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Towards Managed Groundwater Development for Sustainable Urban Growth

Bezawit Adane Demisse

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Towards Managed Groundwater Development for Sustainable Urban Growth

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by
Bezawit Adane Demisse

Supervisor
Prof. Dr. M. McClain

Mentor
Tibor Stigter,PhD, MSc

Examination committee
Prof. Dr. M. McClain
Dr. T. Stigter
Dr. F. van Steenbergen

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Abstract

Many arid and semi-arid regions in Ethiopia rely on groundwater resources for their domestic supply and agricultural production. Therefore, a better understanding of the groundwater systems is important to manage these resources for sustainable urban development. Increasing water demands due to an increase in population and land use change will further increase dependence on groundwater in this region. The development and management of groundwater resources therefore requires estimation of the long-term potential and optimum groundwater availability and assessment of the groundwater vulnerability to contamination, both under present-day land use conditions and future scenarios.

This study was performed in the upper part of the Awash River Basin located east-central part of the country, within the Oromia regional State and covering an area of 2500 km^2. Water demand in the area is among the highest of the country. Due to intensively cultivated agricultural activities the aquifer in the study area is subjected to groundwater contamination. In addition, the rate of groundwater recharge and the potential effect of land use changes on groundwater contamination potential are largely unknown. Therefore, quantifying groundwater recharge and identifying areas of high groundwater vulnerability to contamination is essential for sustainable groundwater development and management in the study area.

In this thesis a soil water balance approach was used to estimate the groundwater recharge. Potential evapotranspiration (PET) was estimated by comparing three different temperature-based methods: Thornthwaite, Hamon and Blaney-Criddle methods. Differences among the results obtained with these methods were assessed and subsequently the Thornthwaite was selected on the basis of a comparison with other existing data on potential evapotranspiration, as well as existing correlations between the methods. Rainfall was estimated based on Thiessen polygons. Daily groundwater recharge values were calculated based on soil PET, crop factors, water storage capacities and runoff thresholds, for which values were obtained and a sensitivity analysis was performed. Results of the study showed that the total groundwater recharge in the study area was in the order of 514 Mm^3. Uncertainties in recharge estimation give emphasis to the need for the application of multiple techniques to increase consistency of the recharge estimates.

The Susceptibility Index, adapted from the USEPA DRASTIC method, was used to assess aquifer vulnerability to contamination. The method calculates the index as a weighted sum of land use and four environmental parameters, namely depth to groundwater, recharge rate, aquifer media and topography, rated on the basis of classification tables. Arc GIS 9.3 was used to apply the index to the area. Results of the vulnerability assessment indicated that the southeastern part of the study area is more dominated by very high vulnerability classes due to the shallow water table, intensive cultivation and aquifer media with course sediments. The western part of the study area is characterized by moderate vulnerability classes, as a result of deeper groundwater levels and higher slopes which have a decreasing effect on the aquifer vulnerability. The Susceptibility Index can be used for assessing the groundwater contamination potential to future land use changes and identifying areas where stronger groundwater protection measures are required.

Keywords: Groundwater potential; hydrochemistry; groundwater demand; land use; vulnerability assessment; Susceptibility Index; water balance

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Abbreviations

AET	Actual evapotranspiration
B&C	Blaney-Criddle
BAU	Business as usual
CSA	Central Statistics Authority of Ethiopia
DEM	Digital elevation model
EC	Electrical conductivity
FAO	Food and Agriculture Organisation of the United Nations
GDP	Gross Domestic Product
Ha	Hectare
ITCZ	Inter Tropical Convergence Zone
Km	Kilometre
Lpcpd	Litre per capita per day
m.a.s.l.	Meters above sea level
MAR	Managed Aquifer Recharge
MCM	Million cubic meters
mm	Millimetres
MoWE	Ministry of Water and energy
NMSA	National Meteorological Services Agency
OWRB	Oromia Water Resources Bureau
PET	Potential Evapotranspiration
SI	Susceptibility Index
TDS	Total dissolved solid
WHO	World Health Organisation
WRDA	Water Resources Development Authority
WWDSE	Water Works Design and Supervision Enterprise

CHAPTER 1

Introduction

1.1. Background

Groundwater is of paramount importance source for many uses in developing countries to supplement the available surface water resources by providing drinking water to its population and for economic development of agriculture, livestock, industry and tourism (Foster et al., 2012). Sustainable resource management planning requires consideration of changes in land use on the quantity and quality of groundwater. Land use changes are recognized to impact the groundwater potential. However, the quantitative effect of land use changes on the groundwater system have been so far poorly studied (Dams et al., 2008). The quantity and quality of groundwater is changing due to human activity. Land use changes are one of the main human induced activities changing the groundwater system (Calder, 1993). Assessing the impact of land use on the groundwater system and predicting the magnitude of change in the future is therefore a major scientific challenge (Anibas et al., 2011). A clear understanding of the significant impact of land use change can create guidelines for sustainable groundwater management.

Groundwater receives recharge where the geological formation constituting the aquifers crop out, and discharges at springs, into streams, wetlands or directly into the lake. The groundwater resource volume available for abstractions for human use can be considered as the difference between recharge and discharge. Human activities can affect the available groundwater resources by causing changes in recharge potential, for instance by changing land use. In fact, change in land use affect any of the variables determining diffuse recharge (e.g. soil type, climate, and vegetation cover) may have an impact on the amounts of water entering to the aquifers (Petheram et al., 2002). Urbanization is an extreme example of human impact on recharge, as it results in an enlarged impervious area contributing to decreased infiltration. Therefore, a rapid growth in urbanization in many countries, including Ethiopia, poses a significant risk to groundwater resource availability, both due to an increase in water demand and decrease in aquifer replenishment**.**

Groundwater recharge estimation is crucial in water resources management, particularly for areas in which groundwater is important for the local water supply. There is a need to understand the hydrological processes in the area that could be greatly altered by global change and human activities for exact estimation of regional groundwater recharge(Nolan et al., 2007).

Quantification of the recharge is essential for a reliable estimation the sustainable yield of the groundwater aquifers (Obuobie et al., 2012). There are different methods for estimating groundwater recharge. These include numerical methods like water balance simulation (Anuraga et al., 2006, Pan et al., 2011, Batelaan and De Smedt, 2007), isotope tracers (Wang et al., 2008), and statistical approaches such as water-table fluctuation (WTF) analysis (Moon et al., 2004, Maréchal et al., 2006). Among these, the impact of land use change on groundwater recharge at the regional scale can be assessed using a distributed water balance simulation method. A numerical groundwater flow model can be applied with a focus on how groundwater processes respond to land use change, and what affect various land uses have on groundwater recharge.

Understanding the relation between land use change and groundwater recharge and demand is very important for sustainable management of water resources development under changing environmental conditions. Therefore this study will consider the impact of land use change on groundwater recharge and demand in the study area, where groundwater plays an important role in water supply.

In addition to land use change groundwater contaminants vulnerability assessment is an important task for identifying the vulnerable area for groundwater contamination. The evaluation of groundwater vulnerability and the evaluation of contamination risk facilitate the planning of protection and control. It is the most important approach to sustaining groundwater quality and the overall resource protection together with the delineation of special protection areas around major sources of groundwater (Stigter et al., 2006).

Susceptibility Index mapping is defined as a technique for measuring the sensitivity of the resource to its environment, and its useful to practical visualization means for decision-making (Stigter et al., 2006). The environmental concerns in relation to human uses are commonly determined on the impact of pollution and quality related to groundwater and degradation. Therefore urbanisation and high population growth the cause of greater amounts of domestic and industrial effluents are discharged into shallow aquifer which can increase the pollution of ground water. The advantages of mapping vulnerability for a specific pollutant or group of pollutants were pointed out by (Mádl-Szőnyi and Füle, 1998) and (Foster, 1998), among others

According to (Rahman, 2008) ground water vulnerability is the tendency and chances for general contaminants to reach the water table after introduction at the ground surface. Susceptibility Index which is the specific vulnerability assessment method, (Stigter et al., 2006), is an adaptation of the DRASTIC method and was developed with the intention of evaluating aquifer vulnerability to diffuse agricultural pollution. In this study case we applied the SI Index to assess the vulnerability extent.

Vulnerability is distinct from pollution risk (Jolly, 2008); pollution risk depends not only on vulnerability but also on the existence of significant pollutant loading entering the sub-surface environment. Therefore it is important to make clear the distinction between vulnerability and risk. It is possible to have high aquifer vulnerability but no risk of pollution, if there is no significant pollutant loading; and to have high pollution risk in spite of low vulnerability, if the pollutant loading is exceptional.

1.2. Problem statement

Ethiopia has a high surface and groundwater resources potential; the preliminary estimated quantity of yearly groundwater recharge of the country is about 28,000 Mm^3 (Kuniansky et al., 2007). Most of the developed groundwater resources are mainly used for domestic and industrial use. Currently, more than 80% of Ethiopia’s drinking water supply comes from groundwater (Awulachew et al., 2007). Notwithstanding, groundwater resources in the country are yet to be exploited to their full potential. Moreover, despite the increase in water access, water quantity, quality and sustainability of urban water service are a huge concern. At present, there are still large gaps in knowledge, skills and experiences for a proper assessment and sustainable development and management of groundwater, as well as the impact of land use changes on the groundwater flow system, including a possible reduction in recharge and increase in demand.

The upper part of Awash River basin in Ethiopia, which includes the study area, is the most developed region of the country. Increasing demand due to an increase in population and climate change will further increase dependence on groundwater. In addition, rate of groundwater recharge and the effect of land use change to groundwater contamination are largely unknown. Therefore, the development of groundwater resources in the study area must be well managed, particularly in areas where these resources could be vulnerable to contamination. Enormous industrial and agricultural activities will cause contamination of water bodies from different sources. On top of that the groundwater resources of the study area are increasingly exposed to anthropogenic activities on the land surface above, due to urbanization and industrialization, but there is no groundwater protection measure of any significance in the area so far. There are uncontrolled discharges of effluents from urban area (solid waste and untreated waste water) and industries. The aquifers and the shallow aquifer systems in the urban area are severely contaminated by these discharges. The overall availability of groundwater resources will be in danger due to the lack of groundwater protection and urbanization causing a reduction of direct recharge from precipitation and an increase in demand. The intensification of agriculture can further result in an increase in groundwater demand and pollution risk.

1.3. Objectives

The main objective of this MSc study is designed to assess the quantitative and qualitative groundwater resource potential of the study area, and understand the potential impacts from different land uses and land use change scenarios, based on recharge and demand calculations, as well as uncertainty and vulnerability assessment. The results will contribute to providing recommendations for best land use practice to protect groundwater quality and optimize sustainable exploitation.

1.3.1. Specific Objectives

- To understand the groundwater flow system with analysis of groundwater levels and chemistry data;
- To estimate groundwater recharge based on the hydrological and meteorological data;
- To build a groundwater contamination vulnerability map;
- To analyze implications of population and development scenarios on groundwater demand and compare it to groundwater potential and optimal availability;

1.3.2. Research questions

To address the objective the following research question are formulated:

1) What will be the best land use practice to protect groundwater availability and quality?
2) How much groundwater can be sustainably developed in the Ada'a Plain?
3) What is the current vulnerability of the area to groundwater contamination?
4) What will be the implication of population development, urbanisation and groundwater demand?

CHAPTER 2

Literature review

This section presents several different reviews based on scientific literature, including: section 2.1 Methods for groundwater recharge estimation; 2.2 Impact of land use change on Groundwater recharge and quality; 2.3 Vulnerability assessment of groundwater contamination

2.1. Methods for Groundwater Recharge Estimation

Groundwater recharge can be classified as (i) direct or indirect on the basis of the origin of the recharging water, (ii) piston or preferential flow on the basis of the flow process through the unsaturated zone, (iii) point, line or areal recharge on the basis of the area on which it acts, and (iv) present-day, short-term or long-term recharge on the basis of the time scale during which it occurs (Lerner, 2002, Scanlon et al., 2006). According to (Simmers et al., 1997), recharge can be classified again as actual, that refers to water that has infiltrated and reaches the water table, or potential, that refers to infiltrated water which may or may not reach the water table because of the unsaturated zone processes or the ability of the saturated zone to accept recharge.

On the other hand a wide selection of methods exists for estimating groundwater recharge. The actual and physically differentiated processes of the recharge estimation methods can be classified according to: (i) hydro-geological provinces (Lerner, 1990), (ii) hydrological zones, on the basis of three zones of study, namely surface water, unsaturated zone and saturated zone.(Scanlon et al., 2002, Scanlon et al., 2006), (iii) physical, numerical modelling, and (iv) tracer techniques (Healy, 2010).

2.1.1. Concept of Groundwater Recharge Estimation

Lerner (1997) defined groundwater recharge as water that reaches an aquifer from any direction, i.e., down, up, or laterally. (Lerner, 1997) Therefore, groundwater recharge as used in this study refers to the downward flow of water reaching the water table from the unsaturated zone (Freeze and Cherry, 1979, Lerner, 2002). Recharge may occur naturally from precipitation, rivers, canals and lakes, and can be man-induced through activities of irrigation and urbanization (Lerner, 1990). Since recharge from precipitation is the most important category of recharge, focus will be given to it in the study area. Factors such as the rate and duration of precipitation or irrigation, the antecedent moisture condition of the soil profile, geology, soil properties, the depth to water table and aquifer properties, vegetation and land use, topography and landform control the recharge to groundwater.

According to (Lerner, 1990), it is not easy to estimate the various processes of the hydrological cycle to quantify the recharge. The groundwater reservoir recharge water may later re-emerge as stream flow. Recharge can be expressed as a percentage of the annual precipitation or as an average rate of water in millimetres per year. The volume of recharge, expressed as cubic meters per year, can be obtained by multiplying the recharge rate by the land area under consideration. As it is not easy to measure the recharge to a groundwater aquifer directly, it is usually estimated by indirect means (Lerner, 1990).

It is necessary to identify the possible flow mechanisms and the important features influencing the recharge in an area before deciding on the recharge method to use. This is because the recharge processes vary from one place to another, and there is no guarantee that a method developed and used for one area will give reliable results when used in another (Vázquez-Suñé et al., 2010). It is recommended to estimate recharge using multiple methods to obtain more reliable values as the accuracy of the indirect estimates is usually difficult to determine (Lihe et al., 2010). Various methods exist for estimating groundwater recharge, which have been designed to represent the actual physical processes of the recharge. The classifications of recharge estimation methods include (i) hydro-geological provinces (Lerner, 1990), (ii) hydrologic zones, (iii) physical, numeric modelling, and (iv) tracer techniques (Scanlon et al., 2006).

According to (Scanlon et al., 2006) the three hydrological zones of study are surface water, unsaturated zone and saturated zones, each of which provides a different set of data that can be used to estimate the groundwater recharge. The recharge techniques are further classified into physical techniques, tracers and numerical modelling within each of the hydrological zones. Physical methods, e.g., channel-water budget, seepage meters and base flow discharge; tracer methods, e.g., stable isotopes of oxygen and hydrogen; numerical modelling methods, e.g., Groundwater flow numerical models are included in methods based on groundwater studies. Methods based on the unsaturated zone studies include physical methods, e.g., lysimeters, Darcy’s law and zero-flux plane; tracer techniques, e.g., bromide, ^{3}H, and visible dyes, ^{36}Cl, and Cl; numerical modelling methods, soil water storage routing, quasi-analytical approaches and numerical solutions to the Richards equation.

Recharge estimation methods based on the saturated zone studies are physical methods, e.g., water table fluctuation and Darcy’s law; groundwater dating using traces such as CFC, $^{3}H/^{3}He$, and ^{14}C; and groundwater flow modelling. A detailed description of the aforementioned techniques can be found in (Scanlon et al., 2002, Scanlon et al., 2006) and (Lerner, 1990). The choice of appropriate methods for a recharge study requires the considerations of several factors based on the differences among the recharge estimation methods. These factors include the goal of the recharge study, the required accuracy and reliability, space and time scale, the range of the expected recharge estimates, the time to be spent on the study, and the financial resources available.

2.1.2. Limitations on estimating groundwater recharge

Indirect methods are used to estimate the recharge of groundwater as it is difficult to measure it directly. However the indirect methods have various limitations that make the recharge rates prone to large uncertainties and errors. For example, unsaturated-zone methods are mostly found on the principle of mass balance(Obuobie, 2008) . The assumption behind such recharge methods is that recharge occurs through a diffuse process or piston flow of water and, therefore, recharge flux through preferred pathways is often not accounted for. This is the case in many arid- and semi-arid- areas, particularly in Sub-Saharan Africa where recharge flux through preferred pathways is the rule rather than the exception and, hence, recharge estimates from unsaturated-zone methods can be questionable (Braune and Xu, 2010, Van Wyk et al., 2011). The four types of errors linked to indirect estimation of the recharge identified by (Lerner et al., 1990) are (i) incorrect conceptual model, (ii) neglect of spatial and temporal variability, (iii) measurement errors, and (iv) calculation errors.

The most serious and common error type is incorrect conceptual model that arises when the recharge process is over-simplified or not properly understood. For instance, recharge estimation in semiarid areas can result in a zero recharge rate that signifies no recharge when using water budget technique with monthly data, whereas occasional wet conditions can overcome soil moisture deficit and result in some recharge.

According to (Obuobie, 2008) the variability of precipitation and evapotranspiration as well as soil and aquifer properties, most recharge processes have a non-linear relationship with time and space. For instance, due to high rate of evapotranspiration, an amount of rainfall over a period of time may result in no recharge, however the same amount of rainfall spread over a shorter time period could be sufficient to cause some recharge by saturating the soil. Hence, errors are likely to occur when the temporal and spatial variability in factors that control the recharge is neglected. Other types of errors such as measurement errors are associated with equipment used to make measurements and are usually considered. Calculation errors, for instance, can result from the use of wrong units of the input parameters.

2.1.3. Overview of Groundwater Replenishment using MAR

MAR (Managed aquifer recharge) is the general term for a diversity of methods of recharging and improving water in aquifers. It plays an important role by providing an opportunity for restoration of stressed groundwater resources. This technology is purposeful for subsequent recovery or environmental benefit of water recharge to aquifers.

MAR is targeted at artificially recharging groundwater for a wide range of purposes, including economic, environmental, and cultural values. According to Dillon et al. (2008) MAR is a method of storing water in aquifers under controlled conditions (Dillon et al., 2008). The use of MAR in urban environments can have enormous advantages for supplementary recycle of water. A wide range of methods are in use for recharging of groundwater water to meet a variety of local conditions. An understanding of the local hydrogeology is fundamental to determine the options available and the technical feasibility of MAR technology. MAR technology selection for suitable sites and option of method will depend on the hydrogeology, topography and land use of the area. MAR is in wide use in many countries to increase water supplies, not only in semiarid and arid areas, but also in humid areas, primarily for water quality improvement (Dillon, 2002).

2.1.4. Groundwater balance estimation methods

In principle the groundwater balance describes the inflow and outflow of groundwater into and out of the groundwater system or part of those systems. Groundwater storing or released from those systems is also part of groundwater balance. Good knowledge and insight into the water balance of a groundwater system is of tremendous help when flow computation have to be carried out and the scope for groundwater development has to be assessed Nonner (2012).

According to (Vörösmarty et al., 1999) groundwater balance approaches for characterizing the inflow and outflow of hydrology cycle. This helps to understanding the hydrologic setting and functioning of the systems, as well as analyzing the sustainability of groundwater.

The basic groundwater balance can be set up when groundwater recharge and discharge mechanisms of a groundwater system area known. The following relationship can be set up for a non equilibrium balance.

$$I - O = \Delta S \tag{2.1}$$

Where, I Total rate of groundwater inflow, O total rate of groundwater out flow, and ΔS is volumetric rate of water stored or released. Even if this approach looks simple in concept, in practice it is difficult to measure exactly the true values of the components in equation 2.1.

Recharge from precipitation

In this method the recharge rate is estimated on the basis of water balance for the root zone. The balance can be expresses as:

$$Q_{perc} = P - E - R - S_{root} \tag{2.2}$$

Where Q_{perc} rate of percolation at the lower boundary of the root zone (m3/day), P precipitation rate, E evapotranispiration rate, R runoff rate and S_{root} volumetric rate of water stored or released in the root zone (m3/day).The rate of percolation at the lower boundary of the root zone (Q_{perc}) in equation (2.2) allows to make an estimation of the recharge rate from surplus precipitation.

2.2. Impact of land use change on Groundwater recharge and Quality

Assessing the impact of land use change on the groundwater system and predicting the degree of change in the future is a major scientific challenge (Dams et al., 2008, Tong and Liu, 2006). Due to rapid population growth, land use change phenomena have strongly accelerated in many regions. Therefore, sustainable development of groundwater in quantity and quality is critical to urban planning and effective land use and natural resource development processes must ultimately be integrated.

Groundwater is a most important source of drinking water across the world and plays a crucial role in maintaining the ecological value of many areas (Dams et al., 2008, Villholth, 2006). However, impacts from land use changes are commonly indicated to be one of the main human-induced factors influencing the groundwater system, by reducing recharge. Land use change has been a key research priority with multi directional impacts on both human and natural systems (Turner et al., 2007), moreover a challenging research topic in the field of land use change science. For land use change, groundwater research has mainly focused on the change in water quality thereby neglecting changes in quantity.

Development of groundwater to meet the rapidly expanding urban, industrial, and agricultural water requirements is significance important for human, especially in arid and semi arid areas (Lerner, 2002). In addition more than 2 billion people in the world depend on groundwater for their daily supply (Kemper, 2004). Therefore assessment of groundwater recharge is a key component for sustainable urban growth.

Relations between land use change and groundwater recharge marked in this study, which needs a better assessment of impacts of existing and future land use changes on the quantity and groundwater contamination vulnerability. As relationships between land use and recharge become more widely known, therefore further impacts of land use changes on the effect of recharge and groundwater vulnerability can be better evaluated by applying field observation.

Many studies highlighted that land use change is a widespread phenomenon in the highlands of Ethiopia (Zeleke and Hurni, 2001, Bewket, 2003, Teferi et al., 2010).These studies found different types and rates of land use change in different parts of the country over the different time periods. In most cases development of existence crop production into ecologically marginal areas, deforestation and afforestation have been the common forms of transitions.

2.3. Vulnerability assessment of groundwater Contamination

Groundwater contamination vulnerability assessment is not a characteristic that can be directly measured in the field. It is an idea based on the fundamental concept “that some land areas are more vulnerable to groundwater contamination than others” (Gogu and Dassargues, 2000).

