THE IMPACT OF LOW COST SANITATION ON GROUNDWATER CONTAMINATION IN THE CITY OF ADDIS ABABA

by

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‘....Lord You will grant us peace;

all we have accomplished is really from You...’

Isa. 26: 12 (NLT)

This work is dedicated to my children

Nahom and Bethany-El

and to my Brother

Yemane Kahssay

Abstract

Ease of abstraction and the general good quality of groundwater continues to make it a preferred source of water supply for urban areas. Groundwater is therefore widely utilized as source of potable water in many parts of the world.

In urban areas where a large concentration of population requires that water be provided at economical cost, groundwater is usually the preferred source. Currently efforts are underway to address the water supply demand of the city of Addis Ababa. The primary thrust of this venture is increasing the supply by abstracting groundwater. While water supply improvement has attracted attention, sanitation service provision has not drawn an equal emphasis. To date a majority of the city's population is still served by low cost sanitary facilities or pit latrines. Of the total population only 0.6 % is served by a sewerage system.

The large number of pit latrines spread out over the city, directly discharge human waste into the ground. This waste eventually finds its way into the groundwater, hence increasing contamination threat. This threat is enhanced in urban areas with high population density, and where groundwater abstraction areas may be located in close proximity.

This research paper attempted to review the quality of water in deep wells and springs, to assess whether groundwater resources in Addis Ababa have been exposed to contamination originating from human waste. The research time frame encompassed 43 years and assessed available water quality records during this period. The findings suggest that groundwater contamination in the city may have been ongoing for some time with the spatial extent increasing over the last few decades. Over abstraction of groundwater resources has also been observed.

In order to mitigate this risk therefore measures including enhancing and empowering the environmental policy objectives, introducing abstraction regulations and radically improving sanitary conditions in the city will be necessary. The study also recommends an integrated groundwater resource management strategy focusing on sustainable usage, protection of resources and a general public awareness. The findings of this study will not only be applicable to the city of Addis Ababa but to all urban areas in Ethiopia and hence will have a nationwide relevance.

Summary

Providing clean water remains a challenge in many African countries. Ethiopia, with the second largest population in Africa is also faced with this predicament. Efforts to improve supply have focused on abstracting groundwater. Although relatively cheaper to utilize, groundwater is prone to contamination, from improperly disposed of waste, particularly urban areas with no appropriate sanitation services. The city of Addis Ababa is faced with this difficult situation.

Currently about 75 % of the population of Addis Ababa has access to sanitation in the form of pit latrines, while 0.6 % has access to sewerage services. The rest of the population is considered to have no access. This proliferation of pit latrines in the city has enhanced the risk of groundwater contamination. This research was initiated with the objective of assessing the temporal and spatial extent of contamination of groundwater due to human waste. It attempted to review the quality of water in deep wells and springs.

The data analyzed indicates that the temporal and spatial extent of contamination has increased over the past few decades. Over abstraction of groundwater has also been observed. Whilst contaminant levels such as nitrates and chlorides in many wells are below maximum permissible values, few wells in the centre of the city have exhibited higher values. This steady temporal increase may soon make some wells unsuitable for human consumption.

Efforts to reduce this risk will need to focus on sewerage services provision, review of existing environmental policy, public awareness drive and sustainable groundwater management.

Key terms

Addis Ababa, groundwater, contamination, pit latrines, boreholes, springs, nitrate, chloride, sanitation, anthropogenic, aquifer, temporal, spatial, pollution.

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Abbreviations and Acronyms

AA	Addis Ababa
AACC	Addis Ababa City Council
AACG	Addis Ababa City Government
AAU	Addis Ababa University
AU	African Union
AAWSSA	Addis Ababa Water Supply and Sewerage Authority
COC	Chamber of Commerce
CSA	Central Statistical Agency
EEPA	Ethiopian Environmental Protection Authority
EPA	Environmental Protection Agency
FMoH	Federal Ministry of Health
FMoI	Federal Ministry of Information
MDGs	Millennium Development Goals
MoFED	Ministry of Finance and Economic Development
OAU	Organization of African Unity
PASDEP	A Plan for Accelerated and Sustained Development to end Poverty
TGE-AAW & SA	Transitional Government of Ethiopia, Addis Ababa Water and Sewerage Authority
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
WHO	World Health Organization

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Girmay Kahssay

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Addis Ababa

1. Introduction

1.1 General

Water is one of the basic necessities for the sustenance of life. Water obtained from the Earth's surface such as, rivers, lakes, and from under its surface, from springs and wells has been used for drinking, washing, agriculture, and manufacturing. Water impacts nearly all areas of life and according to Kofi Anan, former UN Secretary General, it is 'everyone's businesses' (UNESCO-WWAP, 2006).

Groundwater or water obtained from under the earth is generally considered to be of good quality. Hence, in many parts of the world it is a preferred source for water supply, irrigation and industrial purposes. Due to its proximity to the surface and the low cost of utilization, groundwater obtained from springs and wells continues to be particularly attractive as a source of water supply.

With increasing population, there is an increasing demand for more water. This in turn results in increased abstraction and hence a strain on groundwater resource. Not only is more water utilized but more waste is also generated. Consumption of water, consequently, results in the generation of waste, such as human and industrial waste. It also raises the concomitant challenge of how to dispose of this waste.

Groundwater is therefore affected by over-abstraction to satisfy the increasing demand and contamination by waste generated. Waste water when contaminating groundwater is particularly of concern as the consumption of the impurities may threaten human life. Contamination of groundwater may not, however, be readily apparent as it is not as visible as surface water contamination, or as it takes even longer before it becomes evident.

Concerns are now being expressed. Worldwide groundwater is being consumed in increasing quantities, and is also becoming increasingly affected by waste that is continuously discharged into the ground (Drangert & Cronin, 2004). Contamination issues are also a continental concern. In Africa groundwater is increasingly threatened by human activities (Xu & Usher, 2006).

Because it is an essential element for survival, health and development, water needs to be protected from adverse effects. Water shortages and increasing contamination is '…..to a large extent socially and politically induced challenge(s), which means that there are issues that can be addressed by changes in water demand and use and through increased awareness, education, and water policy reform…' (UNESCO-WWAP, 2006).

The primary areas of concern in groundwater contamination study are urban areas. Urban areas have high concentration of people, living in comparatively smaller areas, and demand large amounts of clean water. Urban areas also produce significant amounts of waste. Waste generated in urban areas include human, industrial and agricultural agents. Inappropriately disposed waste may contaminate groundwater.

One of the major challenges of protecting groundwater resources in urban areas is therefore preventing contamination by human waste. This can be achieved through the provision and maintenance of appropriate and environmentally friendly waste disposal facilities.

Providing safe drinking water is therefore related to providing appropriate sanitation and cannot be seen in isolation. These two elements are closely intertwined. Whenever providing clean water and appropriate waste disposal are not addressed simultaneously, it is very likely that a detrimental effect on human welfare may occur. Provision of these two services is also considered a measure of human welfare. Nations therefore endeavour to provide these basic services to their people. Ethiopia in this aspect is striving to meet the United Nations Millennium Development Goal (MDG) set by the United Nations.

The Millennium Development Goal (MDG) aims to halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation (UNICEF, 2006). In the Ethiopian context this requires to '….halve the proportion of Ethiopians without access to improved sanitation which is equivalent to 11 million households in 11 years (1,000,000 households per year)' (FMoH, 2005).

Ethiopian national statistics indicate that access to clean water supply increased from 23% to 41.2% in rural areas and from 74% to 80.3% in urban areas during the period 2001/02 to 2005/06. At the national level access to potable water has reached 47.3% by the end of 2005/06 and about 53% by the end of 2007 (MoFED, 2007).

Efforts to increase water supply coverage are continuing in all regions of Ethiopia, including the capital city Addis Ababa. In addition to this, sanitation service improvement through emphasis on provision of pit latrines is also underway.

Nationwide pit latrine (toilet facilities that directly transmit human waste into the ground) utilization stands at 86% of the urban and 29.4% of the rural population of the country (MoH, 2006). In contrast, only 0.6% of the population of the city of Addis Ababa, the capital city with a population of about three million, use flush/pour toilet connected to a sewer system. The rest of the city's population uses forms of pit latrines which are either individual family type or shared communal ones.

The large-scale use of pit latrines in urban areas poses a serious risk to groundwater quality. Because pit latrines directly transmit human waste into the ground, they expose groundwater to contamination. The contaminating agents include chemicals normally found in human waste such as nitrate as well as coliform bacteria such as e-coli.

Some studies have suggested that nitrate; a chemical closely associated with human waste has been detected in some wells in Ethiopian urban areas including Addis Ababa. This could be considered as indicating groundwater contamination may already have occurred. This therefore necessitates the protection of groundwater sources around urban areas, by utilizing improved sanitary facilities and hence reducing contaminant load.

To provide adequate protection to groundwater, it is vital that the sources of the pollutants, their mechanism of transmission and the potential for mitigating their effects be investigated. Once the source and degree of contamination is identified, then a comprehensive remedial effort may be attempted.

1.2 The Study Area

With a population of over 2,738,248, Addis Ababa the capital city of Ethiopia ranks as one of the major urban centres in the country. Currently it has a total surface area of about 530.14 sq. km (CSA, 2008), and continues to grow. As a major industrial centre and the only city with a population of over one million, Addis Ababa is both an economic and political capital. The presence of major international organizations and Embassies have also made the city a *de facto* capital of Africa.

Addis Ababa is a rapidly growing city. There is a significant work going on in the housing and infrastructure sectors. Established over a 122 years ago it continues to grow primarily southwards, by annexing adjacent farmlands and small towns. Whilst it has grown spatially, the provision of water supply and sanitation services is considered to be low.

1.3 *Ethiopia: Location and General Data*

Ethiopia is located in the horn of Africa and is bounded on the northeast by Eritrea and Djibouti, on the east and southeast by Somalia, on the southwest by Kenya and on the west and northwest by Sudan (Fig.1.1). It has an area of more than 1,133,380 square kms and has currently a population of 79,221,000 of which 65,996,000 or 83.3% is rural population and 13,225,000 or 16.7% is urban (CSA, 2008). By 2030 the total population is forecast to rise to over 118 million (CSA, 1999).

Geographically it is transected by the Great Rift Valley, which rises to form the central plateau on the North West and the eastern plateau on the south west.

Fig. 1.1 Map of Ethiopia

Ethiopia is considered to be the origin of mankind. It is the birth place of *Australopithecus afarensis* or *Lucy*, one the oldest humanoid remnant ever discovered. The fossil was discovered in the Afar plains on the north-eastern part of Ethiopia. An older fossil dating to about 4.5 million years has also been discovered in the same area (Amin *et al*., 1997) (Pankhurst & Ingrams, 1988).

Geographically, it ranges from the highest mountain of *Ras Dashen* at 4550 meters above sea level (CSA, 1998) to the sixth lowest point on Earth, the *Dalol* Depression at 130 meters below sea level (COC, 1954).

Ethiopia's climate varies according to elevation differences, from the locally named '*Bereha'* of low land areas which are less than 500 meters above sea level (a.s.l.), the '*Kolla'* low land areas 500-1500 (a.s.l.), the '*woina dega'* high land areas 1500-2300 meters (a.s.l.), the '*Dega'* high land areas 2300-3200 (a.s.l.), the '*wurch'* high land areas 3200-3700 meters (a.s.l.) to the '*Kur'* high land areas above 3700 (a.s.l).

Non-irrigated agriculture is practiced across most of the country with 21% of the country classified as cultivated (IFPRI and CSA, 2006). The main and long rainy season occurs between the months of June to September and a smaller rainy season in February to March. Eighty percent of the runoff from all the river basins originates from precipitation during the months of June to October (Tamiru, 2006).

The southern part of the rift valley is home to many of Ethiopia's lakes, both freshwater and salty. The numerous rivers and lakes found in Ethiopia, flowing both within and outside its boundaries, have endowed it with a rich source of water resource.

The nine major rivers in Ethiopia flow for a total length of 5785 kms within its boundaries and three of them flow for a total of 1158 kms outside its borders (CSA, 1998). Its fresh water and salty lakes account for an area of about 7023 km^2, with depths varying from 4 meters at Lake Ziway to 250 meters at Lake Shala.

Ethiopia's history can be traced back thousands of years to 100-600 BC when the Axumite Kingdom with its capital at Axum in the north of the country was at its height a powerful economic and military empire. The Kingdom's capital, the city of Axum, had by then a population of over 20,000. The gradual weakening of the Axumite Kingdom was followed by a progressive shift in the power centres further south to Gondar and then towards central Ethiopia. After Axum and Gondar, Addis Ababa became the third permanent capital of Ethiopia and the geographical centre (Bahru, 1992).

The founding of Addis Ababa, is usually credited to Emperor Minilik, who in 1881 moved the capital of his empire to the centre of the country, to the mountains of *Entoto*, north of the city of Addis Ababa. In 1886 he moved further south and founded the city of '*Addis Ababa'* meaning '*New flower'* in *Amharic*, the National language (Bahru, 1992). The city was chosen mainly for its hot springs and its abundant forests. King Minilk erected his encampment near the hot springs and permanently established the capital city of his empire by 1892. The city of Addis Ababa has since then served as the capital city of successive governments. By the end of the 19th century, King Minilik had established a territorially defined empire state with Addis Ababa as its capital city.

King Minilik was succeeded by Empress Zewditu and then by Ras (Prince) Teferi, later Emperor Haileselassie. Hailesellasie consolidated his hold on power and brought Ethiopia into the 20th century. He was instrumental in the establishment of the Organization of African Unity (OAU) predecessor of the current African Union (AU). In 1935 the Italians briefly occupied Ethiopia and the Emperor was exiled to Britain but returned 5 years later to liberate his country. In 1974 he was deposed in a military coup after almost 40 years of rule.

Then followed a 17 year military rule and rampant civil war and much bloodshed. The military government was removed from power by a popular revolt in 1991 and a new government established. Throughout these years Addis Ababa remained the capital city, and is still the main financial, political and administrative centre of Ethiopia. Ethiopia is now administered by a Federal system, comprising of 9 Federal Regional states and 2 City Administrations.

Once in power the new government embarked on an integrated economic development program. It instituted a poverty reduction program focusing on Agricultural Led Economy in line with the United Nations Millennium Development Goals (MDG). Ethiopia has now registered a sustained economic growth, with a 9.5 per cent real GDP growth rate in 2007 thus leading the east African regions (which had registered the highest growth in Africa), followed by Tanzania (7.0%), DRC (6.5%), Madagascar (6.4%), Kenya (6.1%), Uganda (6.0%) and Seychelles (5.8%) (UNECA, 2008).

This sustained growth has, however, been faced with the challenges of rapid population growth, thus hampering the full realization of the advantages gained by the economic growth. Like other developing countries, Ethiopia has been faced by challenges in achieving the MDGs.

1.4 Motivations

Ethiopia is experiencing rapid population growth which currently is estimated at 80 million (CSA, 2008). With this rapid growth many small towns have now become urban centres. In tandem with this, the demand for infrastructure, clean water and basic sanitation services has also increased.

Water demand is particularly acute in urban areas where population growth and unplanned urbanization is causing undue stress on water resources. Many urban areas in Ethiopia are undertaking efforts to address this pressing need by abstracting groundwater.

On the other hand, the increasing abstraction and consumption of water, if unaccompanied by an improved waste disposal system, is likely to result in a gradual contamination of water resources mainly groundwater. Water consumption therefore ought to be accompanied with an improved waste disposal system.

Ethiopia's water resources are substantial, and if properly used, could meet the demands for the foreseeable future. They are nevertheless not inexhaustible. Hence sustainable usage, with a focus on protecting these resources from over-abstraction and contamination sourced from human activity (anthropogenic) causes, becomes a pressing issue. This is particularly of concern in highly populated urban areas, such as, the capital city Addis Ababa.

In providing basic sanitation services, an increasing emphasis is being placed on the provision of low cost sanitation facilities in the form of pit latrines. Pit latrines are predominantly utilized in the city of Addis Ababa since its founding 122 years ago. These low cost facilities discharge human waste directly into the ground thus, raising the possibility of direct contact of human waste with groundwater.

There are now indications that groundwater in many urban areas in Ethiopia may have already been contaminated by chemicals possibly originating from pit latrines. In a number of studies, high nitrate content has been observed in some wells in Addis Ababa. Therefore groundwater resources in the city may have been exposed to large-scale contamination with human waste possibly through the numerous pit latrines in the city. Aside from individual studies, no large-scale comprehensive city wide contamination study, assessing the temporal and spatial extent of contamination appears to have been carried out.

This then raises a concern in cities such as Addis Ababa, whether the groundwater in and around the city might have been contaminated by human waste. If so, what is the degree of current contamination? What is the areal extent of the contamination? How long has it been polluted? What can be done to mitigate this? Are appropriate environmental policies in place and enforced? If so do these policies encompass all that is required to address this risk? And possibly address remedial possibilities? Would the findings in the city have relevance for other urban areas in Ethiopia?

This research attempts to answer these questions and observe, both temporally and spatially, the extent of groundwater contamination due to human waste in the city of Addis Ababa. This served as motivation to investigate the possibility of contamination of groundwater resource due to low cost sanitation.

1.5 Aims and Objectives of the Thesis

Groundwater can be exposed to contamination from many sources. This study attempts to focus on the effect of one potential contamination source, human waste. It attempts to investigate the presence of certain chemicals in water which are closely linked with the presence of human waste, thereby indicating contamination.

The main objective of this research is to establish the degree of contamination of groundwater in and around Addis Ababa. An attempt is made to investigate the link between chemicals normally found in human waste originating from on site sanitation systems and those found in groundwater in the city.

As its main aim, this research attempts to investigate the impact that low cost sanitation has on the quality of groundwater supply in the city of Addis Ababa. It seeks to broaden our knowledge towards a better understanding of the existing situation and propose remedial action. It will attempt to formulate a conceptual framework of future policy direction. This may then contribute to the enhancement and better implementation of the policy in rapidly growing urban centers.

The study will endeavor to investigate and establish whether groundwater contamination has been increasing temporally. It will also attempt to assess the spatial extent of contamination of aquifers in and around the city. It also endeavors to identify pollution prone areas, the extent of the severity of the contamination and recommend mitigation alternatives. It is envisaged that this research will contribute to an understanding of the current situation and assist in the amelioration of existing environmental policy.

More specifically the following research objectives are envisaged;

- To determine the temporal and spatial extent of groundwater contamination in Addis Ababa due to low cost sanitation such as pit latrines.
- To assess the impact of low cost sanitation on groundwater quality and identify the most contamination prone areas of the city.
- To examine the national environmental policy in respect of such issues and recommend changes that may assist efforts to mitigate this problem.

Answering these questions and evaluating their significance will not only highlight the challenges facing the city of city of Addis Ababa, but could also have a nationwide application. It is believed that this will assist in formulating a more environmentally friendly sanitation program. A sustainable sanitation program in conjunction with the appropriate utilization of water resources will contribute towards reducing health costs. This will also contribute towards a better quality of life. The extent of the research work is limited to the vicinity of the city of Addis Ababa, in the range of approximately 550 km^2 area.

1.6 Data Collection and Processing

The main methodology of this research work included field collection of borehole and spring water quality raw data, desk study of previous research work and review of relevant literature. It also encompassed analysis of water quality data and spatial and temporal mapping of key chemical components. The main focus has been on key chemicals which are believed to be indicative of anthropogenic contamination.

Data for the research work has been obtained from the archives and reports of various government and non-governmental agencies, drilling companies, private sources, PhD and Masters Degree research studies, research documents and publications.

Historical water quality chemical data collected covered a time span of 43 years. The earliest water quality data reviewed was carried out in 1967 and the latest one in 2009. Data collection began in 2006 and went through 2009, in which details on more than 1300 boreholes within a 100 km radius of the city was collected and thoroughly reviewed. Newer unpublished geological maps have also been consulted and incorporated in the review work of the study. New borehole data which has not been included in the inventory of the city Water Supply and Sewerage Authority has also been collected.

In general over four thousand individual data sets spanning a 43 year period were reviewed and analyzed, and this was considered sufficient to achieve the objectives of the research.

1.7 Layout of the Thesis

The thesis is organized in 13 chapters. Chapter one presents the introduction and covers the aims and objectives of the research. Chapter two focuses on a review of background on water resources, sanitation coverage and urbanization in Ethiopia.

Chapter three focuses on a detailed review of the study area the city of Addis Ababa. It covers historical background of the development of the city and the provision of water and sanitation services. A detailed review of groundwater resource in the city is also addressed in this section. Chapter four focuses on the research process, data collection, evaluation and analysis. Chapter five addresses estimation of pit latrine density, and their spatial distribution, the extent of waste load on aquifers, aquifer vulnerability and estimation of waste load on aquifers.

Chapters six and seven include the analysis of data related to waste load by aquifer and the mapping of temporal and spatial extent of the contamination of groundwater by human waste. Chapter eight discusses the impact of contamination on groundwater quality. Chapter nine reviews the environmental policy of Ethiopia and discusses groundwater management strategy. An attempt is also made to highlight policy gaps that need to be rectified to address the contamination problem.

In chapter ten the findings of the research are discussed with appropriate conclusion and recommendations drawn in chapter eleven. Further research areas are suggested in chapter twelve. Chapter thirteen includes the Appendix.

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2 Literature Review

2.1 Ethiopia: Water Resources, Sanitation Coverage and Urbanization

2.1.1 Surface Water Resource

Ethiopia is one of the African countries endowed with rich water resources. The aggregate annual runoff from nine river basins in Ethiopia amounts to 122 billion cubic meters of water, on a catchment area of 1,136,816 Km^2. The three largest river basins, the Abbay, Baro-Akobo, and Omo–Gibe contribute 76% of the total runoff from a catchment area comprising only 32% of the total area of the country (MoWR, 2001a). These major rivers have an average flow ranging from 30 to 500 m^3/sec (Tamiru, 2006). The surface water resource is considered to be distributed unevenly, both spatially and temporally.

Between 80 to 90% of the surface water resource is found in the four river Basins, *Abay* (Blue Nile), *Tekeze*, *Baro-Akobo*, and *Omo-Gibe* in the west and south western part of the country. Thirty to forty percent of the population live in this area, while, the rest of the population, about 60%, live in the eastern and central river basins. In these areas the river basins contribute only 10-20 % of the total water resource (MoWR, 2001a). Over 84% originating in the country is trans-boundary and flows to other countries and is thus lost to Ethiopia (Mekonnen *et al*, 2001).

2.1.2 Groundwater Resource

Because of the abundant surface water resources in Ethiopia, a comparatively lesser weight has been given to groundwater utilization. This is reflected in the fact that, to date, little is known of the total potential of groundwater resources both in terms of total potential and spatial distribution (Abera, 2001).

Although sporadic in nature, there are records of attempts at assessing groundwater resources in Ethiopia. In the 1950s a US Technical project support team carried out studies on the development of water supply for the principal cities of Ethiopia. The study also included determining appropriate location of industrial plants and sources of municipal water supply. This appears to have been with the intention of protecting water resources from potential pollution (CoC, 1954). A comprehensive survey of the underground and surface water resource of Ethiopia was also authorized at that time, with much less emphasis placed on waste water drainage (CoC, 1954).

Recent estimates of groundwater potential were made by Zewde (1994). He suggested that the total replenishable groundwater potential of Ethiopia, which could be technically developed for consumption purposes, is about 2.6 billion m^3. Anecdotal evidence suggests that this was an approximation only and was not related to any investigation. This paucity of data has understandably originated from the absence of geological/hydro-geological studies in the country.

The total number of boreholes in the country is also not accurately known. In the period 1975-1982, for instance, Zewde (1994) records that a total of 1,018 deep wells were drilled or hand dug and 31 springs were developed in the country. This figure is now believed to have increased to over 10,000 (Addis Zemen, 2009). Nonetheless data on only 3,779 are documented so far. An inventory on updating this database is now being carried out, in cooperation with the Ministry of Water Resources, the Ministry of Mining and Energy, Addis Ababa University, and the US Geological Survey (Addis Zemen, 2009).

2.1.3 Water Supply Provision

Provision of clean water remains a major challenge in many countries and particularly in Africa. Globally clean water supply coverage has seen an increase from 78% in 1990 to 83%

in 2004. This implies that more than 1.2 billion people gained access to improved drinking water sources over that period (UNICEF, 2006). In sub-Saharan countries the provision of clean water remains one of the challenges faced by many nations including Ethiopia.

Sub-Saharan Africa represents about 11% of the world's population, but almost a third of all people without access to safe drinking water live there. The urban–rural divide in drinking water is at its widest in this region. In this region 81% of people in urban areas are served, compared with 41% in rural areas (UNICEF, 2006).

This suggests that many sub-Saharan countries have to more than double their efforts in order to reach the Millennium Development Goals (MDGs) set by the United Nations. The MDGs aims to halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation (UNICEF, 2006). If the current trend continues, sub-Saharan Africa will end up with 47 million more people un-served than in 2004 (UNICEF, 2006).

Although these efforts have been partly hampered by the rapid population growth, Ethiopia has managed to improve the level of water supply coverage over the previous decades. Ethiopian National statistics indicate that access to clean water supply increased from 23% to 41.2% in rural areas and from 74% to 80.3% in urban areas during the period 2002 to 2006. At the national level access to potable water had reached 47.3% by the end of 2006 and about 53% by the end of 2007 (MoFED, 2007b). The state of water provision in 2006 and 2007 is depicted in figure 2.1.

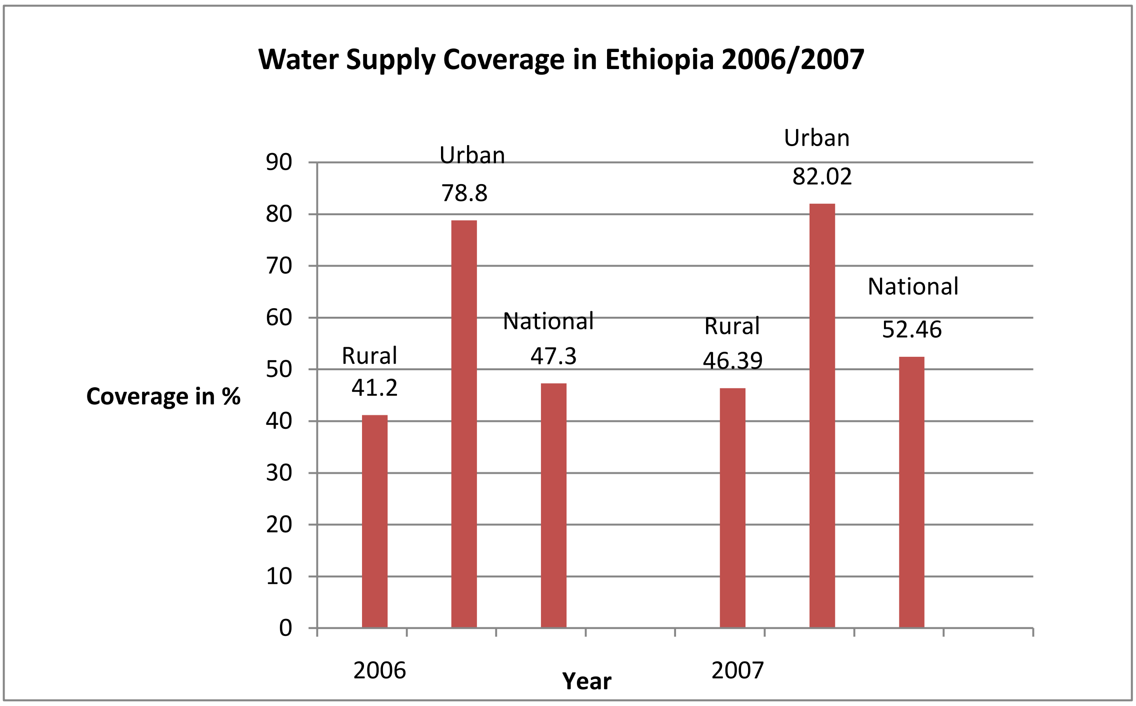


Fig 2.1 Water Supply Coverage in Ethiopia 2005/06-2007 (MoFED, 2007c)

One possible reason for the low rural coverage is attributed to inoperative boreholes. Of the national total rural water supply schemes such as springs, hand pumps and boreholes developed, 26% have been reported to be non-functional and hence contributing to a shortfall in supply schemes (DHV, 2003). This figure has now dropped to 20% in 2007 (MoFED, 2007a)

In terms of water supply, per capita consumption is still considered to be low. In 2003, the average per capita consumption of water in urban areas in Ethiopia was reported to be 15 litres/capita/day (DHV, 2003). This is consistent with the CSA (2005) survey in selected towns which also indicated a per capita consumption of 14.8 litres per day. It is however, a significant reduction from the 30 litres per capita per day reported in 1969 in the city of Addis Ababa. At that time the annual rate of growth of water demand was estimated to be 9% over the previous years (BCEOM, 1970).

One of the reasons for the low water consumption is thought to be the high initial cost of private house connections (DHV, 2003) and the cost of collecting it from sources outside the house. In 2007 more than 82% were accessing water within a distance of one Km (MoFED, 2007b). With the current economic growth, life style changes and the increasing number of new housing with interior plumbing, demand for more potable water is expected to rise. According to the Water Sector Master Plan Study, future demand is projected to increase as indicated in the following table.

Table 2.1 Projected water demand 2000-2020

Projected total urban water demand			
Year	2000	2010	2020
Estimated urban water consumption	89,427,000 m^3	147,896,000 m^3	244,687,000 m^3

To meet this rising demand, considerable financial resources will be needed. At the national level it is estimated that a total investment of up to 11.9 billion birr will be required to bring the level of all urban areas water supply coverage to 100% by the year 2025. Rural areas would also require a significant amount of financing to achieve even a modest 60% coverage by the year 2025 (DHV, 2003). Faced with this demand, it is inevitable that extra resources will need to be tapped and utilized. As developing surface water for drinking purposes would entail significant amount of investment and longer time of implementation, the trend in Ethiopia and particularly in Addis Ababa, has been the utilization of groundwater resources.

2.1.4 Groundwater Utilization

Groundwater utilization is increasing worldwide (Zaporozec & Miller, 2000). In the United States groundwater is the source of domestic water supply for almost 90% of the rural population and for about 50% of the urban population (Power & Schepers, 1989). In Denmark, West Germany, the Netherlands and Great Britain groundwater accounts for 99, 73, 70, and 30%, respectively, of the total water consumption (Strebel, Duynisvel, & Bottcher, 1989).

In Ethiopia a majority of the population utilizes springs and shallow wells as the main source of potable water. In almost all of the 10 river basins in the country deep and shallow groundwater is the main source of potable water. About 80% of towns use groundwater sources (DHV, 2003). In 2006 the Federal Ministry of Health (2006) indicated that, 8.4% of the urban and 56.8% of the rural population of the country utilize groundwater sources for potable water consumption. In the city of Addis Ababa it is estimated that about 40% of the total water supply originates from groundwater sources in and around the city. Recent efforts to boost water supply to the city have also focused on developing new wells.

At the national level, a water supply and sanitation master plan covering a development scenario up to 2025 envisages the construction of more than 60,000 schemes, the majority of which include hand dug wells and springs development (DHV, 2003). Groundwater abstraction for consumption purposes will therefore continue to rise due to increased population and the associated demand. In general however the geology of the country is not favourable for the efficient use of groundwater resources due to excessive extraction costs (DHV, 2003).

In contrast to the traditional abstraction of groundwater for domestic consumption, there is also a recent increasing emphasis on utilizing groundwater resources for irrigation purposes. Until recently the use of deep groundwater resources for agricultural purposes was nonexistent (Tamiru, 2006). This now appears to be changing. Recently about 200 deep boreholes have been drilled in the Raya and Kobo valleys in central northern Ethiopia

(Deksissa, 2009). The feasibility study for these areas was completed in 2007 (MoFED, 2007a). Further feasibility studies were undertaken for 10 medium and large-scale irrigation development projects to develop up to 403,250 hectares of land. It is envisaged that with financing by the World Bank, an additional 80,000 Hectares of land will be developed (MoFED, 2007a). The utilization of groundwater resources for irrigation purposes addressed in the study appears to be possibly the first of its kind in scope and scale.

