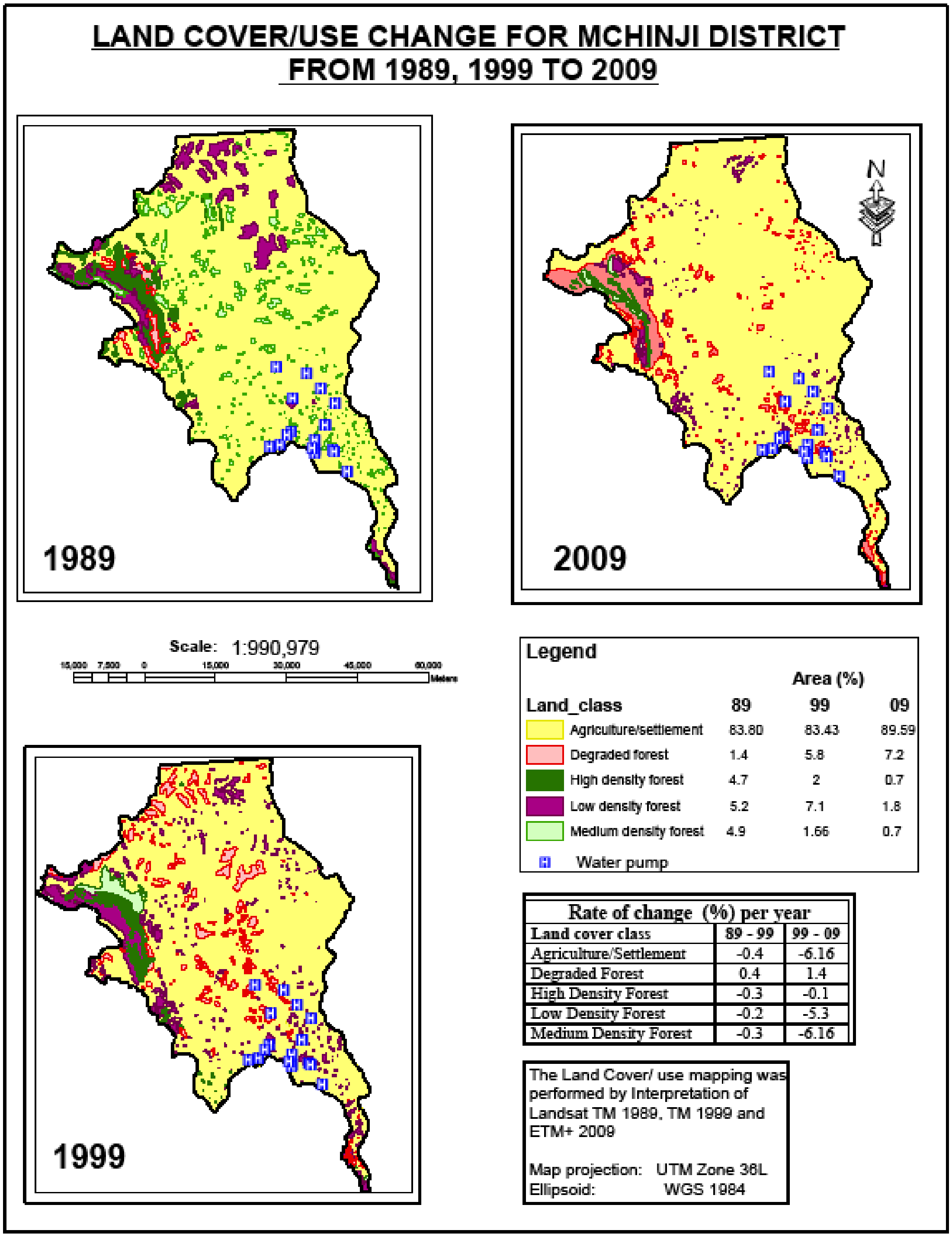

Figure 17: Land Cover Changes in Mchinji and Water Points

Table 5: Table showing land use change in Mchinji from 1989 to 2009

	YEAR/AREA					
Class	**1989**		**1999**		**2009**	
	Ha	%	Ha	%	Ha	%
Agriculture/Settlement	261895.06	83.8	260733.20	83.4	279985.50	89.6
Degraded forest	4398.16	1.4	18019.81	5.8	22619.76	7.2
High density Forest	14755.38	4.7	6276.35	2.0	2132.86	0.7
Medium density forest	15177.18	4.9	5184.09	1.66	2238.72	0.7
Low density forest	16301.09	5.2	22313.42	7.1	5550.03	1.8
Total	**312526.87**	**100**	**312526.87**	**100**	**312526.87**	**100**

It is evident that agricultural or settlement area in Mchinji has increased from 261,895.06 ha in 1989 representing 83.8% of the total land area to 279,985.5 ha in 2009 representing 89.59% of the total land area (Table 5). This clearly shows that vast areas are being de-vegetated for agricultural and settlement use. On the other hand, degraded forest area has increased from 4,398.16 Ha representing 1.4% of the total land area in 1989 to 22,619.76 Ha representing 7.2% of the total land area in 2009. This emphasizes the extent of deforestation in Mchinji. Indeed as UNEP (2008) observed, between 1990 and 2005 Malawi lost nearly 13% of total forest cover due to firewood collection, subsistence and commercial farming. Analysis of the exact positions of the wells (Water pumps in blue depicts the positions of the wells) (Fig. 17) shows that the water points are mostly located in the agricultural/settlement land use category and the degraded forest land category where some of the main activities include land clearance for farming, rearing of animals and construction of dwelling houses.

Qualitative Information

Workmanship and Capacity building

The study has observed through participatory observation and questionnaires that the quality of the physical structures for water supply facilities is good although minor defects were detected. This was mainly observed through participant observation during sampling of water for water quality analysis. It was also noted that the water points' surroundings were clean and well maintained. The study has also established that water point users were collecting maintenance funds from individual households using the water points. It also seems that funds are also properly managed and accounted. The study has also observed that project implementation took full advantage of the trained water point committees and the experienced technical experts from the Ministry responsible for water affairs. This ensured smooth project implementation. Community sensitization meetings at project inception was a critical success factor which ensured that intended beneficiaries were made aware of project components, their expected roles in the water facility operation, maintenance and monitoring of groundwater quality. The community sensitization raised expectations and commitment to transform beneficiaries' livelihoods.

Groundwater Sustainability Guidelines

A number of documents have been reviewed which play a crucial role in governance of water resources in Malawi. These include the National Water Policy of Malawi, the National Sanitation Policy of Malawi, Ministry of Irrigation and Water Development Strategic Plan, the Decentralization Policy, the Malawi Economic Growth and Development Strategy. The review has concluded that the major constraint in achieving a comprehensive integrated water resources management to ensure its sustainability is lack of a solid legal and legislative framework.

The review has discovered that most of the laws are outdated and that they are not supportive of the integrated water resources management. These constraints have made it increasingly difficult to enforce the guidelines in terms of monitoring, planning, assessment, development, conservation and protection strategies to attain water resources sustainability and utilization. Suggestions and recommendations to this effect will be made in the next chapters.

In conclusion, the study has noted that many water users from all the wells where sampling was done were not fully aware that activities taking place in other sectors could have serious effects on the water quality and quantity. The water users were not aware of the interplay amongst various sectors. This conforms to the research objective that integrated groundwater resources management entails the collective participation of the stakeholders in the individual sectors.