The concept involves hydro-geologic and climatic variables; land use and land cover, potential contaminant sources. According to National Research Council (Vulnerability, 1993) existing method to assess groundwater vulnerability can be classified in to three categories: i) Overlay and index method; ii) process based method that applies deterministic models based on physical processes and iii) statistical model. These methods are typically intended to provide a comparative evaluation of areas related to the potential for groundwater contamination.

2.3.1. Conceptual structure in vulnerability

Aquifer vulnerability is one of the concepts among the various techniques and methodologies that have been developed to evaluate environmental impacts associated with GW pollution. This groundwater vulnerability concept was first introduced in France by the end of the 1960s to create awareness of groundwater contamination (Vrba and Zaporozec, 1994). Even though the choice depends on the model used for it; maps are produced from a set of decisional criteria linked to a number of physical parameters. GIS environment can be used to calculate groundwater contamination vulnerability maps. It provides a means for data processing, such as geo-referencing, integration, aggregation and spatial analysis in addition GIS allows spatial data gathering (Burrough and McDonnell, 1998).

The National Water Well Association (Rahman, 2008) developed the DRASTIC model to assess aquifer sensitivity by combining data sets that describe the depth-to-GW, recharge rates, aquifer material, soil composition, land slope, vadose zone materials, and saturated hydraulic conductivity. Though, it is not intended to predict the occurrence of GW contamination, DRASTIC has been the most commonly used aquifer sensitivity assessment method (Secunda et al., 1998). This method has shown further improvements on recent works, evolving the method beyond a simple rating of sensitivity, to a descriptive approach identifying areas with similar hydro-geologic characteristics (i.e. hydrologic setting) and assessing individually these areas for GW susceptibility to potential contamination (Rupert, 2001). Using the data gathered at appropriate scales and with sufficient map accuracy for this type of analysis is much more useful for local decision makers.

The method has been used for vulnerability mapping projects and discussed as a possible tool for such assessments in the United States (Atkinson and Thomlinson, 1994). DRASTIC developed by Aller et al. (1987) provides a viable option as per EPA (2003) overlay and index-based screening tool. It investigates broad geographic areas for susceptibility to GW contamination by contaminant using existing hydro-geologic parameters in GISs (Rahman, 2008).

DRASTIC and Susceptibility Index (SI)

The factors that form the short form DRASTIC are defined depth-to-GW (D), recharge rate (R), aquifer material (A), soil composition (S), Topography (T), vadose zone (I), and saturated hydraulic conductivity (C). Those are the seven hydro-geological factors that form the DRASTIC index. Each factor is subdivided into ranges or significant media types that are rated between 1 and 10 according to their relative impact on the pollution potential. The DRASTIC index can be calculated for various hydrogeological settings and subsequently mapped. The largely important assumptions made when assessing vulnerability with DRASTIC (Aller et al., 1987) are that the contaminant is introduced at the ground surface, flushed into the groundwater by precipitation and has the mobility of water. To get an idea of the influence of each of the hydrological factors on the final index, DRASTIC considers the following conditions as contributing to a high pollution potential

- Shallow depth to water (D) related to a short travel time of the pollutant in the unsaturated zone and consequently little chance for attenuation;
- High net recharge (R), the main means of transport for leaching contaminants to the aquifer;
- Highly permeable aquifer media (A), allowing a rapid spreading contaminant throughout the aquifer;
- Soil media (S) lacking clay and organic material, conferring a low reduction capacity and increasing the mobility of the contaminant;
- Flat topography (T), low slopes decreasing the chance of surface runoff and erosion and as a result facilitating infiltration;
- Vadose (unsaturated) zone media (I) that show no reactivity with regard to the pollutant, thus creating an environment for leaching towards the aquifer;
- High hydraulic conductivity of the aquifer (C), allowing quick spreading through the aquifer (while this also depends on hydraulic gradient);

The susceptibility Index (SI), which is an adaptation of the DRASTIC method, was developed in Portugal (Stigter et al., 2006) with the target of evaluating aquifer vulnerability, with respect to diffuse agricultural pollution in hydrogeological settings. The major difference is in SI addition of a parameter defining land use. The concept is purely intrinsic vulnerability assessment method. The definition of susceptibility is in agreement with the index name, i.e. the lack of ability to resist the impact of contaminants on the quality of groundwater, provided by (Vrba and Zaporozec, 1994).

Therefore for the construction of the Susceptibility Index, three DRASTIC parameters were left out deliberately(Stigter et al., 2006). Two of these include the soil (S) and unsaturated zones (I), hence signifying that their direct influence on the contamination linked to agricultural practices is of little importance. According to (Stigter et al., 2006), soil type is indirectly represented by land use, hereby. However, many authors, including (Foster, 1987) and (Vrba and Zaporozec, 1994), recognize that the soil can have a large attenuation potential, particularly when rich in clay minerals and organic matter. In other words, leaving the soil properties out of the vulnerability assessment is not necessarily an obvious choice. On the other hand, an additional justification can be given by the fact that, the natural soils are frequently disturbed during cultivation of land due to ploughing, tillage and many other techniques applied to improve the soil structure and fertility, so that they lose much of their original characteristics (Stigter et al., 2006).

The hydraulic conductivity of the aquifer (C) is the last DRASTIC parameter not incorporated in the SI. This parameter is extremely difficult to evaluate spatially and there are rarely enough data to provide an accurate picture. Moreover, hydraulic conductivity is already qualitatively represented by the aquifer media (A), resulting in an excessive weight of this factor in comparison with the others. A team of Portuguese scientists also determined the weight sequence for the SI (Stigter et al., 2006), indicated in **Table 2.1**. Since the weights add up to one and the ratings range from 0 to 100 (for land use and the adopted DRASTIC parameters), the final index values also vary between 0 and 100.

Table 2.1: Definition and weight of the DRASTIC and SI parameter

Symbol	Parameters	DRASTIC weight	SI weight
D	Depth to water	5	0.186
R	Net Recharge	4	0.212
A	Aquifer media	3	0.259
S	Soil media	2	-
T	Topography	1	0.121
I	Impact of the vadose zone media	5	-
C	Hydraulic conductivity of the aquifer	3	-
LU	Land use	-	0.222

CHAPTER 3

Study area

3.1. Description of study area

3.1.1. Location and Topography

The study area is located in the upper part of Awash River Basin, in the east-central part of the country, in Oromia regional State, approximately between 38°50E'-39°15E' and 8°30N'-8°53E' within 50 km distance from the capital city, as shown in **Figure 3.1**. There are three boundaries which we consider in the study area. The first one is an administrative boundary which lies between altitudes of 1587 m and 3009 m asl and it covers 2500 km^2. The second one is the hydrological boundary which was used for hydrological data analysis, covering an area of about 3913 km^2. The last boundary is the plain boundary of the so-called Ada'a plain and covers 1650 km^2.

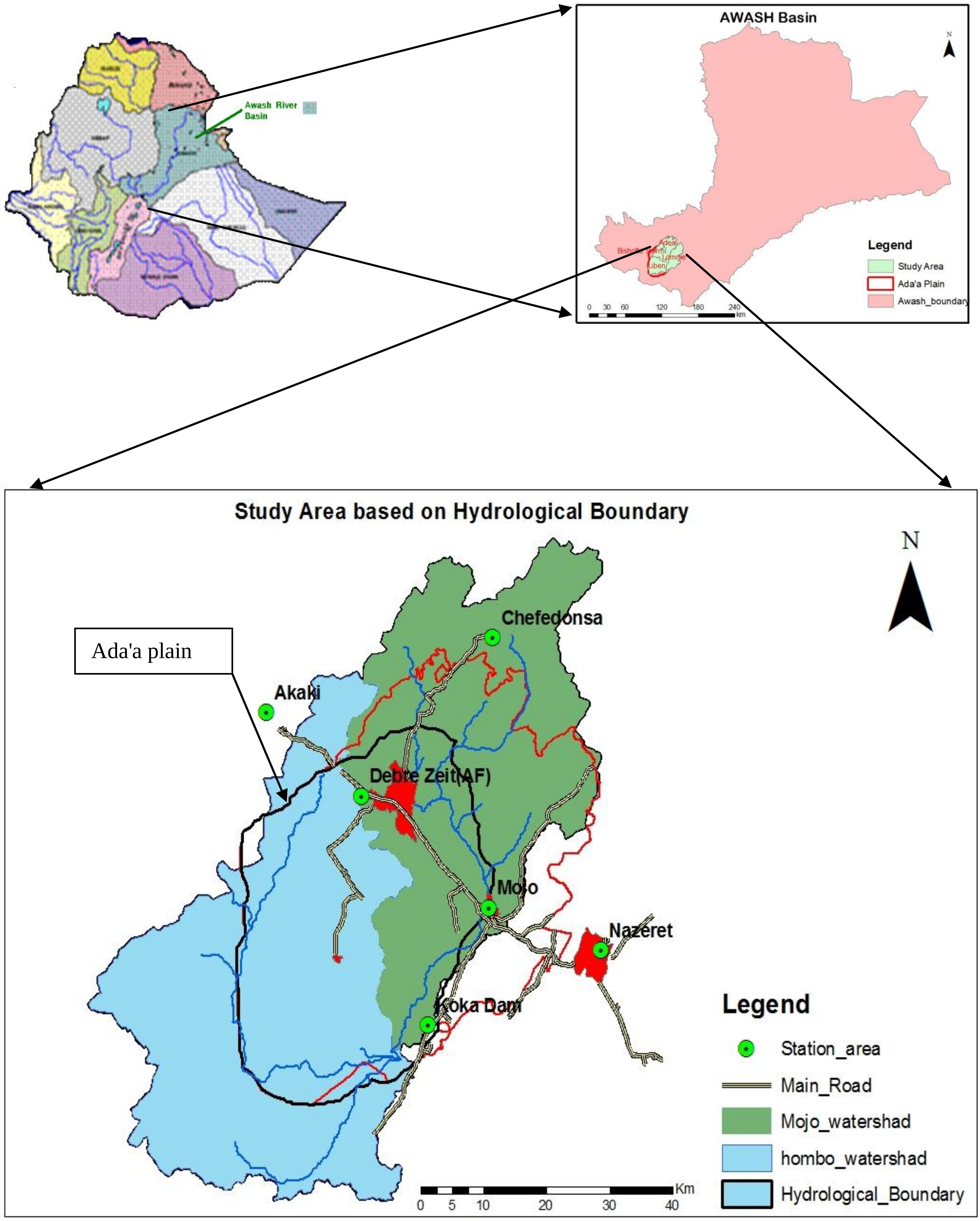

Figure 3.1: Study area of different boundary: red line (administrative boundary) and black line (hydro-geological boundary) on the map

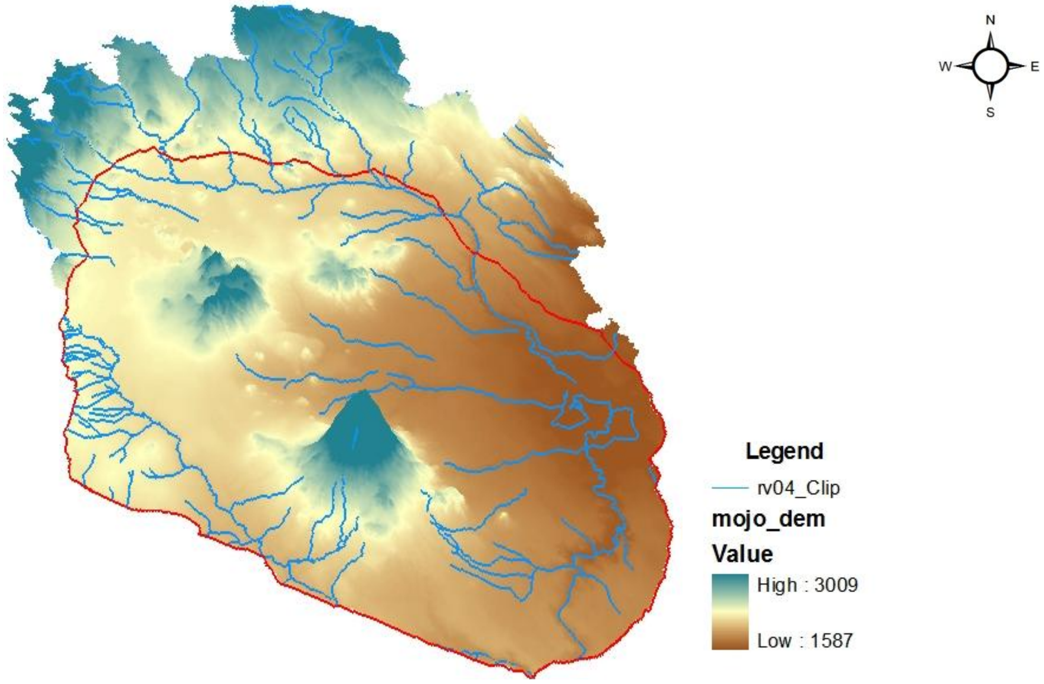

Figure 3.2: DEM of the study area (Projection; UTM , zone 37N, Datum: WGS1984, Ellipsoid: WGS84)

In **Figure 3.2** Digital Elevation Model (DEM) of the study area shows the study area lies between altitudes of 1587 to 3009 m a.s.l and weighted average altitude of 2298 m a.s.l. The topography of the study area is classified into five slope classes based on their inclination, shown in **Table 3.1** and **Figure 3.3**. Inclination of slope class I is 0-8%, class II is 8-15%, class III is 15-25%, class IV is 25-40%, and the steepest class (class V) is > 40%. In general the study area is flat to gently undulating and belongs to slope class I, which covers about 81% of the total area.

Table 3.1: Slope class Classification ,Source: (Wangsaatmaja, 2004)

Slope class	Slope (%)	Area(km^2)	Area(ha)	Area%
I	0-8	2043	204268	81%
II	8-15	272	27177	11%
III	15-30	148	14775	6%
IV	30-40	33	3335	1%
V	>40	29	2898	1%
Total		**2525**	**252453**	**100%**

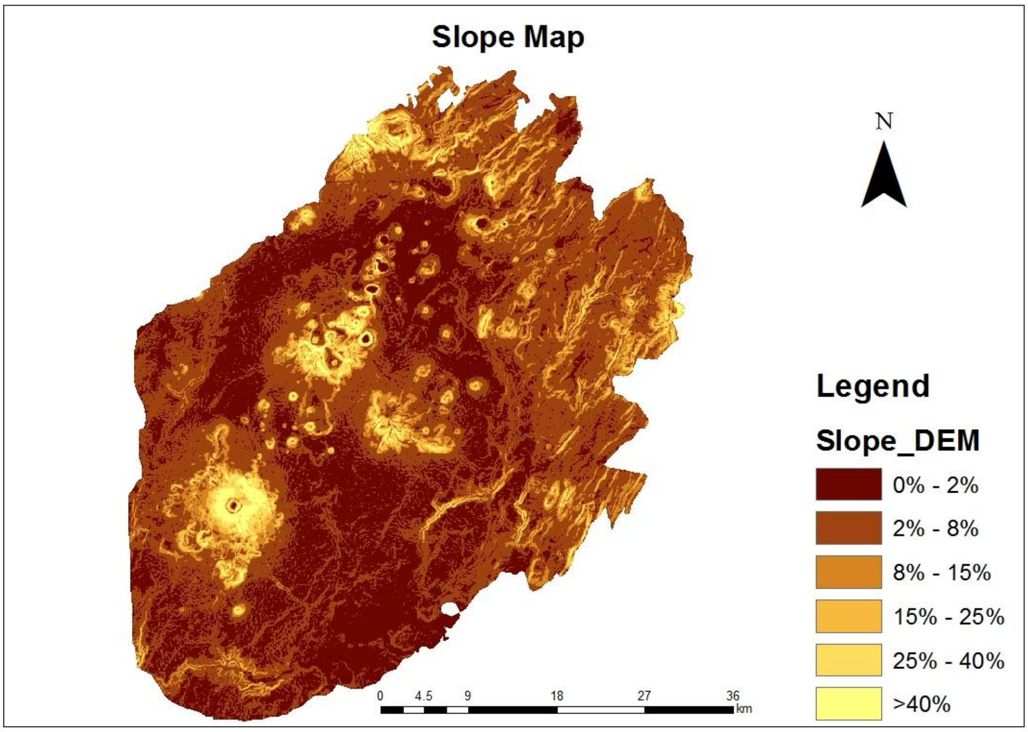

Figure 3.3: Slope map of the study area

3.1.2. Land use

According to the land use map the major type of land use of the study area, shown in **Figure 3.4** consists mainly of intensively cultivated area, covering about 75% of the area. The majority of the farmers produce, on intensively cultivated land, cereal crops like teff, wheat, barley and maize. For each land use classes, i.e. degraded land, urban and rural settlement, forests, inland water and open bush land, etc. the area coverage is indicated in **Table 3.2**. Mojo River is found in the study area and is one of the main tributaries of the Awash River. There are a number of industries found in Mojo town, including tanneries, which dispose their effluents without proper treatment to Mojo River that joins Koka Lake. In addition to this, the upper valley is very rich in lakes created due to volcanic eruption such as: Bishoftu Babogaya, Hora (Kilole), Hora Oda (Arsede) and a basin lake called Cheleleka that is found near Debre Zeit town.

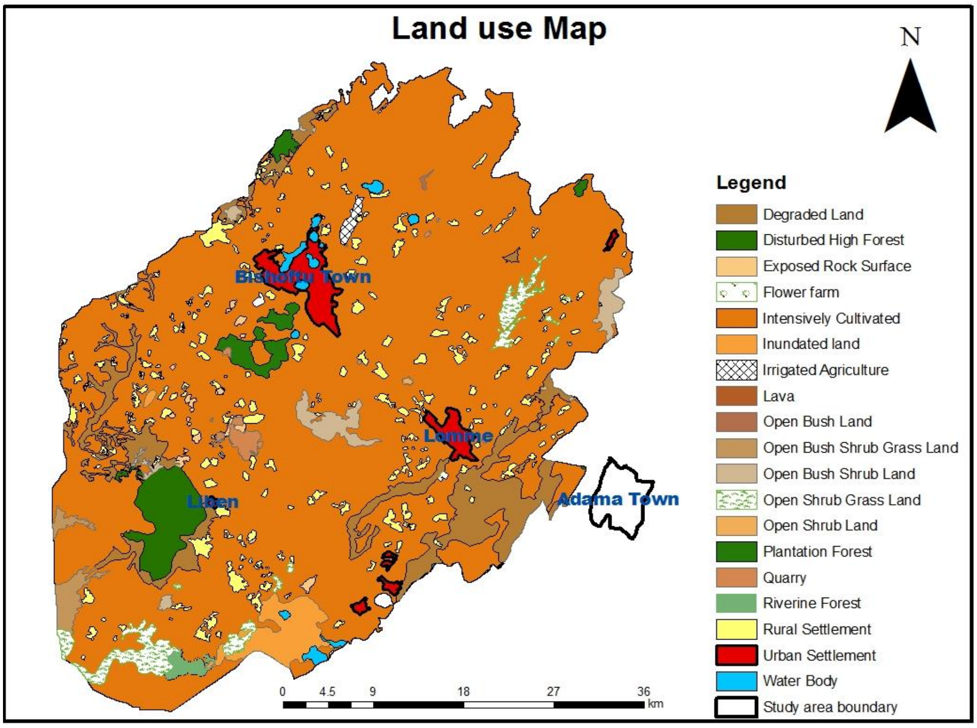

Figure 3.4: Land use map of the study area

Table 3.2: Land use/cover classification

Land Use	Area(Km2)	Area(Ha)	Area (%)
Degraded Land	175.58	17558	7.02%
Disturbed High Forest	53.80	5380	2.15%
Exposed Rock Surface	9.18	918	0.37%
Flower farm	1.74	174	0.07%
Intensively Cultivated	1890.56	189056	75.61%
Inundated land	43.25	4325	1.73%
Irrigated Agriculture	4.88	488	0.20%
Lava	0.38	38	0.02%
Open Bush Land	0.70	70	0.03%
Open Bush Shrub Grass Land	17.49	1749	0.70%
Open Bush Shrub Land	34.58	3458	1.38%
Open Shrub Grass Land	45.14	4514	1.81%
Open Shrub Land	0.81	81	0.03%
Plantation Forest	28.36	2836	1.13%
Quarry	10.17	1017	0.41%
Riverine Forest	7.72	772	0.31%
Rural Settlement	108.46	10846	4.34%
Urban Settlement	53.68	5368	2.15%
Water Body	13.81	1381	0.55%
Total	**2500**	**250029**	**100.00%**

3.1.3. Population

According to 2007 Central Statistics Authority of Ethiopia (CSA, 2007) population data by adopting average national annual population growth rate of 2.6% the population of the study area is estimated to be about **596,956** distributed in to the following percentage Ada'a plain (27%), Lome (24%), Liben (29%) and Bishoftu (21%).

3.1.4. Climate

The climatic characteristics of the study area is determined largely by the yearly movements of the Inter Tropical Convergence Zone (ITCZ) that allows dry wind from east or moist winds from the west dominates the climate of this part of Ethiopia. In the month of March the ITCZ advances across the Awash Basin bringing spring rains in the 'Belg' season. The ITCZ reaches its most northern position when heavy summer rains come from the west. This season is the main rainy season called 'Kiremt' and lasts until September. The dry season called 'Bega' extends from October to February (Yitbarek et al., 2012).

Mean annual areal rainfall in the study area 884 mm per year. 70 to 75% of the total rainfall occurs in the main rainy season from June to September. The mean annual temperature in the study area ranges from 15 to 22^{o}C and is inversely correlated with the altitude.

3.1.5. Geology

The major geological formations of the study area are shown in **Figure 3.5**. And geological units are described in **Table 3.3**. Regarding the geological nature of the study area, lacustrine sediments cover the largest part of the area (46%) followed by Bofa Basalt rock with high permeability with a considerable proportion of 26%. It forms a gentle and undulating topography and becomes slightly steeper towards Chefedonsa. On the other hand, recent to sub recent rhyolite domes and flows represent the smallest areas with 5% of the total area.