2.1.5 Sanitation Coverage

According to the United Nations, in 2004, only 39% or 4 out of 10 people around the world had access to improved sanitation. The rest of the population used unsanitary facilities with a serious risk to exposure to sanitation related diseases (UNICEF, 2006). Although about 1.2 billion people gained access to improved sanitation in the same period, the progress is considered to be too low to meet the Millennium Development Goals (MDGs) (UNICEF, 2006).

Urban sanitation worldwide was more than twice as high as rural coverage in 2004 with coverage ranging up to 80% in urban areas, compared with 39% in rural areas. In the developing world this is even lower, with 1 out of 2 people having access to some sort of sanitation facility. Of the 2.6 billion people currently without access to basic sanitation, 2 billion live in rural areas (UNICEF, 2006).

The trend suggests that rural areas still lag behind urban areas in terms of sanitation coverage. In Sub-Saharan Africa coverage stands at 37%. In Eastern and southern Africa 58% of the urban population and 30% of the rural population has access to improved sanitation facilities (UNICEF, 2006).

In Ethiopia, a 2004 welfare monitoring survey by the Central Statistical Authority (CSA, 2005) showed that, more than 78 % of rural households do not have access to any form of sanitary facilities. In contrast, the urban coverage varied from 19 to 42 % of households. Nevertheless, there is a significant improvement towards acquiring better toilet facilities.

A survey carried in 61 towns in Ethiopia showed the following coverage level Fig. 2.2 (DHV, 2003).

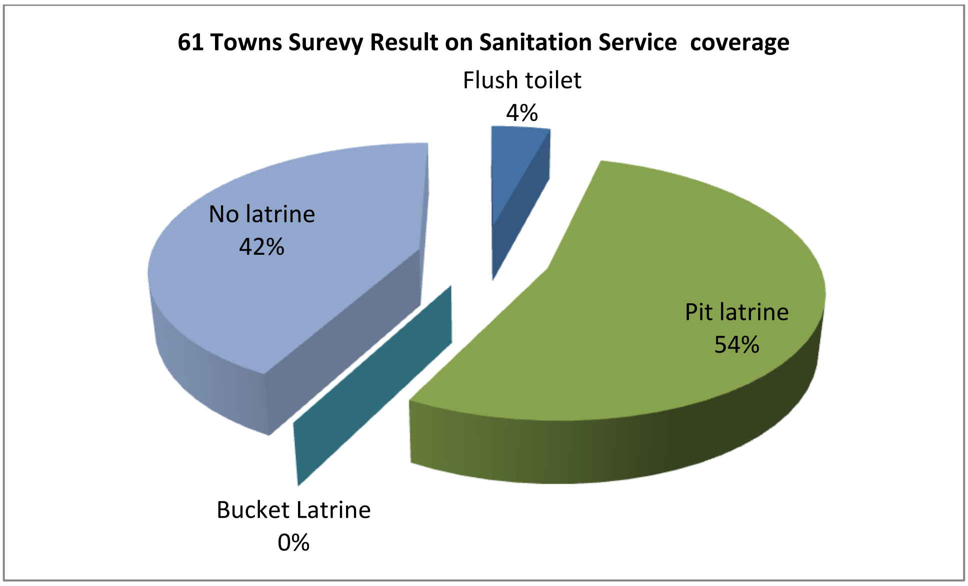


Fig. 2.2. 61 Towns sanitation service coverage survey (DHV, 2003)

The survey also identified that pit latrines were considered to be ‘unhygienic’ or ‘structurally’ unsound. The same study states ‘…a considerable number of the facilities are not in good condition …..and the current sanitation facilities condition requires a great rehabilitation program and funding…’ (DHV, 2003). One of the recommendations of this study was to construct pit latrines with improved construction materials (DHV, 2003). This appears to be a repeat of the situation in the late 1980s, in which of 230,000 latrines built, ‘a high proportion……have either collapsed or been abandoned...’ (Teka, 1991)

In contrast to pit latrines, sewerage services appear to have not been in existence in urban areas. This was not because of technical limitations but rather due to the low per capita water supply. It is argued that due to the low water supply, which currently stands at 15 l/c/d, it is not possible to provide the necessary self cleaning velocity in sewerage pipes.

In 1992 it was estimated that at least 80 litres of water per capita per day was required to generate a self cleansing velocity in sewerage systems in Addis Ababa. In addition to this the construction of approximately 1200 kms of pipes was necessary to achieve sewerage service coverage. This will require increasing the number of connections to 69,000, or about 900-1000 per year by 1996. This figure was to subsequently increase to 4500 connections per year by 2015. A 100% coverage would hence require 848,000 connections for an efficient and economic operation of the system (BCEOM, 1992).

For a sewerage system to be operational therefore, the per capita water consumption would have to be increased by at least 500%. This would result in a threshold of towns with about 250,000 to 300,000 people where sewerage services would be viable. In addition to the financial constraints, this makes the feasibility of providing sewerage services out of the reach of many towns (DHV, 2003). Thus, in the short run, it is not possible to achieve sewerage services, unless water supply is raised. As a result the recourse to the use of pit latrines was based on this argument.

In the meantime, appropriate urban waste collection and disposal will remain focused in the provision of septage collection and disposal. This primarily relies on the use of sludge disposal trucks for collection of waste from pit latrines. At the moment, this in itself is constrained with inadequate service coverage. In 2003, for instance, of the 30 towns surveyed, only 11 had sludge collection services (DHV, 2003).

Given this scenario, pit latrines appear to be the only remaining alternative in the foreseeable future. The amount of financing that may be required to provide pit latrines, is still considered to be substantial. Alternative sources of finance would include those from the private sector.

So far private financing of sanitation services, including construction of pit latrines has been considered low. A number of reasons have been cited as contributing to this. These include, land tenure problems, decreased prioritization in provision of sanitary facilities in relation to income generation, and lack of awareness of the impact of poor sanitation on health.

People living in congested housing areas, lacking land for pit latrine construction, see it as less of a priority than housing needs. Mesfin (1970) suggests land tenure problems as being a major constraint in the provision of sanitation services. He argues that the traditional form of land tenure in the country has not been favourable in encouraging private investment in sanitation facility construction. For instance in the 1960s, 66.8% of all household in Addis Ababa lived in rented houses as compared to 68.5% in Dire-Dawa and 62.0% and 55.6% in Harar and Dessie respectively. Therefore, there was reluctance to invest in sanitation facilities in another's property.

If Mesfin's argument is plausible, then this may have been one of the reasons why the level of sanitation coverage is so low in Addis Ababa. A 2004 survey has shown that about 49.4% of the households or approximately half the population lived in rented housing (CSA, 2005). This, according to Mesfin (1970), has apparently discouraged investment in sanitation facilities.

A second reason is attributed to low income level. Low income groups tend to be completely occupied with income generation activities and less interested in sanitation as a priority

(FMoH, 2005). As the lives of people with incomes below 200 birr/month are completely occupied with income generation, it would be difficult to prioritize sanitation improvements (BCEOM, 1992).

The 20 year National Water Supply and Sanitation Master Plan Framework Study also cites sanitation as being given a much lesser priority, due to lack of awareness of hygienic issues by the general population (DHV, 2003). Thus, the general lack of awareness of the importance of sanitation for human welfare is considered to have hindered improvements in sanitation service coverage.

New policies are now attempting to improve sanitation coverage. This policy promotes the formulation of a housing construction and urban development policy that incorporates sanitation services focusing essentially on providing a pit latrine form of waste disposal (MoWR, 1999a). This may be the reason behind the increased proliferation of pit latrines. In 2005, 86% of the urban and 29.4% of the rural population used toilet facilities that directly transmit human waste into the ground (FMoH, 2006).

Current data indicate that in 2007 a total of 67,490 sanitation units have been built in Ethiopia. Of these 44, 618 are traditional pit latrines, 13, 239 traditional pit latrines with hand wash facilities, and 7, 353 ventilated improved pit latrines with hand wash facilities. The remaining 2098 units are communal pit latrines (MoI, 2007). In the Amhara region with a population of over 19 million 26,400 pit latrines were constructed in 2005, of which 90% are still in use. This figure is expected to rise to 2.2 million latrines by 2015 to reach the MDGs.

In the eastern part of the country the Catholic Relief Service (CRS) constructed a total of 32,666 pit latrines in 2000-2007(Abaire, 2008). This appears to be a follow-up of a decade long strategy which envisaged a plan to build about 6 million pit latrines, thus providing latrines at the rate of 600,000 units a year as a part of the Water and Sanitation Decade for up to 80% of the rural population (Teka, 1990,1991). Rural areas have also continued to register a general 'autonomous growth' of 7.5% a year in sanitation coverage. If this trend is maintained, it is envisaged that coverage would reach 50% by the year 2025 (DHV, 2003).

In the city of Addis Ababa, current estimates indicate that 0.6% of the population or 15,000 people have access to a sewerage system (DHV, 2003). The rest of the city's population, about 99.4%, use pit latrine form of sanitation facilities. It appears therefore that the main thrust of basic sanitation service provision will continue to be the construction of pit latrines in urban and rural areas.

2.1.6 Urbanization in Ethiopia

The Ethiopian population has been fundamentally rural. The urban growth process may be said to have started during the reign of Emperor Minilik when the frontiers of Ethiopia were properly defined (Mesfin, 1970). The capital city Addis Ababa was established by the Emperor in 1896 around the Emperor's palace or '*Gibbi'* as it was locally known. The palace was located on a hill and the nobility settled nearby on land granted to them by the Emperor (Bahru, 1992).

A significant progress in urbanization is believed to have occurred during the brief Italian occupation of 1936-1941. The city of Addis Ababa was the principal urban centre. In the 1960s Mesfin (1970) reports that only one town had a population above half a million comprising 18.7% of the total urban population. About fifty eight percent of the total urban population was concentrated in only 9.1% of the towns.

In the 1990s, a number of urban areas such as Dire-Dawa, Mekelle, Harar, Gondar and Bahir-Dar have grown significantly both geographically and economically, becoming regional centres in their own right. With the current economic growth, many small cities are now becoming urban centres. This will consequently raise the demand for more infrastructure and services. Urbanization will therefore cause the demand for water and sanitation services to increase.

Increased urbanization, and hence, increased consumption of water means a higher generation of both solid and liquid waste. As urban centers increase both in terms of geographical extent and population size, so is the amount of water required to match human utilization and consumption. The volume of waste generated will also increase proportionately. This will pose a serious threat of contamination to water sources.

2.1.7 Urbanization and Contamination of Sources of Water

Numerous researchers have documented that the sources of water in urban areas tend to be affected by human (anthropogenic) activities. Surface waters are the first to be affected followed by groundwater. Urbanization is therefore considered as one cause of water quality degradation and may affect health (Akujieze *et al*. (2003), (Christoph *et al*., 2008).

Not only is the quality of groundwater affected but its quantity may also be reduced. This is as a result of overconsumption and reduction of recharge due to increased built-up areas. Hence the process of urbanization causes changes in groundwater level due to decreased recharge and increased withdrawal (Todd, 1995).

Additionally, chemicals affecting water quality have been shown to increase in regions where land was converted into construction land. These include an increase in pH, and Ca^2+, Mg^2+,

NH_4^+, HCO^-_3, SO_4^{-2},NO^-_3, NO^-_2, Cl^- (Koh *et. a*l, 2007), (Yongjun *et al*., 2008). Yongjun *et al*. (2008) also suggests that when cultivated land is converted to construction land human activities tend to increase sewage. Waste effluents discharged into ground cracks and into groundwater also result in higher values of pH and Chemicals such as NO^-_3, NO^-_2. The increased concentrations generally exceeded drinking water standards. Akujieze *et al*. (2003) reports similar problems in Nigeria with increased urbanization, industrialization, diversification of land use from agricultural use of fertilizers, animal penning in markets, and indiscriminate refuse disposal.

Sadek and El-samie (2001) observed shallow groundwater contamination in Cairo due to urbanization. Lawrence *et al* (2000) also reported a similar occurrence in Hat Yai city in Thailand. Meriano and Eyels (2003) observed that urban and rural sourced contaminants (chlorides and nitrates) present in upper aquifer waters moved rapidly to deeper aquifers in the city of Scarborough in greater Toronto in Canada. Deeper aquifers were also reported to be poorly protected from urban contaminants. Kimmel (1984) reports cesspools and septic tanks contributed a major load of nitrate as well as total dissolved solids (TDS), sulphate and chloride on the groundwater as urbanization spread eastwards on Long Island. Wakida & Learner (2005) have also suggested that 'the major sources of nitrate in urban aquifers throughout the world are mostly related to waste water disposal systems (on site systems and leaky sewers) and solid waste disposal (landfills and waste tips)'. Even well functioning septic tanks, when densely distributed, are major sources of nitrate loads on groundwater (Zaporozec *et al*, 2002).

Adelana (2006) has shown that elevated nitrate levels in groundwater were due to increased urbanization coupled with indiscriminate disposal, and inadequate sanitation facilities in cities. Duah (2006) reports groundwater contamination in Ghana as a result of poorly designed hazardous waste disposal facilities with, among other chemicals, excess nitrate being one contaminant.

Cronin *et al*. (2006) also report of average nitrate loading with values 3 times more elevated in the highly populated urban areas in Lichinga in Mozambique and Timbuktu in Mali compared with respect to surrounding rural area concentration levels, with on site sanitation a major contributor. Elevated nitrate levels linked to increased population densities were also reported in Cotonou city in Benin (Boukari *et al*., 2006). Septic tanks and French drains have also been shown to be causes of contamination of aquifers in Abidjan (Jourda *et al*, 2006).

Shallow wells in Bamako Mali have also been reported to be highly contaminated by, improperly designed individual sanitation installations. These were also correlated with high population density (Orange & Palangie, 2006). Melian *et al.* (1999) observed similar occurrences where concentration of nitrates was significantly higher within residential areas in Moldova.

Infiltration of septic tank effluents, leachate from sanitary landfills and infiltration of sewage from sewage lines have also been considered as sources of nitrates in groundwater (Canter, 1997). In contrast in the city of Doula, Mafany *et al* (2006) report, low levels of pollution in neighborhoods inhabited by high income inhabitants with low population densities and well protected wells and toilets. Love *et al*. (2006) observed similar occurrence in Harare, Zimbabwe.

In general, urban activities were second to agriculture in increasing nitrate concentrations in groundwater consequently affecting water quality (Al-Hanbali & Kondoh, 2008). This suggests increasing population and urban activities contribute to high level of contamination in groundwater. The influence of human activity on water quality may be linked to high concentration of chemicals that are in excess of what may occur naturally. One such chemical is nitrate, a derivative of nitrogen. Nitrate may exist in the ground, with a base line level typically below 2 mg/L (Wakida & Lerner, 2005). Therefore, wells with 3-10 mg/L of nitrate as N may indicate anthropogenic contribution (Power & Schepers, 1989).

Groundwater contamination by nitrate from various sources is a 'widespread problem in many locations in the world' (Canter, 1997). Excessive nitrate concentration is associated with water quality degradation (Koh *et al*, 2007), (Canter & Knox, 1991). The World Health Organization (WHO) and individual nations therefore prescribe limits on the maximum permissible levels in water for drinking purposes. For instance drinking water standards in South Africa indicate an acceptable level of nitrate as N of 6-10 mg/L (Tredoux, 2006). The World Health Organization (WHO) recommends a maximum limit of 10 mg/L of nitrate as N or 50 mg/L of nitrate as NO_3.

Nitrate is also sourced from agricultural activities. Nalini *et. al*. (2007) report a high level of nitrate pollution due to animal waste in the regions of Ganges alluvial plain in Alluvial Plain of Kanpur District, India. Gallardo *et al* (2005) also reports of increased levels of nitrate pollution due to urban agricultural activities in the city of Tsukuba in Japan.

As in other African cities, pollution of water sources is also a problem in many urban areas in Ethiopia. In a study carried out in 2005, Yirga suggests that some boreholes in the city of Dire-Dawa had a higher rate of nitrate concentration than the limit recommended by WHO, possibly as a result of anthropogenic pollution, or due to fertilizer application or from pit latrines (Yirga, 2005), (Samson, 2004). Taye (1988), also confirms that the groundwater resources in Dire-Dawa have shown very high concentration of nitrate, sulphate and chloride.

This is further confirmed in a 2004 survey by WHO/UNICEF, which suggested that contamination may be widespread (WHO/UNICEF, 2007).

This survey showed that the compliance to WHO guideline values of normal nitrate levels in water supply in Dire-Dawa was only 67%, with values as high as 208 mg/L recorded. The reasons were attributed to, a lack of proper sewers and waste disposal facilities, the presence of more than 20,000 open pit latrines, and geological conditions.

A separate study in the northern-central areas of the country, around the city of Bahir-Dar has also revealed nitrate concentrations higher than standard limits. This was attributed to sewage contamination and excessive use of agricultural chemicals (Bayessa, 2004). In the city of Gondar in North West of the country nitrate levels as high as 27.5 mg/L have been observed in some water wells (Tenalem, 2005). Belema (2004) reports that some boreholes and hand dug wells in the town of Debre-Zeit 40 kms south of Addis showed nitrate levels higher than Ethiopian and WHO standards.

Nitrate contamination of groundwater is therefore a major challenge in Ethiopia. With a high population density, coupled with high number of pit latrines, Addis Ababa is perhaps at a higher risk of groundwater contamination due to human waste. This risk may not solely be attributed to urbanization and its concomitant problems, but it can also be due to the general assumption, among water professionals, that water particularly from deep wells is of good quality and may not need monitoring. This is perhaps why water quality monitoring is poorly enforced in Federal Regions. Water Bureaus in Federal Regions check approximately 5-10% of point water sources annually (WHO/UNICEF, 2007).

A study to assess the prevalence of faecal contamination of water sources showed that, of the 1602 samples tested for thermo-tolerant coliforms 72% met the national as well as the WHO guideline values. This compliance was significantly higher for utility piped supplies, with 87.6% of the 838 water samples collected from utility piped supplies (i.e from treatment plants and distribution system) meeting both the WHO Guideline Values and national standards. In contrast only 67.9%, 43.3% and 54.8% of boreholes, protected springs and protected dug wells respectively were in compliance with this standard (WHO/UNICEF, 2007).

The city of Addis Ababa showed a compliance rate with regards to coliforms of 89.9 % for utility piped supplies. The compliance rate for boreholes, protected springs, and protected dug wells was 71.6%, 51.3%, and 75.0%, respectively (WHO/UNICEF, 2007). It is also reported that of the 110 samples analyzed for faecal streptococci, 66.4% were in compliance with both national and WHO guideline values. The city of Addis Ababa again scored low with 56.1% for the 41 samples tested. This suggests that contamination of water resources by human waste in the surveyed areas may have been prevalent. The surveys however, tend to focus on testing contamination level at taps, or after the water is chlorinated.

Other researchers have reported of contamination occurrence in rural areas. Abaire (2008) reports that in a water quality monitoring survey carried out by CRS and Partners, most shallow groundwater and surface water sources contained nitrate and faecal coliform bacteria higher than the maximum limit values. The faecal coliform count is reported to be as high as 23-50 counts and nitrate content as high as 45 mg/L.

Besides the apparent lack of awareness, over-abstraction of groundwater may also have contributed towards quality deterioration. Over-abstraction may cause a steep cone of depression in water wells favouring a higher inflow velocity that enhances bacterial movement to wells from surrounding clayey soils (Drangert & Cronin, 2004).

Over-abstraction of groundwater in Ethiopia has occurred in some urban areas. This unsustainable withdrawal has denied some urban centres a reliable water supply source. Yirga (2005) reports that in the town of Dire-Dawa in East Ethiopia, groundwater resources have been over extracted at a rate of 19,000 m^3/day while the maximum sustainable yield was only 10,000 m^3. This has now resulted in water shortages in the city. This unregulated abstraction has been ongoing in the city for a considerable period of time with some factories such as the Dire-Dawa textile mill known to have abstracted as much as 1 million cubic meters of water annually (2740 m^3 of water per day) from its 'own' well (Taye, 1988).

A cursory look at the above studies suggest a high risk of contamination of water resources which appears to be prevalent in many urban areas of the country. Groundwater quality deterioration is not however exclusively an urban problem. There have also been some individual reports of rural water supply contamination. For instance, in southern Ethiopia rural spring contamination, by nitrates and phosphorous has been reported by McKenzie *et al* (2001).

3 The Study Area

3.1 The City of Addis Ababa

With a population of over 2,738,248, Addis Ababa the capital city of Ethiopia ranks as one of the major urban centres in the country. Currently it has a total surface area of about 530.14 sq. km (CSA, 2008), and continues to grow. As a major industrial centre and the only city with a population of over one million, Addis Ababa is both an economic and political capital. The presence of major international organizations and Embassies has also made the city a *de facto* capital of Africa.

Addis Ababa is a rapidly growing city. There is a significant work going on in the housing and infrastructure sectors. Established over a 122 years ago it continues to grow primarily southwards, by annexing adjacent farmlands and small towns. Whilst it has grown spatially, the provision of water supply and sanitation services is considered to be low.

The city of Addis Ababa has a population of 2,738,248 people (CSA, 2008) and is the only city in Ethiopia with a population of over 1 million. 40% of its water supply is sourced from groundwater while the remaining is obtained from dams located outside the city. The major aquifers are located at the southern and western end of the city, and the shallow minor aquifers are located in the city centre. About 75% of the population use pit latrines for human waste disposal, while over 24% do not have access to sanitary facilities. Only 0.6 % have access to sewerage services. The ‘rivers’ in the city are polluted and flow southwards to a groundwater abstraction area. This may have contributed to groundwater contamination due to human waste.

3.2 Addis Ababa Location and History

Addis Ababa is situated on the western side of the main Ethiopian escarpment. The escarpment located northwest of the East African rift system, is one of the largest structural features of the Earth's crust. It extends for a distance of over 6000 Kms. from Syria to Mozambique (Kebede & Tadesse, 1990). The city is surrounded by the *Entoto* ridge (3199 m asl) in the north, by Mount *Wechecha* in the west (3385 m asl), by Mt. *Furi* (2839 m asl) in the south west and Mt *Yerer* (3100 m asl) in the south east (Tamiru *et al*, 2005). Starting from the *Entoto* ridge, the city's features tend to gently slope towards the south west direction. The central areas of the city are at a lower elevation than the rest of the city.

The present site of Addis Ababa was chosen in 1886. In 1879 Emperor Minlik had set up the Government's seat on mount *Entoto* a few kilometres north of the present city of Addis Ababa. Struck by its natural scenery, Emperor Minilik later decided to move his capital from mount Entoto to the present location.

Before being named Addis Ababa meaning '*New Flower'* in the National language Amharic, its name was '*Finfine'* a reference to the numerous hot springs around the city centre (Foucher, 1987). An early description of *Finfine* being a habited place has been recorded by an Italian missionary Father Taurin in 1868 (Batistoni, 2004). Addis Ababa's early development was in the form of camps or squatter settlements known as the *Safars*, around the tent '*gibbi'* of the King which has over time evolved into a permanent habitation (Zewde, 1987).

The 1907, legalization of private urban land ownership further shaped the development of the city into a municipal administration, albeit as an extension of the palace or '*gibbi'* administration. In 1920 the growing city was divided into 10 zones, these zones were precursors to the later division of the city into ten '*weredas' or* administrative areas (Zewde, 1987).

A decade later the rapid deforestation of trees in and around the city forced the relocation of the capital city to *Metcha*, 30 kms west of Addis Ababa. The discovery of coal and the importation of eucalyptus trees in 1890s (Henze, 1977) from Australia however, prevented the total abandonment of the city as the country's capital city. The eucalyptus trees still form a significant feature of Addis Ababa although this may have contributed to the rapid lowering of the groundwater table in and around the city (Abaire, 2004).

By 1935, on the eve of the Italian occupation the population of the city had reached 100,000 with a built-up area of about 1863 hectares (Chappel, 1987). By 1940, by the time the Italian occupation had ended, the city's population had grown to 150,000 with an area of over 70 square kilometres (AESL 1984). In 1954 the city was granted a legal charter. The city continues to grow in population size and areal extent (IEGCSA, 1964), (IEGCSO, 1965). (Mesfin, 1970), (CSA, 1972, 1975, 1986, 1990, 1995, 2000), (AESL, 1984), (Assen, 1987), (Ahderom, 1987).

A number of Master Plans depicting the city's future growth have been prepared (Ahderom, 1987). In 1965 a French consulting team led by L. De Marien prepared a new Master Plan of which a considerable part was implemented. This Master Plan incorporated proposals for better water and sewage networks.   In 1984-86 a 20 year Master Plan was proposed based on an earlier study by a Hungarian planner C.K. Polony (AACG, 2002).

The previous Master Plans for the city appear to have not fared so well as the city continued to grow in the spontaneous manner which has been its distinctive feature since its founding (Zewde, 1987). The main hindrance for the implementation of the city's Master Plan appears to be lack of legal enforcement as much as lack of implementable information. This has, in effect, hindered the proper management of the city (BCEOM, 1970), (Kebede & Tadesse, 1990). The Current Master Plan has now incorporated significant infrastructure development, including roads and housing.

3.3 Addis Ababa: Climate, Population and Growth

3.3.1 Climate

Located at an altitude of 2500 m (IEG MoI, 1969), and of temperate climate, the city of Addis Ababa enjoys a rather cool temperature. The average temperature for a period of 47 years was observed to be around 16.02 0^{C} (Tamiru *et al*, 2005).

A 35 year analysis of rainfall data indicates that Addis Ababa receives an annual average rainfall of about 1150 mm. The heaviest amount of rainfall occurs in August and the minimum in December (Tamiru *et al*, 2005). Although there is an increasing trend towards the north, rainfall does not vary significantly over the city (BCEOM, SEURECA, & Tropics, 2003). The main rainy season covers the period from June to September, with minor rains during March and April.

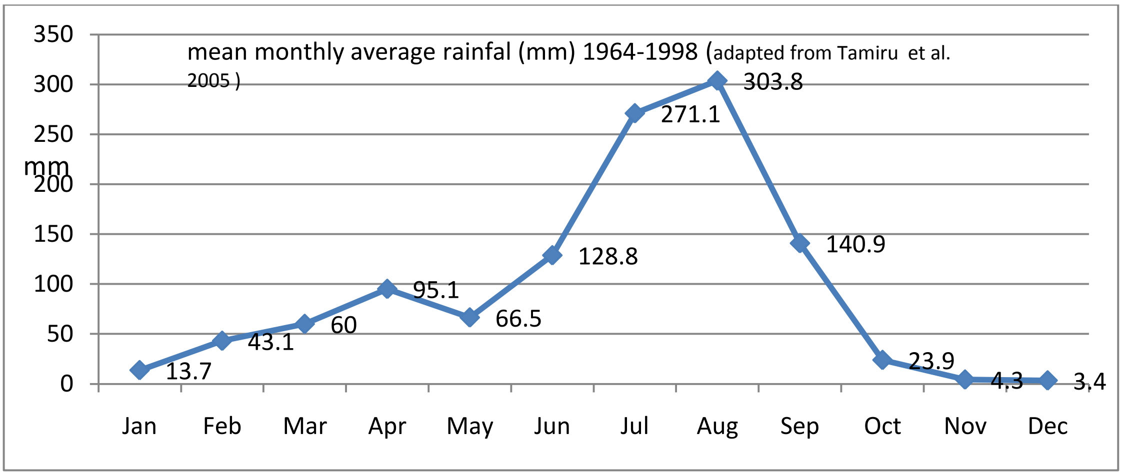


Fig 3.1. 35 year mean monthly rainfall in Addis Ababa

3.3.2 Population

Since its founding in the 1800s, the city of Addis Ababa has grown, both in terms of its geographical extent and population size. From a small village with a population of about 60,000 in 1909 and an area of 3.3 km^2 it has grown to be the largest city in Ethiopia. Currently it has an area of over 500 km^2 and a population of 2,738,248 and an average household size of 4.1, with an annual population growth of 2.1%. Addis Ababa has a population density of 5,328, people per square kilometre (CSA, 2008).

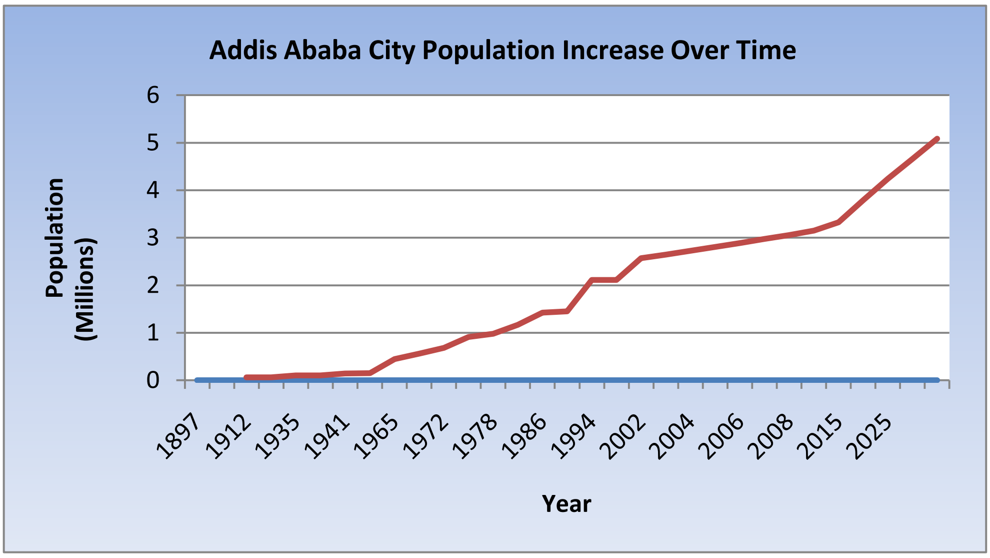


Fig 3.2 Population growth of the city of Addis Ababa

Addis Ababa is by far the largest and most populous city in the country followed by the city of Dire-Dawa in eastern Ethiopia. In terms of urban population it currently accounts for at least 22.9% of the country's total urban population (CSA, 2008). Addis Ababa is divided into 10 sub-cities with the population of each sub city as shown in the Table 3.1 below.

Table 3.1 Addis Ababa sub-cities population in 2008 (CSA, 2008)

Addis Ababa sub-cities population 2008((CSA, 2008)	
Akaki-Kaliti sub-city	181,202
Nefas Silk Lafto sub-city	316,108
Kolfe Keranyo sub-city	428,654
Gulele sub-city	267,381
Lideta sub-city	201,613
Kirkos sub-city	220,991
Arada sub-city	212,009
Addis Ketema sub-city	255,092
Yeka sub-city	346,484
Bole sub-city	308,714
Total	***2,738,248***

3.3.3 Spatial Growth

Addis Ababa continues to grow southwards; with the outskirts developing into an affluent suburbia. This is possibly because the large relatively flat area which gave the city the potential for growth lay predominantly to the south (Zewde, 1987). During the 1980s and 1990s its growth continued by the annexation of peripheral settlements and has at present a total surface area of 530.14 km^2 (CSA, 2008). In the last 20 years alone, the surface area of the city has grown by 167%. The city's spatial extent tends to increase sharply after the 1990s (Fig 3.3). It appears that this corresponds well with the improved economic as well as social situation prevalent after the fall of the military '*Derg'* government. Nevertheless its growth has not been without problems.