CHAPTER IV

DISCUSSION

This chapter discusses the research findings and how they relate to sustainable integrated water resources management. It discusses findings on sampled groundwater composition, groundwater fluctuations; impacts of land use and land cover change on groundwater resources in Mchinji district of central Malawi. The chapter also suggests linkage between the findings and possible causes of spatial variations in groundwater quality and quantity using findings of similar research work elsewhere on the globe. This chapter also discusses with special attention and emphasis the issue of groundwater monitoring. These issues are given in the context of sustainable and integrated water resources with applications to the national requirements of the water sector in Malawi.

Groundwater chemical composition

Groundwater is composed of a number of elements. These elements originate from either the medium in which groundwater percolates through during its transmission, or from the medium in which it is stored before being exploited for utilization. Analysis of the sampled wells in Mchinji district has revealed that there are spatial and temporal variations of some chemical elements of the groundwater. The spatio-temporal variations in the chemical elements such as pH, electrical conductivity, total dissolved solids, iron, manganese, fluoride, sulfates, sodium and chloride have been identified.

In Mchinji the differences in the natural environment at the specific wells could be a possible cause of the spatial variations in chemical composition of the groundwater. Due to the differences in the natural compositions and structures of the formations in which groundwater is transmitted through and stored, the concentrations of the various parameters in the sampled wells depicted different outcomes during analysis. In Mchinji a common cause of changes in water quality variations from one well to the other could be attributed to natural variations within the aquifers. Nelson (2002) suggested that within the aquifer groundwater moves not as an underground stream, but rather seeps between and around individual soil and rock particles. Nelson (2002) further notes that rainwater is slightly acidic; therefore it tends to dissolve solid materials in the soil and in the aquifer.

Research work from elsewhere on the globe (Hill et al., 1997; Mayer, 1999; Atekwana et al., 2004; Burrough, 2006 and Gore, 2008) has suggested that spatial and temporal variations in chemical composition of groundwater have been known to emanate from a number of factors such as mineral weathering (mineralization), residence time of groundwater, rock or soil-water interaction in distinct flow paths of groundwater, and age of groundwater in aquifer.

From the pH analysis of groundwater it seems that almost all the water in the sampled wells in Mchinji is turning slightly acidic. Burrough (2006) observed that spatial variations in groundwater parameters such as pH can be systematic or random and concluded that it is difficult to explain. Hill et al., (1997) noted that spatial variation in groundwater parameters is a complex interaction of hydrological and hydrochemical processes. The factors include the geology, degree of fracturing and hydrological routing. It has been documented that intake of acidic water and acidic foods in modern diet may make the body to work overtime to maintain the blood pH within the healthy range. To do so the body will take alkaline substances from body parts such as bones (ETW, 2009). Examination of spatial variations in the pH in the sampled wells such as Mnamizana, Kamphemvu, Kamlilika, Manthalu, Bua, Ngalule and Chamani could be associated with increased mineralization as advanced by Mayer (1999). Since the trend may pose a health risk, it requires future monitoring.

Gore (2008) noted that chemical weathering or mineralization entails the reaction between rocks and water to form completely new solutions. When infiltration occurs after precipitation, the water reacts with the soil and rock formations in pore spaces before joining groundwater. Such a process has a direct bearing on the composition of the groundwater as the compositions of the different media that the infiltrating water comes into contact with is reflected in the final groundwater composition. Atekwana et al., (2004) noted that in some instances an increase in TDS results from enhanced mineral weathering due to acids produced in biodegradation. In Mchinji, the spatial variation in TDS is likely to result from biodegradation that accounts for higher conductivities in the sediments impacted by the hydrocarbons from cleared and dead vegetation and; reduced mineral weathering in the other wells localities.

Further linkage of chemical weathering as a factor contributing to spatial variations in chemical compositions of groundwater is the residence time of groundwater in the aquifers and wells. Hill et al., (1997) noted that spatial variations of chemical composition in groundwater is a result of complex relationships between factors such as geology of the area and residence times of groundwater in aquifers and wells. It is obvious that the sampled wells in Mchinji are tapping groundwater from aquifers that are located at different depths and associated with different residence time.

Spatial variation in electrical conductivity in groundwater composition according to Mayer (1999) may be controlled primarily by rock – water interaction along distinct flow paths which are generally natural. In Mchinji according to Geological Survey (1968) the overlying formation is generally lateritic in nature which may have a low rock-water interaction hence it can be suggested that the general decreasing trend of spatial variation in electrical conductivity reflect the hydrologic nature of local aquifers from where the wells are tapping the water from. Mayer (1999) observed that differences in iron in groundwater are largely due to differences in residence time of the groundwater within the aquifer as it comes into contact either with big or small pore spaces. It is suggested that at Chidewa and Kamphemvu wells, the water stays longer in the aquifer before being tapped into the well. However the sharp rise in iron especially at Chidewa well from 1992 to 2008 cannot be explained easily and further monitoring is needed to ascertain the causes of the high iron content at this well.

EMA (2002) notes that weathering of rocks and evaporation of groundwater is responsible for high fluoride concentration in groundwater. This shows that meteorological and climatological impacts may lead to formation of evaporites that may have higher concentrations of fluoride in aquifers. Analysis of spatial variation of fluoride in the sampled wells shows that fluoride content from wells such as Mnamizana, Mlamba, Kankhande II, Kachele, Bua T/C, Misale T/C, Ngalule and Chamani is low. Geological Survey (1968) describes Mchinji to fall under the basement complex comprising mainly metamorphosed granite rock minerals. It is likely that at Kankhande II, Kachele and Ngalule, the granitic rocks that form a bigger part of the Mchinji basement complex possess a higher concentration of fluoride content than the areas around Mlamba, Bua, Misale T/C and Chamani.

Age of groundwater in the aquifer and wells affects concentrations of chemical elements in groundwater. However, the amount and frequency of groundwater extraction may mean that groundwater can remain idle for a long time in the aquifer or well. In the aquifer where there is over extraction of groundwater, the aquifer from which the water is tapped can be heavily agitated and demobilized and in the process the chemical and physical compositions of groundwater can be affected. Over pumping of groundwater is one of the well known methods of cleaning aquifers in which case silts and other impurities can be seen in the groundwater. In essence therefore, it can be suggested that spatial variations of groundwater composition in Mchinji can also be affected by the age of groundwater. This can also be affected by the amount and frequency of groundwater extraction in Mchinji, however, precise extraction of groundwater from the wells by the communities should be monitored in future in order to make sound conclusions.

Groundwater Biological Composition

Biological composition is another major issue worth considering before consuming groundwater. The known sources of biological groundwater contamination include agricultural runoff, effluents from septic or sewage discharges and from infiltration of domestic or wild animal fecal matter. Cemeteries are another source of pollution for groundwater. This entails that decomposing bodies within the cemetery release bacteria, breakdown product from decay and chemicals used for embalming of dead bodies into the local and nearby groundwater supply system.

In this research, biological groundwater composition analysis only considered fecal coliform bacteria which according to WSIS (2007) can originate from human excreta and animal droppings. Sapkota et al., (2007) observed that spatial variation of concentrations of fecal coliform suggest that elevated concentrations of fecal coliform are normally detected in down gradient groundwater wells than up gradient groundwater wells.

In essence, McMurray et al., (1998) noted that fecal coliform as regards spatial distribution is not uniform as it normally appear most where drainage flows. Rainfall on a well-structured soil will cause the preferential movement of fecal bacteria and contributes to their concentrations in shallow ground waters (McMurray et al., 1998). It can be suggested that in Mchinji spatial variations of concentrations of fecal coliform in the groundwater from the sampled wells can be affected by the surrounding topography of the landscape since it can determine groundwater flow direction and this require future and further verification.