Table 3.3: Description of Geological nature of the study Area

No	Geo_name	Description	Area(km^2)	Area (ha)	Area (%)
1	Qr	Recent to sub recent rhyolite domes and flows	113	11342.6	5%
2	Qd	Recent to sub recent rhyolite domes and flows	11	1065.6	0%
3	Q	lacustrine sediments	1164	116372.4	46%
4	NQtb	Bofa Basalt	664	66406.9	26%
5	Nc	chilalo and Badda Trachytes and Trachy basalts	64	6430.1	3%
6	Qb	Pleistocene-subrecent basalts	234	23407.2	9%
7	Nn	Ash flow tuffs,pantelleritic ignimbrites and unwelded tuffs	265	26497.4	11%

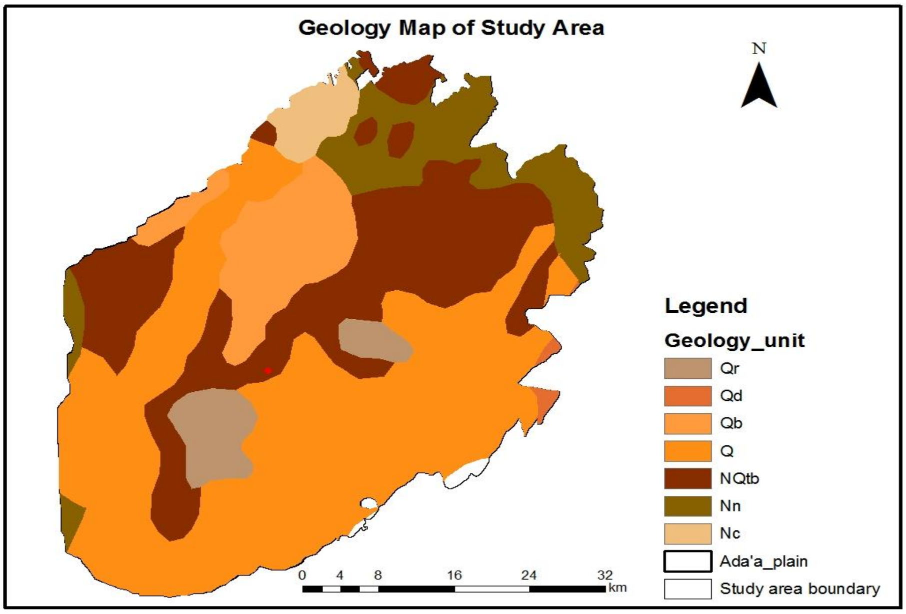

Figure 3.5: Geology map of the study area

3.1.6. Geomorphology

The geomorphology condition of the area is a function of the hydrogeological. The main geomorphologic units of the study area are shown in **Figure 3.6** and described in**Table 3.4**. The area is mainly situated on Volcano-lacustrine sediment, the Ada'a plain in most part, consists of coarse sand and basalt. The area is affected by systems of faults with NE-SE direction.The area has similar morphology and some volcanic hills and young well preserved volcanoes and related volcanic.

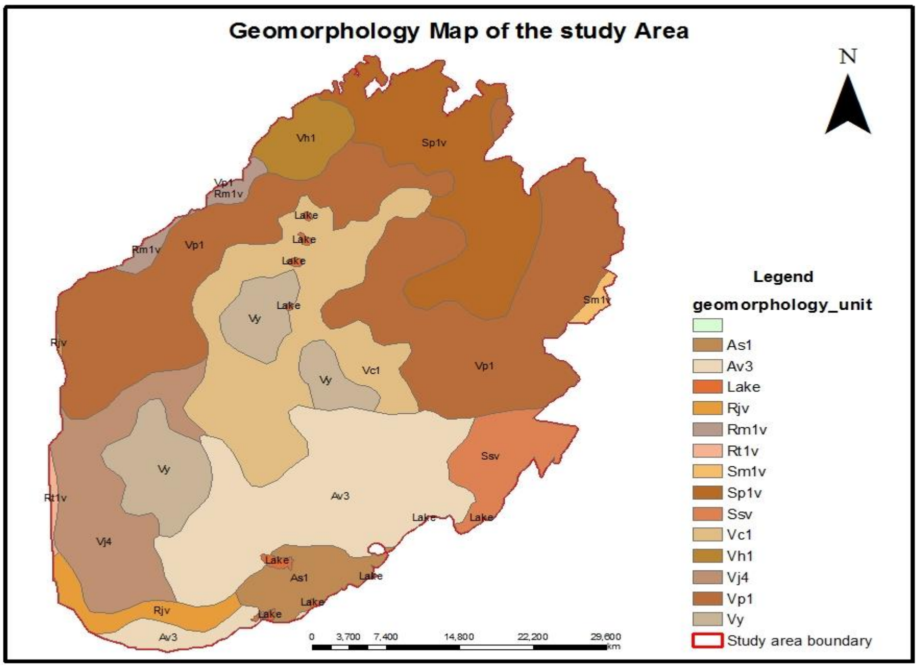

Figure 3.6: Geomorphology Map of the study Area

Table 3.4: Geomorphology description

LANDSC_UNT	Description
As1	Seasonal swamps and marshes-Meki, Awash and sidamo
Av3	Volcano-lacustrine plains-west Lake Ziway
Rjv	Minor river gorges and revines
Rm1v	Moderate to high relief- Central highlands
Rt1v	Moderately dissected side slopes and piedmont zones-central highlands
Sm1v	Moderate to high relief parallel ridge and vally topography associated with extensive fault sets-
Sp1v	Steep faulted plateux of the Ethiopia rift margin-Addis Ababa
Ssv	Steep faulted olain and low plateau complexes of the Ethiopia rift with numerous faults scraps, sag
Vc1	Complexes of volcanic cones,Vents,craters,plugs,piedmont plains and other volcanic remains-Deb
Vh1	degraded extinct central volcanoes, caldera remnants and associated forms of high to mountainous r
Vj4	Moderately dissected side slopes of extinct central volcanoes and other relic volcanic forms
Vp1	Undulating high pateaux formed predominantly on pyroclastic deposits - central highlands
Vy	young often well preserved venteral volcanoes and related volcanic forms

3.1.7. Hydrogeology

The general hydrogeological set up of the Study area is governed by the lithological stratigraphy of the area and tectonic features. The recharge and discharge condition, groundwater flow and aquifer parameters in the study area is highly governed by the general bedding of the sedimentary formation, the tectonic condition and the hydraulic properties of the different volcanic units that outcrops in the basin (Baye et al.). **Figure 3.7** is clearly showing the geological map cross section lines which pass through the Ada'a plain and are representative from southwest to northeast (SW to NE) and northwest to southeast (NW to SE). The cross sections are presented in **Figure 3.8** and **Figure 3.9** and clearly show the conceptual groundwater system of the Ada’a plain with recharge, discharge and groundwater flow.

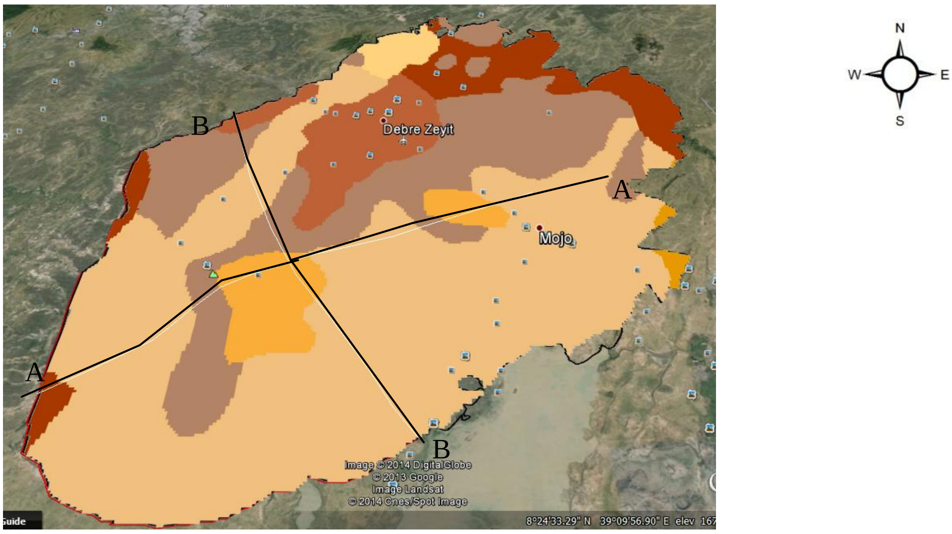

Figure 3.7: Hydro geological map of the study area

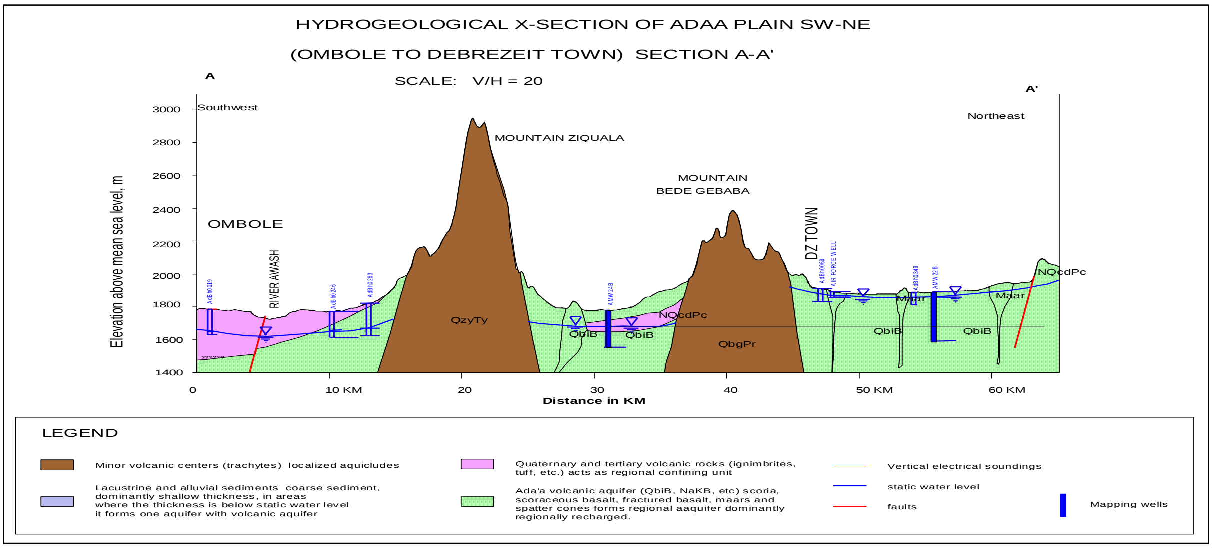

Figure 3.8: Hydro geological cross section of Ada'a plain from south west to North east

source (Ministry of Water Resources, 2009)

The hydrogeological cross section which crosses from northwest to southeast and passes through Ada'a plain is shown **Figure 3.9**. The geological mapping units in the Ada'a groundwater system were differentiated at depth. The aquifers and confining layers (aquicludes) identified are referred to as hydro-geological units; four principal hydro-geological units are recognized in the Ada'a plain's groundwater system (WWDSE, 2008).

- Alluvial aquifers (thickness ranges from 5 to 80 m, [typical thickness 40m])
- Upper basalt aquifer (UBA) (50 to 300m [100m])
- Upper Regional confining (aquiclude) units (60 to 150m [120])
- Lower Basalt aquifer (LBA) (greater than 300m)

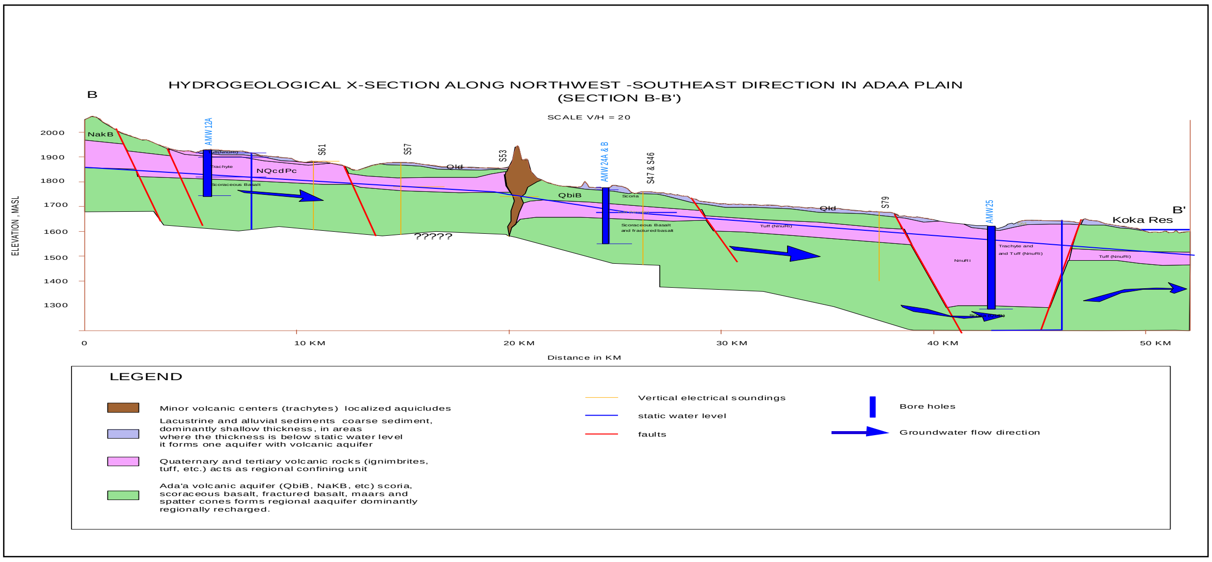

Figure 3.9: Hydro-geological cross section of Ada'a plain along Northwest to Southeast

source (Ministry of Water Resources, 2009)

According to the geological cross-section in the top part there is the Alluvial Aquifer with a thickness in the range of 5 to 80 meter. It is an unconfined aquifer consisting of coarse sediments. Based on the well information the static water level varies from 7.5 to 77.5 meters depth, with an average of 39.5 meter. The static water level is shallower at the Debre Zeit areas and becomes deeper towards the Mojo area. The alluvial aquifer unit is highly permeable and forms one aquifer system with the upper basalt aquifer in the area.

The underlying geological formation is highly variable from place to place i.e. massive basalts, scoraceous basalt and scoria. Where the basalts are faulted and fractured the yield of bore holes increases. The Upper Regional confining (aquiclude) unit acts as a regional aquiclude which separates the upper and lower volcanic aquifer in the study area. The Lower Basalt aquifer (LBA) is composed of tertiary Tarmaber basalt composed of dominantly scoraceous basalt and Amba Aiba basalt. Static water level varies from artesian condition to a depth of 77.5 meters.

CHAPTER 4

Methodology

4.1. Data source and processing

To answer the research questions multiple sources of information were used. Secondary data about hydro-geological and meteorological data were collected from different institutions at different administrative levels. Field observations of the study areas were support the understanding of the practiced methods.

Table 4.1: List of data which used for data processing and source

No	List of data used	Source	Date
1	Precipitation	NMA	1998 - 2012
2	Temperature	NMA	1998 - 2012
3	River discharge	MoWE	
4	GW level data	MoWE	1999
5	GW chemistry data	Water works enterprise	2010 - 2013
6	Areal RF	NMA	1998-2012
7	Geology Map	METAMETA	_
8	Land use(land use plan)	METAMETA	_
9	DEM	srtm.csi.cgiar.org/SELECTION/inputcoord.asp	_

4.2. Hydro-Metrological Data processing

Hydro-meteorological Data processing was carried out in order to assess precipitation and evapotranspiration in the area. Assessment was done based on the daily data collected on six metrological stations within the study area. Precipitation and Evapotranspiration data were assessed, processed and applied in different analysis such as areal rain fall by using Thiessen polygon and Average Depth method. The assessments of Precipitation and Evapotranspiration are specified below.

4.2.1. Precipitation

The daily rainfall data of Six stations was selected to identify the amount of areal rainfall that the study area received from 1998-2012. In this study the areal precipitation were computed using the Thiessen polygon areal rainfall computation method in Arc GIS environment. A study area map with the location of the station points is shown in **Figure 4.1**. The six meteorological stations and the associated defined Thiessen polygon areas are presented in tabular form in **Table 4.2**.

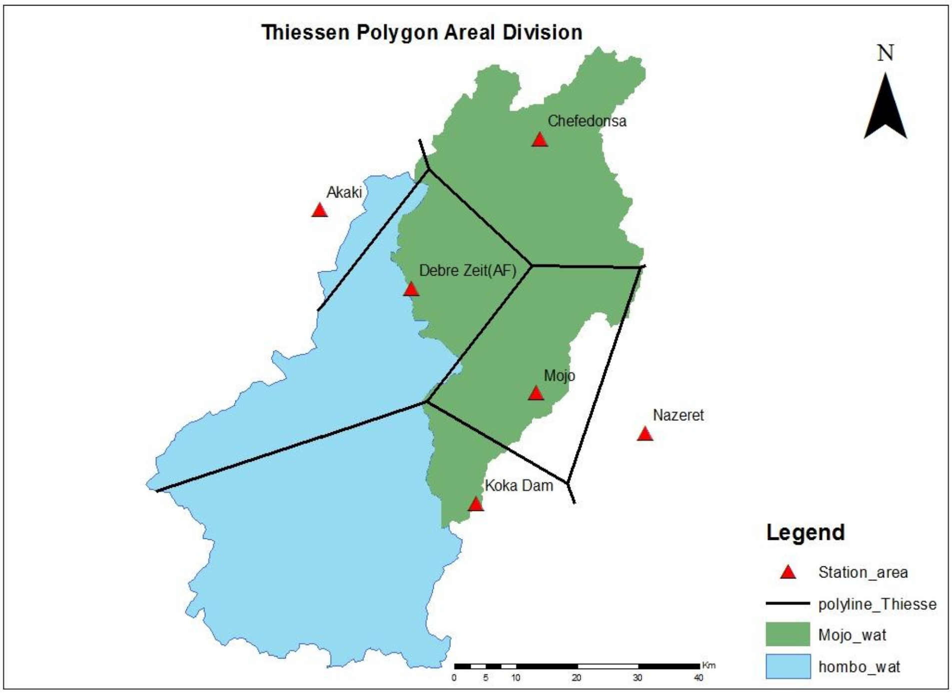

Figure 4.1: Thissen polygon Areal RF Distribution

Table 4.2: Area coverage in Thiessen polygon Method

Station Name	Area_sqkm	Area_ha	Ration	Area%
Akaki	99	9880	0.025	2.5%
Chefedonsa	773	77300	0.198	19.8%
Debre Zeit	1095	109468	0.280	28.0%
Koka Dam	1463	146332	0.374	37.4%
Mojo	477	47691	0.122	12.2%
Nazeret	6	578	0.001	0.1%
Total Area	**3912**	**391249**	**1.000**	**100%**

Computational procedure

Computation of Areal rainfall was done using Thiessen polygon method. This method was adopted because the area is relatively flat which means no influence of mountain in the distribution of areal rainfall station. ArcGIS software was used as a tool to draw area influenced by each of the station to compute areal rainfall. These areas are as shown in the **Table 4.2**.

Each polygon that lies completely within the sub basin boundary, all the points inside the polygon have the same value which is equal to the closest sample value. Equation 4.1 and 4.2 are used to compute mean areal precipitation. Ai and MAPi are computed using the entire polygon area. However, the GIS analyst must make sure to use only the portion of the Thiessen polygon that lies within the sub basin, for those Thiessen polygons that do not lie completely within the Sub basin we only take the area weighted which is touched by the study area.

$$MAP_T = \sum T_i * P_i \tag{4.1}$$

Where MAP_T mean areal precipitation over study area, Ti Thiessen-based station weight (computed as equation 4.2) and pi precipitation

$$T_i = \frac{A_i}{A_T} \tag{4.2}$$

Where: Ai area of each Thiessen polygon, A_T entire sub basin area.

All rainfall station weights which are found in the area are used to transform point precipitation at rainfall gauging stations into an associated areal mean precipitation. Therefore station data over the area that assumed to represent. The thiessen polygon it is essential to use, in order to get a representative estimation of the spatial distribution of areal rainfall. This method assigns weight at each gauge station in proportion to the catchment area that is closest to that gauge.

4.2.2. Temperature

Temperature is an important variable for calculating the evapotranspiration of the study area. There are six meteorological stations which are found in the study area the daily minimum and maximum temperatures are collected from National Metrological Agency (NMA). The mean daily temperature is calculated by using equation (4.3). The weighted average or areal temperature was calculated using the Average Depth Method (IDW) interpolation method.

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \tag{4.3}$$

4.2.3. Potential evapotranispiration (PET) Estimation

The same stations were used in the computation of areal precipitation in the computation of potential evapotranspiration (Akaki, Debre Zeit, Mojo, Koka Dam, Chefidonsa and Nazereat). These stations only contain data for temperature, among other parameters influencing evapotranspiration (wind speed, solar radiation/sunshine hours and relative humidity); for this reason evapotranspiration formula which depends only on the temperature data were used for the computation of potential evepotranispiration i.e.; Blaney-Criddle, Thornthwaite and Hamon methods. The potential evapotranspiration was computed by considering cropping factor for each growing season for Barley/Wheat which is common in the area.

The Blaney-Criddle model

The usual form of the Blaney-Criddle equation converted to metric units is written as:

$$ET_{B\&C} = Kp(0.46 * T_a + 8.13) \tag{4.4}$$

Where: $ET_{B\&C}$ Potential evapotranispiration (mm), K Crop factor (consumptive use coefficient, depending on vegetation type, location and season and for the growing season), P monthly percentage of day light hour in the year and Ta Mean monthly air temperature.

Thornthwaite's formula:

This formula is based mainly on temperature with an adjustment being made for the number of daylight hours. An estimate of the potential evapotransiration, calculated on a monthly basis, is given by:

$$PET = 16 * \left(\frac{L}{12}\right) * \left(\frac{N}{30}\right) * \left(\frac{10 * T_a}{I}\right)^{\propto} \quad (4.5)$$

Where: PET potential ET (mm/month), Ta Mean temperature, N No of days in a month being calculated, L Average day length of month being calculated

$$\alpha = (6.75 * 10^{-7}) * (I^3) - (7.71 * 10^{-5}) * (I^2) + (1.79 * 10^{-5}) * I + 0.4924 \quad (4.6)$$

$$\mathrm{I} = \sum \left(\frac{\mathrm{T_a}}{5}\right)^{1.514} = \text{Heat Index} \quad (4.7)$$

Hamon Potential equation

$$\mathrm{PET} = \mathrm{k} * 0.165 * 216.7 * \mathrm{N} * \left(\frac{\mathrm{e_s}}{\mathrm{T} + 273.3}\right) \quad (4.8)$$

Where: PET potential evapotranspiration (mm day), k proportionality coefficient = 1 (unit less), N daytime length (x/12 hours), es saturation vapour pressure (mb) and T average monthly temperature (°C).

e_s − Saturation vapor pressure

$$\mathrm{e_s} = 6.108 * \mathrm{e}^{\frac{17.27 * \mathrm{T}}{\mathrm{T} + 237.3}} \quad (4.9)$$

4.3. Recharge estimation and data requirements

Estimating the rate of aquifer replenishment of all measures in the evaluation of ground water resources potential is probably the most difficult. In this study the main techniques used to estimate the groundwater recharge rates are the water balance approach. This is based on the geological nature of the study area, consists the lacustrine sediments deposits and basalt. Therefore the recharge estimation is done by considering the area influence of each different geological nature, by applying thiessen polygon to get the areal influence of each geological nature.