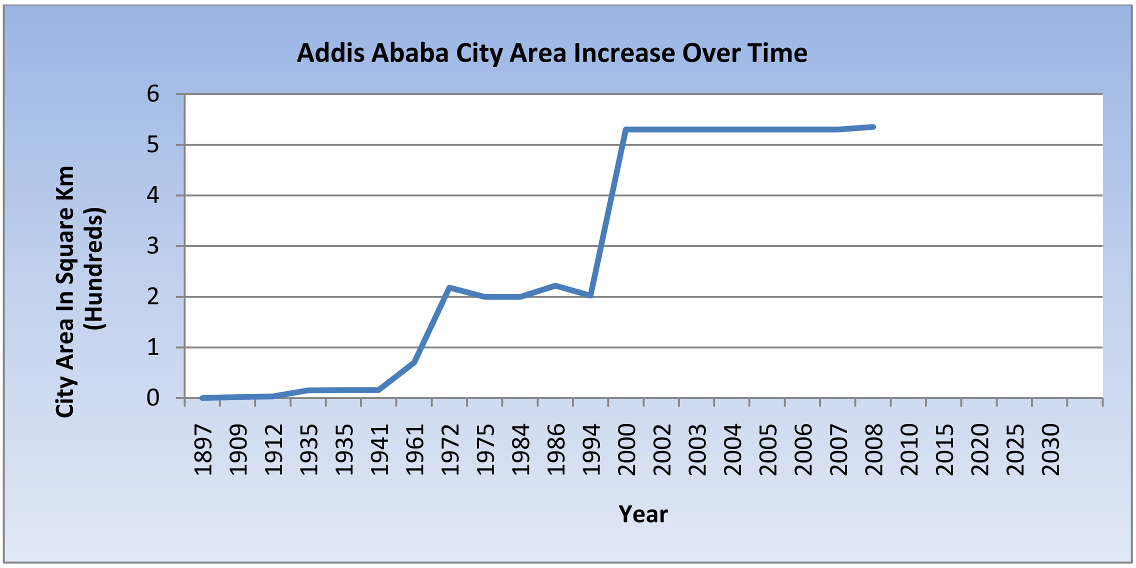


Fig 3.3 Spatial increase of Addis Ababa

The city administration cites ‘lack of explicit urbanization policy, resulting in unbalanced urban growth, weak national urban network and poor linkages and synergies between urbanization and economic development’ as major problems. Absence of adequate facilities, increasing population and its concomitant environmental degradation, uncontrolled rapid horizontal expansion has also been cited as being major challenges (AACG, 2002). Unbalanced, uncoordinated and scattered development in the city is also considered to have contributed to underutilization of development sites.

An estimated 60 % of the city core is deemed to be dilapidated, with a quarter of all housing units considered to be built informally. Lack of provision of adequate services to extension areas of the city has discouraged new housing construction contributing to the growth of slum areas. Eighty percent of the city’s population is believed to be in the low income group (AACG, 2002).

3.4 Addis Ababa: Geology

A frequently cited geological study of the Addis Ababa area is the one carried out by Kebede & Tadesse in July 1990. This study is preceded by another investigation on the hydrogeology of the city done by Vernier *et al*. in 1985. Other studies have also been carried out (Tamiru *et al*., 2005). Recently a newer and updated geological map of the city has been completed by the Geological Survey of Ethiopia (Mulugeta, Assegid, & Kiflemariam, 2007) and is expected to be published soon. This geological study covering a total area of about 3000 km^2 including the area of Addis Ababa (geographically bounded by $8^0$45' and $9^0$15' N latitudes and $38^0$30' and $39^0$00' E longitudes) and has identified the geological features of the city and its surrounding areas. The geological map including cross sections are shown below.

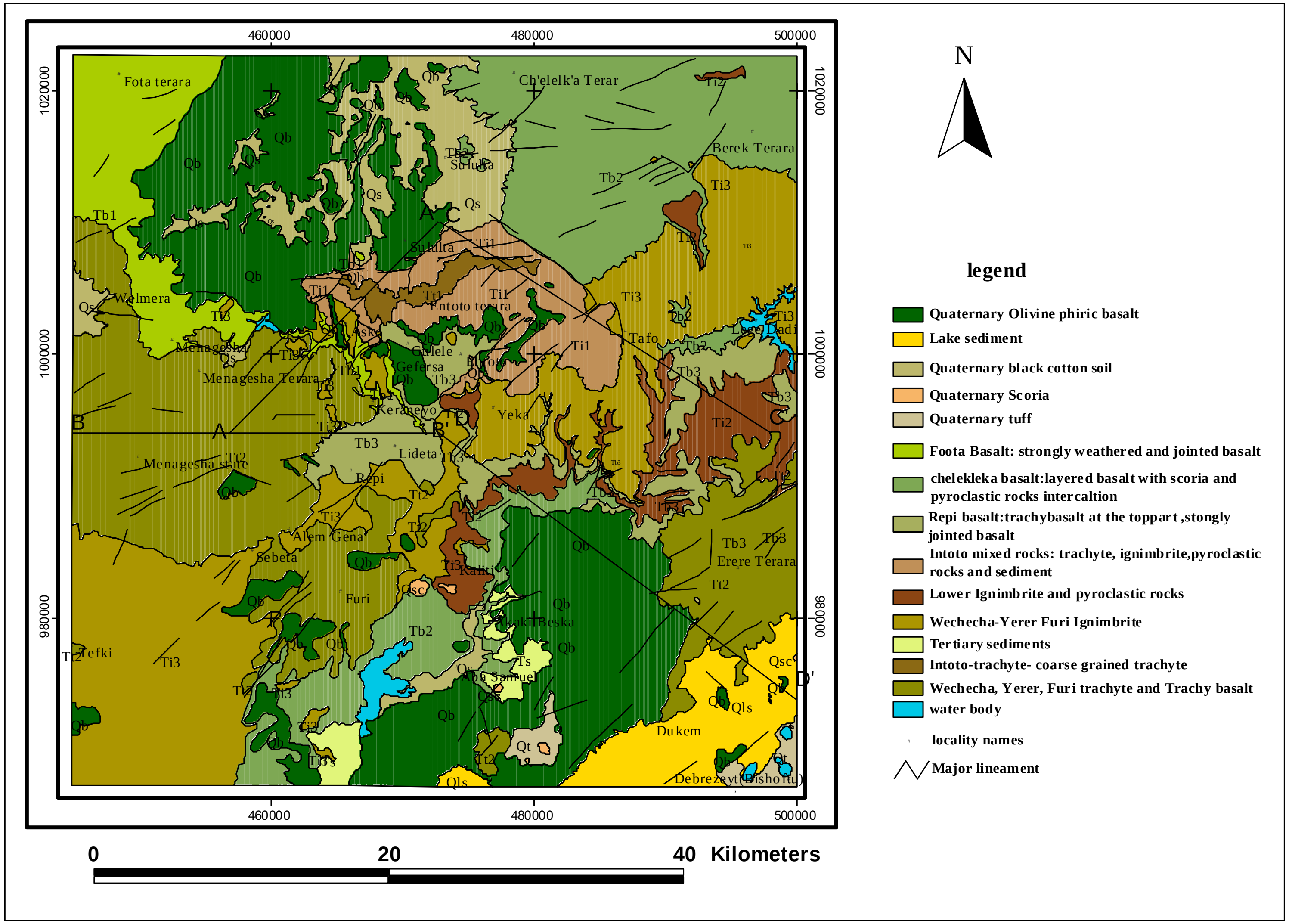


Fig 3.4 Geological map of Addis Ababa and its environs (Source: Geological Survey of Ethiopia)

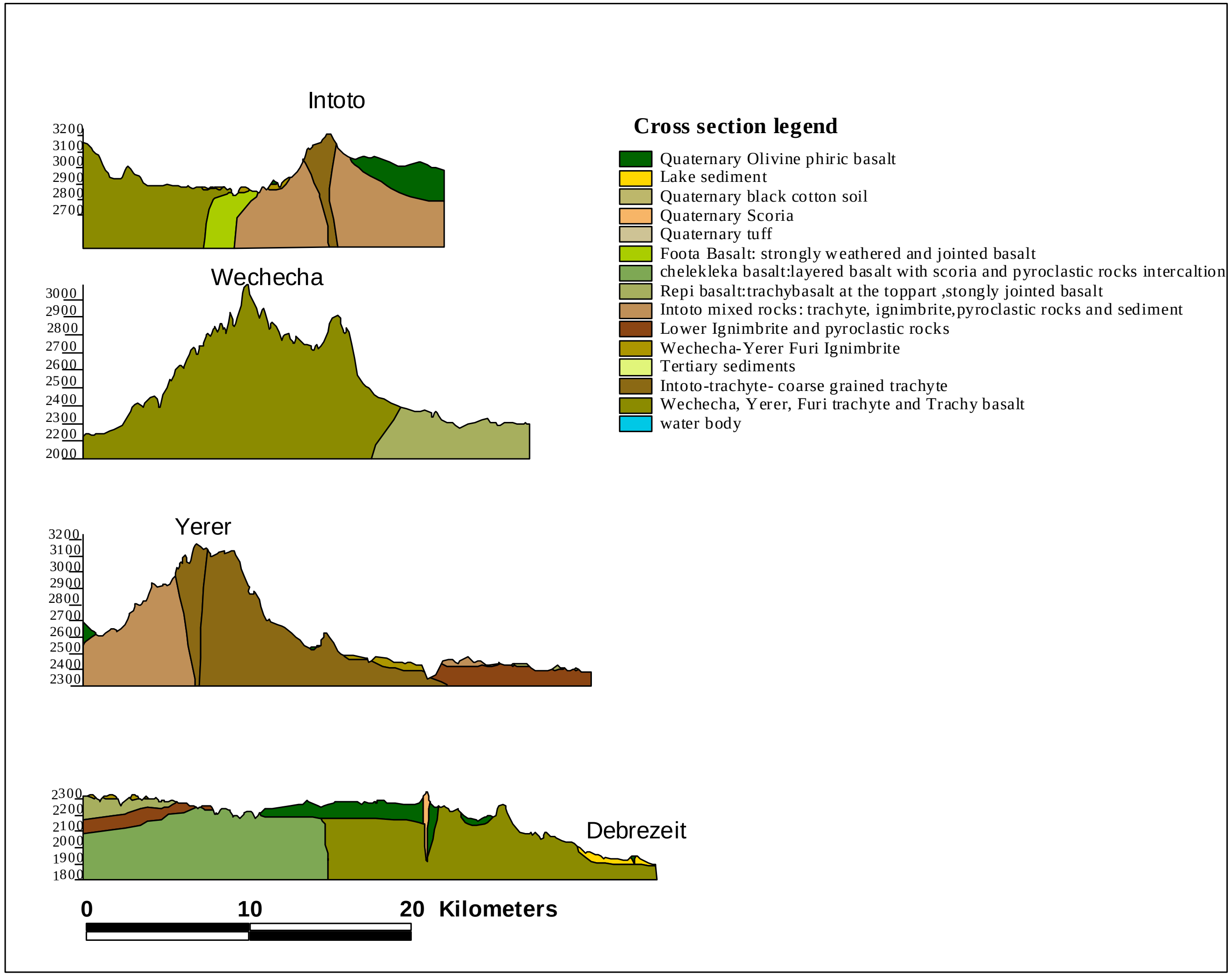


Fig 3.5 Geological cross section of Addis Ababa and its environs (Source: Geological Survey of Ethiopia)

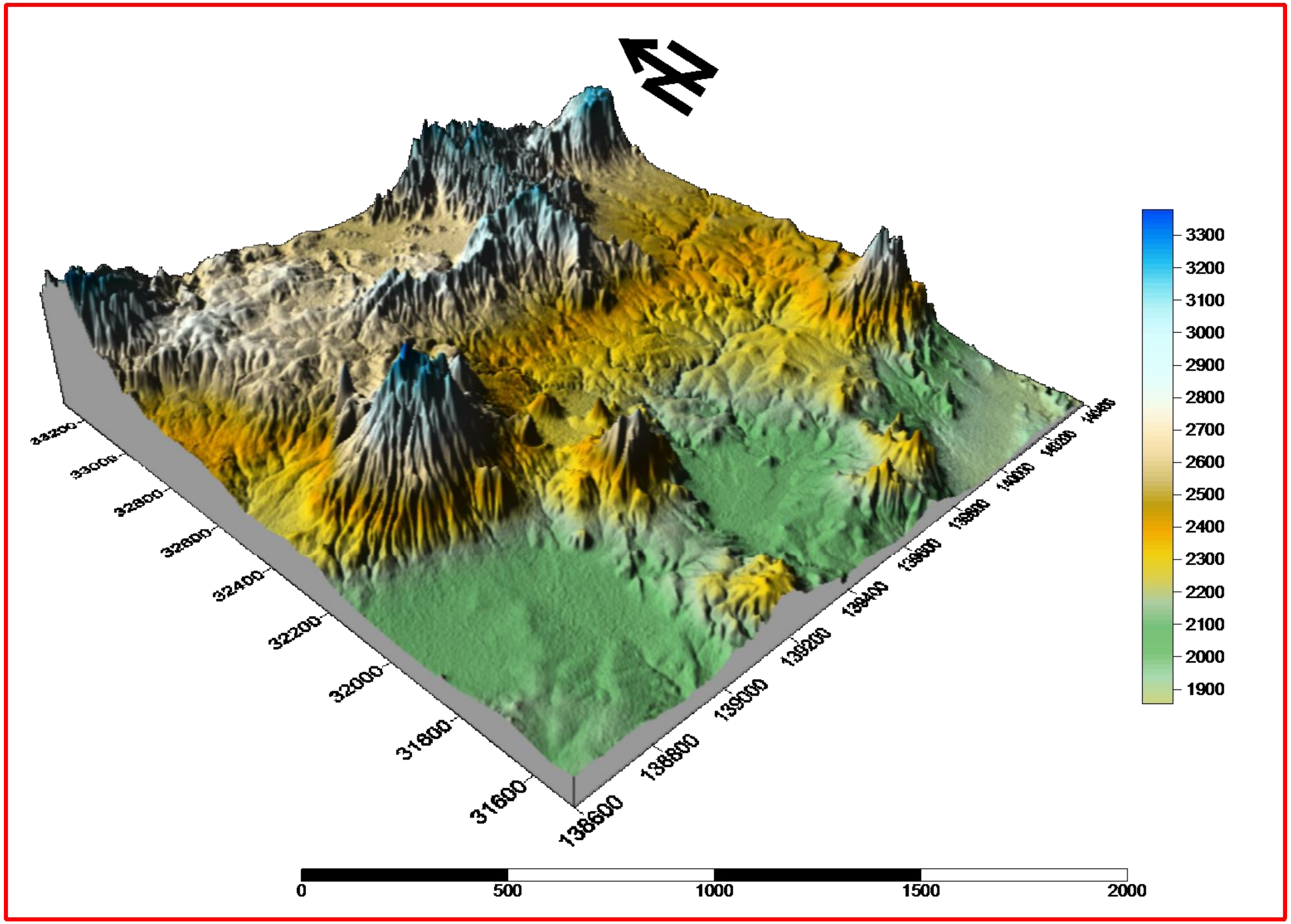


Fig 3.6 Geological cross-sections along lines A-A', B-B', C-C' and D-D' (Source: Geological Survey of Ethiopia)

Situated in the western margins of the rift valley, Addis Ababa is located on different volcanic rocks ranging from basic to acidic composition (Kebede & Tadesse, 1990). The northern part of the city has the distinctive feature of a chain of mountains comprising of Rhyolite and Trachyte, called the *Entoto* silicic of the Addis Ababa area.

The two volcanic mountains of *Wechecha* and *Furi* located to the South-West and South of the city, respectively, and Mount *Yerer* located on South-East of the city are composed mainly of trachytes. They form as the source of ignimbrites, tuff and trachy basalts of Addis Ababa volcanic hills. Basalts are also found at the centre of the city.

Around the eastern side, a West-East fault crosses the central area along the hot springs (Filwoha area), and is covered by ignimbrites and aphanitic basalts. The southern part of the city is also covered with this type of rock.

In general the geology of the Addis Ababa area comprises of the tertiary volcanic rocks comprising of apahnitic, pyroxene-phyric, plagioclase-phyric and olivine-phyric basalt, trachy basalt, trachyte, ash, ignimbrite and agglomerate and tertiary sediments. The soil features of the city tend to be predominately expansive (black cotton) clays in the central and south western parts of the city, while the north-eastern half is predominantly overlain with red clay soils. Tamiru *et al*. (2005) have observed the presence of cambisols in the northern, eastern and western part and vertisols in the central and southern part of Addis Ababa. Kebede and Tadesse (1990) also report of black cotton soils covering large areas of the city.

3.5 Addis Ababa: Hydrogeology

The major rock types forming a reservoir of groundwater in the city are considered to be the volcanic rocks consisting of basalts, trachytes, rhyolites, scoriaes and trachy-basalts. The fractured volcanic rocks, located towards the south of the city also form the main aquifers in the city (Kebede & Tadesse, 1990).

Studies on the geology of Addis Ababa by Vernier *et al*. (1985), BCEOM, SEURECA and Tropics (2003), Tamiru (2005) and Molla *et al* (2007) report the main aquifers in the study area to be;

1. Shallow aquifers: made of weathered volcanic rocks and alluvial sediments along the river courses
2. Deep aquifers: made of fractured volcanic rocks that tap fresh groundwater
3. Thermal aquifers: located at depths greater than 300 m

In addition to these, intense fracturing and faulting of the mainly basaltic formation around the city centre is considered to form a good aquifer. It has long been believed that all the aquifers in the city are hydrologically interconnected and the water table is found in confined, semi-confined, and perched aquifers (AESL, 1984).

The area around the groundwater extraction vicinity of Akaki is composed of olivine basalts, scoria, vesicular and scoriacieous basalts. The combination of varying thickness of scoria, scoriaceous and vesicular basalt form the main aquifer material in the well field (Berhanu 2002). In these young volcanic sequences weathering effect is generally considered to be low and the main porosity and permeability is assumed to arise from the conditions of lava flow (AG Consult, 2004).

Thermal waters under confined conditions have been observed in the center of the city. The eastern areas of the city are believed to be low yield aquifers. In general the complex stratigraphy has made the hydro-geological determination 'extremely difficult' (Vernier *et al*, 1985).

Correlation of the most productive aquifers with the geology of the area also appears to have been a persistent problem. This has been attributed to insufficient detail of geological maps and inappropriate logging of drilled wells (AESL, 1984). A separate study covering nearby areas and urban centers including the Akaki well field, Debre-Zeit, Modjo and Nazreth towns, all within a 100 km radius of the city has also suggested this to be a main problem (WWD&SE, 2007). This study also suggested lack of hydro-geological data as the main reason for underestimating the aquifer depth.

3.5.1 Groundwater Flow

The following piezometric map Fig 3.7 adapted from a study by AG Consult suggests the indicated groundwater table elevations. This indicates the main groundwater flow to be mainly in the north-south direction. There has also been observations of localized flows mainly towards southeast and southwest as common occurrences (AG Consult 2004).

AG Consult also suggest that the 'potentiometer surface indicates that the groundwater is in connection with the surface water mainly with the Big and Small Akaki rivers……' this is most likely a potential threat to groundwater quality as these surface waters are highly contaminated.

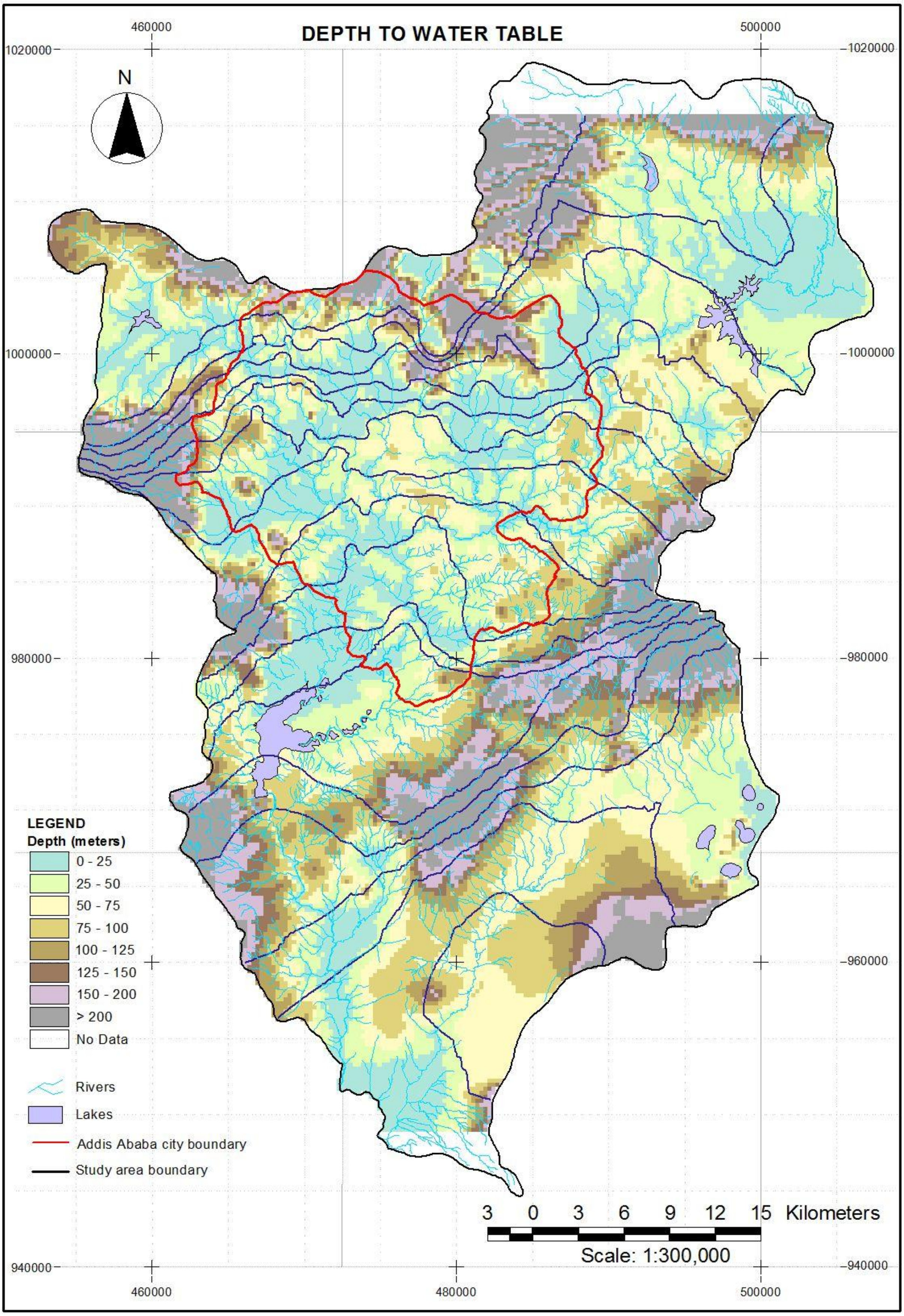


Fig 3.7 Depth to water table (adapted from AG Consult)

3.6 Main Aquifers in Addis Ababa

Given the absence of hydrogeological maps, it appears that exact data on capacity as well as areal extent of aquifers in the city may not be accurately known. Some researchers have, on the other hand, proposed some description of possible aquifers.

Vernier *et al*, (1985) suggest that at least four aquifers occur at different depths. They suggest that the phreatic aquifers that are located in the central areas are shallow, with groundwater occurring at a depth range of 0-200 meters. On the western areas of the city, Tamiru (2005) argues that the fractured propyritic basalt has increased permeability, and is hence a productive aquifer. On the other hand he suggests that the northern central and eastern parts of the study area also covered with welded tuffs and are believed to have developed good secondary permeability.

Aside from the above studies, it appears that there was no comprehensive investigation on the areal extent and capacity of aquifers. AG Consult has recently prepared preliminary aquifer delimitation in and around the city. The map indicates the locations of aquifers, correlated with the geological features. Discussions with hydro-geologists at AG Consult on the other hand suggested that the determination of aquifer depth is still a constraint in their study. The following map is adapted from the study. A close review of this map (Fig. 3.8) indicates that a large section of the centre of the city is classified as 'minor aquifers'. In contrast the Akaki aquifer area is considered to be a major aquifer. Cursory observations of the maps and previous studies would appear to suggest that a firm determination of aquifer depth, capacity and extent may have long been a persistent problem.

AG Consult (2004) indicate that they have used the following categorization in their assessment of aquifers in the city. The main classification they have suggested is categorized into, Major Aquifer System, Minor Aquifer System and Non-Aquifer Systems (Table 3.2).

Table 3.2 Aquifer classification for groundwater in Addis Ababa (AG Consult)

Major Aquifer System	Highly permeable formations, usually with a known or probable presence of significant fracturing. They may be highly productive and able to support large abstractions for public supply and other purposes. Water quality is generally very good (less than 150 mS/m or 1500 mS/cm).
Minor Aquifer System	These can be fractured or potentially fractured rocks, which do not have a high primary permeability, or other formations of variable permeability. Aquifer extent may be limited and water quality variable. Although these aquifers seldom produce large quantities of water, they are important both for local supplies and in supplying base flow for rivers.
Non-Aquifer System	These are formations with negligible permeability that are generally regarded as not containing groundwater in exploitable quantities. Water quality may also be such that it renders the aquifer as unusable. However, groundwater flow through such rocks, although imperceptible, does take place, and needs to be considered when assessing the risk associated with persistent pollutants.

Based on this classification system the aquifers have been categorized as follows.

Major Aquifer System

Young volcanic sequences with wells yielding over 10 l/s with perennial springs yielding over 50l/s. The transmissivity of these aquifers vary between minimum mean value of 616

m^2/day and maximum mean of about 37,000 m^2/day. In this categorization the Akaki well filed is considered to be a major aquifer.

Minor Aquifer System

The old volcanic sequences covering the city of Addis Ababa and the bases of Entoto Mountain and Legedadi plains are classified as minor aquifer systems. But in most cases yield of boreholes vary between 2 l/s and 5 l/s. The transmissivity of these aquifers vary between minimum mean value of 3 m^2/day and maximum mean of about 1700 m^2 day.

Non-Aquifer System

The mountain ranges are classified as non-aquifer systems. The Entoto Mountain range, Wechecha, Furi, Yerer and Ziquala mountain ranges are classified as non-aquifers. They are generally regarded as not containing groundwater in exploitable quantities. However, close to the base of these mountains groundwater does exist although it is not significant for large abstractions. Wells with yields up to 3 l/s can be developed in areas of fractures zones. However, in general most of the wells have yields lower than 1 l/s.

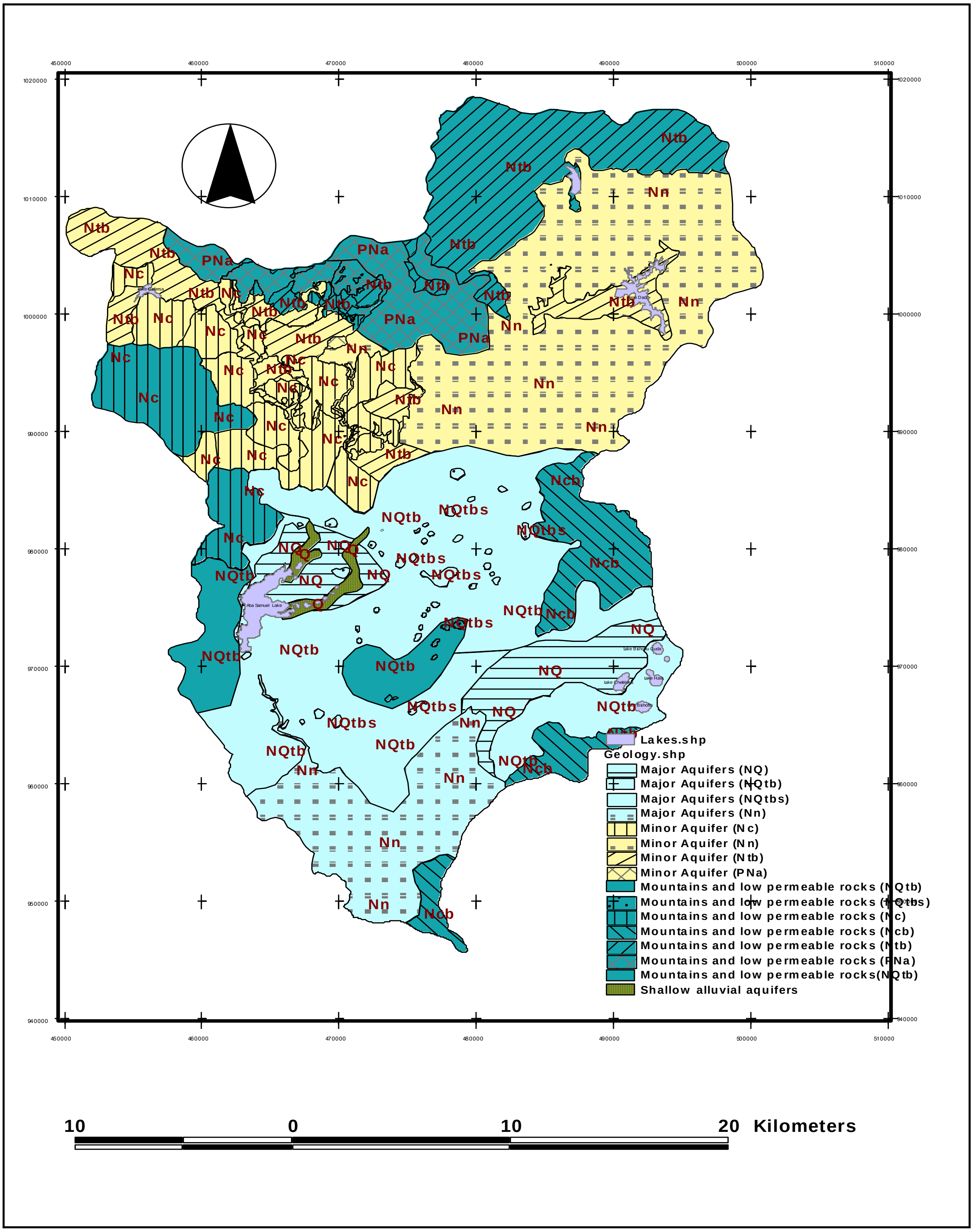


Fig. 3.8 Addis Ababa hydro-geological map (adapted from AG Consult)

3.7 Addis Ababa Water Resources and Supply

3.7.1 Surface Water Resource

The main surface water supplies for Addis Ababa come from the *Gafarssa* and *Legedadi* dams located in north-western and north eastern parts of the city respectively. *Gafarsa* was built in 1944, northwest of the city centre, with a storage capacity of over 6.5 million cubic meters. It's maximum treated capacity stands at 30,000 m^3/day. The current capacity is reduced, due to old age, to around 24,000 m^3/day. Increased shortfall in the supply initiated the construction of two Dams, the *Legedadi* north east of Addis Ababa in the 1970s and the *Dire Dam* in 1999. *Legedadi* had a capacity of 150,000 m^3/day but currently stands at 125,000 m^3/day. In contrast the *Dire Dam* has a total storage capacity of 19, 000,000 m^3 and is able to supply 42,000 m^3/day.

An AWSSA internal report records that, as of the end of 2007 the *Dire* reservoir (augmenting the *Legedadi* dam) supplies a total of 164,397.8 m^3/per day, whereas wells and springs supply 50,019 m^3/per day. other sources yield 22,684 m^3/per day giving a total of 237,100.8 m^3/per day of supply to the city. Of these the Akaki Boreholes and Fanta wells supply 34,945 m^3/per day and 5972 m^3/per day respectively (AWSSA, 2008). In 1969 the output has been 25,000 m^3/per day from *Gafarsa* works, 1800 m^3/per day from other sources, totalling 26,800 m^3/per day (BCEOM, 1970).

In 2001, water supply for the city of Addis Ababa stood at 213,000 m^3/per day, of which about 40% is believed to be wasted due to leakage of the faulty transmission network (MoWR, 2001b). This is higher than the 25% leakage estimated in 1970 (BCEOM, 1970).

At present the rivers of *Kebena*, *Akaki*, and *Ketchene* in the city are so polluted that it would be exorbitantly expensive to rehabilitate them. The little and great Akaki rivers have been cited to be polluted and carry a considerable load of raw sewage and industrial waste. This has made these rivers source of contaminants affecting surface and groundwater resources (BCEOM, SEURECA, & Tropics, 2003), (WWD&SE, 2007). The pollution in these rivers has also been considered to be sources of infection such as diarrhea (FDRE-EPA & MoEDC, 1997). Tenalem (2005) reports that all highland surface and groundwater resources are fresh and characterized by low TDS (50-1200 mg/L). On the other hand, the Akaki Rver in Addis Ababa, polluted by anthropogenic influences, has a high TDS content. This may then be the reason why there is a gradual shift towards utilizing groundwater resource.