Groundwater Availability

The amount of groundwater available is simply judged by fluctuations of the water table over time. Fluctuations of water table can be determined by periodic measurements of depth to the water in wells. The water rise method as advanced by Anuraga (2006) considers the fluctuations in the water table as the best indicator of groundwater availability in space and over time. The method is based on the assumption that a rise or fall in water table elevation measured in wells is caused by addition or reduction or rather recharge and discharge across the water table.

Precipitation is considered to be the main conventional recharge of groundwater (Ministry of Water Resources of India, 2002). When it rains, considerable amount of water trickles down into the ground to become groundwater. Small recharge takes place from lakes, rivers and streams through seepage. In essence therefore, permeability of the rock and soil formations that the infiltrating water encounters determines the amount of water that can percolate to become groundwater. In Mchinji however no strong correlation exists between rainfall and static water levels.

The level of water table fluctuations in Mchinji has rather been linked to the influence of evaporation. Evaporation and extraction of groundwater by human beings are known major causes of discharge of groundwater apart from natural springs and artesian wells. The research in Mchinji has revealed that evaporation influences the static water levels as evidenced by a stronger R^2 of about 0.4 during regression analysis of static water levels and evaporation. Increase in evaporation has been associated with a decrease in water table depicting a reduction in groundwater reserves. An understanding of how water table elevations have changed over time helps in predictions and water management policies to be made.

Impacts of Human Activities

Human activities on the landscape impact the quality and quantity of groundwater. Aimless vegetation clearing, harmful bush fires, poor agricultural practices and unregulated groundwater extraction ultimately affect the quality and groundwater availability. The activities by human beings affect the rate and amounts of infiltration and groundwater transmission to a larger extent.

Geographic Information System and Remote Sensing techniques were used to analyze land use and land cover change in Mchinji. Time series land use and land cover satellite images for 1989, 1999 and 2009 were obtained and used in the analysis. The analysis has revealed that almost all the sampled wells fall under the agricultural/settlement land use class category whose coverage according to the images and calculation increased from about 84% in 1989 to about 90% in 2009. The sampled wells are also associated with the degraded forest category whose coverage increased from about 2% in 1989 to about 7% in 2009.

The analysis of land use change has revealed that land clearing has increased due to opening up of farm lands. Cultivated and settlement area have increased and most natural savanna disappeared in the process. Favreau et al., (2001) noted that this has a direct consequence of a reduction of the transpiration loss and uptake from the water table by roots of plants. In Mchinji however, because of a thick unsaturated zone averaging about 30m (Geological Survey, 1968), land clearing has probably little impact on the groundwater budget. Agricultural/settlement land and degraded land are also associated with devegetation to some extent. This means that spatial variations in infiltration are imminent due to the increase in these land uses in Mchinji. In addition settlement and agricultural land use class categories are associated with the rearing of animals in kraals and grazing areas. As noted earlier, some biological contamination in groundwater originates from droppings of animals and from human excreta in the pit latrines. This in a way could explain the high concentrations of fecal coliform bacteria in some of the sampled wells.

Groundwater Monitoring

Groundwater monitoring is another important exercise to be considered in groundwater studies. Among other issues William (2007) noted that groundwater monitoring tracks changes in groundwater levels to help decision makers understand long term sustainability of aquifers as source of water supply and make informed policy choices. In addition groundwater monitoring provides an idea on groundwater contamination through identification of contamination, their levels, their sources and how to avoid their movements to wells. Furthermore, groundwater monitoring and assessment helps timely warnings, declarations and possible mitigation measures.

In Mchinji groundwater monitoring is not being done on a regular basis. Information obtained through focused group discussions with the authorities for water affairs and the water users have revealed that groundwater monitoring is absent or rather sporadic. In addition water resources monitoring requires abundant hydrological data. It is therefore, important for all the key players in the sector to improve infrastructure and skills for recording hydrological data as it helps in planning and decision making in the course of achieving an integrated water resources management.

Groundwater Sustainability

Linked to the issue of groundwater monitoring is how to sustain groundwater in Mchinji. Water resources sustainability requires meeting the needs of the generation such as drinking, irrigation, industrial, recreational and for energy for social economic development while at the same time protecting the environment and improving social conditions. This implies finding trade-offs between economic, environmental and social goals. Kumambala (2010) notes that sustainability of water resources in a given catchment is directly related to its hydrological, environmental, life and policy conditions that govern the water sector. Despite brief information on groundwater availability and perhaps distribution the major concern in Mchinji and indeed the entire country should be on information on the quantity and quality of the groundwater sustainable yields. This ultimately calls for the need to intensify groundwater monitoring. In the water sector in Malawi and Mchinji in particular according to Kumambala (2010) the existing development, utilization and management of groundwater resources lack sustainable strategies despite its extensive use for water supply to most of the population, where monitoring of water resources is almost non-existent.

Participant observation has revealed that in Malawi some donors, Non-Governmental Organizations and other government departments are utilizing water resources without agreed and consistent control, coordination, regulation and legislation of policies. In some instances, it has been discovered that borehole construction firms are not controlled and regulated to check compliance with standards and measures to protect the water resources from degradation and public malpractice (Kumambala, 2010).

Guidelines for appropriate measures towards sustainable groundwater management and utilization require the combination of both environmental and land use components. According to Colin et al., (2001) the environmental factors include hydrology (water table), physiographic (slope), soil (permeability) and vegetation cover. Land use factors on the other hand include conservation (recreation), agriculture, residential, industrial and commercial. Groundwater sustainability requires the integration of plans and operations with needs of the society.

Analysis of the groundwater sustainability plans also reveal the requirement of public backing for financial support and pollution control. Colin et al., (2001) also emphasized that a civic educated society in groundwater monitoring and groundwater sustainability issues is more ideal. This entails that sustainable water resource management and planning can be achieved in the long run only when land use is ecologically balanced with the carrying capacity of the land in question. Furthermore, it entails that all human needs are fulfilled so that society can focus their concerns and finances on hydrological and environmental objectives. The social factors which should also be integrated in groundwater sustainability issues include education levels of the people, their income, their economic goals and the political system of the area concerned. In Mchinji, the literacy rates and economic incomes are still very low with the local population still dependant on nature as a source of income. This includes charcoal burning coupled generally with poor methods of farming as a means of economic survival. These scenario off-sets the efforts being done in the course of attaining integrated and sustainable water resources management.

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

Conclusion

The research aimed at investigating the levels of concentrations of certain selected chemical and biological elements in the groundwater of the Mchinji district of central Malawi. The elements include pH, electrical conductivity, iron, manganese, fluoride, chlorides, sulfates, sodium, total dissolved solids and fecal coliform in form of bacteria. The study has also examined the amount of groundwater reserves available for extraction from 1992 to 2008 through analysis of groundwater table fluctuations. The research further attempted to highlight the linkage between human activities and their impact on groundwater quantity and quality through land use change. This was done through acquisition of satellite images for different time series from 1989, 1999 and 2009 to analyze changes in land use from one category class to another and its extent. The study has also finally attempted to suggest possible measures to ensure groundwater sustainability through analysis of policies governing the water resources sector. Of particular importance is the highlight of the need for serious groundwater monitoring in Mchinji district and indeed the entire country. The concluding remarks are therefore based on these aims and objectives and are summarized below.