4.3.1. Groundwater recharge

Water balance techniques have been broadly used to make quantitative estimates of water resources and the impact of man's activities on the hydrologic cycle (Kumar and Seethapathi, 2002). This approach is used to evaluate quantitatively the groundwater recharge in the study area and individual contribution of each geological formation of the area. The fundamental concept of water balance is the difference between inflow to the system and outflow from the system gives change in storage of the system (over a period of time).

$$I - O = \Delta S \tag{4.10}$$

Where I inflow (mm/year), O outflow (mm/year) and Δs change in storage (mm/year)

The water balance is the method basically a procedure which estimates the balance between the inflow and outflow of water. This methods were developed by Nonner (2012). To estimate the recharge by using water balance in this study the equation (4.11) was used based on the data source and availability.

$$Q_{perc} = P - ET_a - R - S \tag{4.11}$$

Where, Q_{perc} is groundwater recharge in m^3/year, P is precipitation, ETa is actual Evapotranspiration, R is Surface runoff and S volumetric rate of water stored or released in the root zone.

Equation (4.11) the water balance method allows to study the hydrological process taking place in a catchment area and to determine the unknown and may be the difficult parameter based on the known ones. It is carried out based on water accounting principles in which water inflow to the catchment, leaving the catchment and change in storage for the period considered are taken in to account. By assuming none irrigation water balance or taken to be zero. The water inflow into the catchment area is, therefore, considered to be only from rainfall while the water leaving the catchment area includes runoff (R) and actual evapotranspiration (ETa).

Components that used for the ground water balance model, such as; rainfall, evapotranispiration (were estimated using the relevant hydrological and meteorological information), crop factor, depth of root zone, soil property, runoff threshold. Those are determining the amount of recharge to groundwater.
Sensitivity analyses were done manually by using excels on a water balance model to make sure that how the sensitive parameters affect the output of the groundwater recharge. The estimated mean annual groundwater recharge is very sensitive to the value assigned to the rainfall threshold and soil property.

4.4. Analysis of future prospect based on population scenarios

Population projection is an extrapolation of historical data in to the future under certain explicitly assumption about the future as related to immediate past. The analysis is made based on 2007 Central Statistics Authority of Ethiopia. Based on the analysis the population and water demand was estimated for domestic sector, we forecast the population and water demand from now to 2050. In addition to population projection the water demand is projected for future use is based on assumptions in the increasing per capital consumption. For the purpose of this analysis is called business as usual projections of future water demand

Population projection

Equation 4.12 is the population projection based on immediate past population data and estimated future population with current levels of per capita water use.

$$p_t = p_0(1 + r)^t \tag{4.12}$$

Where, p_t is initial population, p_0 is population at t years later and r is annual growth rate

Groundwater demand

The water demand for domestic consumption can be estimated from existing number of population and growth rate. The water demand is calculated by the multiplication of the number of population with per capita water consumption which gives the anticipated water demand.

$$\text{Water demand (D)} = \text{Number of population} * \text{per capita water consumtion} \tag{4.13}$$

Where: per capita consumption is water use per inhabitants or per family and is mostly prescribed by the central government of the country.

4.5. Groundwater chemistry assessment

The groundwater quality data are used for the water type assessment in the range of from 2010-2013 for 34 production well and 111 data sample in the study area. The groundwater qualities were analyzed with the purpose of assessing the suitability for drinking water and for irrigation. The quality is defined by certain physical, chemical and biological characteristics. The accuracy of chemical analysis of the main constituents of the data quality was checked, through the computation of Electrical Balance (E.B), the formula is as shown below.

$$EB = \frac{\sum C - \sum a}{\sum C + \sum a} * 100\% \tag{4.14}$$

Where EB Electrical balance, Σc sum of cations (meq/l) and Σa sum of cations (meq/l). For the analysis to be accurate Ionic (Electrical) balance should be $\pm 5\%$.

The determination of chemical water types were done to implies the successive calculation of the main type, type, subtype and class of a water sample. In the main type which is determine the chlorinity of the sample, and its significant important to determination of the origin of water. The type of water determines by the alkalinity, the alkalinity is the capacity of water for neutralizing an acid solution. The subtype is the most important cations and anions determine the subtype in the way that hydro-geochemical family members.

4.6. Vulnerability assessment

A parametric method such as the susceptibility index (Stigter et al., 2006) were used by combining data on groundwater depth, recharge, aquifer type, topography and land use. Arc GIS environment was used with application of a susceptibility Index model to evaluate the groundwater vulnerability for contamination in the study area. The method conceded a numerical index that was derived from ratings and weights associated with the five parameters **Table 4.3**. The important media types or classes of each parameter represent the ranges, which were rated from 10 to 100 based on their relative effect on the aquifer vulnerability .The SI Index was computed by applying a linear combination of all factors according to the equation (3.14).

Table 4.3: Assigned weight for SI parameters

No	SI parameters	Description	Relative weight
1	Depth to water	It is depth from ground to water table, deeper the water table lesser will be the chances of pollutants to interact with ground water	**0.186**
2	Net Recharge	It is the amount of water/unit area of land that penetrates the ground surface and reaches the water table, it is the reporting agents for pollutants to the ground water	**0.212**
3	Aquifer media	It is the potential area for water storage, the contaminant attenuation of aquifer depends on the amount and sorting of fine grains, lower the grain size higher the attenuation capacity of aquifer media	**0.259**
4	Topography	It refers to slope or steepness, areas with low slope tend to retain water for longer, this allows a greater infiltration of recharge of water and a greater potential for contaminant migration and vulnerable to ground water contamination and vice versa	**0.121**
5	Land use	In order to evaluate or giving the weight land use parameter of SI, the land use cover maps refers to under the section of recharge were consulted	**0.222**

4.6.1. Preparation of the SI parameter maps

In order to obtain the SI index parameters, it requires mapping all combining data (groundwater depth, recharge, aquifer type, Topography and land use). The vulnerability maps will be obtained by using Arc GIS as a tool to overlaying the individual maps and calculating the index on a fine mesh. The governing equation for calculating SI index involves multiplying each factor weight by its point rating. Which is attributed a qualitative degree of vulnerability ranging from “extremely low” to “extremely high". The model (SI index) is based on five parameters, corresponding to five layers to be used as input parameters for modelling, whose required information were obtained from various Government and semi-Government agencies at a required scale **Table 4.4**.

Table 4.4: Data used for Hydro geological parameters for SI Index

No	Data Type	Source	format	Date	Output layer
1	GW level data	MoWE	Table	1999	Depth of water (D)
2	Areal RF	NMA	table	1998-2012	Recharge (R)
3	Geology Map	METAMETA	Map	_	Aquifer media (A)
4	Slope	METAMETA	Map	_	Topography (T)
5	Land use	METAMETA	Map	_	Land use (LU)

Each of the above Five SI index parameters is mapped and classified based on the Model range and ratting or either into significant media types, which have an impact on pollution potential in **Table 4.5**. The final vulnerability map is based on the SI index which is computed as the weighted sum overlay of the five layers using equation (3.14):

$$SI = D_w * D + R_w * R + A_w * A + T_w * T + LU_w * LU \qquad (4.15)$$

Where, SI Susceptibility Index (SI), D depth of the groundwater, A Aquifer media, T Topography (slop of land surface) and LU land use.

Table 4.5: Range and rating of the SI Index

Depth of water		Net Recharge		Topography		Aquifer media	
D (m)	**Rating**	**R (mm)**	**Rating**	**T (%)**	**Rating**	**A**	**Rating**
< 1.5	100	<51	10	< 2	100	Sand and Gravel	90
1.5 - 4.6	90	51 - 102	30	2 - 6	90	Basalt	70
4.6 - 9.1	70	102 - 178	60	6 -12	50	Upper basalt	60
9.1 - 15.2	50	178 - 254	80	12 -18	30	Lower basalt	50
15.2 - 22.9	30	>254	90	> 18	10		
22.9 - 30.5	20						
> 30.5	10						

The depth to water table was obtained by subtracting the static water level (SWL) from digital elevation model (DEM). The piezometric water table level (PWL) is therefore, an exact interpolation scheme is appropriate for generating a smooth surface representation for the high degree of spatial continuity of the groundwater surface in an aquifer. The inverse distance weight (IDW) average interpolation technique was performed on the point data. The depth to water table map was then classified into ranges defined by the SI index model and assigned rates ranging from 10 (minimum impact on vulnerability) to 100 (maximum impact on vulnerability).The deeper the groundwater the smaller the rating value.

Recharged mainly by direct infiltration from precipitation the recharge map was constructed by using the geological nature of the area. By using the thiessen polygon on Arc GIS environment to get the areal influence of each geological nature of the study are. The recharge map was then classified into ranges and assigned ratings from 60 to 90. High recharge rates were assigned high numerical rates.

The Aquifer media were obtained using a subsurface geology map. The geology map was classified based on geological nature of the area, by using that map the aquifer media were then give a rating system according to the SI index model. The course and gravel was assigned a high rating value compared to the basalt media types.

The topography layer was constructed from the digital elevation model (DEM). The slope map was then sliced into ranges and assigned ratings ranging from 10 to 100. Flat areas obtain high rates because they slow down the runoff allowing more time for the contaminant to percolate down to reach the groundwater, while steep areas increase the runoff washing out the contaminant hence are assigned low rates. The land use map was also constructed in Arc GIS program, to delineate the different land use and land cover units. The land use types were then assigned ratings from 0 to 100 according to SI index model see **Table 4.6**. Intensive cultivated areas have high rates in comparison to natural area.

Table 4.6: Rating of land use classification, source; (Stigter et al., 2006)

Land Use	Rating
Agricultural area	
Irrigation perimeters (annual crops), paddy fields	90
Permanent crop (orchards, vine yards)	70
Heterogeneous agricultural area	50
Pasture and agro-forested area	50
Artificial area	
Industrial waste discharges, landfills	100
Quarries, shipyards, open-air mines	80
Continuous urban areas, airports, harbours,(rail)roads, areas with industrial or commercial activity, laid out green spaces	75
Discontinuous urban areas	70
Natural areas	
Aquatic environments (salt marshes, salinas, intertidal zones)	50
Forests and semi-natural zones	0
water bodies	0

CHAPTER 5

Result and discussion

5.1. Hydro- meteorological data analysis

The analysis on the hydro-meteorological data was based on the available hydro metrological data i.e. precipitation, air temperature and river discharge data. The following sub-sections briefly describe the outcome.

5.1.1. Areal rainfall and distribution

Sequential and spatial distribution of rainfall characteristics is very significant factors that influence runoff generation. The long term daily precipitation are used based on 15 years data (1998-2012) for the six stations which are found in the study area, are used to estimate the areal rainfall. Rainfall over the study area is bi-modal; the mean monthly rainfall is in the range of from 4mm and reaches 300 mm. The majority of the rainfall, between 70 and 75% falls in the main rainy season, from June to September (keremt) and the short wet season from February to May (Belg) provides the rest of the rain. The mean Annual rainfalls for six stations are shown in **Table 5.1**.

Table 5.1: Long term monthly precipitation

Month	Akaki	Chefedonsa	Debre Zeit	Koka Dam	Mojo	Nazeret
Jan	16	12	10	16	12	20
Feb	12	14	17	15	18	23
Mar	44	38	49	40	50	57
Apr	81	63	54	39	84	46
May	72	48	42	57	52	49
Jun	110	94	81	78	95	61
Jul	240	234	215	244	300	236
Aug	240	209	202	206	179	227
Sep	120	77	103	85	103	112
Oct	16	6	29	32	33	44
Nov	8	4	6	11	8	14
Dec	6	4	6	8	3	9
Annual RF	**964**	**803**	**815**	**832**	**937**	**897**

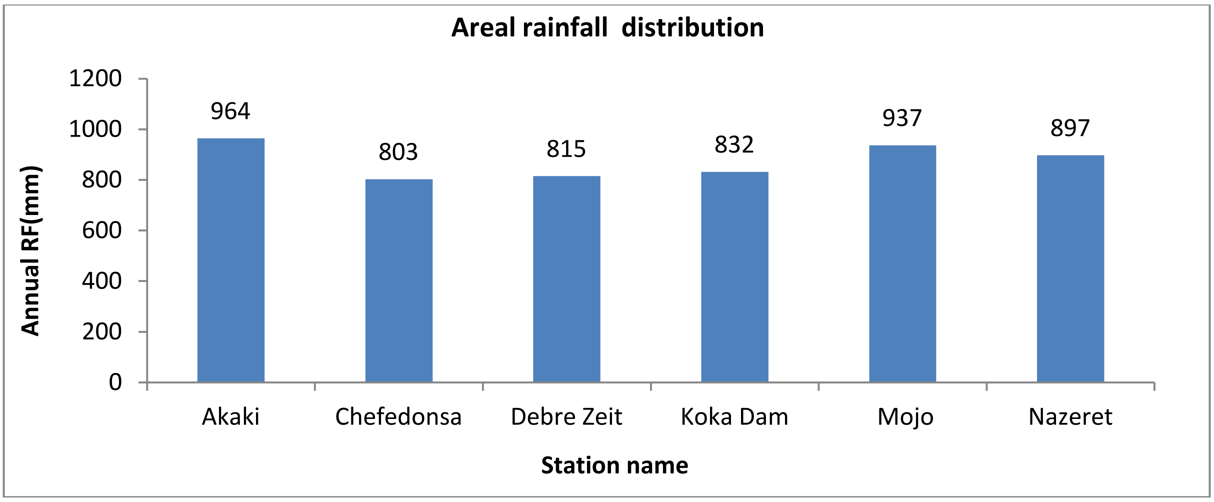

Figure 5.1: Rain fall amount and distribution in the study area

In **Figure 5.1** we can observe that the annual rainfall of the six stations which is found based in the study area, based on Thissen polygon areal rainfall computation method.

5.1.2. Temperature

Air temperature was analyzed based on the available fifty years data (1998-2012) for six stations namely (Akaki, Chefedonsa,Debre Zeit, Koka Dam, Mojo and Nzereat). **Figure 5.2** shows the mean monthly temperature calculated using the Average Depth Method (IDW). Accordingly, the hottest month is May with mean daily temperature of 22.7 ^{0}C and the coldest months are November and December with mean daily temperature of 19.6 and 19.2 ^{0}C respectively.

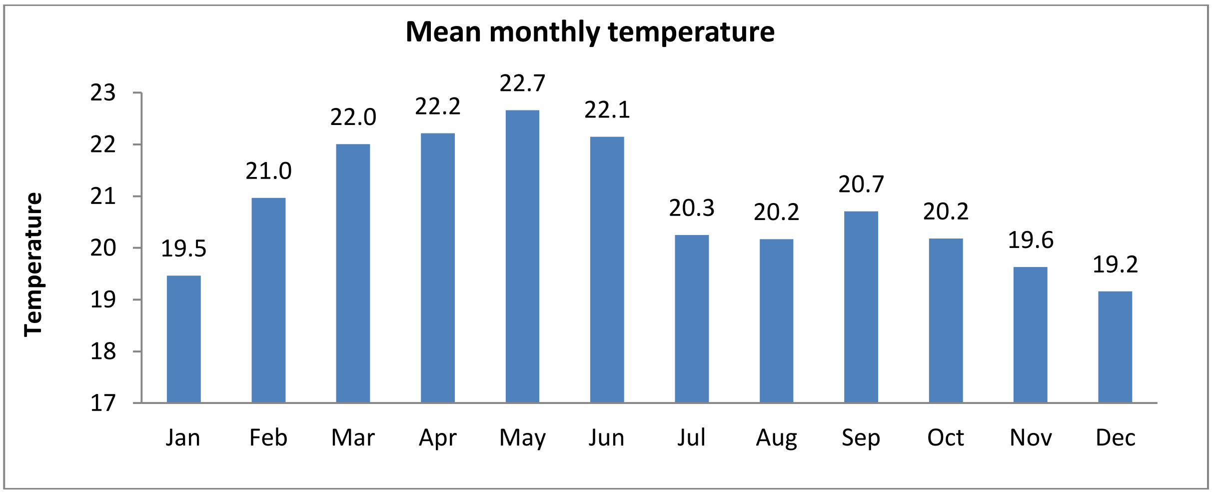

Figure 5.2: Distribution of mean monthly temperature (1998-1999)

5.1.3. Potential Evapotranispiration

According to Thornthwaite (1948) potential evapotranspiration (PET) is defined as the amount of water that would be removed from the land surface by the means of evaporation and transpiration processes. In order to calculate the Potential evapotranspiration three different temperature based methods was applied; Thornthwait, Hamon and Blaney Criddle methods. Among the three PET computation method Thornthwait and Hamon method showing similar pattern on average monthly PET while the B&C method predict the highest values **Figure 5.3 Figure 5.4 Figure 5.5**. Thornthwait was selected based the correlation coefficient of each method on the annual and monthly basis. The B&C method overestimates the value of PET. Therefore in this study we used PET estimation for water balance the value which is computed by using the Thornthwait method. From the bar graphs of monthly rainfall maps in the three station (Debre Zeit, Koka dam and mojo), it was simply recognized that the maximum rainfall occurred in July the value ranges from 200 to 300mm and the minimum in December it's about 12mm.

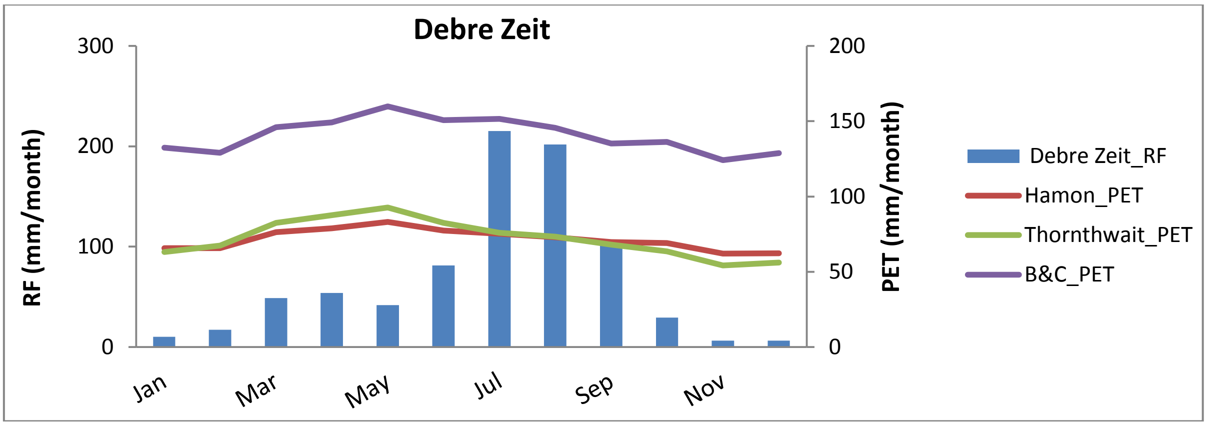

Figure 5.3: Monthly PET by using three method in Debre Zeit station

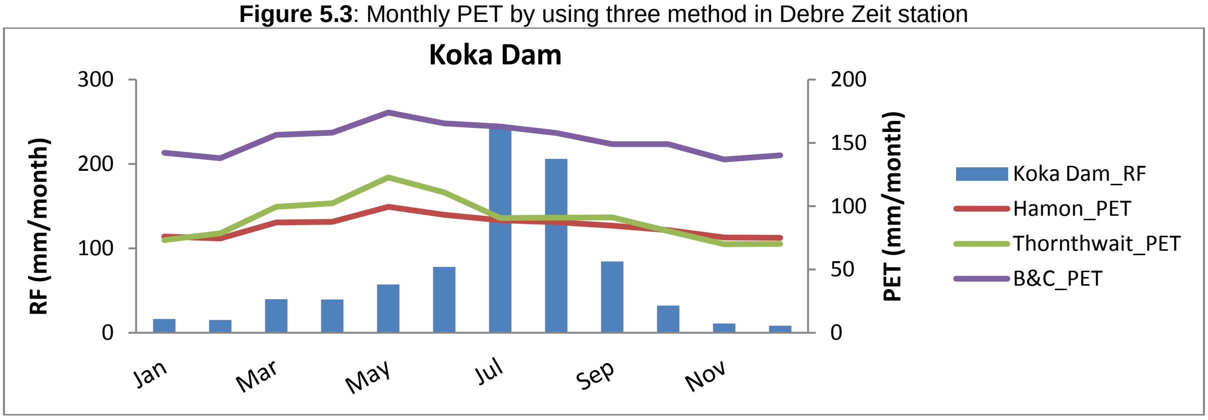

Figure 5.4: Monthly PET by using three method in Koka Dam station

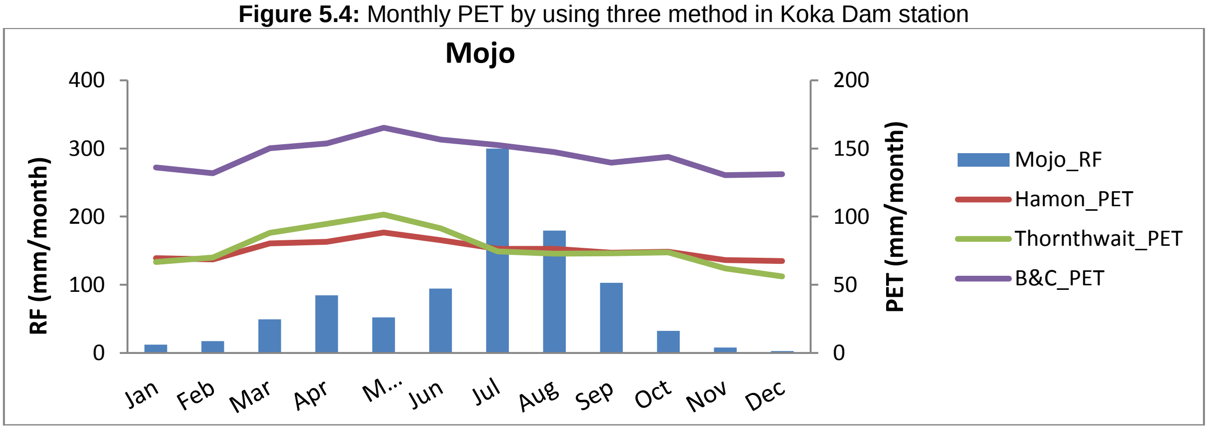

Figure 5.5: Monthly PET by using three method in Mojo station

5.2. Groundwater recharge estimation

Precipitation is the most important means for replenishment of moisture in the soil water system and recharge to ground water (Kumar, 2003). According to (Bushra, 2012) computation of the rate of the natural groundwater recharge is a basic requirement for well-organized groundwater resource management. On the other hand, the rate of the aquifer recharge is one of the most difficult factors to measure in the evaluation of groundwater resources. The main techniques used to estimate the groundwater recharge rates in this study are the Water Balance approach.