3.7.2 Groundwater Resource

Springs and shallow wells have been the main source of water supply in Addis Ababa, since it's founding in 1898. The population increase created a rising demand for more water, which could not be met without tapping more resources. The chronic water shortage then prompted the city administration to take measures to provide sustainable water supply through the development of new groundwater sources. Surface waters outside the city limits are also being considered but the sheer costs involved have perhaps made it a second choice. Understandably therefore, attempts at assessing new sources of water supply for the city have increasingly focused on groundwater manly to supply larger industrial, commercial and government institutions (Alemayehu, 1983).

A study commissioned in 1984 to assess the water resources potential around Addis Ababa recommended development of groundwater sources (AAWSSA, 1984). By 1991, severe water shortages again prompted the government to investigate new water sources for the city. Short term water supply augmentation was envisaged to be addressed with the development of new boreholes around the south western area of the city around Akaki area (AAWSSA, 1992).

By 1998, the water shortage was not yet alleviated and the government embarked on an emergency water supply development. This focused on the same area to the south of the city. This area, by then, had become an industrial zone, and further south of this location is the Aba Samuel Lake, which is one of the most polluted water bodies around the city.

The selection of the Akaki-Kaliti area south of the city as a source of groundwater appears to be a follow-up on an earlier study carried out in 1993. This study estimated a yield of 125,000 m^3 from this area, in which individual wells were expected to produce as much as 60 l/sec. The study had recommended drilling of mapping wells and modelling studies prior to any abstraction effort. This appears to have been overlooked as the work was directly floated to tender and actual drilling and abstraction began (Berhanu, 2002). Failure to heed the recommendations of this study has apparently resulted in abstraction related problems in this area. The Akaki groundwater area is relatively better studied, as relevant literature indicate.

In general, groundwater sources in and around the city are mainly cold water. On the other hand, some areas of the city, notably the central *Filwuha* areas have thermal springs. The existence of these hot springs is considered to be indicative of thermal waters under the city centre. According to an earlier study by AESL (1984), the extent of the hot groundwater has been estimated to cover the area of *Ghion* Hotel, Gandhi Hospital, *Filwoha* Hotel, and Hilton Hotel.

In terms of the yield of these hot springs, the free flow at the *Filwuha* hot springs is recorded to be 18 l/sec with a temperature at the well head of 78 ^{0}C (estimated deep temperature is considered to be about 150 ^{0}C (Berhanu, 2002)), with a pH range of 7.4-8.4 and high silica content in the order of 100 mg/L causing severe incrustation problems in pipes and distribution network (Zenaw, 1997).

In 2008 the Addis Ababa Water and Sewerage Authority admits that it is only meeting 50% of the demand and envisages digging 63 new boreholes to raise the current supply by 30% (The Daily Monitor, 2008), this is a significant increase from the 25% shortfall in 2005 (Tamiru *et al*., 2005) and 29% in 1997-98 (Girma, 2004). To meet the water supply needs of the city of Addis Ababa, the amount of water supply must therefore be increased from its current level to 360,000 m^3 per day in the next 5 years. To achieve this, the City Administration and the Water Supply and Sewerage Authority are also planning to construct new boreholes, to provide an additional 50, 000 m^3 a day (Capital, 2007).

Earlier, during the period 1995-97, AAWSA had embarked in the development of 13 wells and 8 springs, with an abstraction capacity of about 10,000 m^3/day (MoWR, 2001c). Again these wells are located in close proximity to the two sewage treatment plants of the city. This is a potential risk as Incidents of waste water polluting groundwater resource have been recorded (Tang *et al*., 2004).

Aside from the efforts of the city administration, many institutions, industries and Embassies were finding their own means of coping with the water shortage. By 1983, Tamiru (2005) records that groundwater resource utilization was widespread and that industrial, commercial and government institutions used boreholes on their properties. About 70% of the supply required by heavy industries was supplied from these institutions 'own' water wells.

Many industries, particularly those in the beverage industry, abstract significant amounts of groundwater for their own use. The Addis Ababa Apex bottling company could be cited as one example. It abstracts about 600 m^3 per day of groundwater to meet its water demands. Out of this about, 200 m^3 (or one third of the abstracted quantity) is utilized for cleaning purposes and is eventually discharged into a nearby stream). It is believed that the aquifer may be depleted in the next 10 years time (Engida, 2007).

3.8 Water Wells Inventory in Addis Ababa

In spite of the significant role groundwater sources are playing in meeting the demands of the city, the exact number of wells is not known. A number of inventories carried out previously have attempted to compile well data.

It appears that these inventories were carried out, more for the purpose of documentation rather than for groundwater resource management purposes. An inventory in the 1970s records a total of 175 deep wells, some in use and others abandoned, with the oldest one on record, drilled near the old airport in 1937 (BCEOM, 1970). The inventory indicated that, of the 146 wells located within Addis Ababa the average yield for 87 of them was 2.6 liters per second. On the other hand of the 29 wells located in the Akaki-Kaliti area, 24 of them had an average yield of 3.5 liters per second.

A study by AESL (1984) cites an inventory that recorded the existence of 572 hand dug wells and 93 springs in the city, including 175 deep wells. Although groundwater did contribute significantly to the water demands of the city, the study concluded that it was not managed appropriately. It was reported that limited local geological information existed and that borehole log correlation with geologic features was questionable.

Vernier *et al* (1985) also cite an inventory where approximately 600 dug wells and more than 100 springs were identified, of which most were in use. More than 150 wells were drilled since the 1940s. A study by AAWSSA and SEURECA cited by Berhanu (2002) records a total of 275 wells in the city with a recommendation for drilling 146 new boreholes.

A 2004 inventory by AG Consult records at least 1200 boreholes, within 200 kms of the environs of the city. Inventories are still ongoing and a 2005 inventory has revealed that there were at least, 1037 water points in and around Addis Ababa. Of these 925 were boreholes with variable depth, 34 of shallow depth and 78 springs. Of the total number of only 22% have borehole log information. Eighty four percent of these water points were used for domestic water supply while 14% were used for industrial purposes (WWD&SE, 2007).

3.8.1 Akaki Well Field

The Akaki well field covering about 16 km^2 is located 22 km south west of the centre of the city of Addis Ababa. This area has long been considered a major aquifer with a potential of supplying the growing water supply demands of the city. Basalts, rhyolites, trachytes, scoria, trachybasalts, ignimbrites and tuff of varying ages form the main lithologies of the area. It is also overlain by fluvial and residual soils of varying depth (Molla *et al*, 2007).

A number of deep wells have been drilled in this area with the intention of tapping the aquifer. At present there are about 35 wells with 25 of them considered as production wells supplying the city of Addis Ababa. Four of the wells supply the nearby Akaki town, the other four are used for monitoring purposes, while one well is used for isotope sampling and one as a deep test borehole (BCEOM, SEURECA, & Tropics, 2003). Yirga (2004), reports 29 of these boreholes continue to supply water, as much as 25% of the city’s needs (Seifu *et al*, 2008)

The Akaki well field was initially assumed to be a high yield aquifer with a potential supply in the order of 125 000 m^3 /day. This was however later found to be unsustainable, resulting in a re-assessment of the yield of these aquifers. Pumping tests have further shown that the sustainable yield was in the range of 30,000 m^3/day only. It is estimated that if this abstraction rate is maintained, it will result in a drawdown of one meter per year, resulting in depletion of the aquifer in 20 years time. In spite of this, it has been proposed to increase the extraction quantity up to 35 000 m^3/day for a period of 14 to 15 years in order to meet the demands of the city as well as the nearby town of Akaki (BCEOM, SEURECA, & Tropics, 2003).

This partly seems to have been based on initial assumptions by previous studies of high yield in the aquifer in the Akaki-Kaliti and other sites (AESL, 1984). Although this prediction has not been holding, abstraction is still continuing. Lack of detailed knowledge of the hydrogeology of the catchment area appears to have contributed to the overrating of aquifer capacity (Molla *et al*, 2007).

This is not, however, an isolated problem. Similar problems have been encountered in other Federal Regions of Ethiopia. In Tigray Region in the north of the country, around the urban centre Mekelle, 12 wells were developed in 1998 to supply the city's water demand. It was estimated that these wells would produce a safe yield in the range of 220 l/s. However, they produced about 32% of the estimated safe yield (Gebregiorgis, 2004); (Mesfin & Enginda, 2004). As in the case of the Akaki well field, this difficulty regarding the accurate assessment of safe yield appears to have been caused, partly by lack of accurate hydrogeology data.

3.8.2 Fanta Well Field

The Fanta well field was identified and first developed in 1935. Three boreholes were drilled in 1991-92, but were not utilized as a result of better yield obtained around the Akaki area. Work commenced again in 2003. New wells are now supplying a yield of 6220 m^3/day. A geologically poor transmissivity zone has been observed between the Fanta wells location and the Akaki well field with a 110 meter drop in groundwater elevation over a distance of 5 km (BCEOM, SEURECA, & Tropics, 2003).

3.8.3 Wells in the Central and South-Western Areas of the City

A number of deep wells located within the central and peripheral areas continue to contribute towards meeting the city's water supply demands. Boreholes around *Lideta*, *Mekanissa, Lafto*, *Ayertena* are some of them. A number of deep wells around the city centre of *Lideta*, have however been abandoned apparently due to high nitrate content. The reason for the increased level of nitrate has not been investigated. In addition to this, boreholes in newer settlement areas such as *Kara, Kotebe* and *CMC* areas are connected into the water supply network without the water being treated. This was also one of the recommendations of water resources reconnaissance carried out in the 1980s (AESL, 1984). This recommendation appears to have been taken without due consideration of possible groundwater contamination by human or other waste.

Current observations confirm the risk of connecting groundwater without due treatment. Residents of Kara area, north east of Addis Ababa have reported to the Water Resources Authority that water from the newly drilled connected to the supply network 'tasted oily and had a darkening effect on tea and coffee' prepared from such sources. No action was however reported to have been taken to remedy this complaint (Dawit, 2008). In spite of high nitrate content in wells or reports of unsuitability for consumption purposes being encountered in the city, the practice of connecting untreated well water to the main supply network is still continuing (FMoWR, 2001c).

This is perhaps due to the pervasive belief that groundwater may generally be considered to be of good quality, bacteriologically as well as chemically. This appears to be the main reason behind the drive on abstraction of groundwater resource for consumption purposes in many urban areas around the country. Treated in isolation, this will pose a water quality threat. Drilling wells near urban centres will naturally result in lower distribution costs.

However, the groundwater on the other hand may have been exposed to contamination. This practice is argued to be justified in terms of minimizing costs and distribution problems. It has been observed that this is a common practice in both government funded drilled boreholes as well as privately owned wells.

Given this situation, it is likely that the population of the city is at risk. Hence it will be necessary to re-examine this long standing belief in light of the current water quality problems prevalent in many of the city's wells. This is particularly urgent in light of the absence of sewerage services.

3.9 Addis Ababa Sanitation Service Coverage

Data on the sanitation service coverage in the city of Addis Ababa is scant. Paucity of data in relation to water and sanitation has also been reported to be a major constraint in previous studies (Girma, 2004), (Teka, 1991), (BCEOM, 1970). What can be gleaned from observations and scattered studies, is that the main form of human waste disposal facility in Addis Ababa is the pit latrine. Sewerage systems serve only an insignificant percentage of the city's population. The exact number and spatial distribution of pit latrines in the city nevertheless remains unknown.

3.9.1 Sanitation Coverage

Poor sanitation service has been one of the major problems in Addis Ababa. The first attempt to address this problem appears to have been undertaken in the 1920s when the sanitation inspection section was established under the municipal police. A notice of cleanliness and health was also issued in 1927, and in 1928 the *Yetsidat Zebegna* or sanitation guards were set up to ensure environmental sanitation when residents started cleaning dirt and burying it. Public latrines were also instituted in the same year (Assen, 1987). Although there was an increased awareness and massive expenditure on the construction of buildings during the Italian occupation of 1935-1940, little attention was given to sanitation (Pankhurst, 1987).

The firsts recorded sewage disposal system for the city of Addis Ababa (combined for storm and domestic waste) is also reported to be the one constructed by the Italians in the 1930s (BCEOM, 1970). Since then provision of sewerage services has only attracted a cursory attention with the first suggestion proposed in 1959 (Girma, 2004). A study by BCEOM (1970) also proposed increasing sewerage service coverage up to 10% of the city's population and cites it as the most economical solution. This was later abandoned in lieu of addressing the more pressing water shortage, and hence recourse to low cost sanitation.

Nationwide the main focus is now the construction of pit latrines. The Federal Government's Plan for Accelerated and Sustained Development To end Poverty (PASDEP) (MoFED, 2005, 2006) promotes and supports the use of pit latrines, with the aim of providing safe sanitation. This, it is envisaged, will raise coverage from the current level of 50% to 89.4% of the urban population (MoH, 2006) , of which Addis Ababa is the major focus.

In contrast, only 0.6% of the population of Addis Ababa use flush toilets connected to a sewer system. The sewerage system was commissioned in 1981 and serves about 200,000 people. It also serves 25,000 *pe* (people equivalent) of non–domestic institutions. At present only a portion of the sewage collected by this system is believed to reach the treatment plant. The balance is considered to be leaking into water courses due to maintenance problems such as pumping failures and blocked pipes (DHV, 2003). Sewerage service in Addis Ababa may therefore be considered to be very low.

It is clear that the pit latrine is the main human waste disposal system in Addis Ababa. Unfortunately, the number of pit latrines and their spatial distribution is not accurately known. A 1993 study suggests that there were 175,000 'septic tanks' (pit latrines) in the city whose population was at that time estimated to be 1,459,000 (Tesfaye, Zereu, & Abdella, 2002). But considering the area and population of the city, this figure appears to be rather low. If one considers an average family size of 6 accessing one pit latrine, and taking into consideration that only 70,000 people were considered to have no access to any form of sanitation, the figure would be in the range of over 240,000 pit latrines. This suggests that the above figure may have been underestimated.

The 1994 national census also records that of all the 374,742 urban housing units in the city, 168,732 used shared pit latrines and 67,895 housing units had a private pit latrine. In contrast, 89,508 units had no toilet; whereas 30,113 and 14,815 units had private and shared flush toilets respectively. 3,679 housing units were classified as 'not stated' (CSA, 1999). Of these housing units, 338,640 units had no bathing facility and only 14,746 and 14,612 units had a private bath tub and private shower, respectively.

A study in 2003 also cites that of the total housing units 74.1% have toilets with private and communal facilities. The rest (24.9%) do not have any facilities and use open fields to defecate. This, it is estimated, pollutes the environment at a rate of 200 tones of fresh faecal matter and 600 tonnes of fresh urine per day (BCEOM, SEURECA, & Tropics, 2003).

The 2004 Welfare Monitoring Survey found that the highest number of household pit latrine usage was 74.3%, at Addis Ababa, with the next urban centre (the city of Dire-Dawa) at 64.5% (CSA, 2005). With this high percentage of pit latrine utilization and housing congestion, the attendant sanitation problems may be expected to be serious. About 75% of the city's existing housing is considered to be congested (NUPI & Groupe Huit, 1988). Girma (2004) also reports that on average 34 people share the same pit latrine, with 50-60% of households in the densely populated areas using shared pit latrines. In contrast there are only 72 public latrines serving the population, with 25% of them non functional at any one time due to maintenance problems. These are mainly used by men as there are no separate facilities for women. New housing constructions are also required to provide individual pit latrines, as a requirement for obtaining building permits. As a result of this, the *Ayat* real estate, has a target of constructing 25, 000 housing units each with their own pit latrines. It is therefore possible that this high usage, in combination with low levels of de-sluging services, may result in unhygienic situations, with overflowing latrines.

In a survey carried out on 140,250 government owned houses in 1988, it was reported that 42% of latrines were constantly overflowing. Of the total housing units, 93% had access to toilets with 84% shared and 7% privately used (NUPI & Groupe Huit, 1988). In 2007 a total of 3,197,496 m^3 of liquid waste from pit latrines is reported to have been collected and disposed of by vacuum trucks in the city of Addis Ababa (MoI, 2007). This waste is subsequently taken to the two treatment plants at the periphery of the city. These plants were initially designed for 50,000 people (BCEOM & Consult, 1992) and a sewage flow of 7,600 cubic meters (Tamiru *et al*, 2005). Observing the overflow of sewage from these plants it is noted that they are operating over capacity and may not be rendering adequate waste treatment.

Of the two treatment plants, the one located in the eastern side of the city is basically a drying bed, whilst the south-western side plant renders rudimentary treatment only and may not be as effective in reducing pollutant loads. Birhnau (2002) reports that 40% of liquid waste in the treatment plant is discharged into the Small Akaki River, and eventually into the Aba Samuel Lake. As the waste undergoes biological treatment only, it is very likely that a significant portion of the waste load may find its way into the lake.

With the large-scale use of pit latrines, it is likely that the spatial density in Addis Ababa will be high. This may result in groundwater contamination as has been shown in numerous researches studies. Wakida and Lerner (2005) cite of a study by Bicki and Brown (2003), in which density of septic tank systems was found to be the most important factor in groundwater contamination. A minimum lot size of 0.4 to 0.6 ha (4000-6000 m^2) was suggested as needed to insure against groundwater contamination. High density contamination becomes an enhanced risk in areas with permeable soils. Day (2004) observed that inadequate waste water treatment and the siting of septic tank locations in inappropriate soil, have increased the risk of contamination in Cannonsville watershed in New York. In addition as global sewage effluent is steadily increasing (Foster & Chilton, 2004), it follows that the high density of pit latrines may be considered as one of the major sources of contamination of groundwater in Addis Ababa.

3.9.2 Sources of Groundwater Contamination

Groundwater in urban areas may be contaminated by various agents including human waste. This becomes a major threat when sewerage services are inadequate and when low cost sanitation facilities proliferate. This is a typical scenario in Addis Ababa. Hence it can be argued that groundwater in Addis Ababa may be at high risk of contamination due to low cost sanitation.

3.9.3 Pit Latrines

The above discussions clearly indicate that a significant population of Addis Abba uses pit latrines. Observations have also shown that the many pit latrines are merely a pit in the ground. This does not provide any liquid retention and the waste percolates into the ground. The large number of pit latrines and their location, irrespective of soil and geologic structures, is likely to be a significant element in increasing groundwater contamination.

The major threats from the extensive spread of pit latrines include chemical as well as pathogens sourced from human waste. A 2007 nationwide assessment of water samples reported a 90% compliance with the national and WHO guideline values for Addis Ababa. This was not unexpected, as the tests appear to have been carried out at points of distribution or after treatment, and may not have fully gauged the extent of direct contamination of water samples (WHO/UNICEF, 2007). In terms of compliance with the standards for *faecal streptococci*, Addis Ababa showed a much lower compliance at 56.1%. This suggests a much higher contamination of water sources with human waste.

3.9.4 Domestic Waste

Some studies have suggested that the upper Awash basin is becoming increasingly polluted by sewage generated in the city of Addis Ababa (DHV, 2003). Tamiru (2005) indicates that, of the total water supplied to the city of Addis Ababa (163,000 m^3/d from surface and groundwater), about 70% returns as sewage, 60% of the returned flow has an outlet through Big Akaki river and the remaining 40% joins the Little Akaki river. Whether these figures have taken into account the leakage in the city's water supply system is not clear. These considerations may affect the suggested figures and the estimation of recharge capacities. Nevertheless the cited quantities are significant and may pose a serious threat to groundwater.

The recharge zone of the main borehole site located to the south west of the city consists predominantly of expansive soils (commonly called black cotton soil). These soils are considered to be impervious and will not readily absorb water. This, it is argued, inhibits water from penetrating to deeper aquifers (BCEOM, 1970). Based on this, Tamiru (2004) (2005) suggests that the areas to the south west of Addis Ababa fall within a low vulnerability category. This assumption is probably based on aquifer vulnerability assessment using the

DRASTIC approach. This method assumes that the soil cover provides adequate protection to the aquifer. However, some research papers, have suggested that the standard methods of assessing vulnerability to pollution of geographical areas, such as the DRASTIC method, may reflect reduced correspondence with the most vulnerable and the most contaminated areas (Stigter *et al*., 2006). Vulnerability assessment maps produced using DRASTIC method should therefore be used with caution (Chritoph *et al*, 2008).

An analysis of the Tritium content of groundwater has also suggested that shallow aquifers in central Addis Ababa were the most vulnerable, while deeper aquifers of the Akaki plain and some regions of the Entoto ridge (northern part of the city) were least vulnerable (WWD&SE, 2007). This indicates that the Akaki aquifer may not be vulnerable to contamination and thus the contaminant load on this aquifer is low.

However, the increased risk of contamination due to the interaction of the expansive clay soils in the vicinity with the nearby Aba Samuel Lake appears not to have been taken into account. The cyclic swelling and shrinking nature of the soil and the attendant deep cracks that form in the soil may contribute to an enhanced percolation of fluids into lower strata. Moreover, the nearby lake may contribute a steady flow of accumulated waste, which may find its way into the aquifer. The lake is covered with water hyacinths throughout the year, growth of which is favoured by higher concentrations of nitrate and phosphate ions in the river (Tesfaye, Zereu, & Abdella, 2002).

Given the situation, therefore, it is possible that nitrate loads on groundwater aquifers in the city may be high.

3.9.5 Solid Waste

Solid waste collection and disposal coverage is considered to be low in many urban areas in Ethiopia. In Addis Ababa, coverage is cited to have increased from 38% in 1993, to 40% in 1994, 53% in 1995 and 53.9% in 1996. This is a significant increase compared to 21.6% collection in 1986 (Yami, 1999).

In a survey carried out in selected 15 towns in the country, it was observed that 86.6% used open dump sites to dispose of solid waste. In 2002 it was recorded that, of the total solid waste generated, only 60% was collected and disposed of at the dumping site. The remaining is abandoned in open spaces, drainage channels, rivers and valleys as well as on the streets (AACG, 2002). Dumping solid waste into nearby streams and drainage ditches is a common practice in many parts of the city (Girmay, 1990).

A study by Tamiru and Vernier (2000) indicated that the daily volume of solid waste generated in Addis Ababa was about 15 kg per person. It was estimated that this would amount to 450 tonnes if the population of the city was considered to be about 3 million. Of this generated waste, only 55% was collected with the remaining 45% uncollected.

In 2003, it was estimated that the city of Addis Ababa generates about 520 tonnes or 1440 m^3 of solid waste daily. Of this amount 1152 m^3 or 80% of that generated is accessed out of which only 65% is normally collected and disposed of in a land fill located 12 kms to the southwest of the city centre. Nearly 90% of the generated waste is organic in nature with the rest recyclable matter such as plastics, glass rubber and other materials (BCEOM, SEURECA, & Tropics, 2003).

Solid waste collection/disposal in the city of Addis Ababa is managed by municipal dirt trucks which dump the collected waste at the refuse site south west of the city. Over the last few years the number of solid waste collection trucks has shown a steady increase. In 1999 the number of trucks stood at 60, half of which were inoperative due to old age (Yami, 1999). Tadesse (2004) reports that in 2004 the number of trucks had risen to 72, out of which only 35-40 work daily, the rest inoperative due to old age. In 2008 the collection capacity increased to a total of 800 m^3 /day through the purchase of additional 20 trucks out of which 17 are operational (The Reporter, September 21 2008).

At present solid waste collection has taken a new direction. The introduction of private solid waste collection services has significantly enhanced service coverage. In 2004 Tadesse (2004) estimates that 74 Micro and Small enterprises were engaged in the collection of household waste. This is encouraging as an alternative means of widening service coverage in the city.

While service coverage is likely to improve with the introduction of private collection services, lack of alternative waste tip sites may restrain development. The city has only one dump site which has been in use for the last 40 years. Although there has been some suggestion of moving it further out of the city, it is still functional, albeit in an environmentally unsuitable manner. Observations at the site have shown that smoke from this site tends to cover nearby large residential areas. For decades this has been reported to be a constant nuisance for the residents of the vicinity.

Although standard procedures in the management of sanitary fills recommend covering the refuse with fresh soil before laying the second layer, the practice in the city has been to merely pile the waste. The decomposition of the waste and the ensuing generation of gases appear to be fuelling the continuous fire and smoke. Besides generating an almost perpetual smoke, it has also made access difficult to a point where the sanitary trucks have difficulty discharging waste at the site. In addition to this, during periods of heavy rain, the fill site has been observed to flood the surrounding areas.

Other alternative solid waste management techniques such as decomposing and recycling have not been considered (Yami, 1999). Regardless of this potential threat, a number of deep wells have been drilled in the area with a significant housing and industrial development work nearby.

3.9.6 Industrial Waste

Some researchers have shown that industrial contamination of water resources has occurred in some parts of Ethiopia. The upper Awash basin is now considered to be progressively becoming polluted. This it is reported to be caused by chemicals discharged from the Awash tannery and the Fincahaa sugar processing factory (EVDSA, 1990).

Zinabu, and Zerihun (2002) have also observed that the toxic effluents such as selenium and arsenic from a textile factory in the town of Awassa, 275 km south of Addis Ababa, have been discharged into Lake Awassa, a fresh water lake, resulting in eutrophication of the lake, and toxicity to biotic life.

As a major economic centre, the city of Addis Ababa is now home to 65% of all the industries in the country (Tamiru *et al*., 2005). A 2003 inventory records 85 ‘main’ industries located in Addis Ababa (BCEOM, SEURECA, & Tropics, 2003). It is also reported in this study that 96% of the industries discharge waste without treatment into these rivers, (WWD&SE, 2007), (BCEOM, SEURECA, & Tropics, 2003), (Zewde, 1990) (EVDSA, 1990).

Zewde (1994) found that in the 1970s Aba Samuel Lake, located in the southern periphery of the city had been affected by 26 industrial discharges, and that in 1976 the phosphate and nitrogen added to the reservoir has been estimated to be 175 kg/d, although the water was being utilized by 20,000 cattle and 10,000 people on both sides of the river

Zewde also estimates the effluent discharge as follows;

Table 3.3. Industrial Effluent discharge into Aba Samuel Reservoir (Zewde, 1994)

River	% of Addis Ababa Industrial Waste	Flow rate of waste L/sec	BOD kg/day
Little Akaki	80	75-100	4,665
Great Akaki	20	45-70	1,000

A 1990 study by the then Ethiopian Valleys Development Authority (EVDA) also cites of the heavy pollution in the little and great Akaki Rivers in the city of Addis Ababa. These rivers were considered to be so polluted that they were becoming unsuitable for drinking, irrigation, and amenity use without expensive pre-treatment (EVDSA, 1990).

Direct liquid discharge from industrial and other institutions has also been observed by Tamiru and Vernier (2000). In a 2002 study the Addis Ababa city government Environmental Protection Bureau has recorded that 31 industries discharge untreated waste into the Little Akaki River. The chemicals discharged included, heavy metals, which has surpassed the natural assimilation capacity of the river within the city limits making the river highly polluted (Tesfaye, Zereu, & Abdella, 2002).

Another study cites at least 53 industries located in Addis Ababa discharge effluents including sulphides, chromium, organic compounds, ammonia, phenol, carbon monoxide and even cyanide. These chemicals are believed to find their way into the groundwater resource nearby. It is also recorded that the Akaki spare parts factory discharges its effluents directly into the soil overlaying the Akaki well field (BCEOM, SEURECA, & Tropics, 2003).

Industries located on the edges of the Akaki 'rivers', including the Mekanissa Liquor Factory, the Akaki Textile mills and the steel mills around Kaliti routinely discharge untreated effluents into the water courses. Although anecdotal evidence suggests that some industries may have treatment facilities, it is doubtful whether the treatments are effective enough to reduce pollutant concentration. A study by Mohammed (2002) records that nitrate levels as high as 375 mg/L has been discharged into the river from individual tannery industries alone.

The Addis Ababa Abattoir is also a source of waste. Piles of decomposing bones, accumulated for many years can still be seen at the compounds of the abattoir. Waste water, with an effluent BOD of 6100, is discharged into the nearby stream, which eventually discharges into the Akaki river catchment area. The abattoir and wine distillery are considered to have significantly affected the rivers, as measured in the BOD levels upstream and downstream of the factories (Kebede & Tadesse, 1990).

Although the city administration cites the inappropriate location of tanneries and textile factories as causing ground and surface water pollution, posing serious health problems to the population (AACG, 2002), no action appears to have been taken to mitigate this. New industrial plot allocation for instance appears to have not taken this into consideration. New tanneries and other industries are allowed to be erected near streams, where untreated waste is discharged into streams.

In addition to industrial activities, a latent contamination threat in the city may be attributed to the numerous fuel stations. Accidental fuel and gas leaks may become a source of pollution (Abrams & Keith, December 2000).with a considerable effect on soil and groundwater. The city authorities consider leaking underground fuel tanks as one threat in groundwater contamination (AACG, 2002).

There are now about 7 fuel companies operating in the supply of vehicle fuel and oils in Addis Ababa. Numerous fuel stations and vehicle repair garages are also located within the city. One of these companies, The National Oil Company (NOC), for instance, has established more than 22 stations in the city all of them equipped with car washing facilities. Water and oil effluents from vehicle washing activities are separated in a concrete tank, with the water discharged into municipal sewage lines whenever available nearby, or into open drains. The used oil is in turn separated and sold to private vendors for various uses (Dereje, 2008).

A 2008 investigation at an abandoned fuel station near the Bole airport revealed that the Total Petroleum Hydrocarbons (TPH) concentration in the perched aquifer groundwater was as high as 3800 µg/kg whereas the WHO recommended limit was only 90 µg/kg. The Mono-aromatic Hydrocarbon concentration was found to be 2900 µg/kg whereas the WHO recommends limit was 300 µg/kg. The Polycyclic Aromatic Hydrocarbon (PAH) level was found to be 760 µg/l whereas the WHO recommended limit was only 3 µg/l (Musili, 2008). The investigation has confirmed that the soil and groundwater in the vicinity is 'already contaminated'. It is possible therefore that the numerous fuel stations and garages located in and around the city may have contributed to groundwater contamination and quality degradation.

3.9.7 Agricultural Fertilizers and Pesticides

Fertilizer use increases the level of nitrates in the groundwater (Sial *et al*, 2000), (Zaporozec *et al.*, 2002), (Almasri *et al.*, 2003), (Kellman *et a.l*, 2003), (McQuillan, 2004), (McMahon *et al.*, 2008).

A study in the US records a similar increasing trend beginning in the 1960s (Tesoriero *et al*, 2007). Kazemi (2004) reports above average concentrations of nitrate in Shahrood in Iran, which 'may reflect the impact of the excessive use of fertilizers'. Nitrate from nitrogen fertilizers use has been indicated as one of the anthropogenic sources of contamination and decrease in groundwater quality in Jericho area in Palestine (Khayat *et.al*., 2006). It is reported in this study that the nitrate levels were higher in agricultural or animal farm areas or near septic tanks.

Numerous other studies have also observed similar occurrence in many parts of the world. As one source of nitrate in groundwater, fertilizers pose a contamination threat to groundwater resource (Canter, 1997), (Abbi, 2000). Almasri *et al.* (2003) report that 87% of total on ground nitrogen loading on a study area was contributed by inorganic fertilizers.

According to the Central Statistical Agency (CSA), the application of fertilizer In Ethiopia is 'gathering momentum'. in 2007, the volume of fertilizer applied to areas under crops is estimated to be more than 4 million quintals. The extent of area to which fertilizer was applied is also estimated to be 5.3 million hectares. In contrast the area applied with pesticide has increased to about 1.7 million hectares 2007 (CSA, 2006). In 2006, the national average for the percentage of cereal crop area fertilized with inorganic fertilizer during the main *Mehere* crop season has been recorded to be 32% (IFPRI & CSA, 2006).

Extensive application of fertilizers is likely to have an impact on deterioration of groundwater quality. Tenalem (2004) cites a study by Teshome Dechassa of the introduction of fertilizers and other agricultural activities as increasing the level of nitrates in groundwater in the city of Wonji, central Ethiopia (WWD&SE, 2007).