Groundwater composition is not fixed or static since it may change or remain the same in space and over time. Analysis of current concentrations and levels of certain chemical elements such as pH, electrical conductivity, iron, manganese, fluoride, total dissolved solids, chlorides, sulfates and sodium has indeed confirmed that the levels in some cases have changed while in others no significant changes have been detected. The analysis results were compared to either Malawi drinking water national standards or World Health Organization. Notable cause of spatial variations has been attributed to factors like the differences in the natural environment and ecology where the wells exist. Other suggested causes include degree and extent of rock mineral weathering, residence time of the groundwater in the aquifers and wells, the degree and perhaps extent of rock-water interaction in distinct flow paths of the groundwater, age of the groundwater in question and amount of evaporation experienced.

Biological composition was also investigated in the research. Fecal coli form bacteria was traced in excess in some wells considering the World Health Organization standards. Biological contamination in form of fecal coliform originates from human excreta, animal droppings and naturally from soil. In Mchinji spatial variations in fecal coliform can be linked with specific localities of the wells coupled with the nature of the surrounding topography.

Groundwater availability and reserves were analyzed through the water rise method. The response of the water table to either precipitation or evaporation has been known to cause its fluctuations. In Mchinji the amount of evaporation experienced over the years has been the suggested influence for the fluctuations of the water table.

Analysis of satellite images for 1989, 1999 and 2009 has revealed changes in land use and land cover. Considering LU/LC change agricultural or settlement area in Mchinji has increased from 261,895.06 ha in 1989 representing 83.8% of the total land area to 279,985.5 ha in 2009 representing 89.59% of the total land area. This clearly shows that vast areas are being de-vegetated for agricultural and settlement use. On the other hand, degraded forest area has increased from 4,398.16 ha representing 1.4% of the total land area in 1989 to 22,619.76 ha representing 7.2% of the total land area in 2009. This emphasizes the extent of deforestation in Mchinj. In addition most of the wells are located in these two land use category classes.

The changes in land use and land cover play a role in determining the amount of infiltration capacity for water to become groundwater. Groundwater quality may get affected in the process through exposure of groundwater to intensive evaporation leading to accumulation of salts in the remaining groundwater. Some chemical parameters could also be introduced in groundwater through farm and agricultural inputs and farm wastes. This is a future and further research problem to establish the exact link between LU/LC and the groundwater quality and quantity.

Groundwater monitoring tracks changes in groundwater table levels and quality. The information on groundwater quality and quality helps to use the resource sustainably through production of policies that are in tandem with the current status of the water resources (Kumambala, 2010). The research has established that groundwater monitoring in Mchinji was not being done at a regular basis. Furthermore, some shortfalls in the governance of water resources have been established. For instance some policies have existed with no proper legislation to supplement it with an enabling system and structure to make sure that all the key players in the water sector can be aware of specific roles. Adherence to clearly stipulated and updated laws is good for the sustainability of the water resources in Mchinji and Malawi as a whole.

Recommendations

The situation in Mchinji and indeed the entire country of Malawi calls for a strong synchronization of groundwater quality, groundwater quantity, anthropogenic activities with groundwater, sustainability and monitoring issues in order to attain a sustainable and integrated water resources management. It is therefore of paramount importance that ecological concerns should be incorporated into the governance of the water resources agenda. Water resources governance should consider economic status of the people their social requirements while at the same time attempts should be to preserve the environment. In essence viable measures should be put in place which should be generally enforceable. The establishment of such measures ensures that over exploitation of groundwater resources can be checked. The measures can further assist in the rehabilitation of some groundwater areas that are on the verge of degradation. It is therefore recommended that government should take the onus to reconcile the water sector and water resources management so that ecological sustainability can be ensured. The following recommendations are therefore advanced to assist in the establishment of a sustainable water resources utilization and management:

i) The government is called upon to allocate more financial resources to ensure that groundwater quality and quantity levels are monitored on a regular basis in Mchinji and indeed the whole country. This will ensure timely decisions, production and implementation of policies that are in tandem with the existing situation of the water resources. This can be done through construction of observation wells with careful lithology analysis in Mchinji and elsewhere in the country.
ii) Linked to the allocation of financial resources is to make sure that government places a special need on capacity building of relevant key players in the water sector. This will equip the personnel with the expertise to expedite water resources requirements and service delivery with diligence.
iii) The contents of the national policies in documents from the various sectors that are involved in water resources management should be circulated and

explained to members the public. This will ensure that everybody is kept abreast on all water resources agenda. Furthermore, it may prove to be of vital importance if issues to do with hydrology and geohydrology are introduced to learners in schools and universities. This may improve the dissemination of information.

iv) The political leaders, traditional and religious leaders are also called upon to take a leading role in emphasizing for a holistic and harmonized approach amongst the sectors such as agriculture and forestry that play important roles in the water sector. This is because of the interplay that exists amongst such sectors in determining the extent of a sustainable water resources management.

v) Government is also called upon to take a leading role in updating and legislation of laws that govern the water sector. Updated laws with necessary enabling legislation will allow adherence to the stipulated standards and regulations on utilization of water resources. The updated laws and legislation may create room for disseminating valuable information and perhaps punitive measures to offenders that lack compliance with those laws.

vi) The water sector is also called upon to integrate local communities to get assured of grassroots support of water resources management plans. People are always keen to support a management plan when they feel that they were part and parcel of the creation process. This therefore calls for proper consultation process in the formulation and production process of water resource use and management plans. Lack of proper consultation with the local people may entail lack of their support to plans which are sustainably focused.

vii) The water sector is also called upon to improve on hydrological data storage. Pertinent decisions in water resources management require the availability of such data. Information and records of wells should be properly kept for easy reference.

Future Research

The research has revealed that in general sustainable and integrated water resources management issues in Mchinji and indeed the whole Malawi have some shortfalls. The shortfalls appear both on the part of the authorities and the water users. Field observations have shown that people did not have enough knowledge on issues related to water quality and groundwater availability. The authorities and the water users were not aware of the dwindling groundwater chemical and biological elements.

The amount of groundwater available does not seem to be of concern to the general public. It is therefore suggested that since it has been discovered that the general trend of some of the elements like pH, electrical conductivity and total dissolved solids are generally decreasing, future research should be aimed at monitoring the situation and status to take remedial measures on time if the decrease becomes a health risk. Groundwater availability should be followed with keen interest so that a sustainable water resources management can be established while at the same time to ensure that groundwater recharge, utilization and ecology are always in equilibrium and well balanced.

Future research should also aim at determining the exact geological formations encountered during drilling of the wells using cross cutting lithologies to come up with detailed geological maps to make informed decisions on effects of the local geology on some of the water quality parameters. Furthermore, attempts should be made in future research to determine the concentrations of nitrates in the groundwater to ascertain whether the kind of fertilizers applied in the agricultural fields, tobacco and maize estates is affecting the water quality.

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APPENDICES

APPENDIX A: Questionnaire for Water Point Committee (WPC)

1. Village Name………………………………………………………………………
2. How was Committee formed?

   ……………………………………………………………………………………

   ……………………………………………………………………………………

   …………………………………………………………………………………….

   ……………………………………………………………………………………

   ……………………………………………………………………………………

3. Was it trained?

YES	NO

4 If yes, who conducted the training and for how long was it conducted

....

5 No of men………………………No. of women………………………………………

6 What topic/issues were covered during training

- Can communities maintain their wells? State how?

……………………………………………………………………………………….

………………..…………………………………………………………………..