The groundwater recharge for each station was calculated by based on the geological nature of the study area, consists the lacustrine sediments deposits and basalt. In **Table 5.2** the overall groundwater recharge for each station in the study area was estimated using the area weights of the Thiessen polygon method based on geology map. As a result the groundwater potential and recharge is equal to **514.4** MCM/year. In the previous study which is done in (Ministry of Water Resources, 2009) the estimated recharge for the area is equal to **779.6** MCM/year. The difference in the recharge values for the previous study years could be the method of recharge estimation or can be the differences in the annual rainfall distribution and intensity.

Table 5.2: Areal recharge of Ada'a plain

Station Name	Geo_Code	Area (Km2)	Qperc (mm/year)	Qperc (m/year)	Areal Recharge (MCm/year)
Mojo	Q	215	391	0.39	84.1
Koka Dam	Q	628	304	0.30	190.6
Debre Zeit	Qb	805	297	0.30	239.0
Nazereat	Qb	3	259	0.26	0.7
					514.4

5.2.1. Sensitivity analysis

In principle when a small change in an input parameter results in relatively big variation in output are so called sensitive to that parameter. For that reason sensitivity analysis were done on a water balance model to make sure that how sensitive the output of the model when there is a change in the input parameters. In this case we are doing the sensitivity analysis to find out the runoff threshold value. In general the surface runoff can be create after water falling on the ground exceeds the infiltration rate of the soil and all surface depressions are filled to capacity it generate runoff in the wet and dry season. The analysis is done in both single and double runoff thresholds, by using as sensitive parameters in the water balance of recharge estimation method. There is a number of input parameters which are used to estimate the groundwater recharge in water balance method, from that we choose the sensitive parameter that can affect most in the output of recharge i.e. the runoff threshold and the soil property.

In the single runoff threshold **Figure 5.6** (a) it clearly show when the threshold value decrease the recharge also decrease in addition to that when the soil property change from coarse sand to medium coarse sand the recharge become decrease its because when the pore size decrease the groundwater recharge (percolation) decrease. On the other hand **Figure 5.6** (b) shows the double threshold likewise when the runoff threshold increases the recharge increase. In the double threshold are used to apply the two runoff thresholds i.e. for wet and dry seasons.

As a result of sensitivity analysis we choose the double threshold it's because it's more reasonable to have different runoff threshold in dry and wet season. In the dry and wet season the runoff can't be generation at same rainfall amount, therefore in the wet we used runoff threshold 10mm which means after 10mm rain the runoff generate. On the other hand in the dry season we took 20mm since the soil is dry in needs more water to generate the runoff.

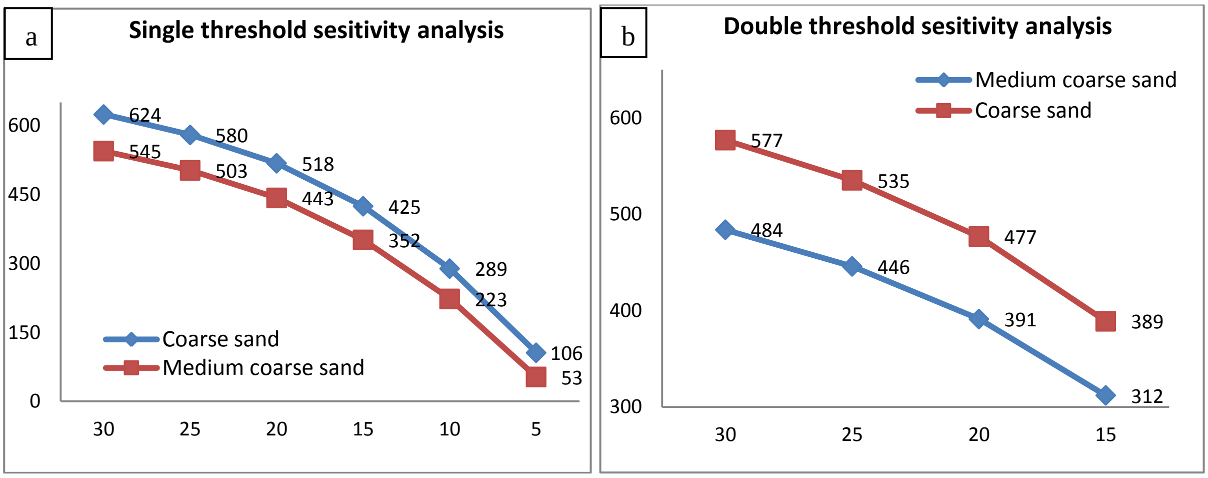

Figure 5.6: Sensitivity analysis for single and double threshold

5.3. Groundwater availability versus demand

5.3.1. Groundwater potential and optimum availability

According to Nonner (2012) the optimum groundwater availability is derived from the potential amount of available groundwater. The optimal accessible can be considered as the groundwater availability taking in to account some constraint. Since the optimal available is less than potential, the constraint should take in to consideration. There are three constraints; technical, environmental and socio economic constraints.

5.3.2. Groundwater demand

Scenarios have been developed to show how population growth and urbanization can affect the water demand and per capita water consumption **Figure 5.7** clearly show that when the population increase the demand increase. Therefore, increasing demand due to an increase in population and land use change will further increase dependence on groundwater. Factors that affect groundwater demand are stated below.

Urbanization

In general the urban surface has been made impermeable and, with less area for rainfall infiltration, lower recharge might be expected relative to rural surfaces. However according to (Lerner, 2002) and others have shown that two key reasons for total urban recharge is similar to or higher than rural recharge. The first reason, excess rainfall is often routed to groundwater through saturate, while covered surfaces are frequently more permeable than they appear. This means that they allow some percolation. The second reason, large volumes of water are transported into and through urban areas with pipe networks, which always leak. Urbanization has to clearly considerable impact on the water demand. The graphical representation of the projected population and water demand is shown in **Figure 5.7**.

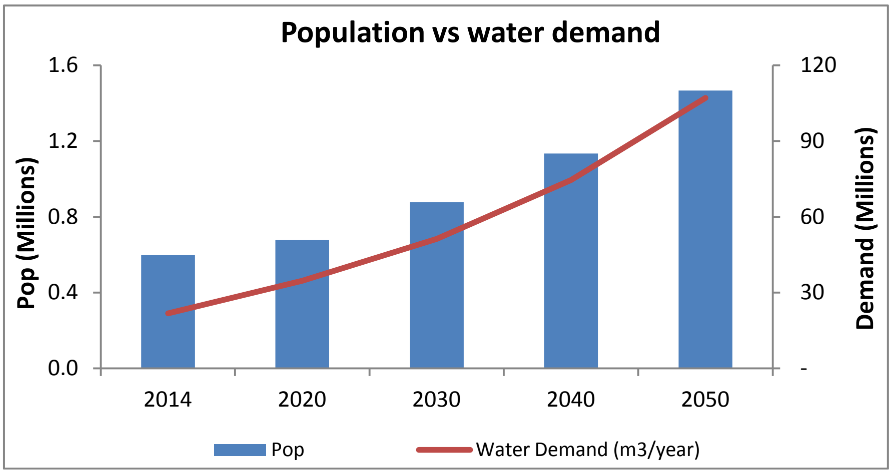

Figure 5.7: Population and demand forecast

Irrigation

The irrigation demand is assess of how much water used to irrigate agricultural crops. Therefore in the area the calculated irrigation water demand is 151mm/year.

5.3.3. Future scenarios

The basis of the scenario analysis is to clarify the implications of future prospect on population and water demand scenarios. The current amount of water demanded by the domestic and irrigation is 21,788.879 m3/year and 151 mm/year respectively which has a direct related to population growth. The total population of the study area 596,956 the population predicted to be 877,309 and 1,465,884 in the year 2030 and 2050 respectively, based on the annual growth rate 2.6%. The study area has high groundwater potentials; the current estimated annual groundwater recharge is 514.4 MCM.

Scenario 1 Increasing per capita water demand, considers population growth and urbanization; the current population of the study areas is 596,956 and the estimated result for the 2050 is 1,465,884 is increasing 391%. However under increasing per capita water demand scenarios which assume the existing per capita water use increased by 20 % from 2014 to 2050, in this case the demand change significantly. The tabular representation is shown in**Table 5.3**.

The Business as usual scenarios (BAU), the total water demand based on constant growth rate. Using this approach we forecast the future water demand is mainly based on water per capita consumption per inhabitants or per family. However the business as usual scenarios does not specifically represent future enhancements in water use efficiency it's because which does not consider the changes in annual growth rates which is set by the government. By the year 2050, population in the study area is approximately 1,465,884 based on the annual growth rate is 2.6% .As a result the water demand increased from 21,788,879 m3/year to 53, 504,772 m3/year the current and 2050 respectively.

Increasing irrigation water demand is a scenario 3, which consider the crop water demands is increasing from time to time. In general irrigation water for crops put additional pressure on groundwater resources **Table 5.3** are illustrates the scenario. Scenario 4 considers constant irrigation for agriculture water demand, this scenarios based on the assumption that the irrigation water demand will follow the same trend.

Table 5.3: Domestic water, irrigation water demand and population forecast in the study area

years	2014	2020	2030	2040	2050
Scenario 1					
Liter per capita per year (lpcpd)	**0.1**	**0.14**	**0.16**	**0.18**	**0.2**
Number of population	596,956	678,702	877,309	1,134,034	1,465,884
Water Demand (m3/year)	21,788,879	34,681,649	51,234,829	74,506,029	107,009,545
Scenario 2					
lpcpd	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Pop	596,956	678,702	877,309	1,134,034	1,465,884
Water Demand (m3/year)	21,788,879	24,772,606	32,021,768	41,392,238	53,504,772
Scenario 3					
Irrigation demand (mm/year)	**0**	**150**	**200**	**250**	**300**
Irrigation demand (m/year)	**0**	**0.15**	**0.2**	**0.25**	**0.3**
Irrigation area (km2)	1,891	1,891	1,891	1,891	1,891
Irrigation area (m2)	1,890,560,000	1,890,560,000	1,890,560,000	1,890,560,000	1,890,560,000
Irrigation demand (m3/year)	0	283,584,000	378,112,000	472,640,000	567,168,000
Scenario 4					
Irrigation demand (mm/year)	**150**	**150**	**150**	**150**	**150**
Irrigation demand (m/year)	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**
Irrigation area(%)	0	25%	50%	75%	100%
Irrigation area(km2)	0	472.75	945.5	1418.25	1891
Irrigation area (m2)	0	472,750,000	945,500,000	1,418,250,000	1,891,000,000
Irrigation demand (m3/year)	0	70,912,500	141,825,000	212,737,500	283,650,000

5.4. Groundwater chemistry assessment

Based on the groundwater chemistry data a classification into water types was made for the sampled wells data. The chemical analysis results for the cation and anion concentration of 34 groundwater sample are presented in **Table 5.4** and on piper diagram **Figure 5.8**, showing the composition of dominant cation and anions. The most important parameters used in this classification of chemical water type the methods combines four fundamental aspects (i.e.) main type, type, subtype and class. Each of which contributes to the total code of the water type. The different compositions of groundwater types in the study area which have a natural origin for each water type, the main processes are a result of several hydro chemical processes. Almost all the samples were alkalinity ranges of 244 to 488 mg/l (Moderately high) in the study area there are four wells which have high alkalinity 488 to 976mg/l. On the other hand according to (WHO 1993) the acceptable limit of TDS in the drinking water is 1000 mg/l. Though in this study, the TDS values were varied between 229 to 1027 mg/l, with an average of 470 mg/l, From the 34 samples 2 of them exceeded the WHO acceptable limit. Calcium and magnesium in the study area ranged between 3.3 to 53 mg/l and 2.3 to 30 mg/l respectively. In the normal groundwater systems, the main origin of these ions is carbonate minerals and their dissolution and depositional processes. Weathering of silicate minerals are also contributing towards the enrichment of these minerals.

According to (Tijani, 1994) the pH of most groundwater ranges generally between 5.0 and 8.0. The pH of groundwater can also be lowered by organic acid decaying by vegetation or by dissolution of sulfide minerals. In this study the pH values also vary between 4.9 and 8.9, mostly representation a little acid and alkaline. Relatively less loads of the carbonate minerals in the study area indicate that the major origin of Ca and Mg is silicate weathering. Na and K concentrations were varied between 27 to 269 mg/l and 2.8 to 42 mg/l. However, Na and K in the study area is derived from the weathering of the hard rocks. A relative lower concentration of Ca than Na shows the effect of cation exchange between these minerals.

In the study area the concentration of Cl in the groundwater was 3.3 to 53 mg/l, with an average of 19 mg/l. sulphate in the study area varied between 0 to14 mg/l. The major origin of sulphate is the dissolution of Gypsum and anthropogenic activities. Bicarbonate was the dominant anion in the study area, with an average concentration of 429 mg/l. In the result most of the water type shows the groundwater quality is fresh and the alkalinity is moderate. The alkalinity of a solution may be defined as the capacity of its solutes to react with and neutralize acid. In most natural waters the alkalinity is primarily due to the presence of dissolved carbon specious particularly bicarbonate and carbonate other constituents that may contribute minor amounts of alkalinity to water (Hem, 1985).

In general, the classification of chemical water type was done for each water sample. In the piper diagram and in the Table 5.4 are shown the water type classes into 8 fields. Those are g3CaHCO3, g3MgHCO3, F3CaHCO3, F3NaHCO3, g3NaHCO3, g4NaHCO3, F4NaHCO3 and F4CaHCO3.

Table 5.4: Groundwater Quality and water type

No	TDS (mg/l)	EC (µs/cm)	PH	Na^+ (mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Mn (mg/l)	Fe (mg/l)	F^- (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	CO_3^{2-} (mg/l)	HCO_3^- (mg/l)	$SO4_2^-$ (mg/l)	$PO4_3^-$ (mg/l)	Total Hardness (mg/l)	GW_Depth (m)	Chlorinity	Alkalinity	Chemical water type	POLIN_Class
1	439	632	7	50	8	74	15	0	0	1	15	14	0	382	32	0	249	340	g	3	g3CaHCO3	slightly polluted
2	438	667	9	62	11	45	30	0	0	1	15	9	52	264	42	0	238	361	g	3	g3MgHCO3	Moderately polluted
3	443	694	7	53	11	84	13	0	0	1	15	9	0	459	21	0	265	360	g	3	g3CaHCO3	quasi unpolluted
4	456	691	7	61	12	57	20	0	0	0	18	10	0	420	4	0	224	364	g	3	g3CaHCO3	quasi unpolluted
5	395	670	8	61	13	48	27	0	0	1	19	8	0	381	2	0	233	400	g	3	g3CaHCO3	quasi unpolluted
6	373	635	7	50	11	57	18	0	0	1	15	16	0	384	11	0	218	348	g	3	g3CaHCO3	quasi unpolluted
7	427	703	7	67	12	54	26	0	0	1	19	5	0	423	7	0	243	333	g	3	g3CaHCO3	quasi unpolluted
8	471	724	7	55	22	74	18	0	0	1	53	7	0	389	0	0	261	366	F	3	F3CaHCO3	quasi unpolluted
9	387	635	7	101	4	20	10	0	1	1	33	1	0	307	36	0	90	350	F	3	F3NaHCO3	quasi unpolluted
10	430	639	7	58	13	61	15	0	0	1	17	44	0	344	24	0	175	350	g	3	g3CaHCO3	Moderately polluted
11	501	826	8	93	3	51	25	0	0	1	33	8	0	453	18	0	231	344	F	3	F3CaHCO3	slightly polluted
12	479	750	8	162	11	10	3	0	0	2	38	4	0	354	58	1	37	462	F	3	F3NaHCO3	quasi unpolluted
13	307	481	7	77	12	23	9	0	0	1	12	0	0	281	6	0	97	356	g	3	g3NaHCO3	Unpolluted
14	480	685	8	140	11	20	2	0	0	1	12	10	0	327	114	0	60	455	g	3	g3NaHCO3	slightly polluted
15	229	351	9	48	3	23	8	0	0	1	8	12	34	144	13	0	88	602	g	3	g3NaHCO3	Moderately polluted
16	370	633	7	49	11	57	19	0	0	1	15	16	0	384	11	1	220	348	g	3	g3CaHCO3	quasi unpolluted
17	377	624	7	55	11	49	26	0	0	1	13	9	0	373	8	0	230	359	g	3	g3CaHCO3	quasi unpolluted
18	632	968	7	138	37	76	12	0	0	1	19	4	0	603	39	0	240	397	g	4	g4NaHCO3	Unpolluted
19	505	719	7	98	17	37	29	0	0	1	21	6	0	530	15	0	212	456	g	4	g4NaHCO3	Unpolluted
20	466	738	7	84	15	52	15	0	0	1	16	4	0	398	21	0	191	414	g	3	g3NaHCO3	Unpolluted
21	425	637	7	68	11	54	18	0	0	1	21	16	0	402	14	0	209	354	g	3	g3CaHCO3	Unpolluted
22	455	720	7	86	21	46	17	0	0	1	15	6	0	440	16	0	184	340	g	3	g3NaHCO3	Unpolluted
23	427	664	7	57	19	56	16	0	0	1	14	2	0	420	13	0	205	266	g	3	g3CaHCO3	Unpolluted
24	395	670	7	60	13	52	23	0	0	1	15	15	0	380	8	1	229	420	g	3	g3CaHCO3	slightly polluted
25	1027	1530	7	269	42	64	18	1	0	1	33	1	0	967	89	0	233	366	F	4	F4NaHCO3	Unpolluted
26	1017	1526	7	174	36	136	29	0	0	1	31	5	0	931	78	1	463	367	F	4	F4CaHCO3	quasi unpolluted
27	614	1004	7	145	31	44	18	0	0	1	36	3	0	585	37	0	185	420	F	4	F4NaHCO3	Unpolluted
28	440	684	7	62	18	51	29	0	0	1	15	6	0	447	14	0	248	424	g	3	g3CaHCO3	Unpolluted
29	308	478	7	42	13	41	10	0	0	1	8	1	0	291	8	1	143	420	g	3	g3CaHCO3	Unpolluted
30	383	688	7	63	4	55	16	0	1	1	15	4	0	378	15	0	203	351	g	3	g3CaHCO3	Unpolluted
31	410	664	7	55	12	61	20	0	0	1	12	10	0	403	15	0	237	365	g	3	g3CaHCO3	quasi unpolluted
32	598	912	7	106	29	65	13	0	0	1	15	3	0	545	28	0	219	350	g	4	g4NaHCO3	Unpolluted
33	622	947	7	102	35	68	13	0	0	1	19	2	0	547	32	0	227	420	g	4	g4NaHCO3	Unpolluted
34	237	408	7	27	6	58	3	0	0	1	3	4	0	255	0	1	159	414	g	3	g3CaHCO3	Unpolluted

A Piper diagram **Figure 5.8** which is a graphical illustration of the chemistry of a water sample and clearly shows the overall chemical characteristics. It's formed by using the data obtained from the hydro-chemical analysis. As a result the alkaline water group, that is the dominant cations and anions Ca and HCO3 respectively. In the piper diagram the majority of the samples about (50%) are plotted in the Ca-Mg-Cl field and about 25% of the samples showed Na-Cl type. Rest of them was fall in the Ca-HCO3and Na-HCO3 types.

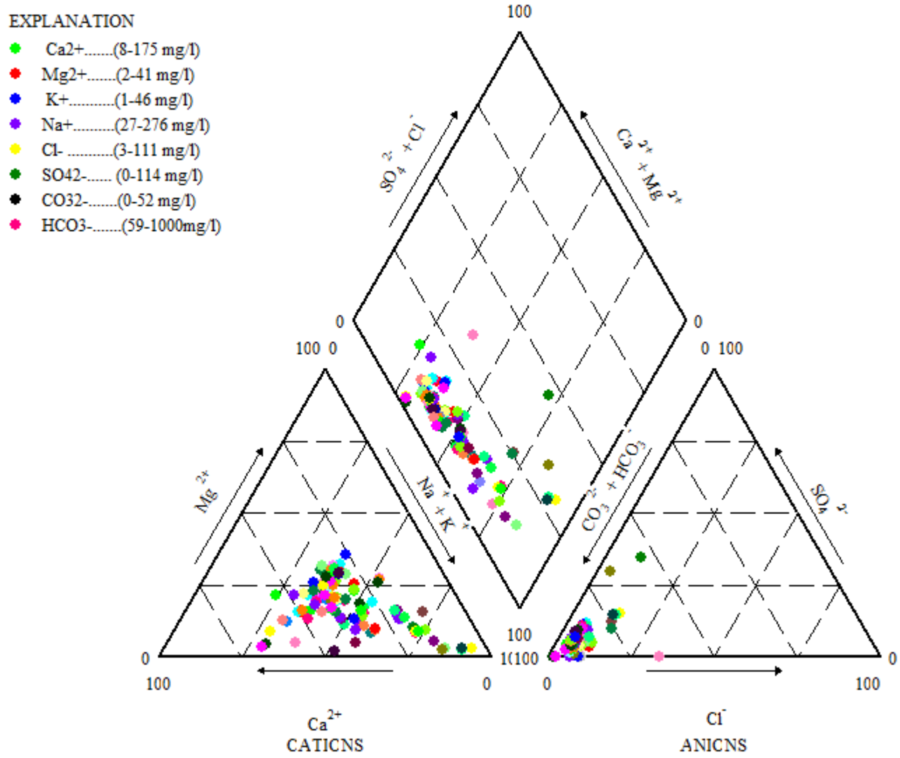

Figure 5.8: Groundwater quality Piper diagram of chemistry data

Figure 5.9 are shown different water types based on hydro-chemical facies and total of 34 boreholes location.