As cities expand to annex previously farmed land, or locate groundwater abstraction wells, in the middle of farms, such as the main water supply wells in Addis Ababa, the contamination potential may be heightened. The areas around the Akaki well field a comparatively sparsely populated area and used as farming land, extensive fertilizer utilization has been reported. It is therefore possible that chemicals from the fertilizers used may have found their way into the groundwater. In 2003, of the total land farmed in this vicinity, 78% has been fertilized, which is considered to be high compared with the national average of 28%. The fertilizers consisted of Diammonium phosphate (P_2O_5 46% and N-18%) being used at 96 kg/ha and Urea (N-46%) used at 80 kg/ha (BCEOM, SEURECA, & Tropics, 2003). It also observed that areas along the edges of the Akaki Rivers further up stream of the well fields are used as vegetable farming plots. These farms use the river's polluted waste water.

Urban farming in the city is considered to supply a significant part of the vegetable demand of the city. It is estimated that about 160 hectares of land in Addis Ababa are irrigated to grow crops year round (Girma, 2004). This appears to be a slight increase from 158.6 Ha of land cultivated for horticulture purposes in 2002. It is reported that about 269 farmers were involved in this activity (Tesfaye, Zereu, & Abdella, 2002).

As part of agricultural activity, domestic animal waste localized mainly to the periphery of the city area has also been cited to be one source of contamination. Wakida and Lerner (2005) cite a study by Bonnet and Duteurtre of the presence of about 23,000 dairy cows in the urban and peri-urban areas of Addis Ababa. They suggest that animal waste can be a significant source of nitrate in urban groundwater in cities in developing countries but not in developed countries.

Another potential threat could also be the numerous flower farms that are springing around the city. Nitrate levels as high as 368 mg/L were observed in waste water draining from some of the flower farms outside Addis Ababa (Tilahun, 2008).

3.9.8 Over-abstraction of Groundwater

Over-abstraction may cause steep cone of depression in water wells favouring a higher flow velocity that enhances bacterial travel to wells from surrounding clayey soils (Drangert & Cronin, 2004). Over-abstraction may also contribute to deterioration of quality such as an increase in Total Dissolved Solids (TDS), bacterial and chemical contamination. (Abderrahman *et al*., 1995). Cronin *et al*. (2003) also suggests similar mechanism may have enhanced contaminant penetration in an urban sandstone aquifer in Nottingham in the UK.

Coupled with the high number of pit latrines in the city, excessive withdrawal of groundwater may be a serious concern in Addis Ababa. It is therefore possible that because of over-abstraction, waste generated in the city may have found its way into deeper aquifers.

3.10 Contaminant Chemicals in Pit Latrine

Groundwater may be contaminated by manmade (anthropogenic) activities. Anthropogenic activities consist of the activities of agriculture, animal husbandry, industries and on site sanitation. In urban areas, where sewerage service is low or is not available, on-site sanitation may cause significant contamination of groundwater. Identifying trace elements found in groundwater which may be sourced from human waste, may therefore be used as indicators of contamination.

In order to get a meaningful assessment, the tracing elements have to be soluble in water (and hence easily transported to water bodies), and remain unchanged for a considerable period of time. These chemicals also ought not to be adversely affected by the soil. Considering these factors, nitrates and chlorides are two of the chemicals found in human waste that could be good contamination indicators.

Nitrate has been associated with groundwater pollution by septic tank systems (Scalf & Dunlap, 1977). Chloride has also been utilized as a tracer of anthropogenic pollution (Canter & Knox, 1991). Due to its anionic nature and mobility in water, and the ineffectiveness of septic tank systems to remove it, chloride can, in conjunction with nitrates, be a useful indicator of groundwater contamination.

Nitrate can be derived from various sources, and exist in seven oxidation states, which are environmentally of interest (Sawyer *et al*, 2006). These are, NH_3, N_2, N_2O, NO, N_2O_3, NO_2 and N_2O_5. Of these, three forms combine with water to form inorganic ionized species that can reach high concentrations.

$$NH_3 + H_20 \longrightarrow NH^+_4 + OH^-$$

$$N_2O_3 + H_20 \longrightarrow 2H^+ + 2NO^-_2$$

$$N_2O_5 + H_20 \longrightarrow 2H^+ + 2NO^-_3$$

The water soluble elements formed, ammonium, nitrite, and nitrate are the main elements of concern in environmental engineering. Excess nitrate either from agricultural or human waste sources if unutilized is leached to the groundwater causing health concerns. Ammonia and Nitrites are decomposed in the soil and change to nitrate which is soluble in water and can therefore be used as a tracing element (Sawyer *et al*, 2006). Nitrates may also occur naturally in groundwater but seldom exceeding a concentration of 2 mg/L as N. Excessive concentrations may then indicate sources of past or present pollution. Septic systems are considered to be one of the sources nitrate in groundwater contamination (McQuillan, 2004), (Todd, 1995:Hounslow, 1995), (Power & Schepers, 1989).

Additionally, chlorides may be sourced from sewage, connate water and intruded seawater (Todd, 1995; Hounslow, 1995). The correlation of nitrate with chloride in groundwater with that of Dissolved Organic Carbon (DOC) may therefore suggest contamination with wastewater (Foster, 1990). Because chloride is present in all sewage and is not subject to adsorption, ion exchange or oxidation reduction ‘redox’ reactions and it increases linearly with an increase in nitrate, it can be used as a good indicator parameter of sewage impact on groundwater (McQuillan, 2004) (Canter & Knox, 1991). Tamiru *et al.*, (2005) suggest chloride levels in unpolluted water is less than 10 mg/L and may often be less than 1 mg/L.

Nitrates and chlorides are therefore valuable trace elements in the identification of contamination by human waste. As both chemicals are soluble in water and do not easily break down, both may be used as an indicators of contamination. Nitrates have been known to have penetrated hundreds of feet into aquifers as most soils do not affect chlorides and nitrates.

The presence of nitrate in groundwater due to contamination by human waste has been reported in various literature. Tredoux *et al.* (2006), reports high levels of nitrate due to pollution by anthropogenic activities with excess sludge application and inappropriate on-site sanitation considered as the main culprits in South African groundwater. Foster (1990) cites Nitrogen compounds (nitrate or ammonium) as impacting groundwater resource as a result of un-sewered sanitation in Latin America. In West Africa wells located in highly populated areas, with poor waste disposal facilities have shown high level of nitrate, an indicator of pollution due to anthropogenic causes (Langenegger, 1994).

McQuillan (2004). reports of septic systems polluting groundwater in numerous areas of New Mexico with nitrate concentrations exceeding the allowable limits Almasri reports nitrate as being the most common pollutant found in shallow aquifers due to both point and non point sources in the United States, with septic tank contribution being of significant local effect (Almasri *et al*, 2003).

Widespread use of individual waste disposal systems such as cesspools and septic tanks have been reported to be 'largely responsible for the increase of nitrates in groundwater' on Long Island in the United States (Kimmel, 1984). Sadek and El Samie (2001)also report a high nitrate content in the city of Cairo as possibly due to, among other sources, that of septic tank effluents. Nitrate and phosphate are considered to be the main inorganic pollutants indicated in groundwater pollution due to effluents from septic tank (Harman *et al*., 1996).

It may therefore be possible that, contamination of groundwater by chemicals sourced from human waste may have occurred in Addis Ababa. At least 74% of the population of Addis Ababa use pit latrines (CSA, 2005), and this may have increased the level of nitrates and chlorides in the groundwater.

Studies by Yirga (2008), Molla, (2007), WWD&SE (2007), and Birhanu (2002) have suggested the possibility of anthropogenic pollution in the central areas of Addis Ababa. Tamiru *et al*. (2005) suggest abundant chloride level in groundwater as indicators of sewage contamination of water resources. A study done on water quality on boreholes, in the second largest urban centre in Ethiopia the city of Dire-Dawa, has also identified a strong correlation between the level of nitrate and chloride leading to the conclusion that the source of the pollution may be of sewage origin (WWD&SE, 2004).

On the other hand Berhanu (2002) notes that '...the level of chloride in the Addis Ababa waters was found to be low with no exception'. While this appears to be at variance with observations by others, it nonetheless merits close examination. The level of chlorides may be 'low', but what would be of interest is whether this chemical is increasing temporally.

This temporal increase may then serve as a latent indicator of increasing contamination. Therefore, identifying the presence of nitrate and chloride may be considered suitable as an indicator of groundwater contamination by human waste.

3.11 Groundwater Quality in Addis Ababa

Groundwater quality refers to its physical chemical and bacteriological characteristics measured and compared with standards fit for human consumption or particular use. Melian *et al*. (1999) consider most groundwater quality to be of good quality, until contaminated by human activity. This is especially of concern in urban areas, where it can be exposed to contamination from anthropogenic sources.

A comprehensive assessment of groundwater quality appears to have not been carried out in Addis Ababa. Data reviewed indicates a rather infrequent assessment of general quality, with no specific contamination extent evaluation. A 1970 census of wells carried out in Addis Ababa, while confirming the general good quality of groundwater in the city, indicated that high nitrate concentration have been observed on at least 5 wells (BCEOM, 1970). The contaminants were considered to have originated from leaking drains, sewers or polluted springs.

Another investigation carried out in 1975 on a dairy plant borehole in the city revealed high Boron content, in the order of 21.6 mg/L. The origins of this chemical was believed to have been from the detergents used in the plant. The mechanism of how the contaminant entered the ground and finally reaching the aquifer is not however known (Ecceleston, 1975). Low Boron concentration is a characteristic of the Addis Ababa waters (Berhanu, 2002) and hence this observation may suggest contamination.

A subsequent inventory carried out in the 1980s has observed that all wells were unsuitable for domestic usage due to high level of nitrate (AESL, 1984). Another assessment showing 'abnormal' concentrations of nitrate, sulphate and chloride in shallow groundwater in the city has been attributed to sewage contamination (Kebede & Tadesse, 1990). Yirga (2004) suggests that particular areas of the city have been subject to high degree of contamination, as indicated in the elevated concentration of nitrates in the springs, as well as high concentrations of nitrate and chloride in boreholes in the city.

As a study by Adane and cited by WWD& SE (2007). reports, ‘the spatial distribution of the boreholes, dug wells and springs which are considered to be polluted are concentrated in Addis Ababa town’. Yirga (2008), has also suggested that the high level of nitrate observed around the central western sides of the city (Army officer’s club borehole) could possibly be linked to a very high level of urban pollution from areas upstream of this location notably around Merkato. The explanation is linked with the geological fault lines believed to exist north-south of this location. This may have enhanced subsurface flow, hence aggravating contamination. High groundwater contamination in highly populated areas has also been observed in the city, possibly due to pit latrines (WWD&SE, 2007).

Mauro (2004) records that nitrate levels as high as 10 mg/L have been observed around the city centre. Sastri *et al*. (2004) also report of nitrate levels in boreholes in the city of Addis Ababa in the range of 0.72-35 mg/L, while springs showed levels in the range of 2.7-728.1 mg/L. Compared to the other two major urban centres included in the study by Sastri *et al*. (2004), Addis Ababa appears to show higher levels of contamination.

Tenalem (2005) has also observed that major urban centres including Addis Ababa have shown signs of anthropogenic pollution with high nitrate levels observed. This may have perhaps been the cause of a relatively elevated nitrate content observed in the Akaki wells. Nitrate levels in the order of 0.03-19 mg/L have been observed in the Akaki area boreholes (Sintayehu, 2007). In another study 17% of water samples analyzed had nitrate levels higher than the WHO recommended maximum limit of 50 mg/L with a maximum of 241 mg/L (Berhanu, 2002). Hence the potential impact on health may be considerable.

3.12 Sanitation and Health

The Ministry of health report that up to 60% of the current disease burden in Ethiopia is attributable to poor sanitation. Some 250,000 children die each year (FMoH, 2005) and 15% of total deaths among the population of children under five is attributed to diarrhoea. Unsanitary conditions in smaller urban areas have also been cited as being the cause of infections in both children and adults (Abera *et al.*, 2006), (Girum, 2005).

Human excreta is also considered to be the source of over 30 different common diseases in Ethiopia (Teka, 1993). Tadesse and Beyene (2009), report of *A. lumbricoides* and *T. trichiura* infections as being prevalent in urban areas including Addis Ababa, which have been attributed to high population density and poor sanitary conditions. This finding is quoted to be consistent with earlier studies cited in the same study.

Another study by (Worku and Solomon, 2007) in Jimma town also suggested the prevalence of *Ascaris lumbricoides* ova as an indicator of poor sanitation and hygiene. This was attributed to irregularities in water supply where residents were forced to use alternative sources which exposed them to infections. A separate study by Amare *et al.* (2007) also confirmed the high prevalence of intestinal parasitosis and attributed it to poor personal and environmental sanitation. Poor sanitation practices have also been cited as being a serious health risk in Mekelle town, another urban centre in the north of Ethiopia (Kinfe and Abera, 2007). Pathogenic organisms including bacteria, viruses and parasites may therefore pose health threats, as a result of contamination of water resources by human waste.

The detection of pathogens in water samples in the city is carried out by checking for the presence of E. coli bacteria. Standard tests in Addis Ababa mainly check for total coliform count and the count for E coli. Water quality data reviewed shows that there is a relatively infrequent assessment of E. coli in water samples. Of the data reviewed, a majority of coliform counts are correlated with springs. The high count could possibly be due to the proximity of the springs to the surface and hence vulnerability to contamination by human waste.

In the 1990s sanitation related health risks were reported to be rising (BCEOM and GKW Consult, 1992). An assessment of water supply and sanitation sector in the country also cites many of the health problems in Ethiopia as related to unsafe and inadequate water supply and unhygienic waste management including that of human excreta (DHV, 2003). This appears to be a long standing problem. Teka (1991) suggests 50% of the health problems in Ethiopia as being related to improper sanitation while, Mesfin (2003) suggest a figure of 80 %. Current estimates put 75% of all health problems in the country as ‘preventable communicable diseases and under nutrition’ (Abebe *et al*, 2008). Regardless of the difference in these figures, there appears to be a general consensus about the seriousness of sanitation related health problems in Ethiopia.

The Ethiopian Environmental Authority (EPA) also admits that ‘serious deficiencies in sanitation services and the inadequacy of sewerage infrastructure and random defecation in urban areas have created dangerous health and environmental problems’. The rivers and streams in urban areas are so polluted that they have become ‘main sources of infections resulting in diarrhoea and other diseases’ (EPA and MoEDC, 1997). The seriousness of this problem is also attributed to lack of awareness of water quality and its health related impact. This has been described as ‘very low’ (DHV, 2003).

The ubiquitous presence of nitrate may therefore pose a health threat. The World Health Organization classifies nitrate as one of the few chemicals that can cause large-scale health problems through exposure in drinking water (WHO, 2006). The global number of fatalities associated with nitrate pollution is likely to increase with the global trend of rise of nitrate in groundwater (Adelana, 2006).

Nitrate concentrations greater than 45 mg/L have been reported to cause methemoglobenemia in infants (Canter and Knox, 1991). Adelana (2006) citing a study by Spalding and Exner, reports that high nitrate content may also aggravate hypertension. Although data on the effect of nitrate on human health in Addis Ababa, has not been reported, it may be a significant health burden. This assumption would however, presuppose that nitrate detected in groundwater is sourced from human activity. Considering the geological features of Addis Ababa, it appears this may indeed be a significant possibility. For instance an investigation in the *Ada Becho* groundwater basin showed that nitrate concentration decreased with increasing well depth 'confirming that the main source of nitrate is not from the rock but from contamination from the surface of the earth'. Additional nitrate and chloride correlation graphs have also suggested contaminants were from on site sanitation systems (WWD and SE, 2007). It is possible therefore, inappropriately disposed human and agricultural waste, coupled with fertilizer application as well as improper waste disposal from industries and fuel stations may have contributed towards groundwater quality deterioration. This deterioration is likely to have a negative health impact.

4 Research Process, Data Collection and Methodology

4.1 The Research Process

The research process began with the development of a conceptual framework of the research questions. Once this was formulated, the research process was carried out in five stages (Fig. 4.1)

Stage 1 of the research work focused on defining the research questions, conceptual formulation, and objectives and charting out the methodology of the process. Stage 2 focused on a review of available literature related to the study. It encompassed reviewing records on water resources with a focus on groundwater particularly within the geographical area of the city of Addis Ababa. Available related research work, both national studies and from other countries were also reviewed. Discussions and interviews were also held with professionals actively engaged in water resources management. These people were helpful in the assessment of the gravity of the contamination threats, as well as in elucidating the extent of the problem.

In addition to the literature review Stage 2 of the work also focused on collection of records on water quality analysis on boreholes, shallow wells and springs in Addis Ababa. The collection included historical as well as recent data. This was obtained from the archives of various government and non governmental agencies, drilling companies, private sources, published and unpublished Masters and Doctoral research papers and publications. In order to obtain a fairly large geographical coverage, all water quality samples gathered were incorporated in the data compilation. Additional field work was also carried out to visually ascertain locations of some wells and obtain coordinates.

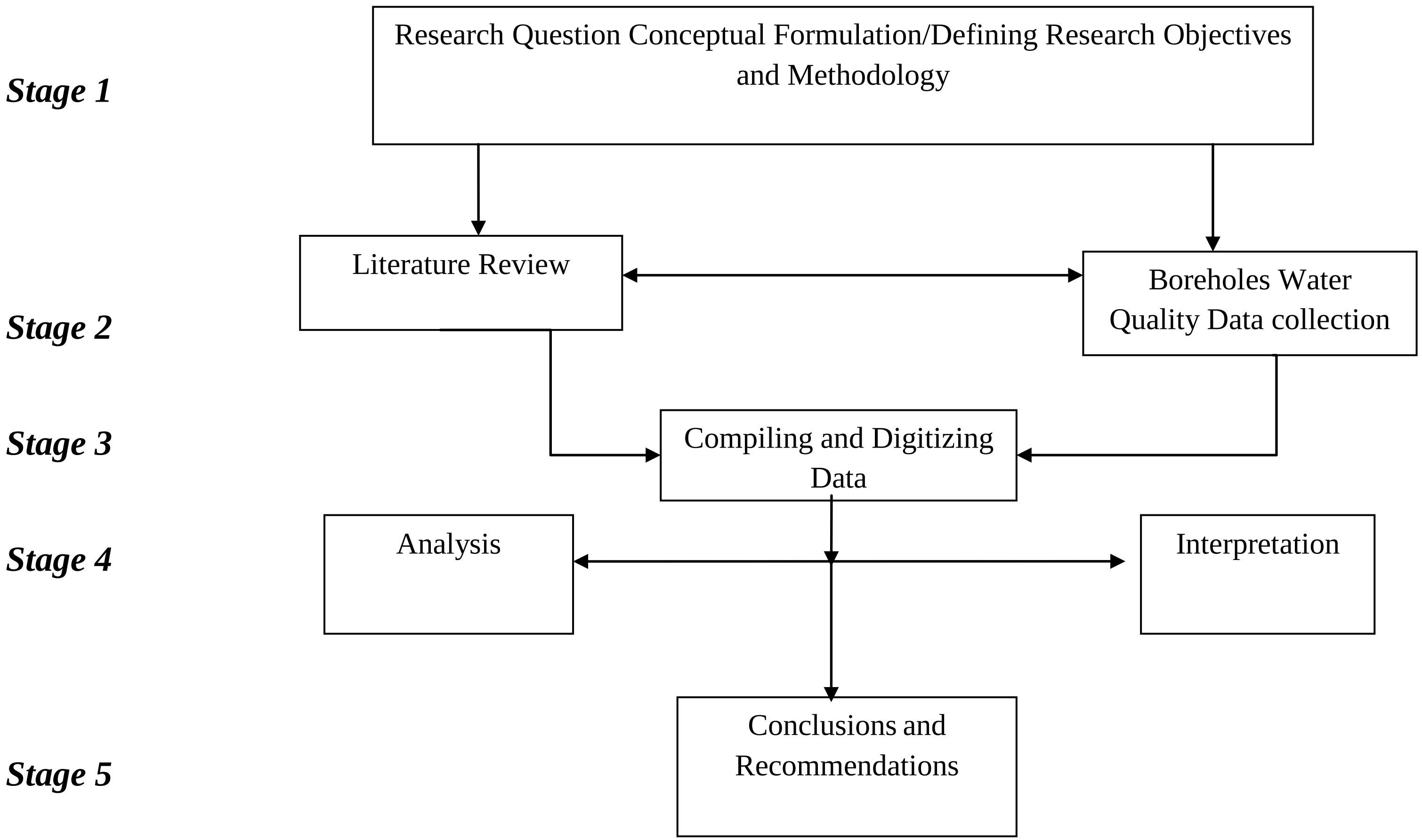


Fig. 4.1. The research Process

Stage 3 consisted of compiling and digitizing water quality test data, and arranging it temporally. All samples obtained were compiled in Microsoft Excel software and later converted into a Data Base format for incorporation into the ArcView GIS 3.2a software. Stage 4 of the work consisted of analyzing data using the ArcView GIS 3.2a software for both temporal and spatial assessment of the extent of contamination. Subsequently, the maps were critically analyzed and interpreted. Additional statistical analysis of data was carried out using the Microsoft Excel and SPSS V-15 Statistical analysis software. Findings were then evaluated and interpretations formulated. Appropriate conclusions were then drawn and recommendations made in stage 5 of the work.

4.2 Data Collection

The main research methodological approach used collection of extensive data on water quality tests. It was established at the commencement of the research work that, in order to achieve the objectives of the study, the collection of extensive historical data was crucial. Therefore, as much as was possible, a complete census of all boreholes, shallow wells and springs was taken as the main focus.

Although water quality chemical data collected has not been evenly spread over the years or as plentiful, the time span covered was 43 years, from 1967 to 2009. As new wells are also being drilled during this time, the data base was continually updated.

For the purpose of the study the time span of 2000 to 2008 was emphasized. The number of wells on which data analysis was carried out for this period are listed below. The total number of wells for the period of 2000 and 2008 were considered to be representative and thus satisfy the objectives of the study. A purposive sampling analysis revealed that about 223 wells would adequately represent the study area; hence the number of data analyses is believed to be representative.

The data collected was frequently hand copied from old archives for incorporation into the data base. It was also noted that older wells and some newer wells as well as some springs did not have location coordinates. Site visits were carried out to obtain the required Universal Transverse Mercator (UTM) coordinates using a Garmin GPS 12 GPS instrument. The position accuracy of the instrument was 15 meters. This was then later incorporated into the contamination contour maps. A summary of the data collected for the period 1999-2008 is indicate in Table 4.1 below.

Table 4.1 Summary of data collected for 1999-2008

Year data was collected	No of wells
1999	120
2000	675
2001	56
2002	69
2003	191
2004	124
2005	67
2006	241
2007	164
2008	419
2009	10

The boreholes evaluated in the survey were subsequently plotted on a watershed and aquifer map to determine areal distribution. Regardless of the available water quality data, all wells and spring data obtained in the process of the research work were incorporated. This was to assist in observing the geographical spread of wells and springs in the city.

As it was not possible to obtain information on the number and spatial distribution of pit latrines, an estimation exercise was carried out. The number of pit latrines was hence estimated on the basis of population size and housing units in each sub city. Subsequently an assessment of possible nitrate loading on aquifers in the city sourced from pit latrines was also made. This is discussed in detail in chapter 5.

4.3 Types of Data Collected

The data were primarily collected from the Addis Ababa Water and Sewerage Authority, the Addis Ababa Water and Sewerage Authority Addis Ababa Sanitation Project Office, the Ministry of Water Resources, The Ethiopian Environmental Authority, and the Ethiopian Geological Survey. A large amount of data were obtained from their archives. Private companies included AG Consult, Hydro Water Well Drilling and Engineering Enterprise, Al-Nile Group, SAVA Engineering Test Center, and individual private owners. A typical water quality analysis data set is shown in Fig. 4.2.

ADDIS ABABA WATER AND SEWERAGE AUTHORITY

LABORATORY RECORD

Sorurce of sample .....Well Water....... Date of Sampling 20/06/97

Site of Sampling ....Akaki B-H-6........ Date of Analysis 20-22

Sampled by ....AAWSA............. Analysis Requested by .....AAWSA..........

N.	Physic Chemical Parameters	
1	Temprature C°	21
2	Turbidity (F.T.U)	Nil
3	Colour (Pt-Co Units)	Nil
4	Odour	non-objectionable
5	Taste	non-objectionable
6	PH	7.85
7	Total Dissolved Solids (mg/l)	313
8	Conductivity (us/cm)	456
9	Total Alkalinity CaCo3 (mg/l)	246
10	Total Hardness as	246
11	Calcium Hardness	150
12	Magnessium Hardness	96
13	Carbon Dioxide as Co_2	15
14	Oxygen dissolved	6.7
15	Naitrate as No_3	22.8
16	Nitrate as No_2	0.021
17	Ammonia as NH_3	0.152
18	Iron as Fe	0.012
19	Manganese as Mn	0.042
20	Chloride as Cl	3
21	Fluoride as F	0.022
22	Hexavalent Chromium as Cr	Nil
23	Copper as Cu	Nil
24	Phosphate as Po_4	0.184
25	Silica as Sio_2	54
26	Sulfate as So	12
27	Saturation Index (SI)	+ 0.37

REMARKS :- Physio-Chemically, this water is suitable for human consumption. However, the Water has a tendency of scale formation in conveying pipes.

Analysed by .... Approved by

Chemist Head of Laboratory Service

Fig. 4.2 Typical water quality data set

The data collection process commenced in 2006 and continued until the end of 2009. Details on more than 1300 boreholes within a 100 km radius of the city were collected and thoroughly reviewed. An unpublished new geological map was also consulted and incorporated in the review work of the study.

It was noted that water quality test centers used differing reporting formats for tabulating test results. The number of individual chemical tests carried out were, on average, about 26. The test results were subsequently compiled into a master format for later analysis and interpretation. A significant portion of the research field work focused on obtaining historical water quality test data. In the process, in excess of 420 test results were obtained for the period covering 2008-2009. This was considered to be recent and statistically representative to assess the current degree of contamination in groundwater.

In the process of collection of data, it was noted that some of the older wells were inoperative. Water quality tests for these inoperative wells were considered for their historical value. Tests for 2008 and 2009 were from old but operative as well as newly drilled Wells.

Of the 26 water quality tests carried out the main cations included NH_3, Na, K, Ca, Mg, Fe, Mn, Al, Cu, Cr. The major anions included Cl, NO_2, NO_3, F, HCO_3, CO_3, SO_4, PO_4, and Boron. In general over 4000 individual water quality tests were reviewed and incorporated in the study. In line with the objectives, two chemicals, nitrate and chloride were reviewed in detail. Other indirect parameters such as Total Dissolved Solids (TDS) measurements were also analyzed to confirm reliability of analysis outputs.

Whilst almost all test results had nitrate and chloride chemical content of the samples indicated, very few wells had E. coli test results shown. In terms of the objectives of the research, E. coli test results were considered to indicate recent contamination of groundwater and may not be as effective, in gauging the extent of temporal contamination. The primary focus was therefore on nitrates, and chlorides as primary indicators of long term temporal and spatial groundwater contamination. On the other hand indicative E. coli test results have been incorporated to elaborate and corroborate the nitrate and chloride contour maps. Nonetheless, nitrates and chlorides were among the most frequently tested.

Whilst the test results may be considered acceptable for the purpose of the study, one area of concern was the absence of nitrate and chloride test data in some of the laboratory test result documentation reports. Since these parameters were not recorded in the document as zero, '(0)', 'nil', or 'Not detectable', it was not possible to evaluate the particular value. For analysis purposes however, it was assumed to be 'non available'. In these cases, the associated chloride values, if recorded, were omitted in order to reflect better correlation with recorded nitrate values only.

Consequently the data so obtained were categorized in a Microsoft Excel format, with well names, locations, GPS coordinates, and all chemical and bacteriological tests results recorded for the specific period. All water quality chemical test data were incorporated in the database regardless of their immediate relevance to the objectives of the dissertation. This was carried out in order to record all data as it was initially obtained. All records were then converted to a Data Base format, for utilization in the ArcView GIS 3.2a software. Each temporal data point was associated with the specific coordinate for the well and spring. In order to avoid duplication, cases of repeated tests for identical periods were segregated and were not included in the analysis. For analysis and mapping purposes, the data were categorized on a yearly basis.

To accurately identify whether the observed nitrate in water is from human waste or other sources, one possible method could be isotope analysis, particularly nitrogen isotopes. The absence of nitrogen isotope testing service in Addis Ababa, and the exorbitant costs of sending samples abroad necessitated alternative methods of evaluation. The research work therefore focused on correlation of relevant chemicals.

4.4 Data Collection Process

The data collection process started with the identification of possible sources of data. These included compiling a list of government as well as private organizations that are actively engaged in water drilling and supply works as well as those that are not currently active but had done related work in the past. Each organization was then approached and requested to access their archives as well as any documentation rated to the study. The extensive archives of the Addis Ababa Water Supply and Sewerage Authority were made available for review and have been included in the study.

The next stage in the process included interviewing company owners, drillers, private consultancy firms, owners of wells, professionals, as well as a review of historical archives and research papers. It also included a fieldwork including visual observations of the 'rivers' or open sewers that cross the various parts of the city. Observation with a small airplane of the location of the water treatment plants to the east and southwest of the city and wells were also carried out. This enabled the visual assessment of the waste flowing to the main groundwater abstraction area, the ground situation around it, the extent of flooding during heavy rains and a means of correlating these with the GIS information obtained. The observations by air of the main groundwater abstraction areas were carried out during the relatively dry seasons and during times of heavy rains. This has enabled the observation of extent of heavy rain flooding on the surrounding areas.

A review of all available data in relation to the hydrogeological study of the study area was also carried out. This included interviews with professionals involved in the preparation of a recent and more comprehensive geological map of areas including that of Addis Ababa. Interviews with professionals involved in groundwater resource abstraction, distribution and quality control also revealed valuable insight into the current situation of groundwater resources management and future trends in this regard.

4.5 Shortcomings on Data Collected

In the process of the research work a reasonably comprehensive data was collected from the above sources and was thoroughly analyzed. A review of the data however, revealed that not all recorded information was of the desired format or was occasionally ambiguous. Hence all the available data was carefully reviewed to exclude those that were not clearly recorded or were ambiguous. These included wells for which only a single chemical quality test was carried out. These were considered irrelevant to the objectives of the study and were excluded. Some data were also found to be illegible and not clearly recorded, and was excluded from the review.

In line with the objectives of the study, chemicals pertinent to the assessment of human waste contamination on groundwater were given emphasis. This meant that the two main chemicals utilized in the assessment, nitrate and chloride, if recorded concurrently for the same time period were utilized in the assessment. On the other hand if only one chemical was recorded it was disregarded. Another constraint has been the non-uniformity of water quality laboratory test result recording formats. Various drilling agencies and laboratories utilized differing test recording paper formats, and this took a considerable time to compile them into a common format usable on the appropriate software. In some cases extreme values were also noted on recorded values of water quality results. But as these values appeared to be very high compared to the generally observed values and as it was not possible to ascertain the correctness of these individual data, these data were systematically excluded from the analysis. This it was believed will assist in avoiding undue influence on historical as well as spatial extent of contamination.

4.6 Data Evaluation and Methodology

The collected data was initially systematically organized and compiled and subsequently tabulated for easy manipulation on the computer. The next stage of the data evaluation process included a careful analysis using Geographical Information System (GIS) software the Arcview 3.2. This enabled the plotting of spatial contamination maps. A second stage of the data evaluation process also included a statistical analysis of the water quality data particularly the level of nitrates and chlorides. It utilized Microsoft XL and SPSS V. 15 statistical analysis software to determine the coefficient of correlation, statistical significance and confidence intervals. Graphs of temporal variation of contaminants were also plotted.

4.7 Results of Data Evaluation

The results of the data evaluation consisted as an output of spatial contaminant distribution maps as well as statistical analysis graphs. These were evaluated to arrive at an appropriate conclusion. This stage of the work consisted of a critical review and comparison of the maps, and evaluating the extent of contaminant distribution. Each of the maps was analyzed and the values displayed compared with other maps. This helped to observe whether the spatial extent of contaminants was increasing and whether there was an increase in terms of the degree of the contamination.