Which Water quality parameters do you know? State them

…………………………………………………………………………………

…………………………………………………………………………………

- Which anthropogenic activities can affect groundwater quality?
…………………………………………………………………………………
………………………………………………………………………………..
- What is the importance of groundwater quality knowledge
………………………………………………………………………………..

………………………………………………………………………………..
- Which physical water parameters can you see in water with naked eye…………………………………………………………………………
…………………………………………………………………………………
………………………………………………………………………………..
- Any change in well performances in the project area since construction of the facilities. Explain………………………………………………………………..
…………………………………………………………………………………
………………………………………………………………………………..

- Any change in water quality (deterioration) since construction of the facilities in the project area.

YES	NO

- If yes explain the causes……………………………………………………….

………………………………………………………………………………………

……………………………………………………………………………………..

Did the area experience any water borne diseases since the facilities were constructed?

YES	NO

If yes explain the remedy…………………………………………………………

- How frequent is data collected on water quality from the wells…….............

………………………………………………………………………………………

How accurate is the data collected ……………………………………............

- Do meteorological effects have impact on groundwater

YES	NO

If yes explain how?

………………………………………………………………………………………

……………………………………………………………………………………..

- What problems affect data collection if any?

………………………………………………………………………………………

……………………………………………………………………………………..

- Is groundwater monitoring important

YES	NO

- If yes, explain why……………………………………………………

………………………………………………………………………….

7 Did you find the training useful?

YES	NO

8 If yes, how useful was the training……………………………………………..................

………………………………………………………………………………………………

………………………………………………………………………………………………

9 If no, what was wrong with the training or topics covered?

……………………………………………………………………………………………………

……………………………………………………………………………………………………

11. Do you have a revolving fund for the well for maintenance and repairs?

YES	NO

If yes, when was it established?

……………………………………………………………………………………………………

……………………………………………………………………………………………………

12. How much money has been raised?

……………………………………………………………………………………………………

…………………………………………………………………………………………………..

13. How many times did the well breakdown and how long did it take to repair the well?

……………………………………………………………………………………………………

APPENDIX B: Questionnaire for Water Officer & District Assembly

1. Officers' name…………………………………………………………………………….
2. Officers' duty station………………………………...
3. Work experience ………………………………………………………………....................
   ……………………………………………………………………………………………...……
   …………………………………………………………………………………………………
4. Technical knowledge on the following topic or issues
   - Can communities maintain their wells? Stat how? ………………………….
     ………………………………………………………………………………………
   - Which Water quality parameters do you know? State them………………...
     ………………………………………………………………………………………
     ……………………………………………………………………………………..
   - Which anthropogenic activities can affect groundwater quality?
     ………………………………………………………………………………………
     ……………………………………………………………………………………..
   - What is the importance of groundwater quality knowledge………………..
     …………………………………………………………………………………….
     …………………………………………………………………………………….
   - Which physical water parameters can you see in water with naked eye………………………………………………………………………………
     ………………………………………………………………………………………
     ……………………………………………………………………………………..

- Any change in well performances in the project area since construction of the facilities. Explain…………………………………………………………………
…………………………………………………………………………………………
……………………………………………………………………………………..

Any change in water quality (deterioration) since construction of the facilities in the project area.

YES	NO

- If yes explain the causes…………………………………………………………
…………………………………………………………………………………………

Did the area experience any water borne diseases since the facilities were constructed?

YES	NO

If yes explain the remedy ………………………………………………………..

- How frequent is data collected on water quality from the wells……………
…………………………………………………………………………………………

How accurate is the data collected ………………………………………...........

- Do meteorological effects have impact on groundwater

YES	NO

If yes explain how……………………………………………………………………..

- What problems affect data collection if any?

…………………………………………………………………………………………

………………………………………………………………………………………..

- Is groundwater monitoring important

YES	NO

If yes explain why…………………………………………………………………….

……………………………………………………………………………………….

……………………………………………………………………………………….

APPENDIX C: Checklist of Issues for Focused Group Discussions

On human impacts affecting groundwater, attempts will be made to get information on the following issues:

- Trend of forestry cover degeneration or depletion through land clearance for new farms, charcoal burning and tobacco curing during the observation period. This will involve a focused group discussion as a source of information gathering with the forestry department officials in Mchinji district. Depletion of vegetation especially in sloppy areas will be given special emphasis.
- Portion of the land being used for farming at the present as compared to the time the wells were being constructed.
- Type of farming practices and methods. Attempt will be made to find out if the farming technologies and strategies are modern or traditional as regards water conservation. The department responsible for agriculture in Mchinji will be visited for a focused group discussion.
- Type of fertilizers being applied to the agricultural fields whether inorganic or organic. What kind of herbicides and pesticides are applied to crops?
- Number of people extracting groundwater from the wells. An attempt will be done to consider the original planned population to utilize the wells and the current population to find out current abstraction. The department responsible for water affairs will be visited for a focused group discussion.

In short agriculture and other human activities must co-exist with groundwater.

On guidelines for sustainable groundwater resources management attempts will be made to get information on the following:

- Get an appraisal of existing national water policy to find out what it says on groundwater protection. Assess its setbacks and shortfalls (weaknesses).
- How to address loopholes of the existing water policy through assessment of its legislation and related enforcement of by-laws pertaining to the water policy and Water Act as enacted by Parliament. Policies of other countries may be sampled to see if Mchinji and Malawi can benefit and adopt some strategies.
- The water users will be asked how often they see people from the water department coming to collect information on groundwater from the wells.
- The water users will be asked about their knowledge on safe and health groundwater.
- The water users will be asked if they know the importance of groundwater monitoring as it relate to sustainable groundwater utilization. They should explain their roles and responsibilities to that effect. What plans are there on groundwater monitoring by the department of water affairs.
- The level of public awareness on dangers of groundwater contamination will be assessed through focused group discussions with the water users and the personnel responsible for water affairs and other necessary key stakeholders.

APPENDIX D: Laboratory Data for Chemical & Biological Analysis

LAB No.	429	430	431	432	433
DATE SAMPLED	22/09/08	22/09/08	22/09/08	22/09/08	22/09/08
DATE ANALYSIS COMPLETED	24/09/08	24/09/08	24/09/08	24/09/08	24/09/08
WELL NAME	Mnamizana	Kankhande II	Kankhande I	Mzingo	Kamphemvu I
pH Value	7.33	7.10	7.07	7.29	7.12
Conductivity (µs/cm at 250C)	169	342	233	411	226
Total dissolved solids, mg/l	85	174	120	215	115
Carbonate (CO32-), mg/l	0	0	0	0	0
Bicarbonate (HCO32-), mg/l	86.4	164	92.0	164	112
Chloride (Cl-), mg/l	6.8	3.4	6.8	33.4	13.5
Sulphate (SO42-), mg/l	4.2	27.9	28.1	58.5	5.1
Nitrate (NO3-), mg/l	0.04	0.01	0.19	<0.01	0.39
Fluoride (F-), mg/l	0.22	1.05	0.68	0.54	0.55
Sodium (Na+), mg/l	9	11	10	27	7
Potassium (K+), mg/l	2.8	1.9	0.7	3.7	3.3
Calcium (Ca++), mg/l	15.6	38.8	20	33.0	23.4
Magnesium (mg ++), mg/l	5.8	12.6	9.7	12.6	7.7
Iron (Fe ++), mg/l	0.21	0.12	0.18	0.20	0.758
Manganese (Mn ++), mg/l	<0.001	<0.001	<0.001	<0.001	<0.001
Total hardness (CaCO3),mg/l	62	148	89	134	91
Total alkalinity (CaCO3), mg/l	70	134	75	134	91