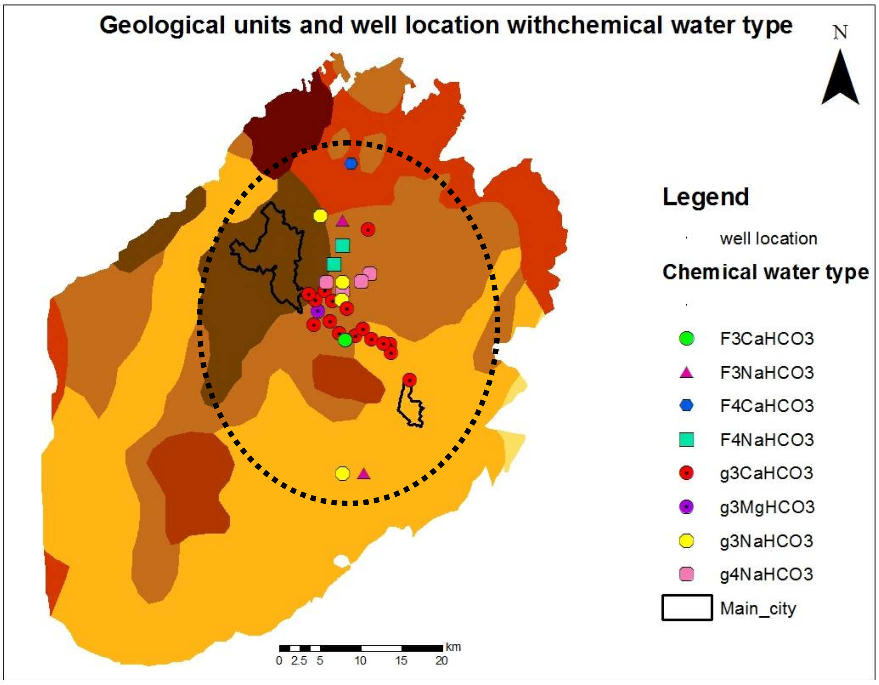

Figure 5.9: Well location with chemical water type and geological unit

In the following **Figure 5.10** the 1:1 correlation (mca+mg: mHCO3) line and the graphs are used to show the available groundwater quality data i.e. Na vs HCO_3, Ca + Mg vs HCO3, NO_3 vs Cl and EC vs HCO_3.

Figure 5.10 (a) the Na^+ concentration in groundwater ranges from 1.2 to 11.7 meq/l and the high concentrations of Na^+ and Ca^{2+} in the groundwater is recognized to cation exchange among minerals. The bicarbonate is the dominant anions in the area, as a result of the primary carbonate mineral such as basalt. Calcium concentrations in the study area range from 0.4 to 6.8meq/l. In most case the major source of magnesium (Mg^{2+}) in the groundwater is due to ion exchange of minerals in rocks and soils by water.

Figure 5.10 (b) is show Ca^{2+} + Mg^{2+} vs HCO_3^-,calcite and dolomite dissolution are settle on for the chemical composition and large difference of carbonate mineral dissolution.

Figure 5.10 (c) shows the graph between NO_3 vs Cl, in general high concentration of NO_3 is attributed to decaying organic matter and increased usage of fertilizers (Sattur and Karanth, 1989). Source of chloride in the groundwater is the result of erosion and weathering of crystalline rocks basalt. The concentration of chloride ranges from 0.1 to 1.5 meq/l; some variation is attributed to geochemical processes. According to (Stigter et al., 2006) Cl concentration raise in the cause of groundwater recycling process is accompanied by an increase in NO_3^-concentrations. There are a number of factors in the soil zone; which can increase of nitrate concentration, such as fertiliser type, fertilisation process and rate, crop uptake and biogeochemical transformations of nitrogen. Nitrate concentration in the study area varies in the range 0 to 0.7meq/l.

Figure 5.10 (d) bicarbonate is the dominant anion in the study area ranges from 159 to 549 mg/l. EC and HCO_3 have a higher correlation which indicates when EC increase the HCO_3 of ions increase.

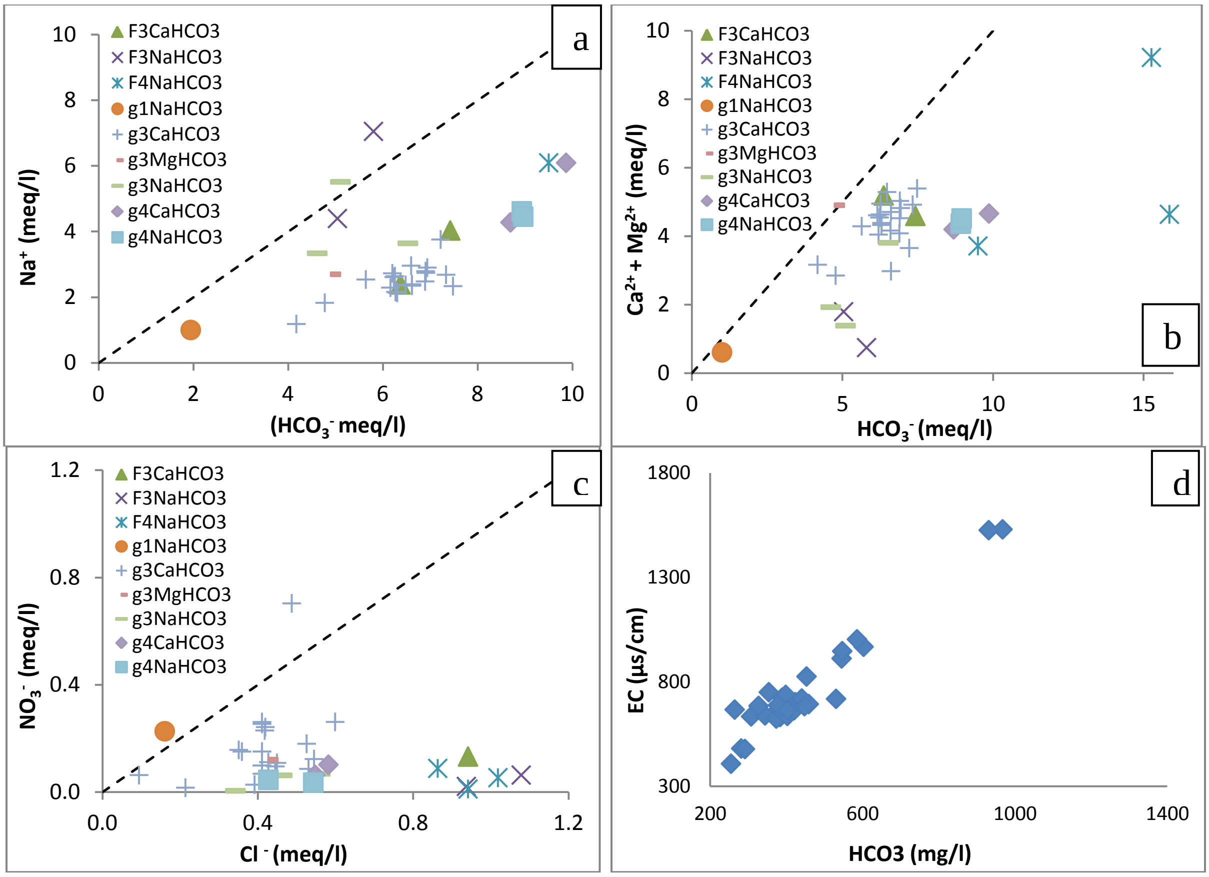

Figure 5.10: Scatter plots: (a) Na^+ vs HCO_3^- ; (b) Ca^{2+} + Mg^{2+} vs HCO_3^- ; (c) NO_3^- vs Cl^- and (d) EC vs HCO_3^-

In **Figure 5.11** (b) the hardness of the water is caused mainly by the presence of cations such as calcium and magnesium. Hard water is unsuitable for domestic use. In the study area, the total hardness varies between 30 to 463 mg/l. According to (Sadashivaiah et al., 2008) classification for hardness, about 80% of samples fall under very hard class and the remaining samples fall under moderately hard to hard. The hardness classification is given in Table below.

Table 5.5: Classification of water based on hardness (Sadashivaiah et al., 2008)

Class	Hardness	Hardness degree
1	0 - 75	Soft
2	75 - 150	Moderately hard
3	150 - 300	Hard
4	>300	Very hard

Figure 5.11 (c) the groundwater of chloride concentration showed a high values in the red colour in the range of 25 to 55 mg/l, which could be because of their occurrence near tectonically active zones.

Figure 5.11 (d) In order to investigate the relationship between land use map and nitrate concentrations in groundwater, the well location with the nitrate (NO_3) concentration was overlaid on the land use map. This illustrates on the map below **Figure 5.11** (d) are clearly show high concentration it's because the study area is more than 75% of the land use is intensively cultivated, as a result of this found in high and high NO_3 concentration.

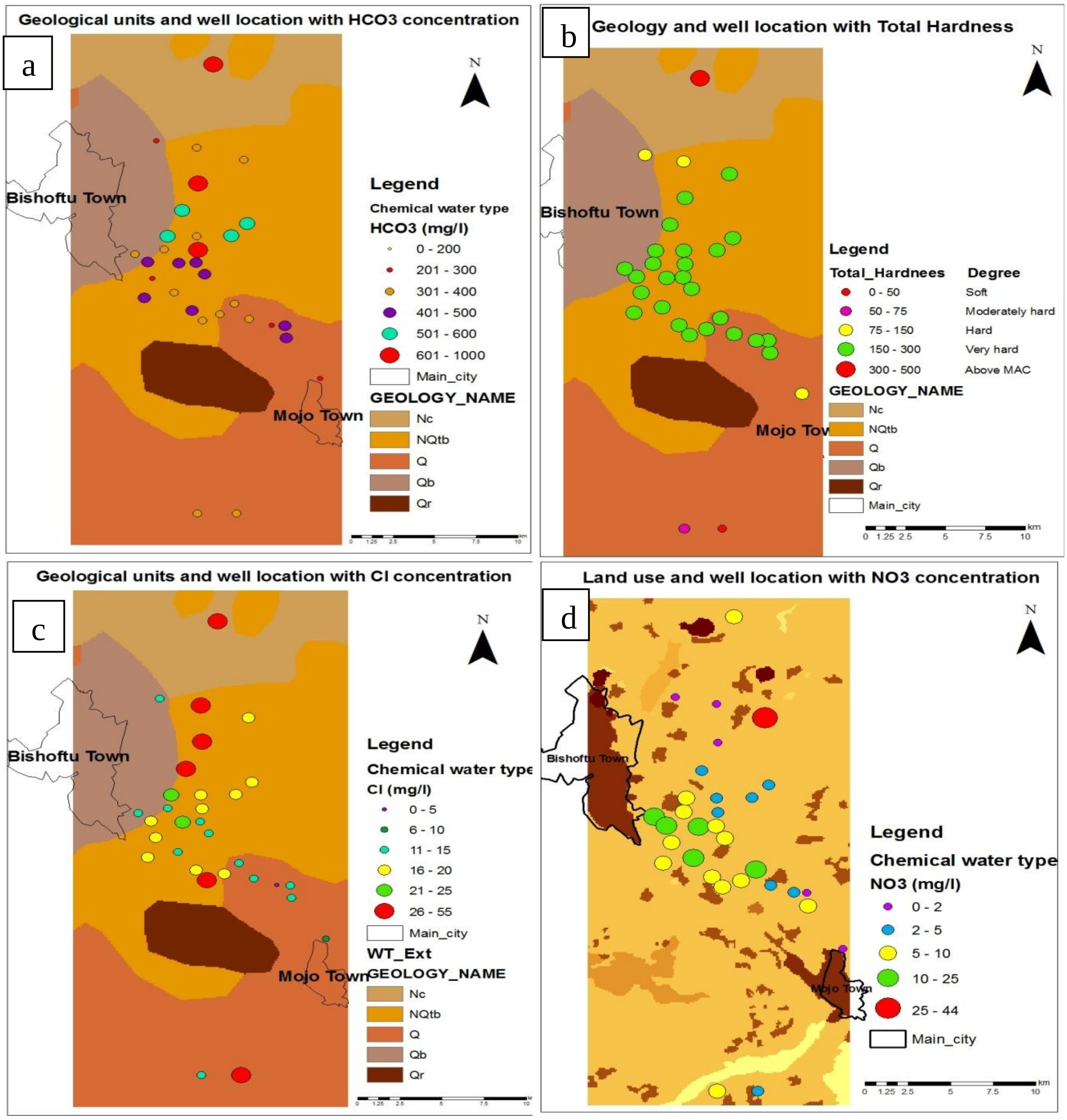

Figure 5.11: Well location with different chemical concentration

5.5. Groundwater vulnerability assessment

5.5.1. Depth to water level (D)

In the groundwater vulnerability assessment, from the five significant parameters one of the determine factors is depth to water. This can determine the distance downwards of aquifer material throughout which passing though water should travel before getting the aquifer-saturated zone. The depth to groundwater made by using the IDW (inverse distance weighed) interpolation method is shown in the **Figure 5.12**. Which accordingly as a result of impacts on the extent of interaction between the percolating contaminant and sub surface materials for instance air, minerals and water. Therefore, on the degree of extent for physical and chemical reduction and degradation processes in general, the aquifer possible protection increases with depth to water. In **Figure 5.12** the depth to water interval range and ratings are clearly shown in the legend. The area with shallow depth in the range of less than 1.5m is the rating of 100 has high vulnerable to pollutant. The smaller the depth to groundwater is originated in the topographically smooth areas towards Lake Koka. The deeper the groundwater has less rating value, depth to water greater than 30m have a rating of 10.

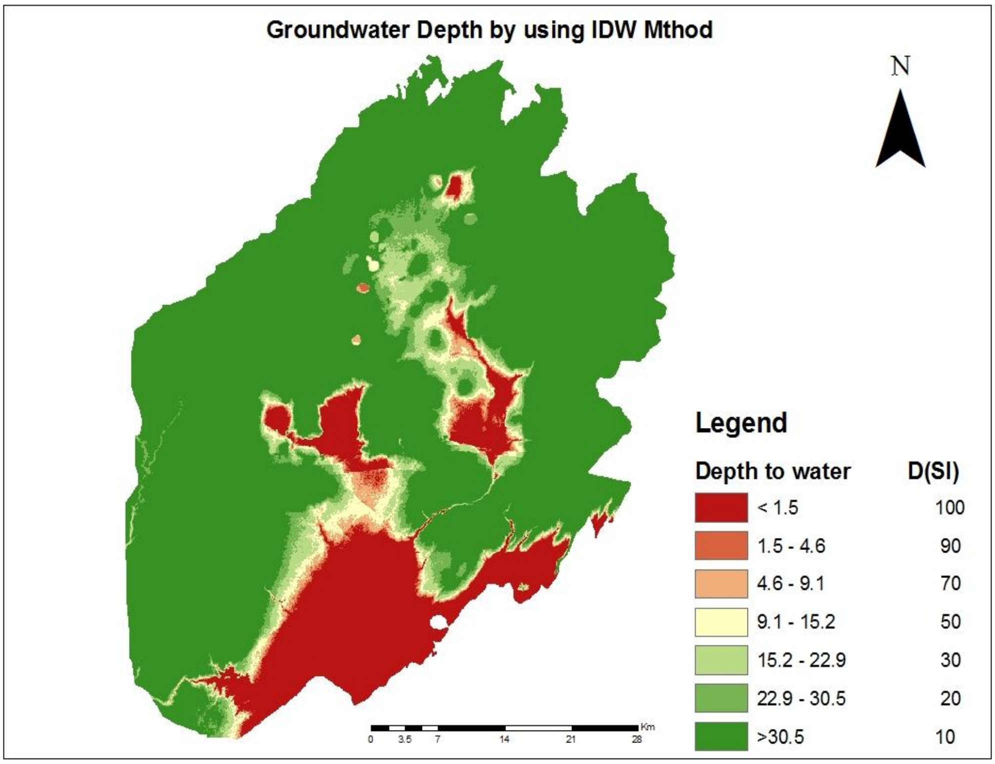

Figure 5.12: Depth to groundwater of study area

5.5.2. Recharge (R)

The recharge is the quantity of water goes down to the groundwater it can be natural or artificial recharge. Therefore percolating and carrying contaminants is a major means of recharge water inside the saturated zone. It transports the solid and liquid pollutant to the water table and it can increase the water table. Therefore in the study area 75% of the land use is intensively cultivated; there could be the fertilizer and pesticide application in the use of agriculture in such a case the contaminant can increase in the area of high recharge. The high recharge can increase the leaching of fertilizer down to the groundwater and cause of increasing the contamination.

In general an area with high recharge has high risk of vulnerability to contamination so high recharge rates were assigned to these areas see **Figure 5.13**. In **Figure 5.14** the urban areas Debre zeit and Mojo city which are found in the study area are considered zero recharge because of impermeable pathway from the surface to the water table. The area received recharge from precipitation varies from place to place based on the geological nature of the area. For instance in the lacustrine sediments the recharge is greater than 254mm and the rating reaches 90, the two basalt type are lower natural recharge compare to cores sand, recharge in the areas basalt and fractured basalt its various from in the range of 178mm to 254mm and ratting is 60 to 80 respectively. An area with high recharge is at high risk because of the high permeable pathway from the surface to the water table.

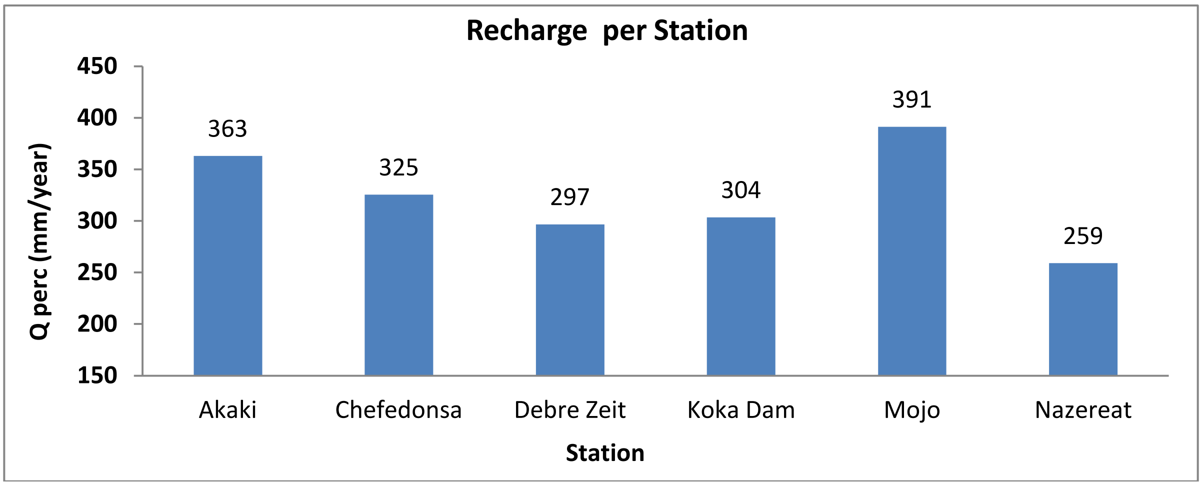

Figure 5.13: Net recharge per station

When the recharge water reaches to the ground from precipitation it percolates down to water table, transport solutes as well as pollutants with it. Because of this groundwater is exposed to point sources pollution which is diffuse from the surface. As a result, huge quantities of pollutant can build up and be stored in the groundwater system. Disperse or diffuse pollution which can frequently created by agriculture and increases across the landscape by percolating to the groundwater with high recharge. Therefore in this study the high recharge areas have high rating because of high risk of vulnerability of contamination due to percolation.

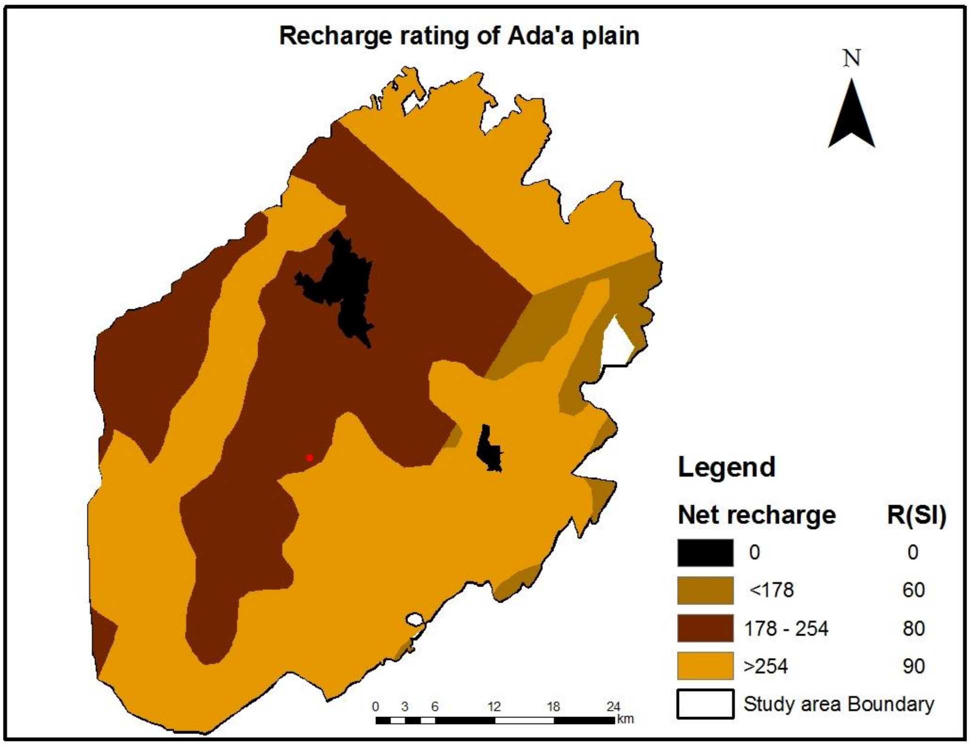

Figure 5.14: Net recharge of the study area

5.5.3. Aquifer media (A)

The aquifer is defined as a rock (consolidated and unconsolidated rock) formation which will yield sufficient quantities of water for use (Rahman, 2008). **Figure 5.15** clearly indicates the SI index ratings assigned to the aquifer media.

Aquifer ratings were assigned based on the geological nature of the study area. The highest rating 90 is assigned to the sand and gravel aquifers, which are extremely permeable due to the presence of large pore space. In general the larger the grain-size and the more fractures or openings within the aquifers the higher the permeability and the lower the attenuation capacity will be; as a result the greater the pollution potential (Rahman, 2008). Therefore the course and gravel media was assigned a high rating value 90 compared to the fine media. The upper and the lower basalt aquifer in the study area are given a rating of 60 and 50 respectively it's because of low permeability. According to (Ministry of Water Resources, 2009) feasibility report the upper basalt aquifer it's found in the range of thickness of 50 to 300 meter. The geological formation is highly varied from place to place i.e. massive basalts, scoraceous basalt and scoria. In addition lower basalt aquifer composes dominantly scoraceous basalt. Therefore However for basalt the rating is assigned to 70. The basalts when it is faulted and fractured the permeability is higher, as a result its move vulnerabel to groundwater contamination.