Additionally the statistical analysis and temporal variation graphs were scrutinized to arrive at a conclusion in regard to temporal variation trends. A careful comparison of the observed values was made with the national as well as international recommended limits and appropriate conclusions were drawn.

5 Distribution and Extent of Low-cost Sanitation Waste Load on Aquifers

Pit latrine usage in Addis Ababa is extensive. With only 0.6 % of the population having access to sewerage services, the rest of the population has to make use of pit latrines. This may therefore contribute to significant nitrate loading on the aquifers in and around the city. In order to estimate the nitrate loading on aquifers, the exact number of pit latrines would have to be known. To date, however, the exact number in the city is not known. Indirect estimates can nevertheless be made. Evaluating this parameter has given an indication of which aquifers may be exposed to high nitrate loading.

5.1 Estimation of Pit Latrines Density in Addis Ababa

The majority of the population of the city use pit latrines for human waste disposal. About 25% of the population do not have access to sanitation at all. In spite of this large usage, the exact number pit latrines or their spatial distribution is not accurately known. Estimates of the number of pit latrines can be made based on either the size of the population or the number of housing units in an area.

Considering the population of the city to be about 2.8 million and an area of about 530.14 sq. km, and with 75% of the population with an average family size of 4.1 having access to a pit latrine, the total number of pit latrines in the city may be estimated to be around 966 latrines per square kilometre. Alternatively considering the total number of housing in the city to be 374,742 and with 75% having access to a form of sanitation while assuming each house has one pit latrine, the total number of pit latrines in the city may be considered to be in the range of 281,057 latrines. This amounts to about 530 latrines per square kilometre. Alternatively, taking the 61 major urban centres survey of sanitary facility availability (DHV, 2003) as the norm and considering 40% as having private latrines, with approximately 18% as using shared facilities, this will yield;

40/100 * 374,742 =149,897 individual latrines

18/100 * 374,742= 67,454 shared facilities,

In total,

149,897 + 67,454 = 217,351 pit latrines. This would yield a spatial distribution of

217351/530.14 =409.99 or about 410 pit latrines per square kilometre.

If the 1994 National Census is considered, in which of the total 374,742 urban housing units in the city:

168,732 used shared pit latrines,

67,895 housing units had a private pit latrine and

30,113 and 14,815 units had private and shared flush toilets respectively.

This would add up to 281,555 pit latrines spread over the total 530.14 square kilometres of the city, yielding an average density of 531 latrines per square kilometre. This is based on the assumption that, 25% of the houses did not have any form of toilets, while 49 % and 26 % used shared and private facilities, respectively.

In general, therefore, the total density of pit latrines may be considered to be in the range of 410 to 966 latrines per square kilometre. If new housing developments in the city are taken into consideration, this figure may be higher.

5.2 Spatial Distribution of Pit Latrines in Addis Ababa

Considering the above analysis and utilizing the lower and higher values of pit latrine distribution over the city an approximate number of pit latrines may be obtained. Table 5.1 shows the number of pit latrines when a lower value of 410 latrines per square kilometre is considered.

Table 5.1 Addis Ababa sub cities pit latrine distribution over aquifers at 410 lat/sq. km

Name of Sub City	Population	Area Sq Km	No of pit latrines at 410/sq km	Location in aquifers
Akaki-Kaliti	181,202	124	50,840	Major Aquifer
Nefas Silk Lafto	316,108	59	24,190	Minor Aquifers
Kolfe Keranyo	428,654	63	25,830	Minor Aquifers
Gulele	267,381	31	12,710	Minor Aquifers
Lideta	201,613	11	4,510	Minor Aquifers
Kirkos	220,991	15	6,150	Minor Aquifers
Arada	212,009	10	4,100	Minor Aquifers
Addis Ketema	255,092	7	2,870	Minor Aquifers
Yeka	346,484	80	32,800	Minor aquifers
Bole	308,714	119	48,790	Minor Aquifers
Total	***2,738,248***	***519***	***212,790***	

On the other hand considering the higher value of 966 latrines/sq. km the number of pit latrines may be estimated as shown below (Table 5.2)

Table 5.2 Addis Ababa sub cities pit latrine distribution over aquifers at 966 lat/sq. km

Name of Sub City	Population	Area Sq Km	No of pit latrines at 966/sq km	Location in aquifers
Akaki-Kaliti	181,202	124	119,784	Major Aquifer
Nefas Silk Lafto	316,108	59	56,994	Minor Aquifers
Kolfe Keranyo	428,654	63	60,858	Minor Aquifers
Gulele	267,381	31	29,946	Minor Aquifers
Lideta	201,613	11	10,626	Minor Aquifers
Kirkos	220,991	15	14,490	Minor Aquifers
Arada	212,009	10	9660	Minor Aquifers
Addis Ketema	255,092	7	6,762	Minor Aquifers
Yeka	346,484	80	77,280	Minor aquifers
Bole	308,714	119	114,954	Minor Aquifers
Total	***2,738,248***	***519***	***501,354***	

The above analysis suggests the degree of uncertainty involved in estimating the number of pit latrine distribution in the city. Alternatively as the population of each sub-city varies, a more preferable method to estimate the number of pit latrines may be used by taking into consideration the number of people residing in each sub-city.

The spatial extent of the built-up areas of the city, shows that habited areas are not uniformly distributed over the whole city (Fig. 5.1 and 5.2). This would suggest that the spatial distribution of pit latrines, while useful as an indicator of pit latrine density, may not yield an accurate value. It would therefore be more appropriate to take the number of people living in an area, reflected in the built-up area extent, as an indicator of pit latrine usage and density. These values are shown in column 7 of Table 5.3.

The maps of the built-up area superimposed over the sub city area shows the non uniform distribution of habited areas over the city (Fig. 5.2).

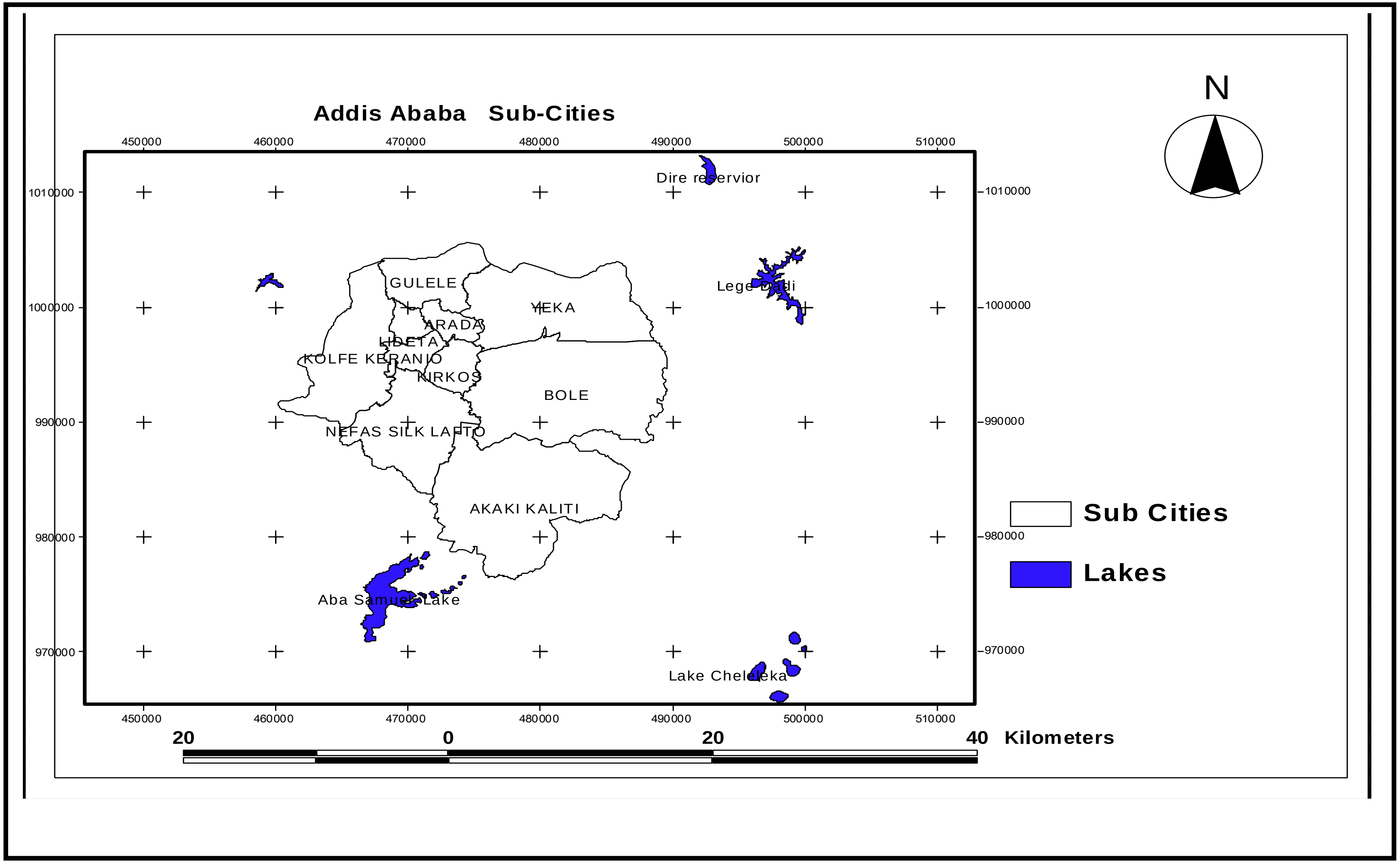


Fig. 5.1 Addis Ababa Sub Cities (adapted from AWSSA)

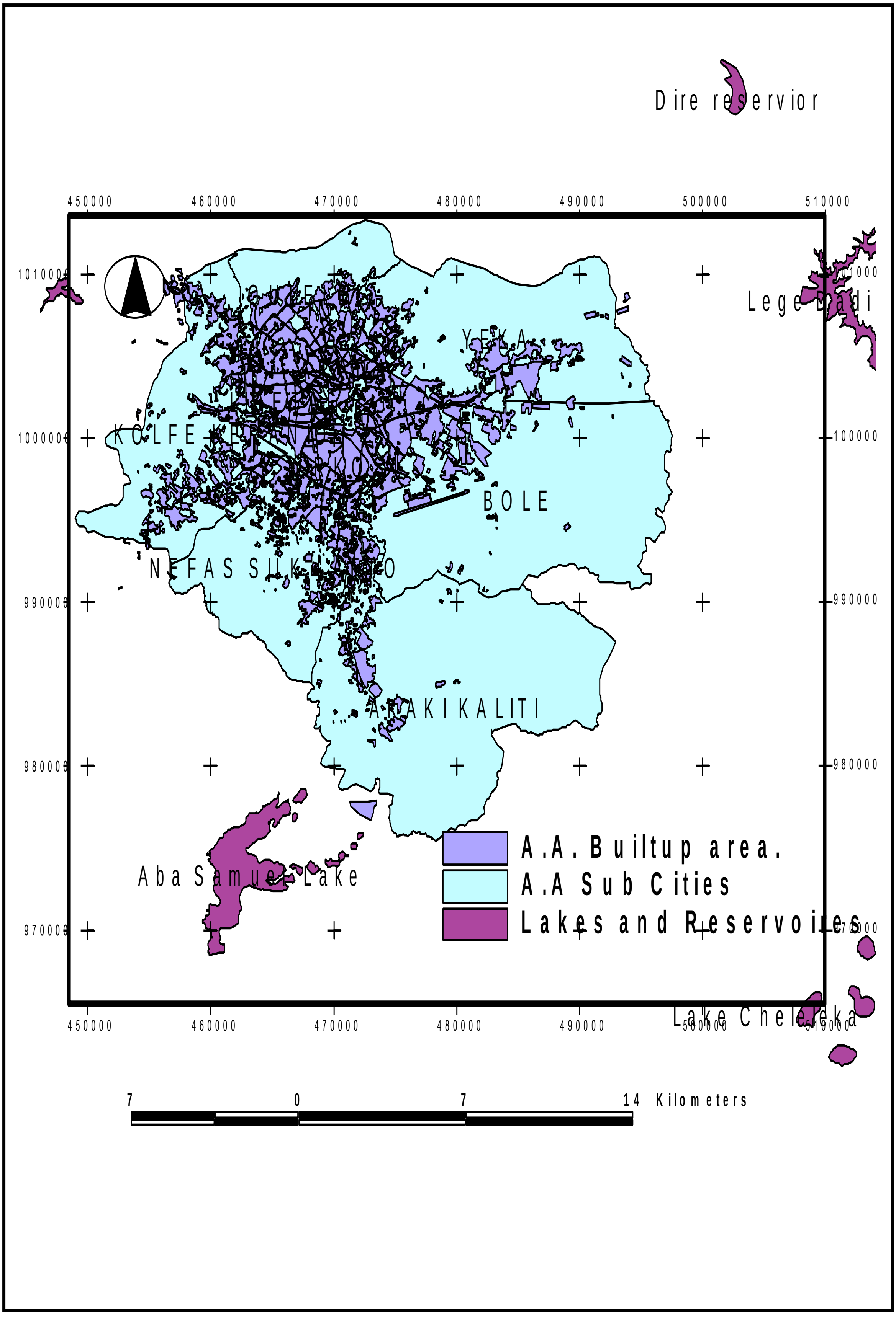


Fig. 5.2 Addis Ababa sub cities and built-up area spatial distribution (adapted from AWSSA)

Table 5.3 Addis Ababa sub-cities and estimated nitrate loading on aquifers

Name of sub city	Population	No of people with no access to pit latrines (25%)	No of people with access to pit latrines (75%)	No of families using private latrines 26% (at 4.1 people per family)	No of families using shared latrines, 49% (considering one latrine for two families at a house hold size of 4.1 people)	Total no. of pit latrines in sub-city	Nitrate loading Tons/year (at 4kg/person/year)	Location in aquifers
Akaki-Kaliti	181,202	45,301	135,902	8,618	8,121	16,739	725	Major Aquifer
Nefas-Silk Lafto	316,108	79,027	237,081	15,034	14,167	29,201	1264	Minor Aquifers
Kolfe Keranyo	428,654	107,164	321,491	20,387	19,211	39,598	1715	Minor Aquifers
Gulele	267,381	66,845	200,536	12,717	11,983	24,700	1070	Minor Aquifers
Lideta	201,613	50,403	151,210	9,589	9,036	18,625	807	Minor Aquifers
Kirkos	220,991	55,248	165,743	10,511	9,904	20,415	884	Minor Aquifers
Arada	212,009	53,002	159,007	10,083	9,502	19,585	848	Minor Aquifers
Addis Ketema	255,092	63,773	191,319	12,132	11,432	23,565	1020	Minor Aquifers
Yeka	346,484	86,621	259,863	16,479	15,528	32,008	1386	Minor aquifers
Bole	308,714	77,179	231,536	14,683	13,836	28,518	1235	Minor Aquifers
Total	***2,738,248***	***684,562***	***2,053,686***	***130,234***	***122,720***	***252,954***	***10,953***	

The results shows that on average at least 252,954 pit latrines exist in the city. This spatial distribution appears to suggest a more realistic distribution. The less populated areas in the major aquifer zones show lesser number of pit latrines.

Considering a nitrate loading of 4 kg/person /year the total nitrate loading on the aquifers would be in the range of 10,953 tons/year. The estimated nitrate loadings from pit latrines in each sub city are listed in column 8 of Table 5.2.

In terms of the number of population in aquifer areas, 181,202 or 6.62 % of the residents of the city are located around the major groundwater abstraction area. The remaining 93.38 % or 2,557,046 of the residents occupy the central areas of the city. This area is considered to be underlain by a minor aquifer.

5.3 Low Cost Sanitation as Diffuse Source of Pollution

The above analysis suggests that the density of pit latrines over the habited areas of the city may be high. Besides new housing development areas are also required to provide pit latrines as a means of human waste disposal.

New housing developments in the city have an average plot sizes ranging from 90 m^2 to 175 m^2 area. Each new housing plot is required by regulation to provide a pit to collect human waste and dispose it off into the ground. With no technical guidelines as to the size of pits, residents commonly dig pits of size with an average surface area of 9 m^2 and a depth of 3 meters or an approximate volume of 27 m^3.

In a 175 m^2 area plot size this accounts for about 5.14% of the plot area and in a 90 m^2 plot it is as high as 10% of the area which is utilized as a pit latrine. Once the hole is dug, a dry masonry lining is built in the pit. The pit cover is prepared by lining the pit top with timber poles, and then covering it with earth or similar materials with a small hole left for squatting.

In recent housing construction areas this basic construction system is still used, with the top cover replaced by a concrete slab, but the rest of the construction basically remaining the same.

This is an accepted practice in almost all areas of the city, regardless of the type of the soil or rock or proximity to water resources. Whenever the pits fill, vacuum trucks desludge the contents for disposal at the two treatment plants. Spread out over the number of new housing in the city, this is a significant percentage of land used as a human waste handling area. The areal density of pit latrines within the city may therefore be high.

In highly congested areas of the city, the toilets also serve as showers, and when communally used tend to get full and overflow frequently. Instances of toilets overflowing and contaminating surrounding areas are a common sight in some highly congested areas of the city. In areas where lack of space prohibited the construction of pits, it is a common practice to connect pit latrines to river courses or streams nearby (Girmay, 1993, 1990).

Recent communal pit latrines have an 'improved' design called 'ventilated improved pit' latrines or VIP latrines. These VIP latrines are a slight modification of the traditional pit latrines, which include a pipe to ventilate the pit and covers to squatting holes. In terms of overall design and their effect on groundwater contamination impact however they may not be different from the traditional pit latrines (Girmay, 1995).

New housing construction around the city as well as new real estate ventures on the peripheries utilize the same principles. A slight difference is observed in the *Ayat* Real estate housing, where pit latrines are built with circular open bottom concrete pit lining. This construction although much improved in reducing the collapse of surrounding soil contributes little towards mitigating contamination of groundwater. It has also been noted that no standard design of a pit latrine exists in the city. There are also no guidelines or codes to define standards.

The construction techniques coupled with the high rate of use, pit latrines in Addis Ababa could be considered to be a non point or diffused source of pollution. Hence high density of pit latrines does contribute to a heightened contamination risk as the waste is directly released into groundwater.

5.4 Aquifer Vulnerability

Assessing the spatial distribution built-up areas of the city, the majority of housing units and by implication the highest number of people, live in the central areas of the city. These areas are thought to be underlain by shallow and minor aquifers. It is possible therefore, that the most vulnerable aquifers may be in these central areas. Considering the relatively smaller number of people living in the southwestern areas of the city, the Akaki Aquifers may be less vulnerable.

The northern part of the city is classified as 'mountains and low permeability rocks'. This in turn would suggest, low yield aquifers. The major areas of concern may therefore be considered as the central and southern areas of the city where there is high concentration of wells and where the built-up area of the city is almost exclusively located. A study carried out by AG Consult suggests an aquifer layout as shown in Figure 5.3 below. The distribution of boreholes and wells in the aquifer area, watershed and city boundary is indicated in Figs. 5.4 and 5.5. These figures also show the distribution of boreholes with respect to the built-up areas of the city and the ground elevation.

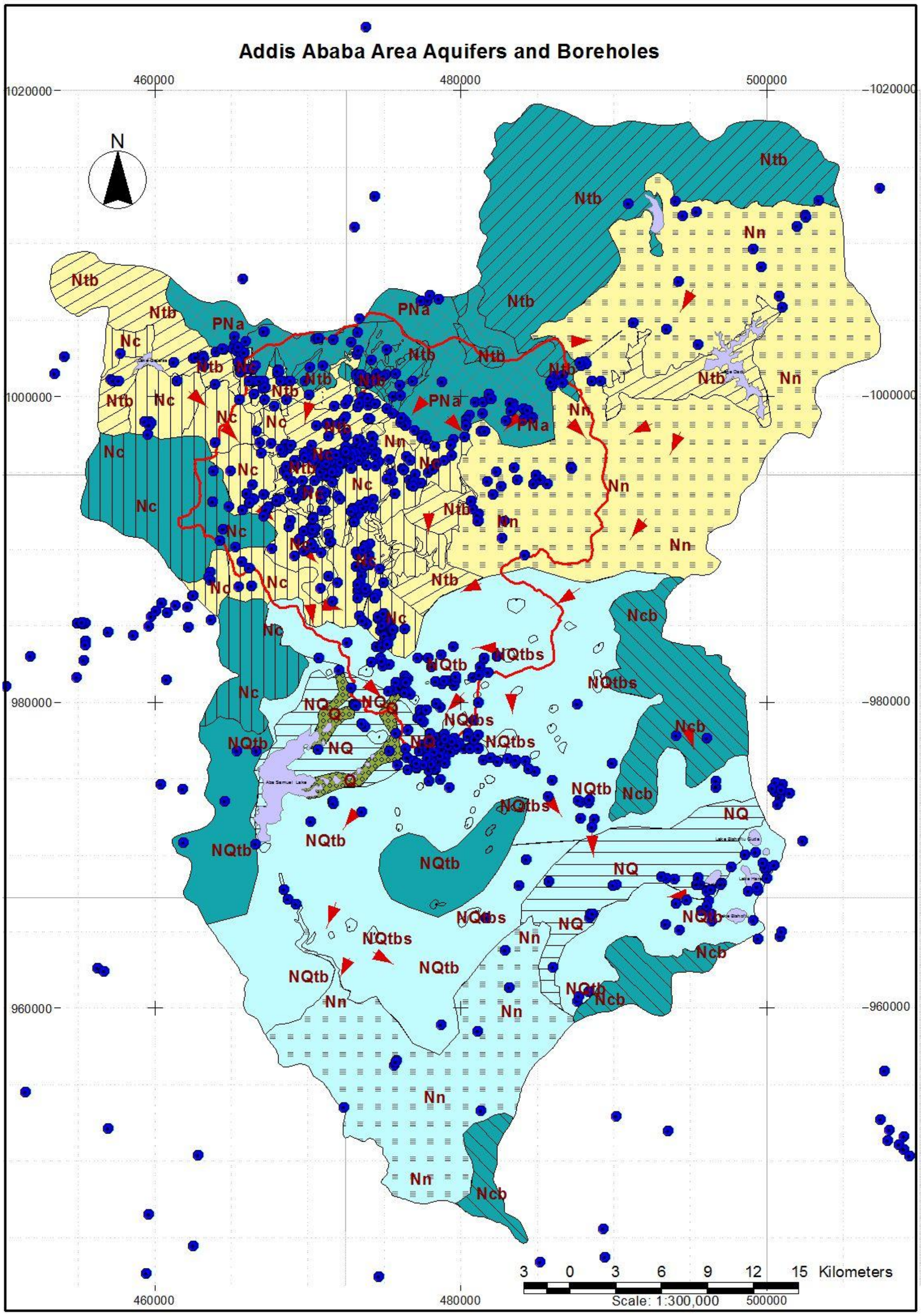


Fig. 5.3 Addis Ababa area aquifers and boreholes distribution (Adapted from AG Consult)

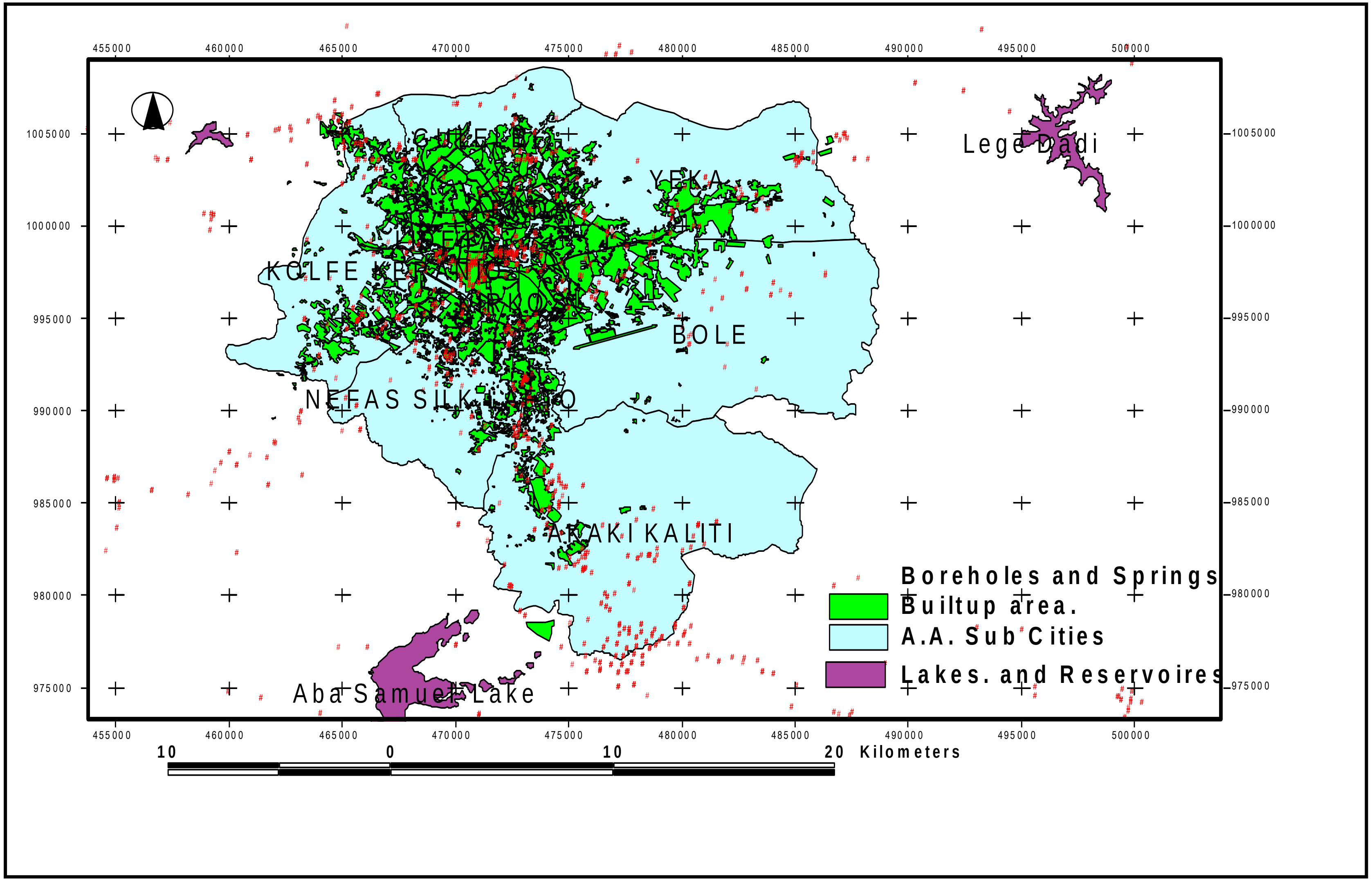


Fig. 5.4 Addis Ababa built-up area and boreholes location (Adapted from AAWSSA)

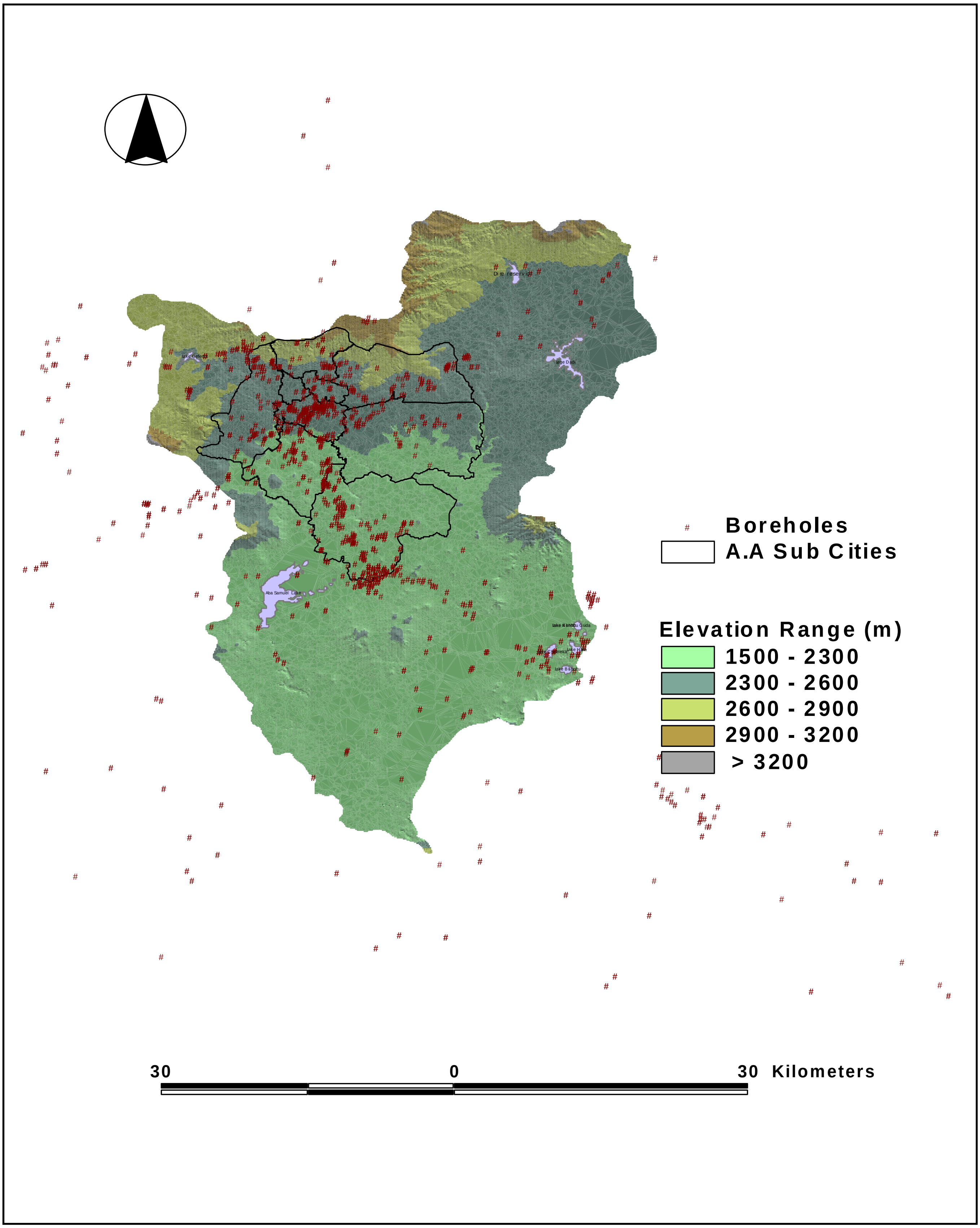


Fig. 5.5 Addis Ababa area watershed, elevation, city boundary and boreholes distribution (adapted from AG Consult)

5.5 *Estimation of Pollution load on Groundwater Resource*

As indicated Table 7.3 the total nitrate loading into the aquifers sourced from pit latrines over the geographic limits of the city adds up to 10953 tons per year. This averages about 21 tons/square kilometre per year. In addition to this, the 25% of the population which is believed to have no form of sanitary service is also contributing a nitrate loading to the ground. This input may be significant. This is not, however, the only source of potential nitrate loading into the groundwater. Industrial and farming activities also contribute to the nitrate loading. This may particularly be higher as the groundwater flows from the north towards the southwester areas of the city. It follows the natural slope of the ground, and along the way receives significant loading from the surrounding industries and farming activities. The pit latrine waste taken to the treatment plants also finds its way into the groundwater as shown in Fig 5.6 below, and subsequently to the Aba Samuel Lake (Fig. 5.7). The locations of the treatment plant and Aba Samuel Lake are shown in Fig. 5.8

Fig. 5.6 The treatment plant in the vicinity of the Akaki aquifer

Fig. 5.7 The Aba Samuel Lake (photo taken on March 26 2009)

The location of the two treatment plans and their proximity to the groundwater abstraction area is shown in fig 5.8 below.