Silica (SiO2) mg/l	13	15	13	15	17
Turbidity, NTU	1.6	1.8	1.4	2.4	3.0
Suspended solids, mg/l	0	0	0	0	1.0
Faecal coliform, Count/100ml	0	0	25	4	0
Faecal streptococci, Count/100ml	0	0	4	4	10

LAB No.	434	435	436	437	438
DATE SAMPLED	22/09/08	22/09/08	22/09/08	22/09/08	22/09/08
DATE ANALYSIS COMPLETED	24/09/08	24/09/08	24/09/08	24/09/08	24/09/08
WELL NAME	Kamphemvu I	Mlamba	Kamlilika	Manthalu	Jusi
pH Value	7.31	6.99	6.84	6.41	6.90
Conductivity (µs/cm at 25^0C)	210	114	176	170	234
Total dissolved solids, mg/l	106	57	88	89	118
Carbonate (CO_3^{2-}), mg/l	0	0	0	0	0
Bicarbonate (HCO_3^{2-}), mg/l	118	56.4	78.2	57.8	118
Chloride (Cl^-), mg/l	3.4	3.4	6.8	3.4	6.8
Sulphate SO_4^{2-}), mg/l	5.6	4.5	12	24.9	7.7
Nitrate (NO_3^-), mg/l	<0.01	0.02	0.20	<0.01	0.12
Fluoride (F^-), mg/l	0.58	0.30	0.58	0.78	0.78
Sodium (Na^+), mg/l	9	9	7	14	12.0
Potassium (K^+), mg/l	4.2	3.2	0.8	3.5	3.7
Calcium (Ca^{++}), mg/l	22.3	9	13.0	10.4	20
Magnesium (mg $^{++}$), mg/l	6.7	3.0	9.4	4.7	9.7

Iron (Fe^{++}), mg/l	0.071	<0.01	0.134	0.156	0.171
Manganese (Mn^{++}), mg/l	<0.001	<0.001	<0.001	<0.001	<0.001
Total hardness ($CaCO_3$), mg/l	83	34	72	45	89
Total alkalinity ($CaCO_3$), mg/l	96	45	63	47	96
Silica (SiO_2) mg/l	15	18	14	22	15
TurbiditY, NTU	2.0	0.8	2.2	5.0	1.2
Suspended solids, mg/l	0	0	0	3.0	0
Faecal coliform, Count/100ml	8	8	0	0	0
Faecal streptococci, Count/100ml	0	4	0	0	0

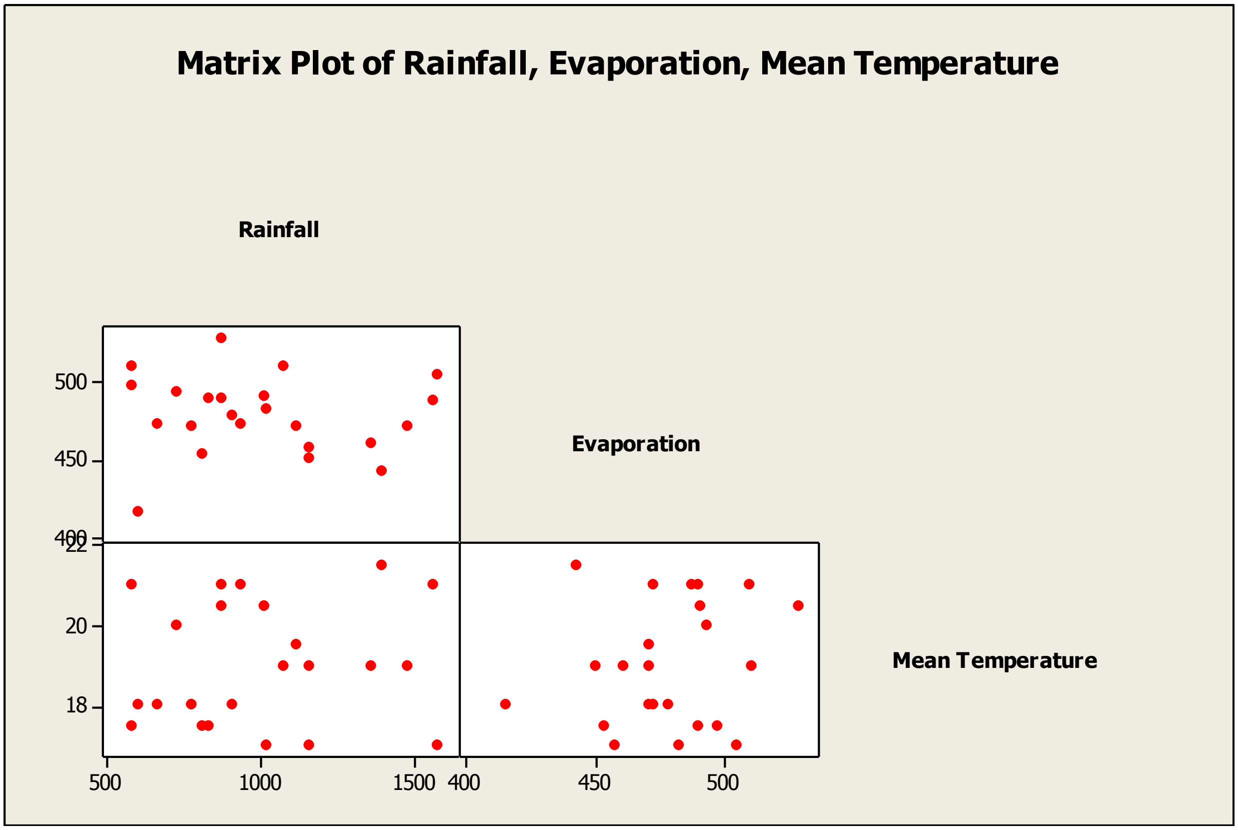
LAB No.	439	440	441	442	443
DATE SAMPLED	23/09/08	23/09/08	23/09/08	23/09/08	23/09/08
DATE ANALYSIS COMPLETED	24/09/08	24/09/08	24/09/08	24/09/08	24/09/08
WELL NAME	Kachere	Bua T/C	Chalema	Mando	Chidewa
pH Value	6.64	6.70	7.44	7.13	7.37
Conductivity (µs/cm at 25^0C)	227	214	416	206	231
Total dissolved solids, mg/l	114	109	210	105	119
Carbonate (CO_3^{2-}), mg/l	0	0	0	0	0
Bicarbonate (HCO_3^{2-}), mg/l	121.2	112	142	109.4	129
Chloride (Cl^-), mg/l	3.4	3.4	17	5.1	6.8
Sulphate (SO_4^{2-}), mg/l	8	9.1	53	6.6	6.4
Nitrate (NO_3^-), mg/l	0.03	<0.01	0.02	<0.01	0.01
Fluoride (F^-), mg/l	1.21	<0.01	0.62	0.90	0.80