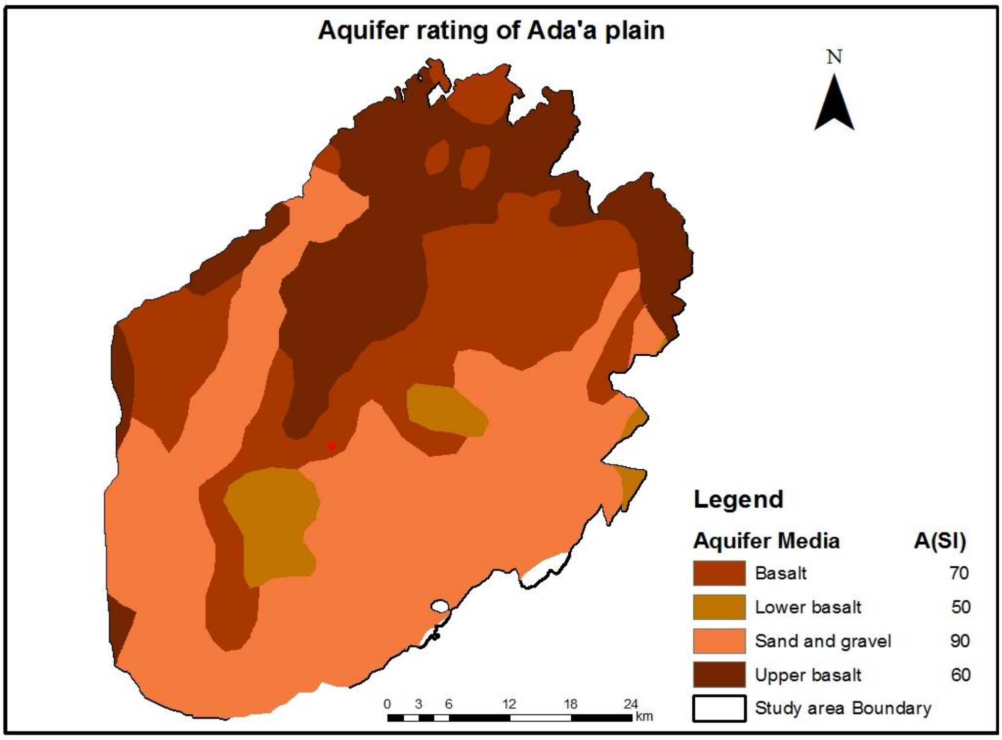

Figure 5.15: Aquifer media of study area

5.5.4. Topography (T)

The topographic (slope) map of the study area prepared by using digital elevation model (DEM) in Arc View GIS environment. Thereafter from the DEM slope was extracted and it was divided into five slope classes based on **(Wangsaatmaja, 2004).** The percent slope values were assigned ratings on the basis of the corresponding ranges defined by SI index. In **Figure 5.16** shows the resulting parametric map.

According to (Lynch et al., 1994) topography or slope will give an indication on a pollutant will run off or remain on the surface long enough to infiltrate into the groundwater. Slope deviation in the study area is ranged i.e.< 2 m, 2-6 m, 6-12 m, 12-18m and >18 m. The southeast parts study areas have the highest ratings, as topography here is very flat (<2%). Therefore at areas were given high rates since the runoff rate is less in flat areas, so groundwater percolation of contaminants become high. Slopes between 2 and 6% are found in the largest part of the remaining area, which has been assigned the SI index rating scores of 100 and 90 respectively. This is because the areas with low slope tend to keep water for longer period of time. This allows a greater groundwater percolation or recharge of water and a greater potential for contaminant migration. The slope percentage increases from southwest to northeast of the study area associated with the mountain range. The areas with steep slopes (>18%) are covered 153 sqkm from the total area of 2500sqkm, were typically assigned a low rating score 10 indicating their minimal effect on the aquifer vulnerability. The reason for low rating having low vulnerability, it's because a large amounts of runoff and smaller amounts of infiltration.

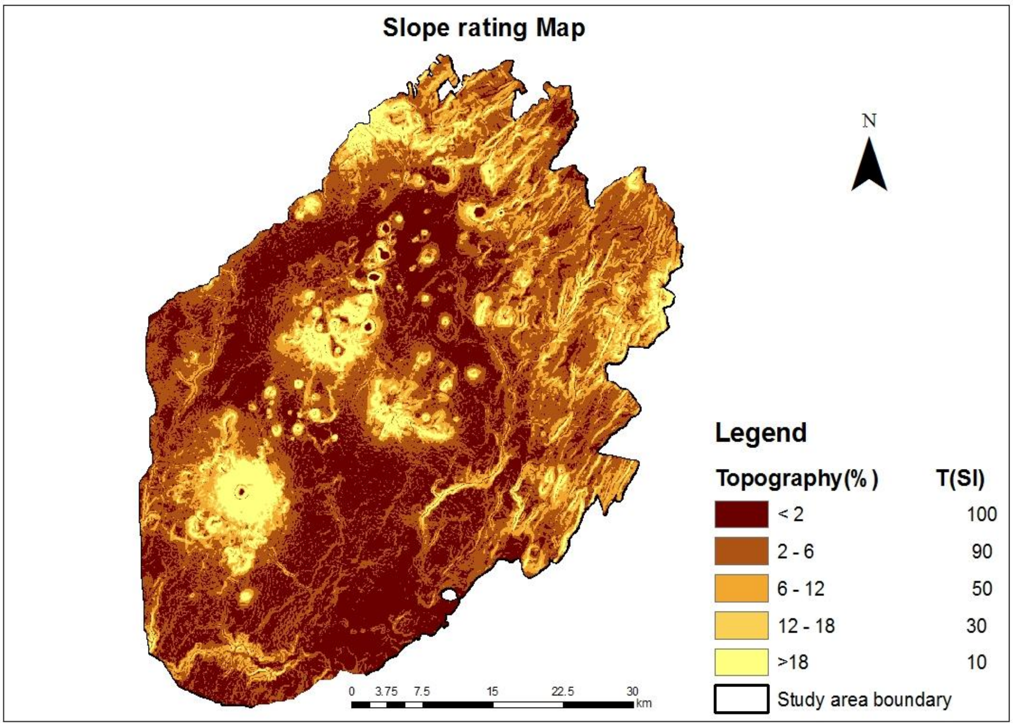

Figure 5.16: Topography of the study area

5.5.5. Land use (LU)

Cultivated land is the major form of land use in the study area; more than 75% of the area is intensively cultivated. However in order to calculate the SI index land use parameter, the map of land use and land cover referred in **Figure 5.17**. The maps present the land use classes for the study areas. Eleven categories are made based on the land use classification, however we merge them in to four rating unit in SI index model. The highest rating 90 is assigned to Continuous urban area and lower rating 80 for quarries and 70 for heterogeneous agriculture and irrigation perimeters which occupy a large area in the study area. On the other hand for degraded land, aquatic environment and pasture assigned a rating is lower compared to the other we gave rating of 50. In semi-natural areas, forests and water bodies are considered non-polluting areas and hence the assigned rating is 0. By assuming that in the area which have less agriculture or not intensively practiced their influence on the contamination potential is lower.

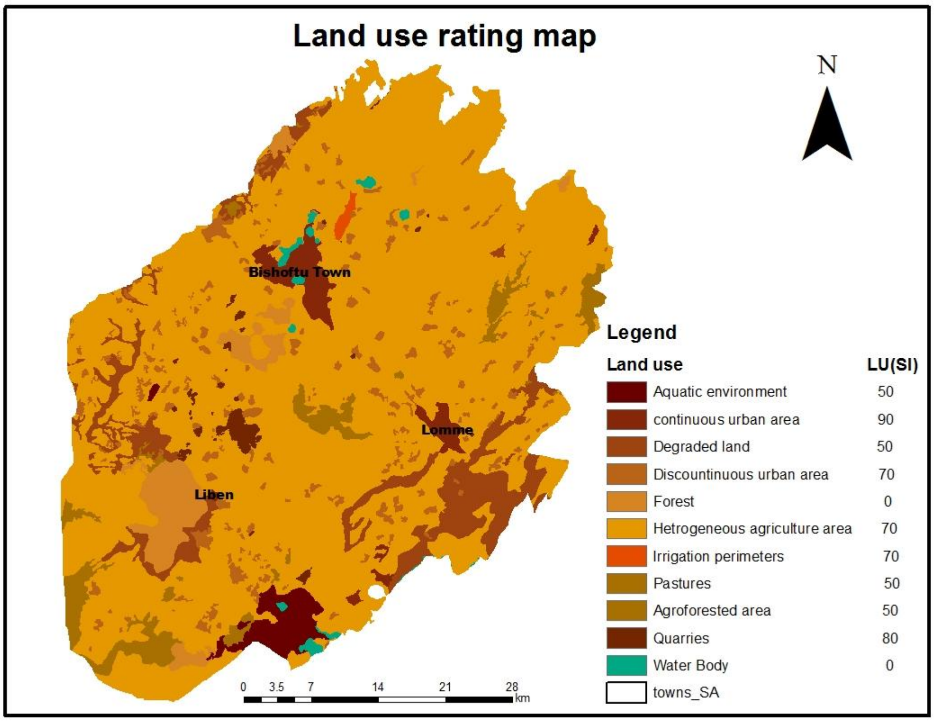

Figure 5.17: Land use of the study area

5.5.6. Susceptibility (SI) Index

The combined vulnerability assessments are presented on **Figure 5.18** and **Figure 5.19** by using the existing and future land use plan respectively. **Table 5.6** Is clearly described the tabulated result of the overall extent of vulnerable to contamination in the study area. A large part of the area is classified as moderate to high vulnerable index 60 to 70 to contamination. Intensive cultivation is the dominant land use in the study area and together with a high recharge contributes to the high vulnerability. Whereas the shallow groundwater, land use is occupied by intensive cultivation and aquifer media have course sediments unit has very high vulnerability index 80 to 90. On the contrary, where slopes are steeper, deeper groundwater and land use is less polluting, vulnerability is reduced to moderate to low index 50 to 60. In the study area SI Index output extremely high vulnerability areas are found in some place which is covered 181 sqkm from the total of the study area, we gave a rating greater than 90. The steep slopes and deep water table depth are lower the index from 'moderate to low' to 'low' vulnerability. The course sediment unit is almost entirely classified as 'highly' vulnerable owing to its flat topography, deep groundwater depths, high recharge and intensively cultivated land being the dominant land use. In general vulnerability can be categorising from high and moderate to high category.

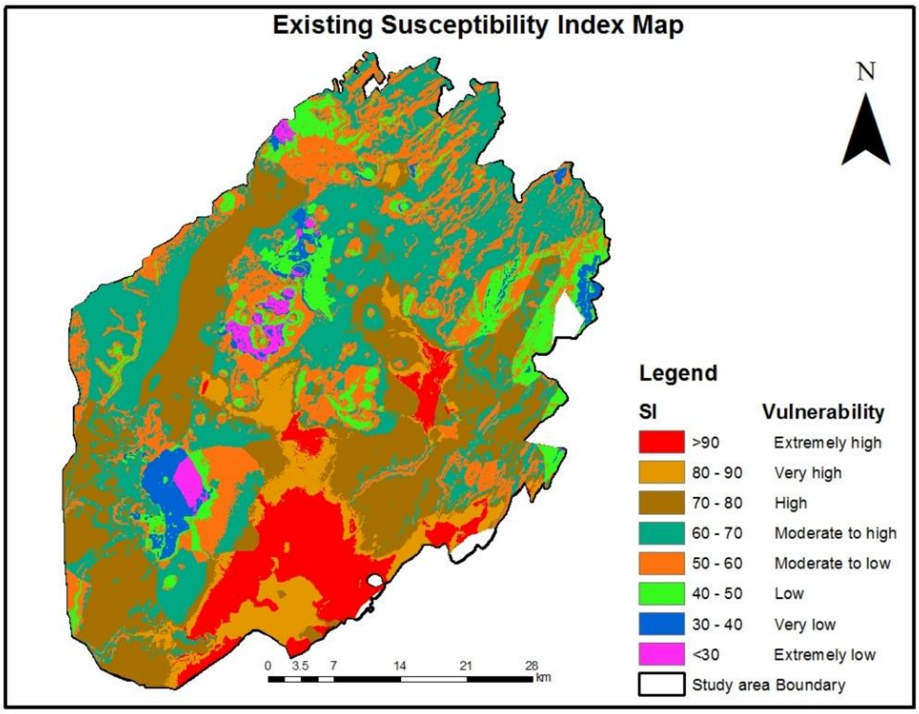

Figure 5.18: Existing index of vulnerability map in the study area

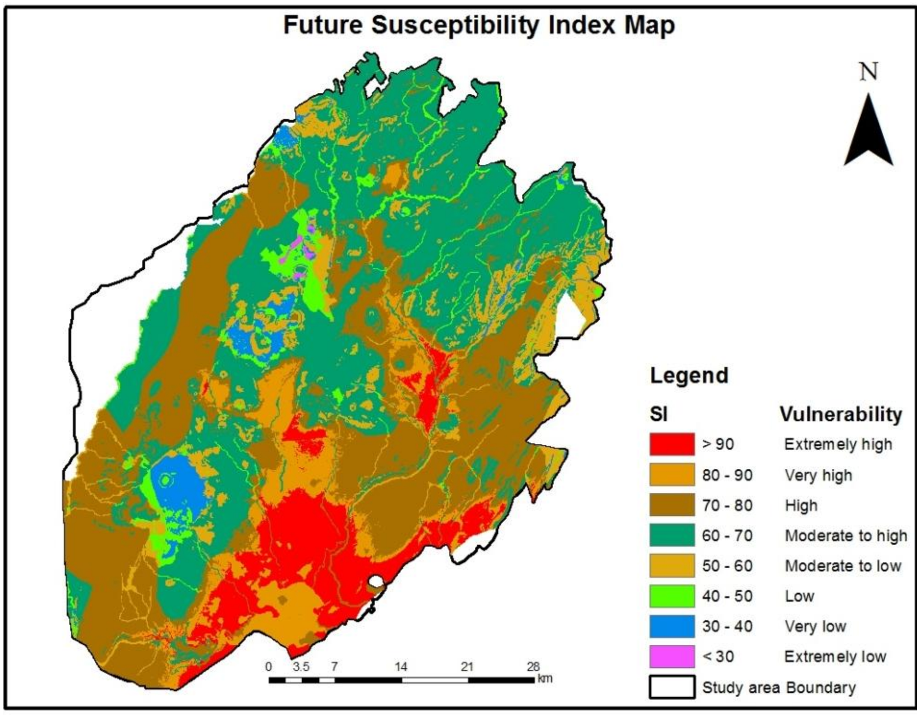

Figure 5.19: Future index of vulnerability map in the study area

5.5.7. Impact of future land use on vulnerability

In order to find out the difference between existing vulnerability map and future vulnerable area by giving different rating weight, for existing land use and future land use planning 70 and 90 respectively. For each land use we overlay on the SI combined map by including zero recharge for urban areas. This is done to understand the difference of vulnerability to contamination and the possible source of contaminant by dividing the future vulnerability map to existing vulnerable map.

The rating 90 given for intensively cultivated area for the future land use plan and 70 for the existing land use. This is because we assume that land use become more vulnerable in the future compared to now, due to urbanisation and continuous intensive cultivation. On the future vulnerability map we expect some increase of the vulnerable area since the land use rating are increase by 20. Therefore the difference between the existing and future vulnerability map are shown in the following **Figure 5.20**. As a result there is 5 to 10% increase of vulnerability to contamination about 80% of the total area; it's due to agricultural activity. In addition to this there are also parts of the study area which show the vulnerability to contamination area increase more than 10%.

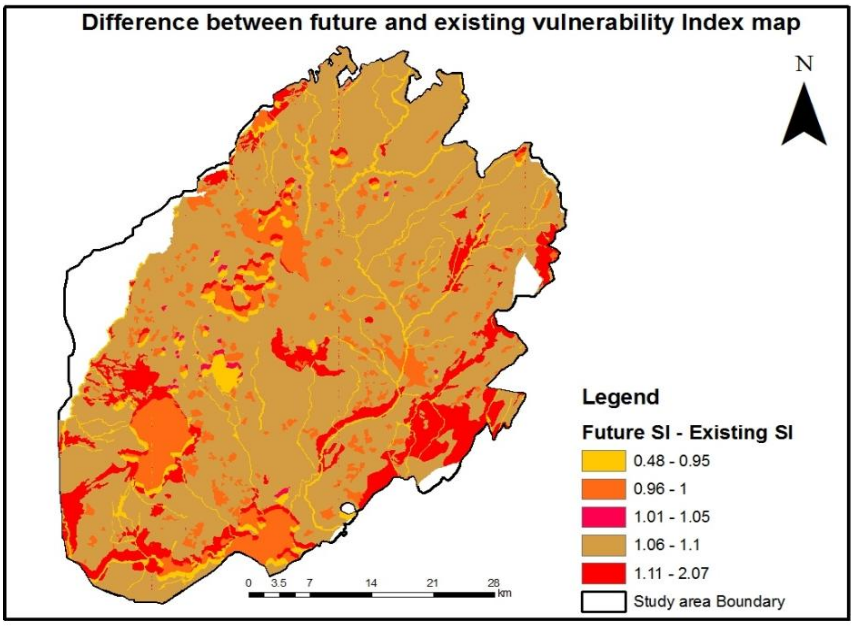

Figure 5.20: The change in future vulnerability and existing vulnerability

Table 5.6: SI model vulnerability of study area coverage from extremely low to extremely high

No	Vulnerability	Range	Area (sqkm)	Area (Ha)	Area (%)
1	Extremely low	<30	0	1	0%
2	Very low	30 - 40	56	5561	2%
3	Low	40 - 50	62	6207	3%
4	Moderate to low	50 - 60	201	20132	9%
5	Moderate to high	60 - 70	986	98614	42%
6	High	70 - 80	667	66652	28%
7	Very high	80 - 90	214	21369	9%
8	Extremely High	>90	181	18126	8%

5.5.8. Validation with nitrate (NO_3) concentration

In order to investigate the relation between vulnerability map and nitrate concentrations in groundwater, the well location with the nitrate (NO_3) concentration was overlaid on the vulnerability map. This illustrates on the map **Figure 5.21** are clearly show high concentration of NO_3 are found in high and very high areas of vulnerability. On the other hand NO_3 concentration is low from 0 to 5 mg/l, in spite of high and very high vulnerability assessed, this could be due to geological nature of the area for instance; in the basalt area the percolation of contamination is less compared to sand and gravel. In the study area the nitrate concentration varies between 0-44 mg/l, the entire samples are within the permissible limit for human use based on WHO guidelines. There are five concentration classes (0-2 mg, 3-5mg/l, 6-10mg/l, 11-25mg/l and 26-44mg/l of NO_3) which are done by Arc GIS environment. The concentration varies between 6mg/l to 25mg/l in the high vulnerable area whereas groundwater in the largest part of the study has nitrate concentrations between 6 and 10mg/L in the area of high and very high vulnerability map.

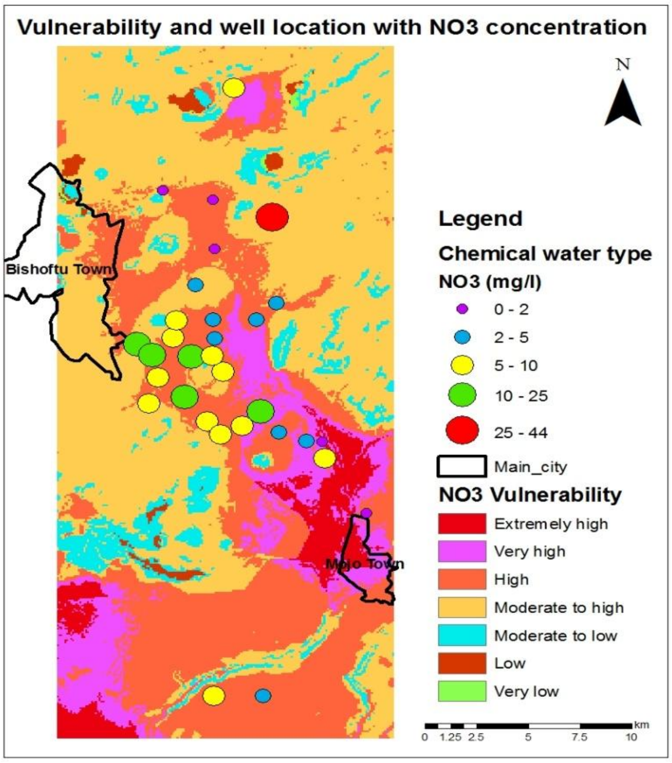

Figure 5.21: Vulnerability map and NO_3 concentration

CHAPTER 6

Conclusions and Recommendations

This section presents the conclusions and recommendations based on the study findings.

6.1. Conclusion

- The groundwater potential for each metrological station was calculated using Thiessen polygon method based the geological map. From the result the groundwater potential values for each station has shown variability. We can conclude from this the recharge is spatially varied based on the geological nature of the study area.

- In this study, the sensitivity analysis of input parameters for water balance model was done to make sure that how the sensitive parameters affect the output of the groundwater recharge. The analysis helps to identify the most sensitive parameter whose variation in the model highly affect the output. From the result, it can be concluded that runoff threshold and soil property were most sensitive parameters for the output.

- Scenarios have been developed to understand the implications of future prospect on population growth and water demand. By assuming, increasing per capita water demand and constant growth rate (business as usual) scenarios. Therefore a conclusion can be drawn from the scenarios analysis result, when the number of population increased the water demands also increased. On the other hand business as usual scenarios does not specifically represent future enhancements it's because which does not consider the changes in annual growth rates.

- Nitrate concentration on groundwater is caused by due to intensively cultivated agriculture and usage of fertilizers. In this study the nitrate concentration has shown relatively high in agricultural land. This could be, due to fertilizer application, since more than 75% of the land use in the area is intensively cultivated. Therefore we can conclude high NO_3 concentration is a result of intensive agriculture and application of fertilizer.

- Existing land use and future land use planning for intensively cultivated area were given the rating of 70 and 90 respectively for vulnerability assessment. This is because we assume that land use become more vulnerable in the future compared to current uses due to urbanisation and continuous intensive cultivation. As a result this there is 5 to 10% increase of vulnerability to groundwater contamination. Therefore we can conclude from this the future vulnerability is increased due to land use change.

- The results of the Susceptibility Index (SI), which was used to calculated groundwater vulnerability to contamination, indicate that the south-eastern part of the area is dominated by high vulnerability classes due to very flat topography, intensive cultivation, the high permeability linked to the sand and gravel aquifer and shallow water table.