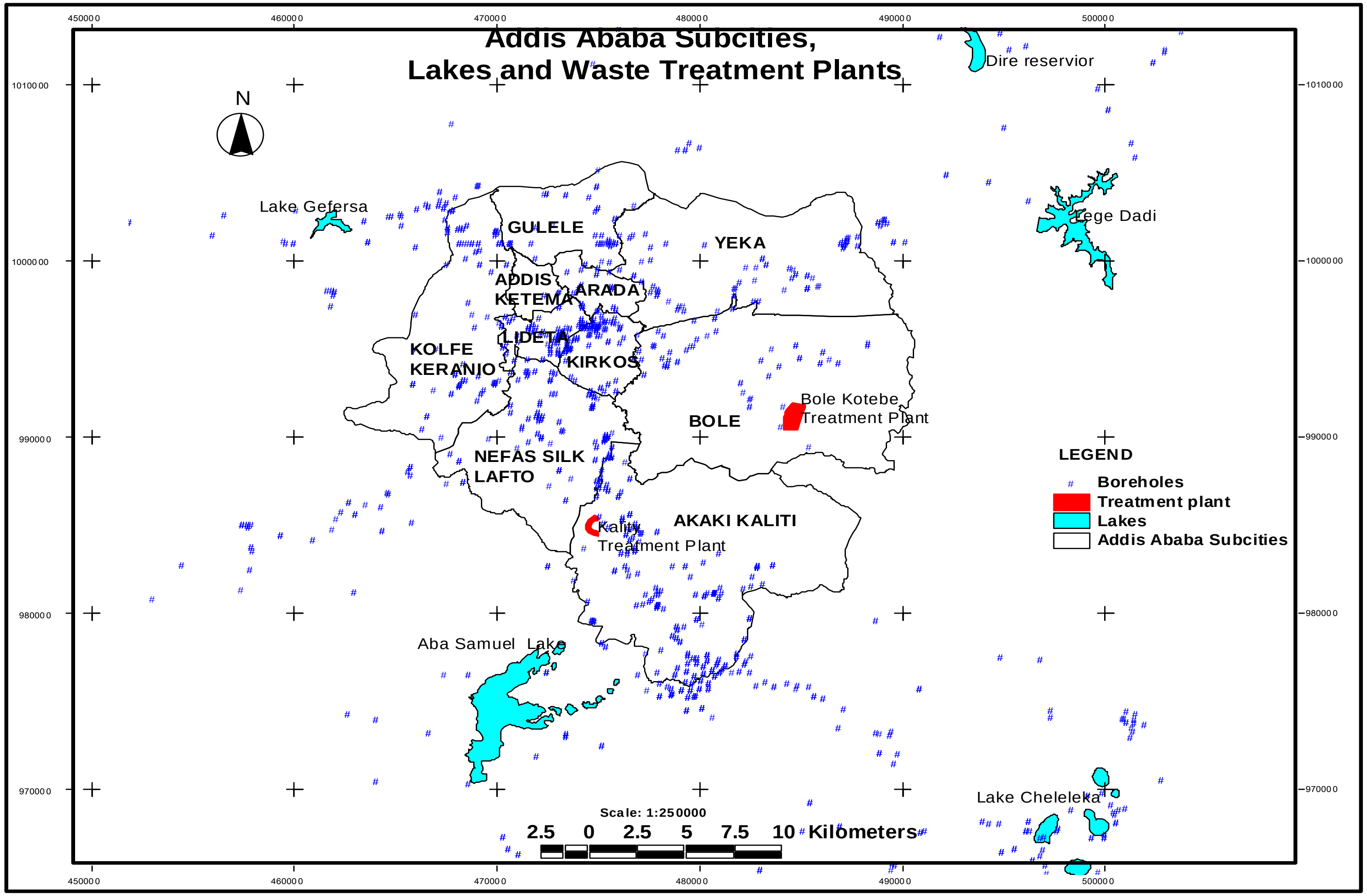


Fig 5.8 Addis Ababa sub-cities, lakes and water treatment plants (adapted from AWSSA and AG Consult)

The Aba Samuel Lake is the confluence point of the city's waste. The groundwater around the city is also believed to flow in this direction. As the soils cover is likely to crack during the dry season, it may further aggravate contamination.

The stream shown in the foreground of Fig. 5.7 also receives waste from the treatment plant. In addition to this the recharge zone of the main borehole location site towards the south west of the city is predominantly expansive soils (commonly called black cotton soil). This type of soil is generally believed to be impervious once it becomes wet. This is due to its expansive reaction upon exposure to water, which seals the pores hence limiting permeability. On the other hand, during period of dry season, the soil cracks and opens up to a depth of 3 meters. This zone is normally considered active, because the swell-shrink potential of the soil in this depth range is considered to be significant (TAMS, 1994).

The deep cracks that characterize these types of soils may create a ready flow path to groundwater. In addition to this, the area bisecting Addis Ababa east west at least in the middle section and the area south of this line can be considered to be lying in a rather low altitude compared to all of Addis Ababa. In this area the groundwater table is observed to rise up significantly during the rainy season and recede during the dry season. This would suggest that as the soils cracks during the dry season and the water table rises during the rainy season a potential interaction of waste water and groundwater may be possible contributing towards contamination.

During the dry seasons the Aba Samuel Lake dries up, not only from evaporation but also from possible infiltration into deeper layers. The above photo (Fig. 5.7) was taken during the relatively dry season of March shows a reduced water cover but nevertheless showing signs of being flooded earlier.

This threat of flooding is further exacerbated, by the general slope of the city surface, the flow direction of the groundwater, underlying geology and the location of the treatment plant. It is therefore possible that the pollution load on groundwater resource around the city, including the Akaki-Kaliti areas may be significant. Given the situation therefore, it is possible that nitrate loads on groundwater resource in the city is high.

In addition to the above contaminants sources, over-abstraction of groundwater resource may also contribute towards aggravated contamination. Nevertheless waste disposal in general, and pit latrines in particular, are perhaps the single most detrimental factor contributing to water resources contamination. The exorbitant costs of providing sewerage services, the lack of awareness of the general public, the absence of enforcement capability of the existing environmental policy have all combined to create a serious situation. The geographical spread and density of pit latrines would categorize them as diffuse sources of pollution. It can therefore be considered that the city of Addis Ababa is a massive non-point source of contamination on the groundwater.

6 *Degree of Nitrate Contamination: Temporal Variation*

A large number of the pit latrines in Addis Ababa are concentrated in the built-up area transecting the city in a north south direction and covering a relatively narrow area. This section as shown in Fig. 6.1 below is also located in low elevation areas. Fig 6.1 shows the larger watershed area, superimposed over the built-up areas and boundary of the city. The parks and vegetation areas cover the northern section of the city. These areas are at a higher elevation and are sparsely populated. The minor aquifer is located in the central and northern areas (colored beige and dark blue in Fig. 6.2), while the major aquifer (pale blue)is located in the south-western periphery of the city. A majority of the boreholes and springs are located in the built-up area.

Analysis of over 4000 water quality test data on boreholes and springs in the city was carried out for different periods to obtain an indication of the temporal degree of nitrate contamination. The data collected spanned 43 years. In the interest of brevity and in line with the research objectives, two main evaluation scenarios were considered. The primary evaluation was conducted on test data obtained in 2000. The second was for the period covering 2008. Statistical calculations were conducted to obtain an indication of temporal change in contaminant levels. In order to determine whether contamination could be ascribed to human waste the relationship between the chloride and nitrate concentrations was determined using Pearson’s product-moment correlation coefficient (r). Spearman’s Rank Correlation Coefficient (r_s) was used in cases where there were fewer than 10 data points. The distribution of the wells and springs over the two aquifers covered in the subsequent analyses is shown in Figure 6.2.

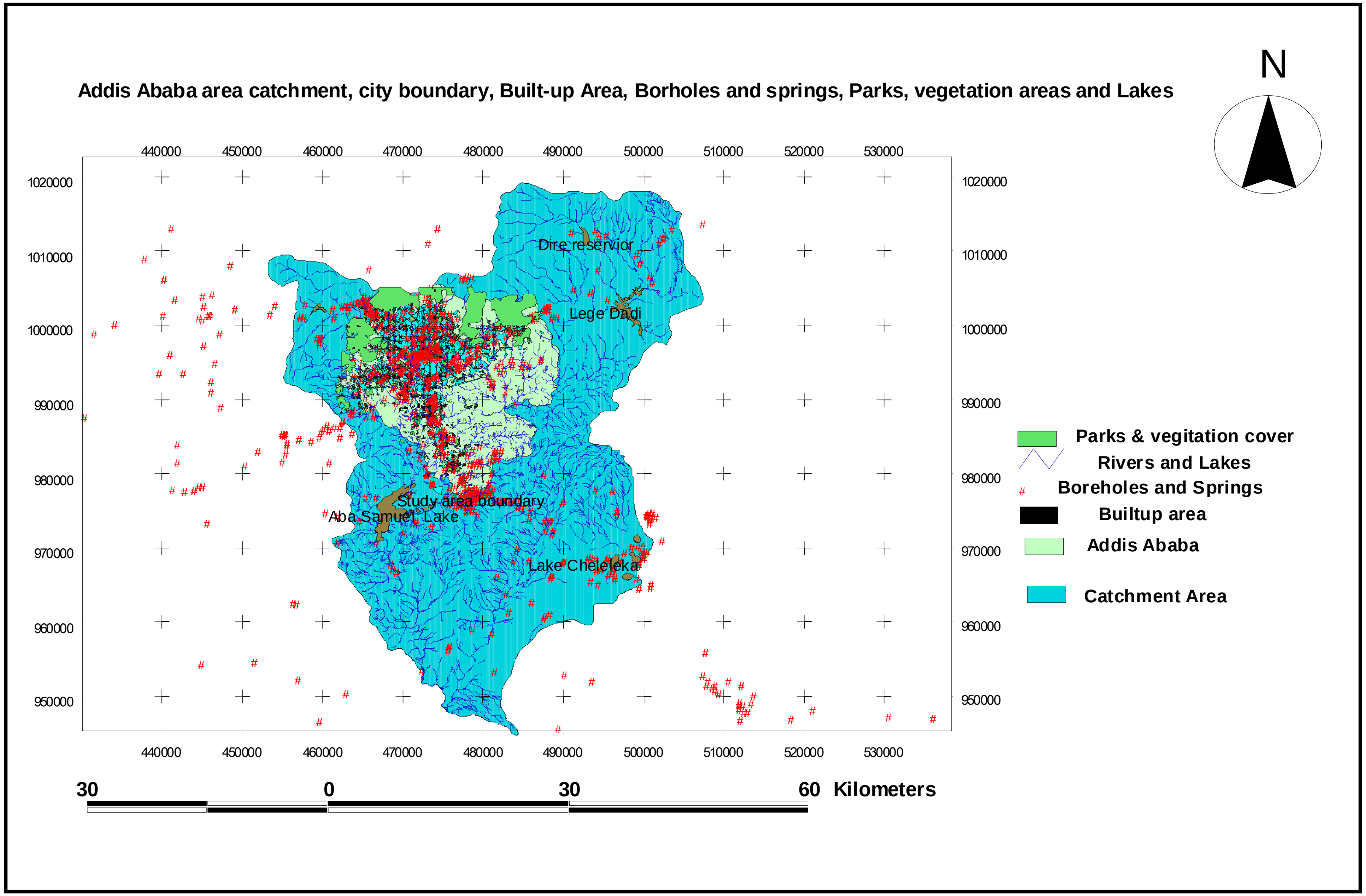


Fig. 6.1 Addis Ababa catchment area, city boundary, built-up area, parks and vegetation areas, lakes and distribution of boreholes and springs (Adapted from AG Consult)

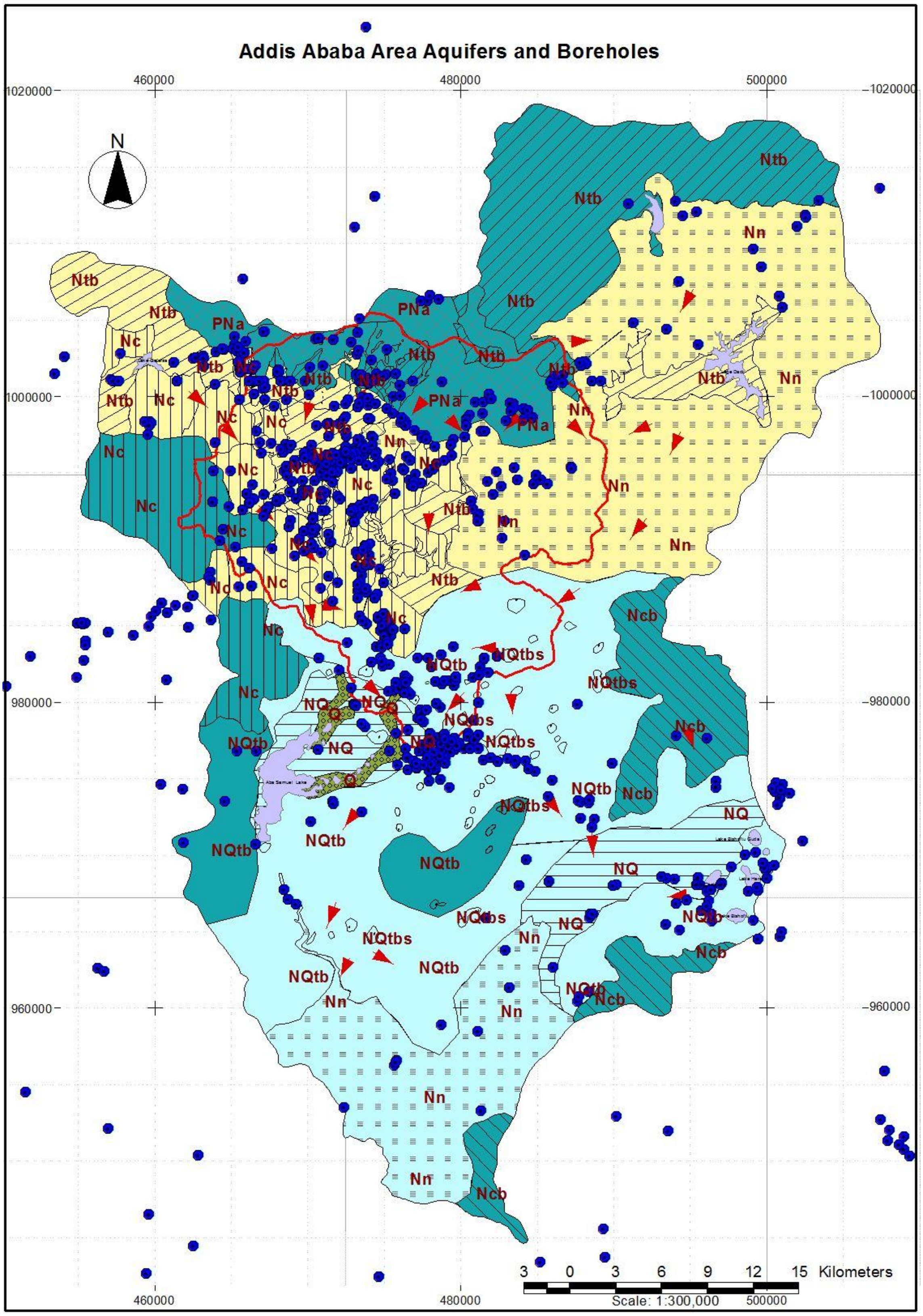


Fig. 6.2 Boreholes and springs distribution over aquifers

6.1 Variation of Nitrate and Chloride in Minor Aquifers 1977-2009

When evaluating the historical water quality data it was noted that a limited number of chemical analyses were conducted on many of the springs and wells. This appears to have been with a purpose of monitoring contamination-prone areas for specific contaminants. In many cases a value for nitrate only was reported, while values for chloride were not reported or vice versa. In this study, instances where only one variable was available were not included in the analyses.

The following section presents data on chloride and nitrate concentrations in well-water for 1977, 1999, 2000 and 2008/09. For 1977 data for only eight wells were available. A correlation coefficient (r) of 0.96 was found between the two chemicals for this period (Fig. 6.3). This value is statistically significant at the 0.01 level, indicating that these chemicals might have originated from human waste.

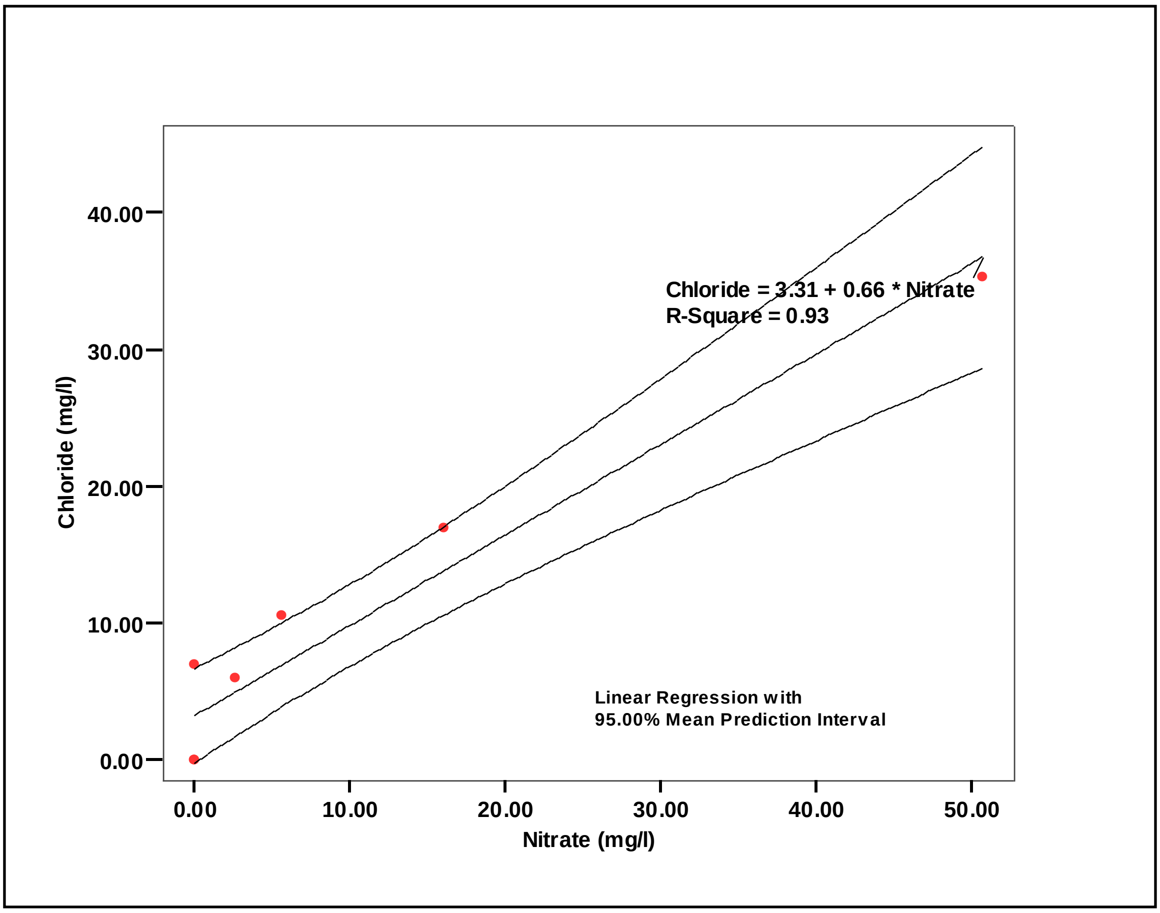


Fig. 6.3 Nitrate and chloride correlation in 8 wells in the minor aquifer area in 1977. (Note: data for some wells are identical and hence points overlap.)

The 1999 test data for 22 wells in the same minor aquifer area, but covering a slightly wider spatial extent showed a low correlation between nitrate and chloride, of 0.42 (Fig 6.4). This value falls just outside the 5% significance level and hence there was no linear relationship between the two chemicals.

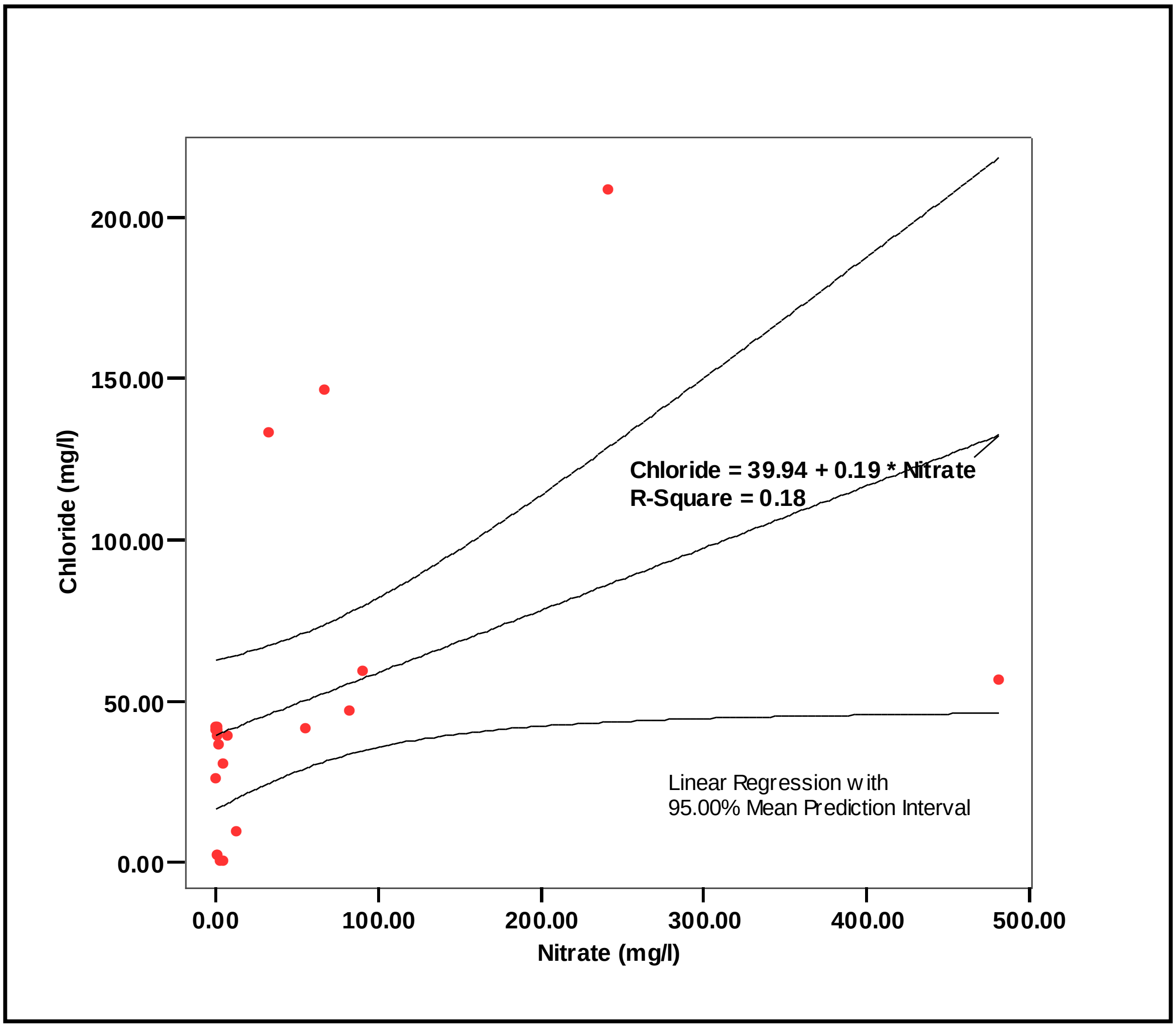


Fig. 6.4 Nitrate and chloride correlation in 22 wells in the minor aquifer area in 1999

Evaluation of water quality data for 261 wells in the minor aquifer area in 2000 showed a moderately strong correlation coefficient of 0.58 (Fig 6.5) (significant at the 0.01 level.)

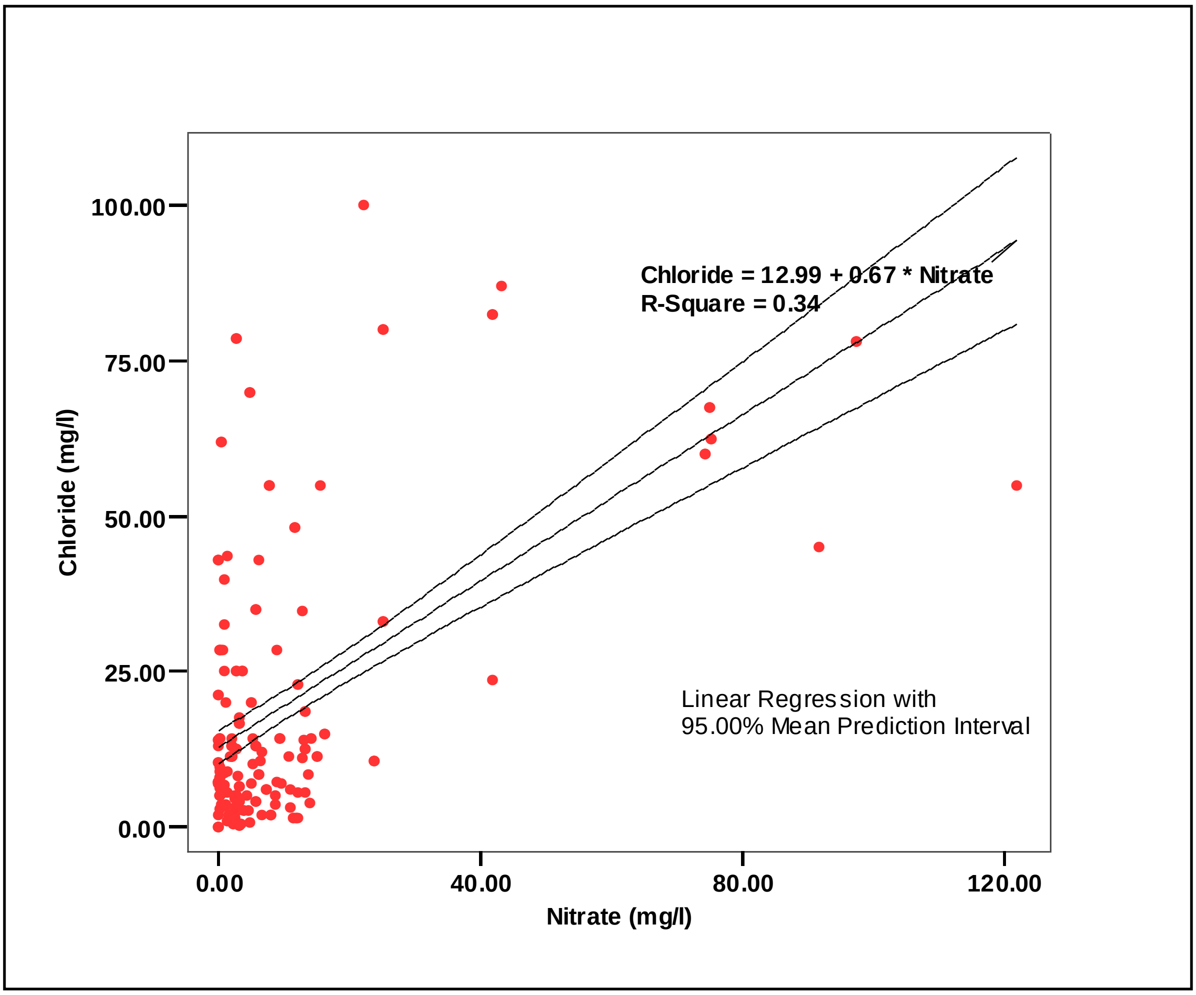


Fig. 6.5 Nitrate and chloride correlation in 261 wells in the minor aquifer area in 2000

Data from 1977 and 2000 indicate that the two contaminants exhibit a moderate degree of correlation. This would suggest that contamination due to nitrate and chloride occurred and that this might have originated from human waste.

In order to show the more recent situation, water quality tests were carried out in 2008/09 from 12 wells from the same location. This gave a correlation coefficient of $r = 0.62$ (Fig 6.6), between chloride and nitrate levels. The correlation was significant at the 0.05 level.

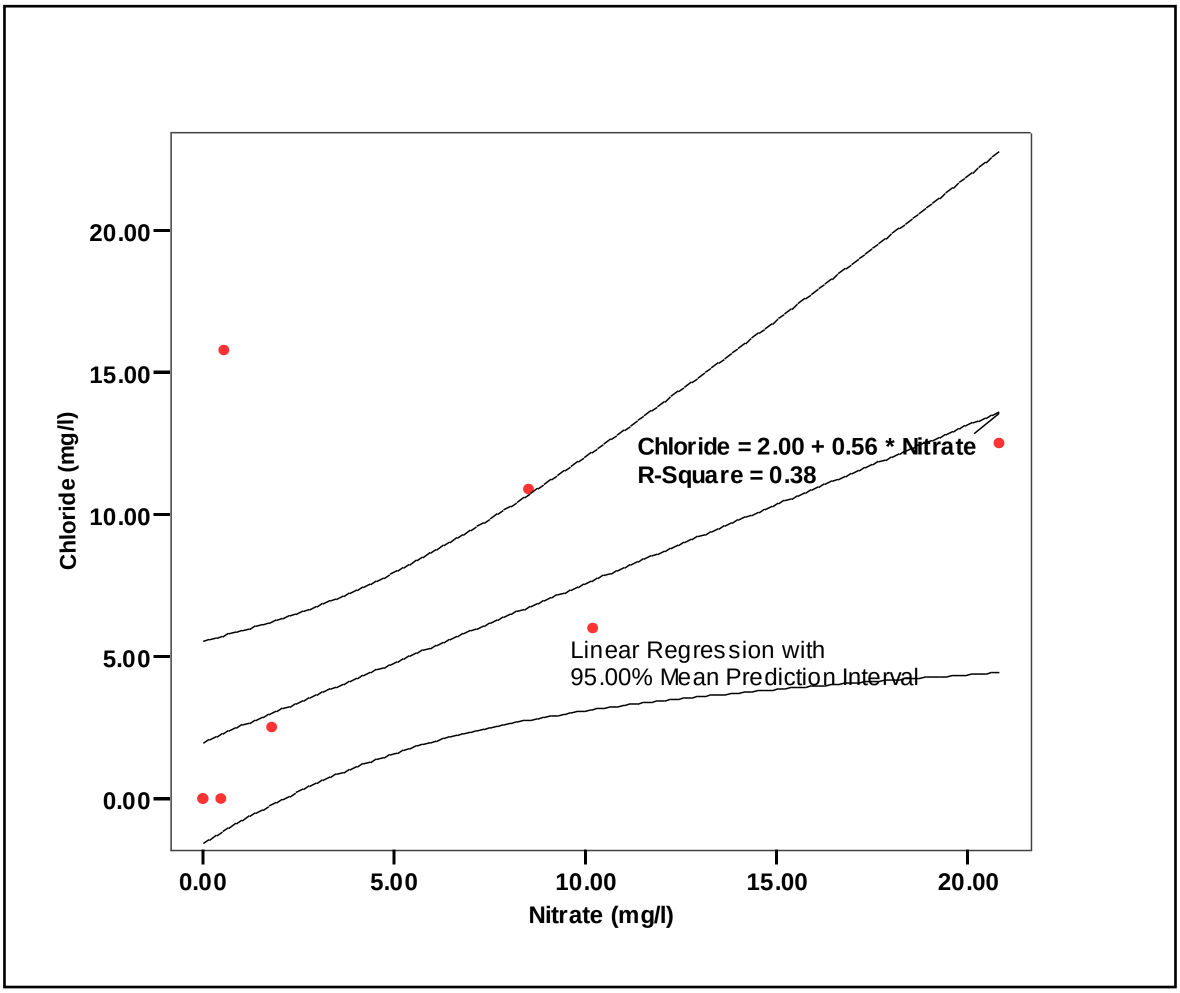


Fig. 6.6 Nitrate and chloride correlation in 12 wells in the minor aquifer area 2008

The correlation coefficient between chloride and nitrate levels collected from another 169 wells in 2008 were also calculated and found to be 0.27 (Fig 6.7). Despite the low r-value, the correlation was found to be significant at the 0.01 level.