Sodium (Na^{+}), mg/l	9	12	13	11	6
Potassium (K^{+}), mg/l	1.8	4.1	2.7	3.7	4.1
Calcium (Ca^{++}), mg/l	23.8	20	45.4	18.8	19.2
Magnesium (mg $^{++}$), mg/l	9.7	7.6	11.7	7.6	11.7
Iron (Fe $^{++}$), mg/l	0.162	0.144	0.127	0.141	3.526
Manganese (Mn $^{++}$), mg/l	<0.001	<0.001	<0.001	<0.001	<0.001
Total hardness ($CaCO_3$), mg/l	99	81	161	78	102
Total alkalinity ($CaCO_3$), mg/l	99	91	116	89	105
Silica (SiO_2) mg/l	15	19	17	20	16
Turbidity, NTU	4.4	3	7	6.6	1
suspended solids, mg/l	2.0	1	5	2.0	0
Faecal coliform, Count/100ml	0	0	0	0	0
Faecal streptococci, Count/100ml	0	3	0	0	2

lab no.	444	445	446	447	448
date sampled	23/09/08	23/09/08	23/09/08	23/09/08	23/09/08
date analysis completed	24/09/08	24/09/08	24/09/08	24/09/08	24/09/08
Well name	Misale T/C	Mselela	Mselela	Ngalule	Chamani
pH Value	7.37	6.72	6.84	6.60	6.76
Conductivity (µs/cm at 25^{0}C)	158	144	162	238	76

Total dissolved solids, mg/l	81	77	81	119	39
Carbonate (CO_3^{2-}), mg/l	0	0	0	0	0
Bicarbonate (HCO_3^{2-}), mg/l	68	74.2	76	115.7	38.6
Chloride (Cl^-), mg/l	10.1	3.4	6.8	10.1	<0.01
Sulphate (SO_4^{2-}), mg/l	5.9	5.8	5.8	4.8	5.5
Ntrate (NO_3^-), mg/l	0.23	0.07	0.15	0.12	<0.01
Fluoride (F^-), mg/l	0.22	0.66	0.78	0.84	0.27
Sodium (Na^+), mg/l	11	8	9	12	6.0
Potassium (K^+), mg/l	6.8	2.0	2.4	3.0	1.5
Calcium (Ca^{++}), mg/l	10	13.6	11.6	18.8	5.8
Magnesium (mg^{++}), mg/l	4.5	4.7	7.8	11.7	2.7
Iron (Fe^{++}), mg/l	0.012	0.027	0.111	0.122	<0.01
Manganese (Mn^{++}), mg/l	<0.001	<0.001	<0.001	<0.001	<0.001
Total hardness ($CaCO_3$), mg/l	43	53	61	95	25
Total alkalinity ($CaCO_3$), mg/l	55	60	62	95	31
Silica (SiO_2) mg/l	16	17	17	19	15
Turbidity, NTU	1.6	4.2	11	2.2	1.0
Suspended solids, mg/l	0	1.0	4	0	0
Faecal coliform, Count/100ml	4	43	39	3	0
Faecal streptococci, Count/100ml	0	1	7	0	0

APPENDIX E: Correlation Matrix of Rainfall, Evaporation & Temperature



APPENDIX F: Regression Data of Variables with Interaction

Regression Statistics, explanatory variables with interaction	
Multiple R	0.4799
R Square	0.2303
Adjusted R Square	0.1088
Standard Error	23.7143
Observations	23

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	3,197.2611	1,065.7537	1.8951	0.1647
Residual	19	10,684.9650	562.3666		
Total	22	13,882.2261			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	(8.8673)	211.0384	(0.0420)	0.9669	(450.5758)	432.8412
Rainfall (mm)	0.4098	0.1944	2.1077	0.0486	0.0029	0.8168
Mean Temperatures (oC)	26.0619	11.1124	2.3453	0.0300	2.8033	49.3205
rainfallxtemp	(0.0219)	0.0102	(2.1524)	0.0444	(0.0432)	(0.0006)

APPENDIX G: Regression Data of Variables without Interaction

Regression Statistics, explanatory variables without interaction	
Multiple R	0.20649
R Square	0.04264
Adjusted R Square	- 0.05310
Standard Error	25.77818
Observations	23

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	591.93593	295.96797	0.44539	0.64678
Residual	20	13,290.29015	664.51451		
Total	22	13,882.22609			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	423.88423	69.71976	6.07983	0.00001	278.45136	569.31709
Rainfall (mm)	- 0.00721	0.01776	- 0.40607	0.68900	- 0.04426	0.02984
Mean Temperatures (oC)	3.25819	3.64448	0.89401	0.38195	- 4.34405	10.86044

APPENDIX H: Rainfall and Evaporation Data

		RAINFALL	EVAPORATION
Year	Month	236.7	
1986	January	236.7	
	February	236.7	
	March	118.8	
	April	87.4	
	May	0.0	
	June	0.0	
	July	0.0	
	August	0.0	
	September	0.0	
	October	28.6	
	November	95.6	
	December	189.2	
1987	January	234.8	
	February	160.9	
	March	70.1	
	April	0.0	
	May	0.0	
	June	0.0	
	July	0.0	
	August	14.2	
	September	20.0	
	October	0.0	
	November	46.8	
	December	113.3	
1988	January	266.7	
	February	296.8	
	March	234.5	
	April	124.7	
	May	10.6	
	June	0.0	
	July	0.0	
	August	0.0	
	September	0.0	
	October	33.6	
	November	34.0	
	December	76.4	

1989	January	485.7	
	February	335.1	
	March	282.6	
	April	52.6	
	May	6.2	
	June	0.0	
	July	0.0	
	August	6.7	
	September	0.0	
	October	3.5	
	November	128.1	
	December	281.6	
1990	January	182.0	
	February	159.1	
	March	105.6	
	April	79.5	
	May	104.9	
	June	0.0	
	July	0.3	
	August	0.0	
	September	0.0	
	October	0.0	
	November	17.9	
	December	157.8	
1991	January	264.9	
	February	208.4	
	March	84.9	
	April	20.9	
	May	10.6	
	June	0.0	
	July	0.0	
	August	0.0	
	September	0.0	
	October	37.4	
	November	72.2	
	December	72.2	
1992	January	189.9	45.1
	February	15.6	51.8
	March	267.5	42.3
	April	17.4	38.6

	May	0.8	31.5
	June	0.0	28.5
	July	0.3	28.9
	August	0.0	34.6
	September	0.0	46.8
	October	0.6	54.4
	November	62.6	51.1
	December	168.8	40.2
1993	January	317.2	35.7
	February	274.9	39
	March	289.5	36.4
	April	116.2	35
	May	0.8	34.3
	June	0.0	29.5
	July	3.2	28.5
	August	1.5	34.2
	September	17.3	45.7
	October	5.0	52
	November	150.0	46
	December	189.0	44.2
1994	January	273.8	42.5
	February	74.9	44.1
	March	49.8	45.1
	April	40.9	40.1
	May	0.7	33.6
	June	0.0	27.1
	July	0.0	28.6
	August	0.0	38.8
	September	0.0	46.5
	October	36.5	44.4
	November	12.2	57.9
	December	91.2	48.8
1995	January	185.0	38.3
	February	177.3	43.6
	March	36.8	43.8
	April	0.0	38.5
	May	0.0	32.7
	June	0.0	31.9
	July	0.0	28.6
	August	0.0	35.8

	September	0.0	43.3
	October	0.0	53.6
	November	71.2	55.3
	December	252.9	44.5
1996	January	152.4	40.2
	February	324.3	39.4
	March	0.0	34.6
	April	0.0	35.6
	May	61.8	29.7
	June	0.0	27.1
	July	3.0	29.4
	August	2.1	36.6
	September	0.0	47.9
	October	20.7	49
	November	31.7	56.1
	December	157.7	38.3
1997	January	261.0	35.6
	February	270.0	35.5
	March	55.5	39.3
	April	50.0	36
	May	0.0	33.8
	June	0.0	31.9
	July	0.0	26.3
	August	0.0	35.4
	September	0.0	38.5
	October	67.0	45.3
	November	147.2	49.8
	December	552.9	36
1998	January	244.6	39.5
	February	159.9	46.3
	March	142.1	38.6
	April	24.9	34.8
	May	0.0	36.5
	June	0.0	30.2
	July	0.0	29.8
	August	0.0	38.1
	September	0.0	44.9
	October	49.2	48.9
	November	147.6	53.8
	December	246.8	49.2