- The western part is characterized by moderate vulnerability classes, and the higher elevated northern part of the study area around Chefedonsa displays low aquifer vulnerability. This is due to a deeper groundwater levels and higher slopes which have a decreasing effect on the aquifer vulnerability

- The study shows that 42% of the total study area is under the moderate to high vulnerable zone; about 28% of the area is under high vulnerable zone.

6.2. Recommendation

Based on the study findings the following recommendations are made:

- The SI model can be used for assessing the groundwater contamination vulnerable areas in order to avoid further contamination, as currently there are some polluted areas. It can also help to identify areas where additional protection measures are required. There must be an in-depth and regular monitoring of groundwater quality in high to extremely high vulnerable zones in order to monitor the changing level of pollutants.

- The alluvial deposits (coarse sediments) are more vulnerable to pollution and for this reason continuous monitoring is recommended to maintain the present groundwater quality status.

- The study enables any further study to predict the impact of vulnerability to contamination, based on shallow well data and needs a detail study for recharge estimation.
- The results of water balance in this study have not been validated using field collected data such as stream discharge measurements. More research is recommended to validate and integrate these results with models.

- Uncertainties to estimate recharge give emphasis to the need for application of multiple techniques to increase consistency of recharge estimates.

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Appendices

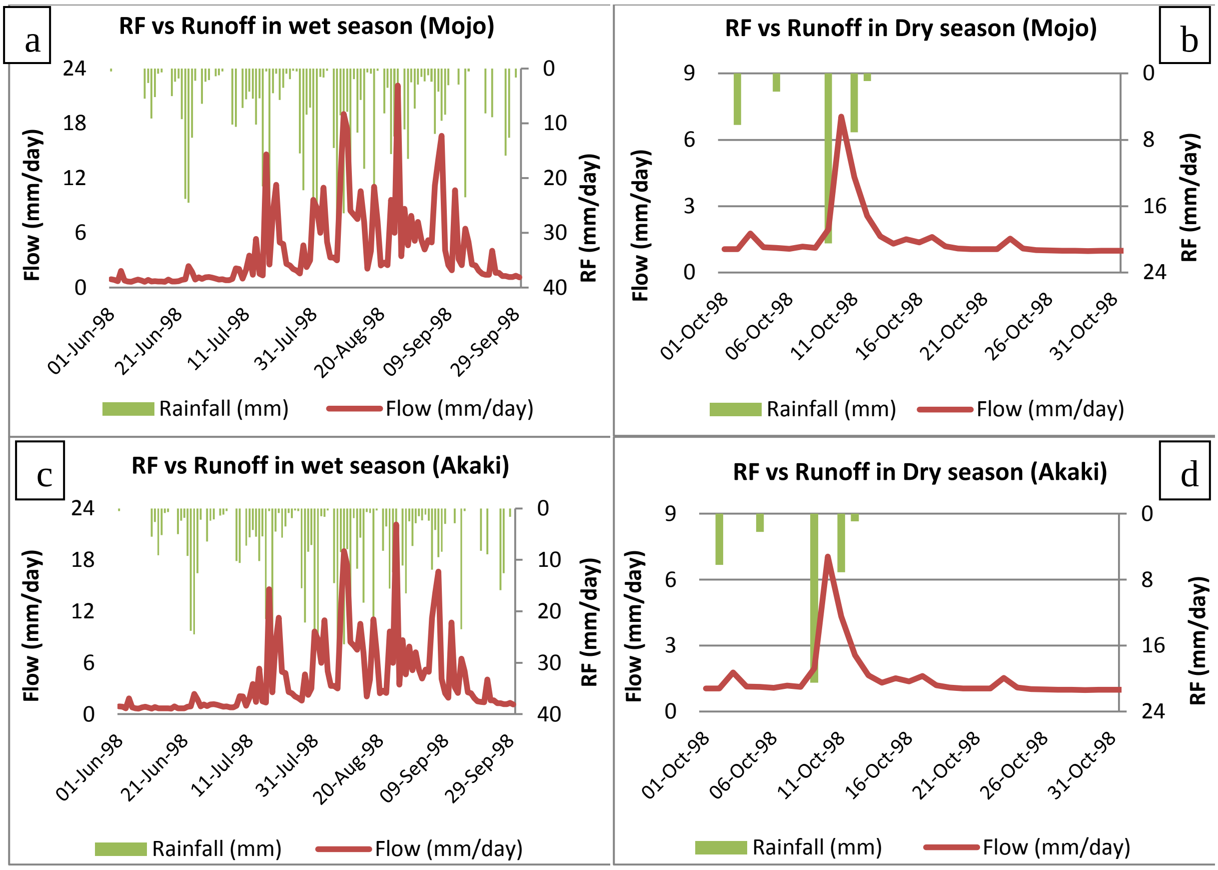
Appendix A : Monthly water balance in the root zone

Months	Rainfall (mm)	Groundwater level dgw (cm)	Groundwater level to the bottom of the root zone(cm)	Capillary factors (-)	Pot evap Penman (mm)	Pot evap Crop (mm)	ET soil moisture (mm)	ETact total	Capillary Q_{cap} (mm)	Runoff (mm)	Q_{prec} (mm)	Moisture (mm)	Sum comp. moist. storage	Days in month	Q_{prec}-Q_{cap} (mm)
			Monthly water balance in the root zone												
Jan	14.5	3900.0	3775.0	0.0	69.6	31.3	8.8	8.8	0.0	0.1	2.2	4.3	133.0	31.0	2.2
Feb	16.4	3900.0	3775.0	0.0	68.7	37.4	14.4	14.4	0.0	0.0	3.2	6.0	169.0	28.0	3.2
Mar	46.2	3900.0	3775.0	0.0	80.4	75.0	35.3	35.3	0.0	0.1	8.1	7.1	220.7	31.0	8.1
Apr	61.3	3900.0	3775.0	0.0	81.5	93.7	50.2	50.2	0.0	1.1	10.8	8.7	262.0	30.0	10.8
May	53.3	3900.0	3775.0	0.0	88.3	81.5	42.1	42.1	0.0	0.7	8.2	8.3	256.4	31.0	8.2
Jun	86.3	3900.0	3775.0	0.0	82.8	37.3	31.8	31.8	0.0	0.6	39.1	16.6	499.4	30.0	39.1
Jul	244.7	3900.0	3775.0	0.0	76.4	34.4	34.4	34.4	0.0	6.2	204.1	24.9	770.4	31.0	204.1
Aug	210.6	3900.0	3775.0	0.0	76.3	34.4	34.4	34.4	0.0	6.3	170.1	24.9	772.0	31.0	170.1
Sep	99.9	3900.0	3775.0	0.0	73.5	33.1	33.0	33.0	0.0	0.1	71.7	23.6	709.0	30.0	71.7
Oct	26.6	3900.0	3775.0	0.0	74.3	33.4	25.0	25.0	0.0	0.6	13.4	12.7	381.0	30.0	13.4
Nov	8.6	3900.0	3775.0	0.0	68.2	30.7	10.0	10.0	0.0	0.0	3.9	4.6	143.0	31.0	3.9
Dec	6.1	3900.0	3775.0	0.0	68.2	30.7	6.3	6.3	0.0	0.0	0.5	2.8	85.6	31.0	0.5
Monthly average	74.6	3900.0	3775.0		76.3	47.4	28.8	28.8	0.0	1.4	48.5			30.4	48.5
Yearly average	873.6				890.2	544.6	324.2	324.2	0.0	15.7	535.2	144.1		356.7	535.2

Appendix B : Sensitivity Analysis for water balance in the root zone

MOJO														
Coarse sand														
Double threshold sensitivity analysis														
DrySeason Runoff threshold (mm)	***30***	***25***	***20***		***30***	***25***	***20***	***15***		***30***	***25***	***20***	***15***	***10***
WetSeason Runoff threshold (mm)	***15***	***15***	***15***		***10***	***10***	***10***	***10***		***5***	***5***	***5***	***5***	***5***
Rainfall	1034	1034	1034		1034	1034	1034	1034		1034	1034	1034	1034	1034
Runoff	275	288	303		388	401	416	435		565	578	593	613	642
Qperc	462	449	438		362	349	338	324		209	196	185	170	146
MOJO														
Medium coarse sand														
Double threshold sensitivity analysis														
DrySeason Runoff threshold (mm)	***30***	***25***	***20***		***30***	***25***	***20***	***15***		***30***	***25***	***20***	***15***	***10***
WetSeason Runoff threshold (mm)	***15***	***15***	***15***		***10***	***10***	***10***	***10***		***5***	***5***	***5***	***5***	***5***
Rainfall	1034	1034	1034		1034	1034	1034	1034		1034	1034	1034	1034	1034
Runoff	275	288	303		388	401	416	435		565	578	593	613	642
Qperc	407	398	387		307	298	287	272		154	145	135	120	95
MOJO														
Coarse sand														
Single threshold sensitivity analysis	***30***	***25***	***20***	***15***	***10***	***5***								
Rainfall	1034	1034	1034	1034	1034	1034								
Runoff	125	177	241	322	465	685								
Qperc	589	540	489	423	299	114								
MOJO														
Medium coarse sand														
Single threshold sensitivity analysis	***30***	***25***	***20***	***15***	***10***	***5***								
Rainfall	1034	1034	1034	1034	1034	1034								
Runoff	125	177	241	322	465	685								
Qperc	528	489	439	372	247	62								

Appendix C : Rainfall versus runoff



Appendix D : Monthly potential evapotranspiration

Thornthwaite_PET						
Date	**Akaki (mm/month)**	**Chefedonsa (mm/month)**	**Debre Zeit (mm/month)**	**Koka Dam (mm/month)**	**Mojo (mm/month)**	**Nazereat (mm/month)**
Jan-98	72.4	57.9	71.5	68.0	74.8	73.7
Feb-98	73.9	61.6	74.9	66.0	71.7	86.8
Mar-98	90.2	71.0	90.0	84.5	90.6	94.8
Apr-98	97.6	77.7	98.8	97.9	99.8	109.3
May-98	95.2	81.1	98.8	91.4	101.6	119.7
Jun-98	84.3	76.3	89.9	90.1	100.6	81.8
Jul-98	75.7	63.8	76.8	74.4	82.1	64.6
Aug-98	68.5	59.6	70.4	73.1	76.0	79.7
Sep-98	69.9	58.1	69.9	69.6	73.4	76.1
Oct-98	73.3	56.1	68.5	68.6	74.4	73.7
Nov-98	58.8	68.4	51.2	54.1	52.0	65.8
Dec-98	52.4	42.8	48.6	58.9	49.0	55.7
Jan-99	62.7	55.0	63.5	46.9	63.2	67.0
Feb-99	61.9	58.2	66.0	63.8	75.9	76.9
Mar-99	79.7	68.8	83.6	108.0	94.8	87.5
Apr-99	89.4	77.7	93.9	107.8	91.2	98.7
May-99	95.9	83.7	98.9	142.2	92.6	115.7
Jun-99	83.3	63.7	85.2	118.8	88.0	110.7
Jul-99	70.8	61.0	70.5	103.4	88.3	77.6
Aug-99	68.9	61.6	72.1	99.9	85.0	79.8
Sep-99	74.3	60.0	70.8	111.9	79.0	79.7
Oct-99	70.4	59.6	70.3	128.9	79.2	73.4
Nov-99	58.7	46.4	50.1	97.6	59.7	53.0
Dec-99	56.4	46.7	53.5	115.2	57.9	46.4
Jan-00	59.0	53.6	59.8	64.2	64.8	56.6
Feb-00	59.3	54.7	64.1	68.8	66.3	69.4
Mar-00	83.7	73.3	87.2	101.6	93.8	96.3
Apr-00	86.8	75.1	92.9	116.2	98.1	101.1
May-00	94.1	81.2	92.4	150.1	103.9	113.5
Jun-00	79.9	69.5	82.1	154.2	89.1	111.8
Jul-00	76.1	63.3	75.8	104.8	73.7	84.3
Aug-00	72.5	59.5	70.7	93.7	70.5	83.0
Sep-00	71.9	55.1	70.1	90.6	72.8	78.8
Oct-00	72.5	54.9	65.8	84.1	72.2	70.0
Nov-00	63.9	50.5	58.9	72.0	62.7	61.7
Dec-00	60.9	48.7	59.3	75.7	57.1	57.2

Jan-01	60.2	51.8	62.1	61.0	57.3	58.0
Feb-01	63.5	56.8	69.5	74.7	66.7	68.5
Mar-01	74.6	65.8	83.2	128.4	84.4	88.5
Apr-01	88.3	71.3	88.5	129.5	92.1	95.0
May-01	90.7	75.5	91.8	143.2	98.0	109.0
Jun-01	76.4	65.1	79.3	131.5	85.5	100.1
Jul-01	73.8	63.8	74.6	116.4	78.4	84.7
Aug-01	76.3	62.5	72.2	113.9	78.0	82.9
Sep-01	72.0	60.2	73.2	126.0	74.5	76.1
Oct-01	76.2	62.3	75.0	58.3	77.1	82.0
Nov-01	74.8	51.2	60.1	59.0	70.2	68.5
Dec-01	79.5	53.1	65.2	70.8	59.6	68.5
Jan-02	77.3	51.6	66.2	66.4	65.8	67.8
Feb-02	81.5	56.5	72.3	74.2	62.2	72.8
Mar-02	81.8	69.2	89.9	95.5	82.5	95.9
Apr-02	84.2	68.7	94.8	86.3	85.3	103.4
May-02	97.8	81.0	101.9	101.4	92.1	131.0
Jun-02	83.3	75.1	90.7	80.3	87.2	118.2
Jul-02	79.1	66.2	82.7	83.8	88.4	107.6
Aug-02	71.9	64.1	73.2	96.6	86.6	84.1
Sep-02	71.9	67.2	71.1	88.2	78.0	80.4
Oct-02	77.4	66.6	74.5	93.5	71.3	83.4
Nov-02	66.2	49.6	62.2	72.1	64.8	71.2
Dec-02	71.4	53.8	66.7	87.1	61.2	71.2
Jan-03	66.8	56.0	67.5	97.3	68.4	69.8
Feb-03	72.3	60.8	75.0	83.3	74.3	80.4
Mar-03	84.5	75.6	88.8	98.9	80.3	85.3
Apr-03	84.7	77.1	88.1	92.0	86.3	94.2
May-03	96.7	91.7	99.8	110.0	106.3	110.6
Jun-03	86.5	72.9	85.6	93.9	89.6	105.7
Jul-03	70.1	59.8	71.3	99.7	58.8	81.3
Aug-03	68.2	61.1	72.5	103.4	61.8	81.4
Sep-03	72.9	59.6	69.6	96.5	72.9	80.5
Oct-03	81.4	57.3	67.9	74.2	70.8	79.7
Nov-03	76.2	51.0	63.1	85.2	67.0	71.6
Dec-03	65.8	44.4	54.2	88.3	52.0	58.6
Jan-04	79.7	57.2	67.4	87.6	68.1	81.0
Feb-04	72.0	50.0	70.4	76.0	64.6	68.4
Mar-04	84.2	62.8	73.6	91.1	79.1	83.8
Apr-04	83.5	64.7	74.5	96.2	86.3	92.5
May-04	100.1	75.0	83.2	101.2	107.8	75.7
Jun-04	84.0	64.0	77.7	88.7	91.8	109.0

Jul-04	74.9	76.5	73.9	94.6	59.1	88.0
Aug-04	71.6	74.6	72.7	95.8	67.0	85.2
Sep-04	74.5	73.9	69.4	102.7	73.7	82.2
Oct-04	75.9	74.1	59.2	64.5	69.7	73.6
Nov-04	72.2	66.3	52.3	81.9	63.0	69.2
Dec-04	75.6	65.6	56.1	80.1	59.2	70.1
Jan-05	73.6	54.0	58.4	88.2	68.3	67.0
Feb-05	81.7	62.1	62.0	92.2	71.8	80.6
Mar-05	94.4	73.3	81.0	116.7	94.1	100.1
Apr-05	90.3	75.0	84.3	69.2	97.0	100.9
May-05	90.2	75.5	85.9	125.5	93.6	102.8
Jun-05	82.5	68.9	80.6	107.1	86.6	108.0
Jul-05	74.7	64.5	72.5	74.1	61.1	82.6
Aug-05	75.6	65.8	78.2	77.8	60.9	86.6
Sep-05	72.3	63.1	72.4	73.0	58.5	85.1
Oct-05	82.8	60.5	63.1	66.1	68.2	85.3
Nov-05	72.1	52.6	53.4	54.9	57.0	73.6
Dec-05	69.0	46.5	44.2	46.4	51.0	60.8
Jan-06	78.4	72.0	59.6	57.6	67.0	74.2
Feb-06	78.0	44.3	66.3	66.3	78.2	80.9
Mar-06	88.3	53.6	73.5	107.6	79.8	88.6
Apr-06	87.2	55.3	77.1	108.6	75.9	89.9
May-06	100.2	57.5	85.3	125.9	103.9	111.6
Jun-06	80.8	53.3	84.0	131.5	77.5	110.6
Jul-06	74.4	56.3	76.4	93.6	61.1	85.5
Aug-06	71.9	57.1	74.4	89.9	74.2	78.4
Sep-06	72.8	49.2	62.8	94.9	72.4	79.4
Oct-06	82.0	49.9	69.8	94.5	86.2	84.2
Nov-06	71.8	37.9	56.4	73.4	66.7	72.7
Dec-06	71.9	41.8	62.7	72.4	66.1	66.4
Jan-07	75.1	59.6	64.3	84.3	67.6	69.7
Feb-07	73.8	62.3	69.9	97.6	89.4	80.3
Mar-07	92.0	73.2	83.1	111.6	106.2	99.0
Apr-07	88.0	73.7	85.6	112.4	97.8	94.6
May-07	98.2	83.4	91.1	124.5	112.0	120.3
Jun-07	77.3	69.5	80.6	100.2	92.7	100.8
Jul-07	77.9	64.8	74.1	87.9	59.4	86.0
Aug-07	74.9	63.8	72.2	76.5	65.7	78.1
Sep-07	78.8	63.7	67.4	75.3	79.4	82.2
Oct-07	87.3	57.9	52.8	58.9	68.3	71.2
Nov-07	79.4	48.2	61.4	49.5	64.3	66.2
Dec-07	78.7	46.1	60.6	64.7	55.0	56.7

Jan-08	90.5	59.6	63.3	81.1	69.9	72.9
Feb-08	83.2	52.2	61.3	80.3	62.8	66.6
Mar-08	126.6	67.2	75.6	62.6	88.1	92.4
Apr-08	125.5	75.5	85.8	68.5	96.4	102.0
May-08	107.7	79.5	91.7	120.3	104.0	112.4
Jun-08	81.5	92.2	82.1	113.4	87.1	99.1
Jul-08	66.8	64.0	74.8	98.0	74.2	80.1
Aug-08	62.4	62.0	69.5	83.4	72.2	77.1
Sep-08	70.7	63.3	68.1	96.9	73.6	82.8
Oct-08	81.0	62.9	64.4	83.9	76.7	78.9
Nov-08	63.3	48.7	52.4	69.7	55.3	58.3
Dec-08	68.1	51.0	47.9	32.0	51.3	58.7
Jan-09	73.1	55.8	57.5	70.6	61.2	64.3
Feb-09	80.6	54.9	60.4	90.3	68.7	74.7
Mar-09	66.4	79.5	83.9	110.7	96.3	103.7
Apr-09	97.8	76.7	85.7	122.5	96.9	102.3
May-09	115.6	86.1	92.9	133.2	105.7	111.8
Jun-09	110.6	85.4	91.5	112.1	104.1	119.6
Jul-09	74.9	68.7	79.3	83.9	80.3	90.9
Aug-09	75.0	59.5	74.9	89.8	72.1	85.4
Sep-09	80.3	58.0	69.6	90.5	71.1	90.9
Oct-09	79.1	57.1	60.9	84.4	72.6	75.7
Nov-09	66.2	49.1	48.2	73.9	60.7	62.8
Dec-09	64.8	45.8	61.4	74.4	55.6	61.2
Jan-10	56.8	58.9	57.7	80.0	62.9	71.2
Feb-10	52.8	65.0	68.4	83.7	76.2	73.5
Mar-10	65.2	70.4	76.3	82.7	85.8	80.9
Apr-10	64.6	78.4	84.6	110.4	92.4	98.8
May-10	101.5	84.1	87.5	116.3	94.9	113.0
Jun-10	87.9	74.2	81.7	109.9	95.4	110.3
Jul-10	72.8	65.0	74.6	82.4	78.8	93.4
Aug-10	72.8	67.7	76.1	86.5	78.9	86.5
Sep-10	70.5	64.0	70.4	78.4	73.6	77.1
Oct-10	67.6	65.9	67.4	85.2	76.3	82.8
Nov-10	55.9	53.3	53.0	75.6	65.6	70.6
Dec-10	56.6	53.4	50.6	58.5	55.9	58.7
Jan-11	61.1	62.3	64.4	79.7	78.9	69.3
Feb-11	58.4	61.1	68.0	82.8	62.8	76.8
Mar-11	69.1	71.5	84.7	92.7	81.7	89.9
Apr-11	85.7	83.2	86.2	102.3	85.4	110.3
May-11	90.8	84.3	93.2	116.3	103.6	109.8
Jun-11	86.7	68.4	84.0	107.2	101.6	104.3

Jul-11	74.1	69.7	76.9	84.1	98.1	92.9
Aug-11	52.2	60.0	74.5	93.7	72.3	85.9
Sep-11	69.2	64.2	63.5	83.7	71.2	78.3
Oct-11	80.4	57.6	56.9	72.9	72.7	79.3
Nov-11	70.8	49.3	58.0	56.0	60.8	71.6
Dec-11	70.0	46.2	45.0	54.6	55.6	61.4
Jan-12	101.1	58.6	62.6	65.4	61.6	72.3
Feb-12	97.1	55.5	62.6	79.1	58.6	73.9
Mar-12	108.2	79.2	81.3	101.2	83.9	106.2
Apr-12	119.3	77.5	92.4	114.6	139.6	103.7
May-12	96.4	84.2	96.1	137.6	103.8	118.1
Jun-12	73.4	78.5	62.2	122.2	95.0	115.8
Jul-12	64.2	68.1	84.2	79.8	74.7	79.4
Aug-12	62.1	60.4	75.8	90.5	72.3	80.1
Sep-12	72.4	59.1	51.0	90.4	71.2	80.2
Oct-12	76.3	58.0	37.4	84.7	72.7	76.1
Nov-12	66.8	49.7	31.7	74.0	60.8	72.5
Dec-12	65.8	46.6	64.3	73.7	55.6	72.9
Annual PET	**933**	**760**	**867**	**1080**	**925**	**1011**