1999	January	272.4	37.3
	February	186.6	38.7
	March	408.7	36.1
	April	121.9	35.3
	May	0.0	31.7
	June	0.0	28.9
	July	0.0	29.7
	August	0.0	33.2
	September	0.0	43.6
	October	10.7	50.3
	November	11.7	48.4
	December	151.9	45
2000	January	184.9	37.1
	February	170.9	38.3
	March	206.8	35.8
	April	88.5	34.9
	May	0.0	30.3
	June	0.0	27.1
	July	0.0	31.4
	August	0.0	33.2
	September	0.0	45.2
	October	25.0	52.4
	November	254.9	42.6
	December	233.3	42.3
2001	January	420.0	35.9
	February	324.1	38.7
	March	332.3	33.4
	April	115.8	35.6
	May	0.0	30.7
	June	0.0	27.4
	July	0.0	30.6
	August	0.0	40.4
	September	0.0	44.1
	October	12.5	50.6
	November	53.2	53.6
	December	225.7	49.6
2002	January	360.3	39.6
	February	150.0	41.8
	March	34.0	41.3
	April	33.8	35.9

	May	0.0	32.5
	June	0.0	28.6
	July	0.0	33
	August	0.0	37.3
	September	0.0	38.4
	October	0.0	50.7
	November	37.2	53.4
	December	323.0	41
2003	January	283.4	43.2
	February	233.1	40.8
	March	283.0	36.7
	April	13.6	36.2
	May	0.0	33.5
	June	0.0	27.8
	July	0.0	29.1
	August	0.0	41.7
	September	24.0	44.2
	October	0.0	55.5
	November	0.0	53.3
	December	180.7	41
2004	January	236.8	43
	February	140.0	49.8
	March	115.5	37.9
	April	143.3	33.5
	May	0.0	31.9
	June	0.0	28.4
	July	0.0	29
	August	0.0	35.3
	September	0.0	45.7
	October	4.9	46.3
	November	114.7	50.4
	December	144	39.5
2005	January	219.8	43
	February	54.3	46.6
	March	50.3	41.8
	April	15.8	42.3
	May	18.6	35.8
	June	0	29.6
	July	10.9	30.6
	August	0	38.4

	September	0	43.9
	October	0	50.7
	November	54.4	59.3
	December	152.3	48
2006	January	255.2	38.6
	February	181.9	39.1
	March	276.7	40
	April	54.5	35.4
	May	0	35.4
	June	0	32.5
	July	0	31.9
	August	0	37.2
	September	0	44.3
	October	0	49
	November	146.9	45.7
	December	203	41.7
2007	January	327.7	
	February	139.9	
	March	123.1	
	April	48	
	May	0	
	June	0	
	July	0	
	August	0	
	September	0	
	October	1	
	November	2.2	
	December	267.8	
2008	January	200	
	February	119.7	
	March	89.7	
	April	14.6	
	May	0	
	June	0	
	July	0	
	August	0	
	September	0	
	October	31.1	
	November	82.5	
	December	264.9	

APPENDIX I: Static Water Levels for Sampled Wells

	1992	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	Average
Kachele	6.4	6.4	11.0	9.4	12.0	5.4	4.6	9.2	4.6	12.5	6.2	4.0	4.2	8.2	15.0	2.5	3.0	7.3
Mzinga	7.1	6.6	6.0	10.7	4.0	4.7	5.2	4.9	11.0	6.0	7.0	7.1	5.8	7.9	3.6	2.2	7.2	6.3
Kamphemvu II	2.2	3.0	13.0	7.8	9.0	6.1	6.2	5.5	5.8	6.7	7.0	6.3	7.3	6.1	4.4	3.1	2.9	6.0
Mlamba	2.7	2.7	8.0	10.0	4.0	5.2	6.0	15.3	8.8	7.6	7.2	3.8	13.2	3.6	3.2	13.0	2.7	6.9
Kankhande II	6.0	6.5	5.0	6.1	2.0	4.9	3.0	4.8	2.0	4.3	6.9	6.4	4.2	6.1	6.0	14.6	5.7	5.6
Kankhande I	3.4	3.7	6.5	3.0	5.0	5.7	5.2	14.4	4.9	7.0	7.2	3.8	3.7	1.5	5.0	3.1	3.3	5.1
Mnamiza	4.0	4.0	3.0	6.1	2.0	2.3	2.4	7.6	7.0	6.1	5.1	5.5	1.9	2.1	4.6	13.7	3.2	4.7
Masitala	3.4	3.0	6.0	3.4	1.0	4.1	6.1	3.7	6.4	2.1	7.1	4.0	9.1	7.7	5.2	15.0	3.3	5.3
Bua	6.2	5.9	9.0	5.0	4.4	3.8	3.1	4.0	16.0	5.2	7.0	1.7	10.4	6.8	2.9	7.9	5.4	6.2
Jusi	4.0	3.2	6.0	6.0	1.0	4.3	3.4	6.1	5.0	2.7	3.8	4.2	6.2	4.3	7.8	2.0	3.7	4.3
Lumelo	4.9	4.8	11.3	9.0	3.8	3.5	7.6	7.0	5.0	6.9	6.0	7.7	27.2	9.2	7.3	6.4	4.5	7.8
Mavwere	9.3	14.6	6.2	12.2	5.0	2.6	3.7	4.8	2.4	6.7	3.9	6.8	3.6	13.4	4.2	5.2	10.4	6.8
Mthawila	3.7	3.0	7.0	4.8	3.0	3.4	4.6	3.6	3.1	4.6	4.2	5.0	3.3	5.3	3.3	1.8	3.5	3.9
Msemwe	5.6	6.2	7.0	12.2	-	3.4	6.3	3.1	5.5	6.1	2.8	4.0	6.9	10.7	6.0	3.8	4.3	5.5
Chidewa	6.3	5.7	9.0	2.4	1.0	1.9	12.2	3.5	4.0	12.2	5.8	2.8	2.6	12.2	3.0	4.5	4.6	5.5
Average	5.0	5.3	7.6	7.2	3.8	4.1	5.3	6.5	6.1	6.5	5.8	4.9	7.3	7.0	5.4	6.6	4.5	

APPENDIX J: Linear Regression for Rainfall & Static Water Level

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.17314
R Square	0.02998
Adjusted R Square	-0.03469
Standard Error	1.17322
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.63808	0.63808	0.46357	0.50633
Residual	15	20.64662	1.37644		
Total	16	21.28471			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	6.51606	1.06452	6.12116	0.00002
Rainfall	-0.00071	0.00105	-0.68086	0.50633

APPENDIX K: Linear Regression for Evaporation & Static Water Levels

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.60457
R Square	0.36551
Adjusted R Square	0.32321
Standard Error	0.94886
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	7.77973	7.77973	8.64095	0.01015
Residual	15	13.50498	0.90033		
Total	16	21.28471			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-6.66637	4.25315	-1.56740	0.13787
Evaporation	0.02618	0.00890	2.93955	0.01015