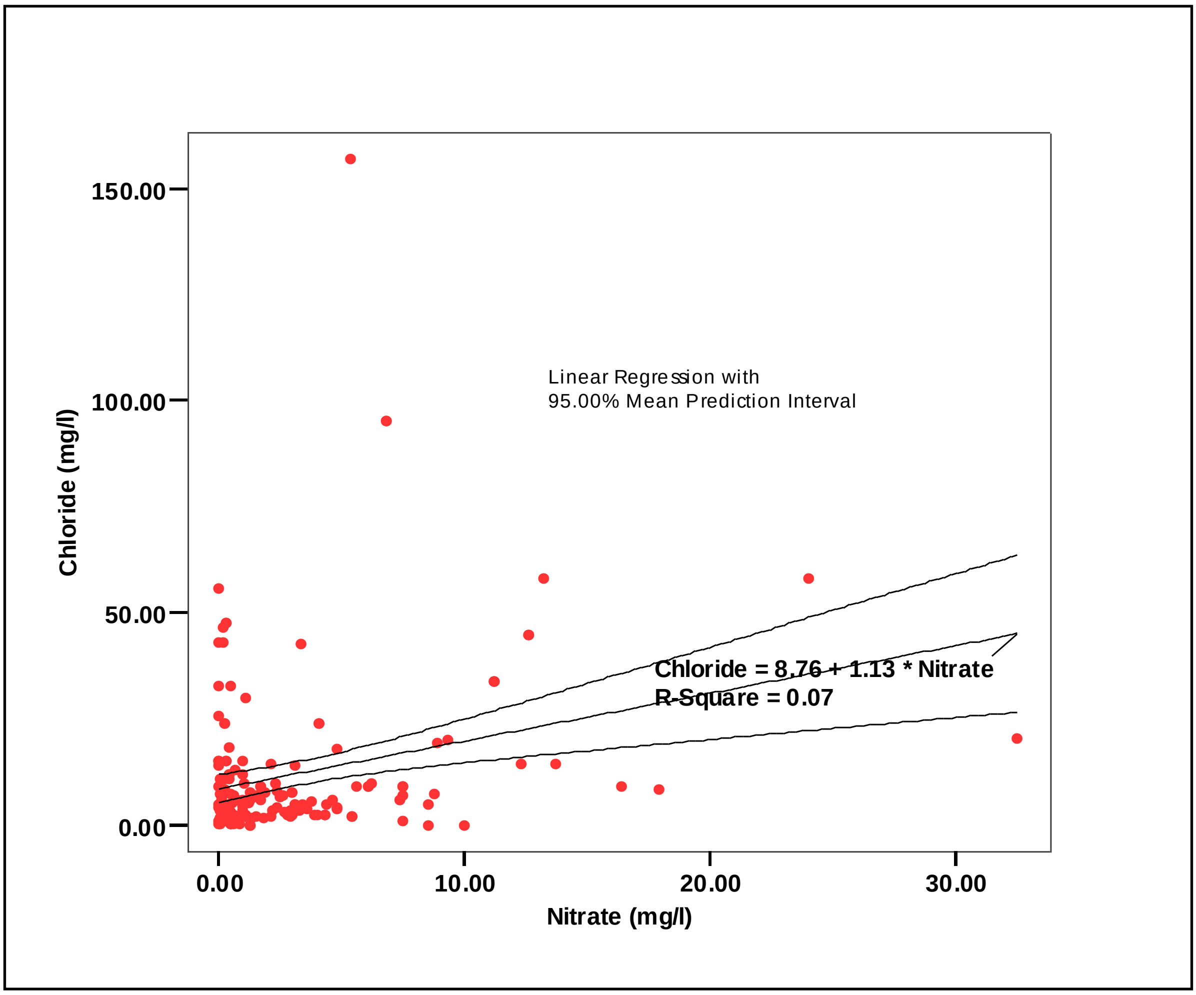


Fig. 6.7 Nitrate and chloride correlation in 169 wells in the minor aquifer area in 2008

The results obtained from wells in minor aquifers during the study period are summarized in Table 6.1 below.

Table 6.1 Summary of results obtained for the period 1977 to 2008/09

Year	No. of wells	Correlation coeff. (r)	Level of significance	Significant relationship
1977	8	0.96	1%	yes
1999	22	0.42	>5%	no
2000	261	0.58	1%	yes
2008/09	12	0.62	5%	yes
2008	169	0.29	1%	yes

From these results it appears that water from minor aquifers were already contaminated in 1977 and that this situation has not improved. The significant linear relationship between chloride and nitrate indicates that contamination is probably due to human waste.

6.2 *Temporal Variation of Nitrate and Chloride in Major Aquifers 1978-2008*

An analysis of 1978 data on nitrate and chloride level in nine wells in the major aquifer area (Fig 6.8), gives a correlation coefficient of r = 0.24. This is not statistically significant, thus showing no linear relationship between the two chemicals.

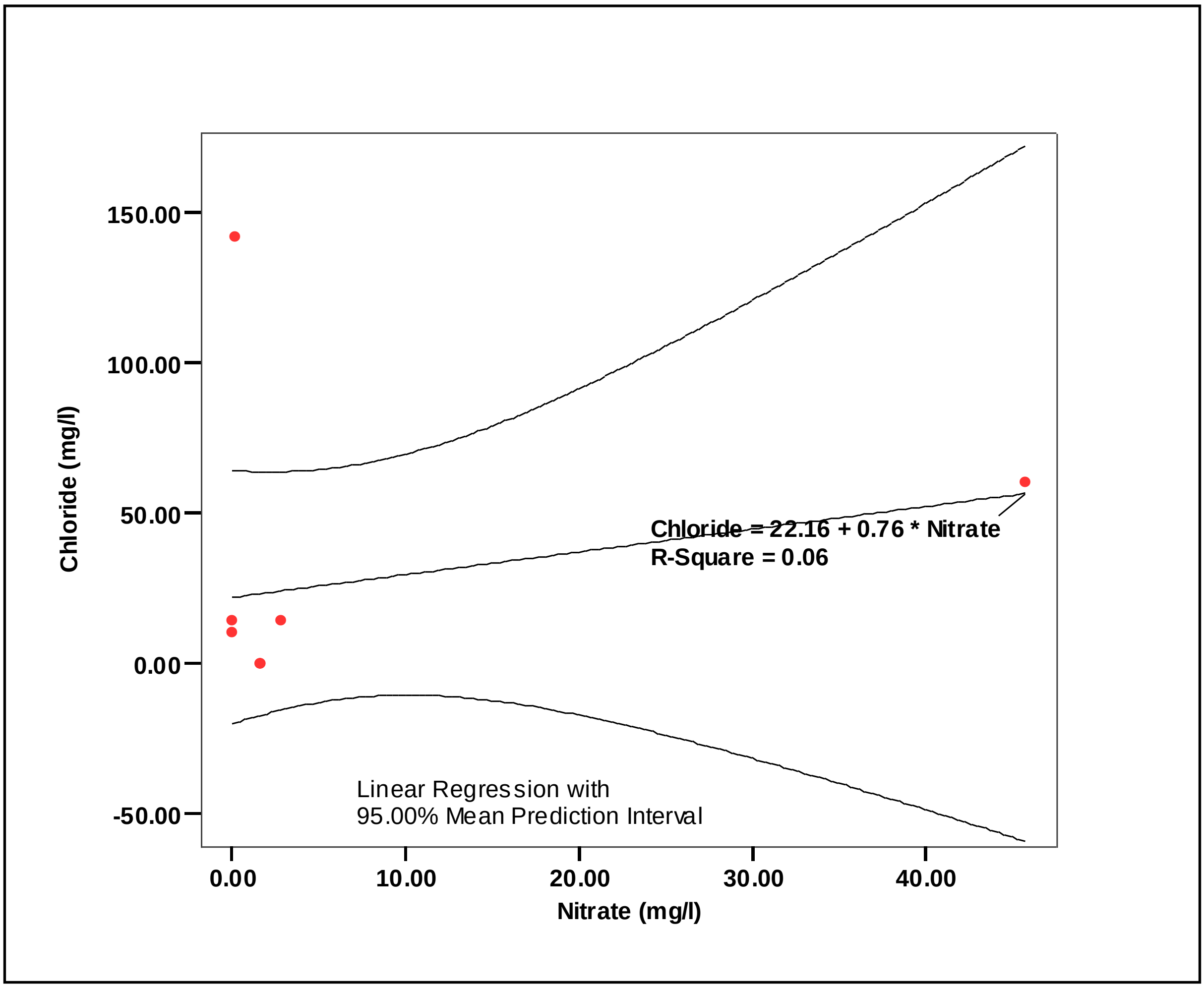


Fig. 6.8 Nitrate and chloride correlation in 9 wells in the major aquifer area 1978

A decade later an assessment of 10 wells in the same area showed a correlation of 0.43 between nitrate and chloride (Fig 6.9), but still does not indicate a statistically significant linear relationship.

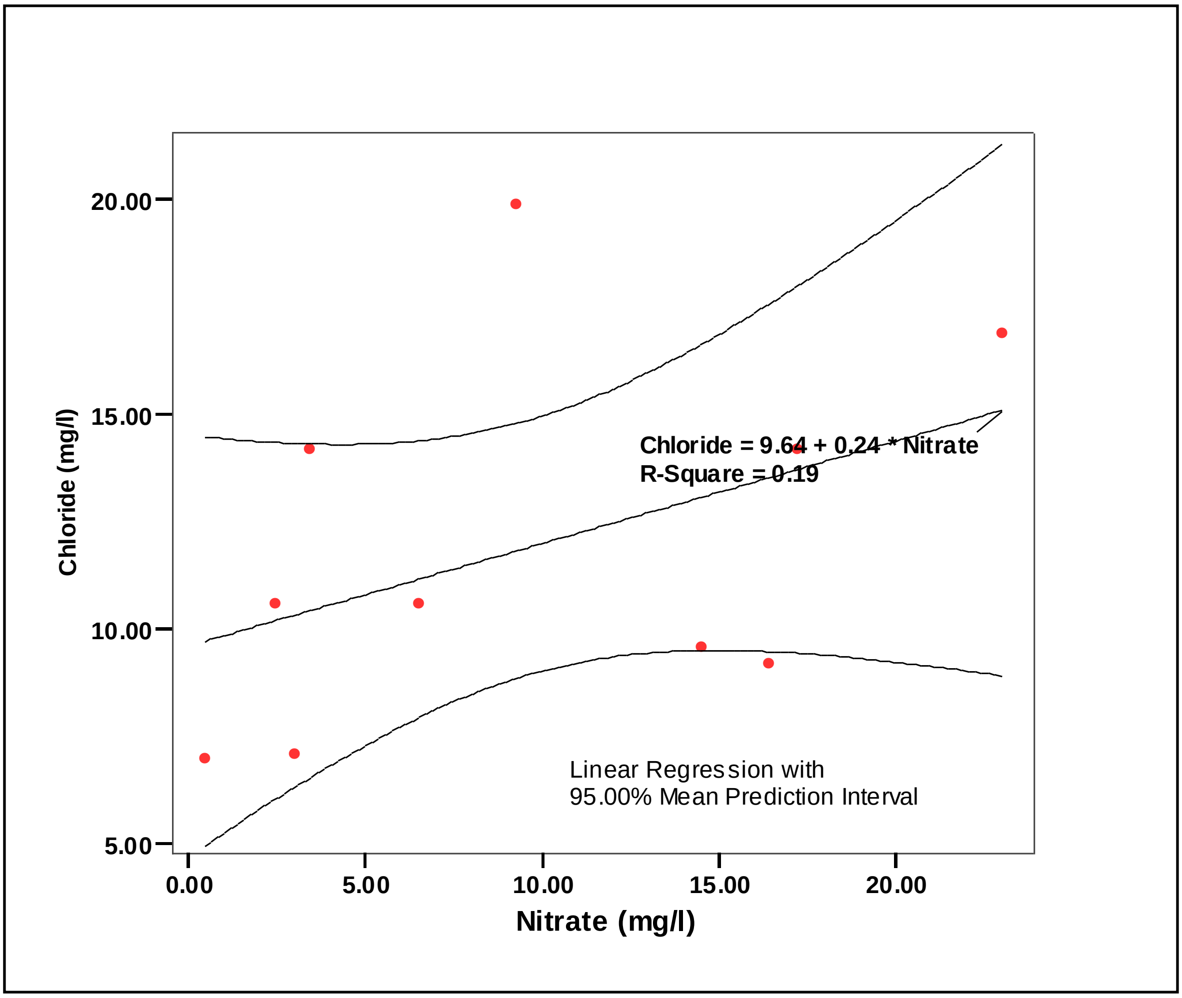


Fig. 6.9 Nitrate and chloride correlation in 10 wells in the major aquifer area 1989

An evaluation of 1999 data for 31 wells in the major aquifer area indicates a correlation coefficient of 0.12 between nitrate and chloride concentrations (Fig. 6. 10). Again, there is no evidence of a linear relationship.

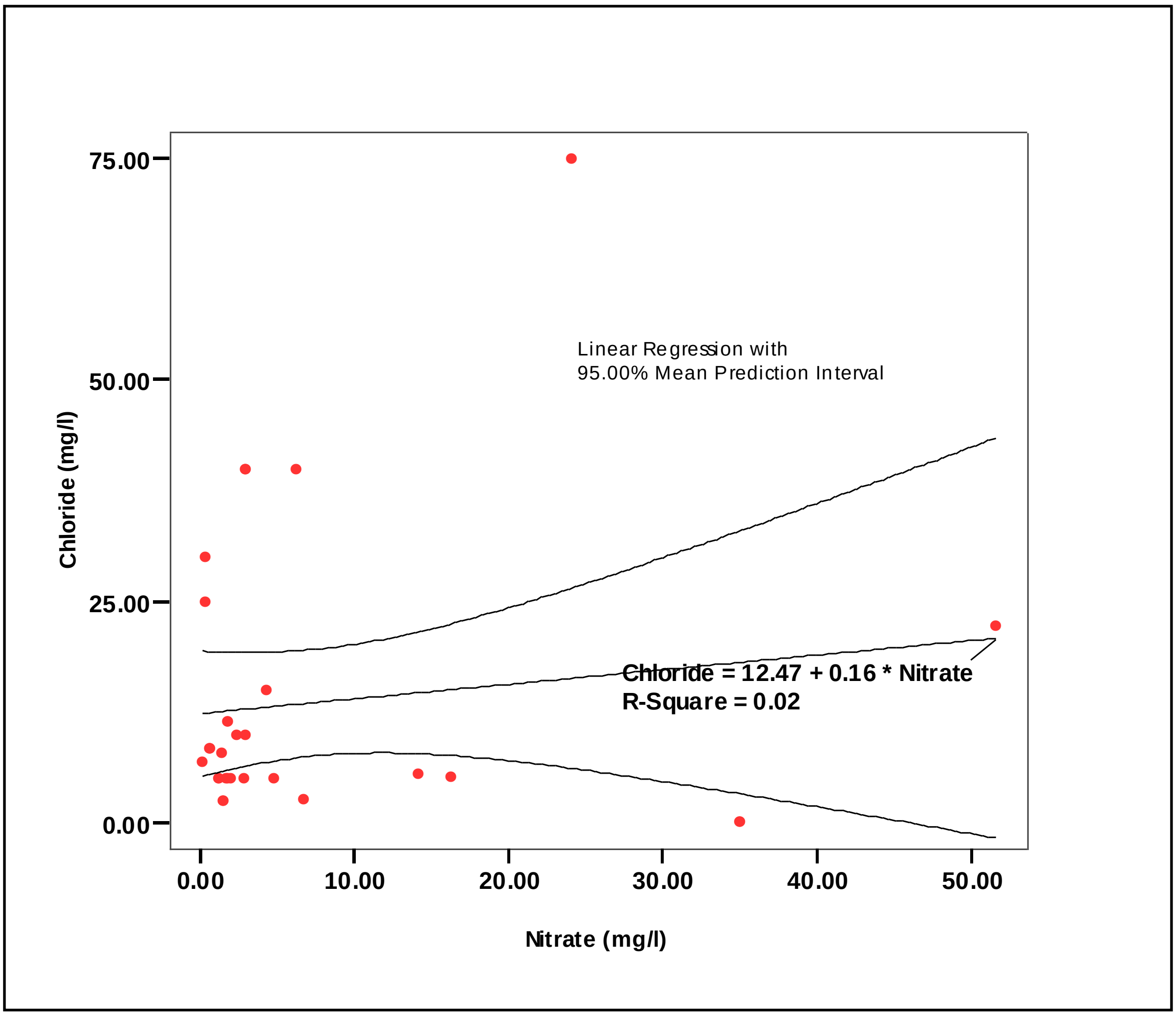


Fig. 6.10 Nitrate and chloride correlation in 31 wells in the major aquifer area 1999

However, when spring water is tested, another picture emerges. For 1999 data, the level of contaminants in 21 springs in the major aquifer area indicates a moderately high correlation coefficient of r = 0.45 between chloride and nitrate content (Fig. 6.11). This correlation is significant at the 0.05 level and indicates that the contamination in spring waters could have originated from human waste.

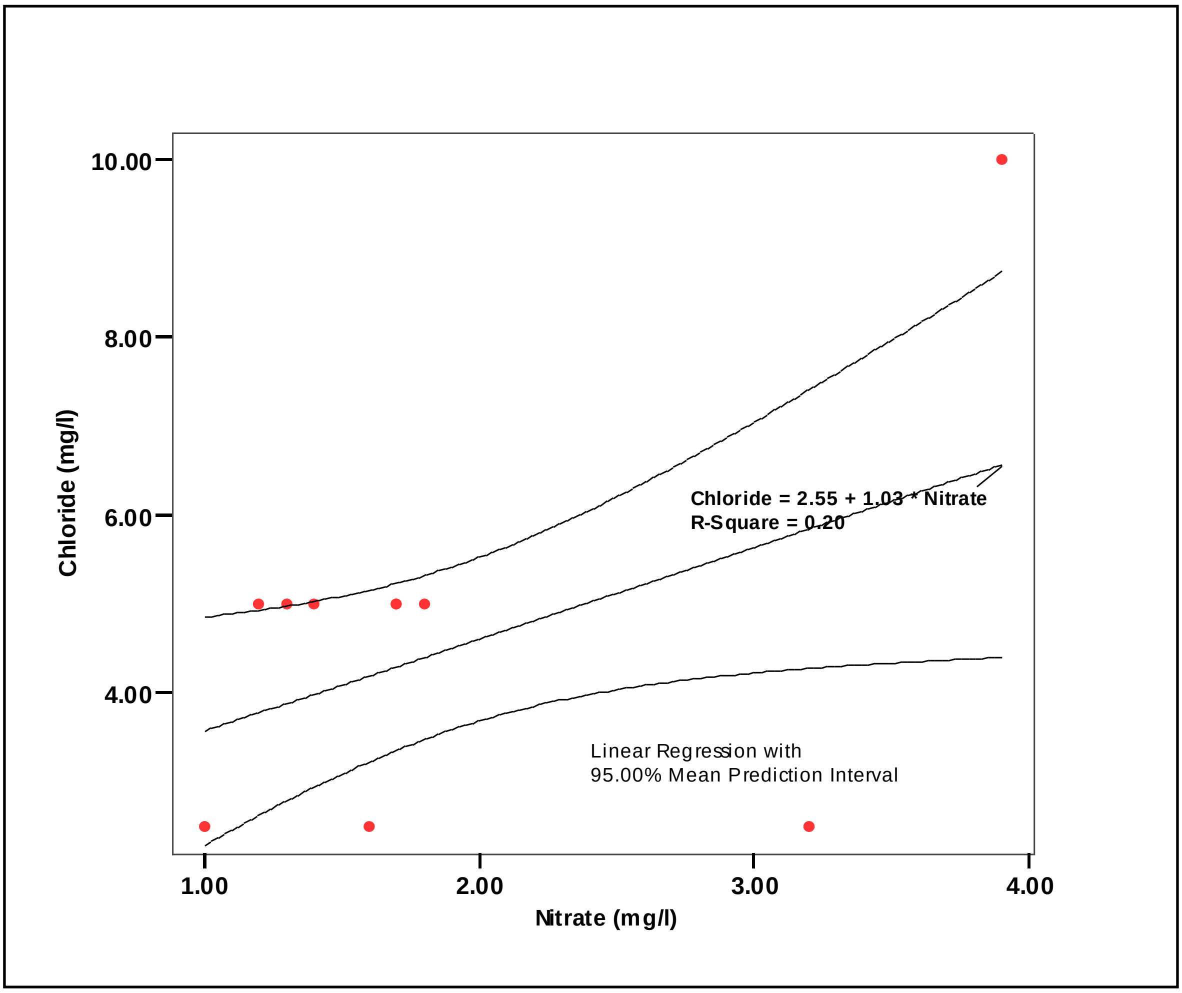


Fig. 6.11 Nitrate and chloride correlation in 1999 in 21 springs in the major aquifer area

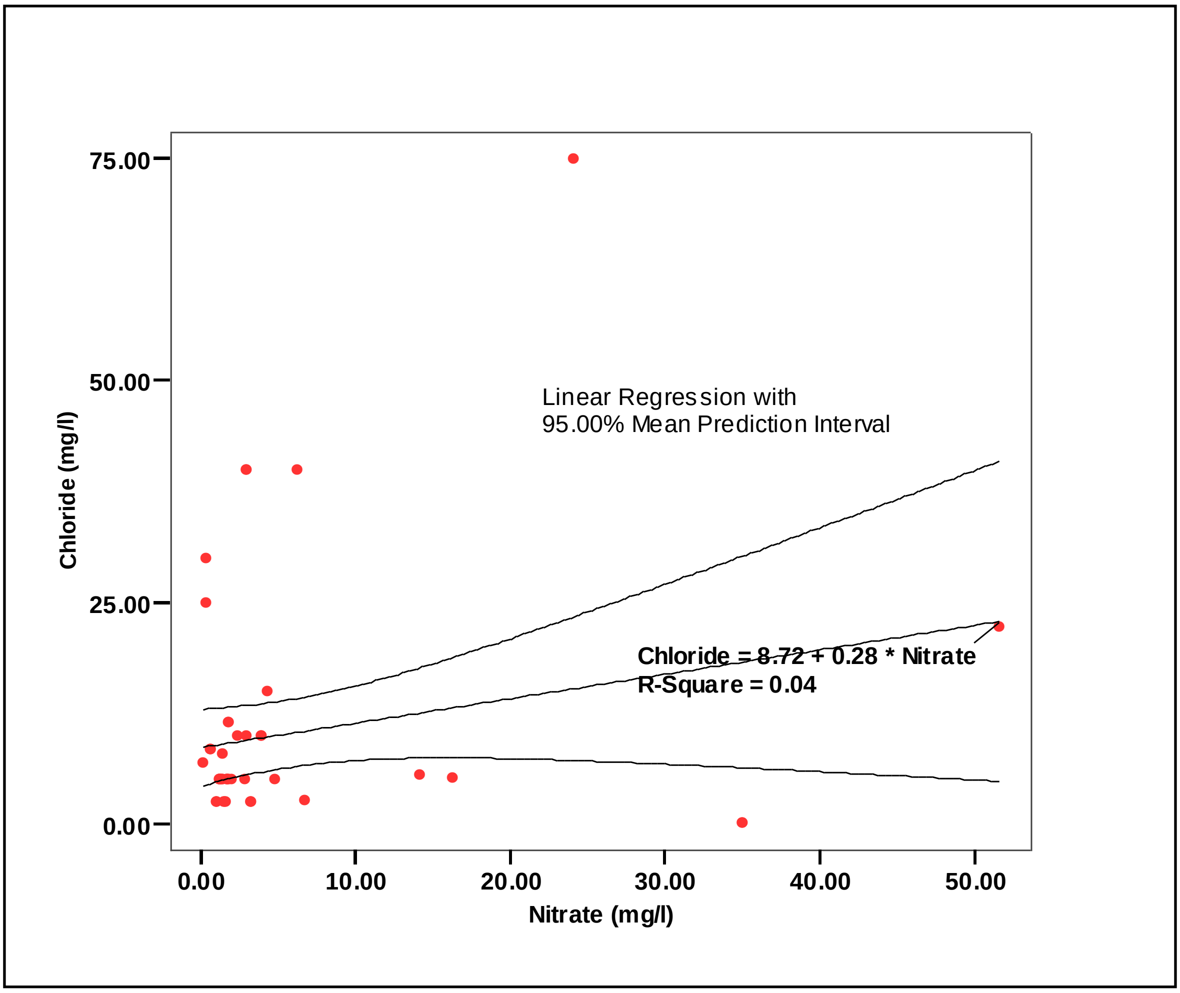


Fig. 6.12 Nitrate and chloride correlation in the major aquifer area 1999

When data for 52 springs and wells in the major aquifer area are combined, a correlation of r = 0.21 was obtained (Fig. 6.12). Since this value is not statistically significant it clearly indicates that there is no linear relationship between chloride and nitrate in major aquifers in Addis Ababa and hence, the major aquifers had not been contaminated by human excreta before 2000. It is not clear why spring water was contaminated, but this might have been due to surface runoff.

The 2000 data on level of nitrates and chlorides in 230 wells suggest a limited tandem occurrence of the two chemicals. This is shown in Fig. 6.13. Pearson's coefficient of correlation between the two chemicals is only 0.01, again showing no linear relationship.

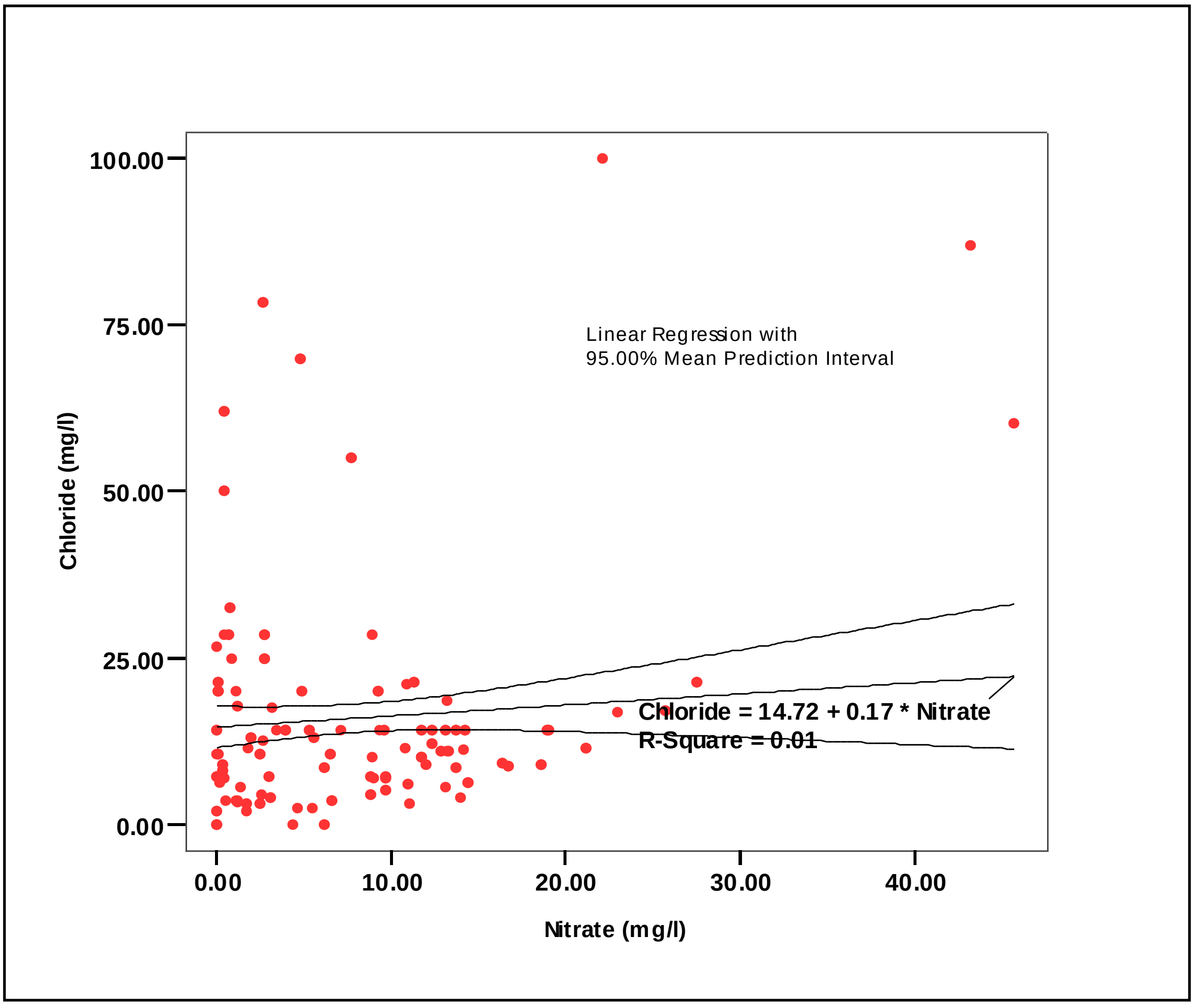


Fig. 6.13 Nitrate and chloride correlation in 230 wells in the major aquifer area in 2000

A similar situation is evident in the more recent 2008 data for 34 wells in the major aquifer area. There is no linear relationship between the two chemicals as shown Fig. 6.14, with r = 0.1.

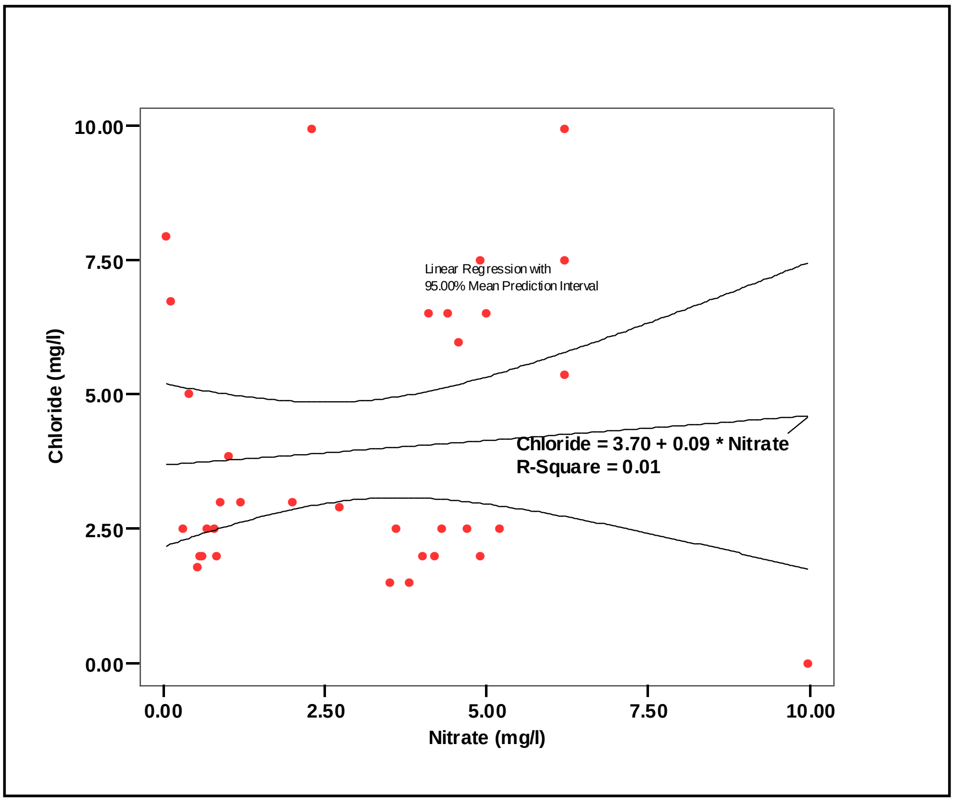


Fig. 6.14 Nitrate and chloride correlation in 34 wells in the major aquifer area in 2008/09

This is confirmed by an analysis of 2008 data for 189 well and springs located in the major aquifer area (Fig. 6.15). This also showed low correlation between levels of nitrate and chloride with r = 0.1. The low correlation between the two chemicals suggests that the nitrates and chlorides may have been sourced from anthropogenic sources other than human waste.

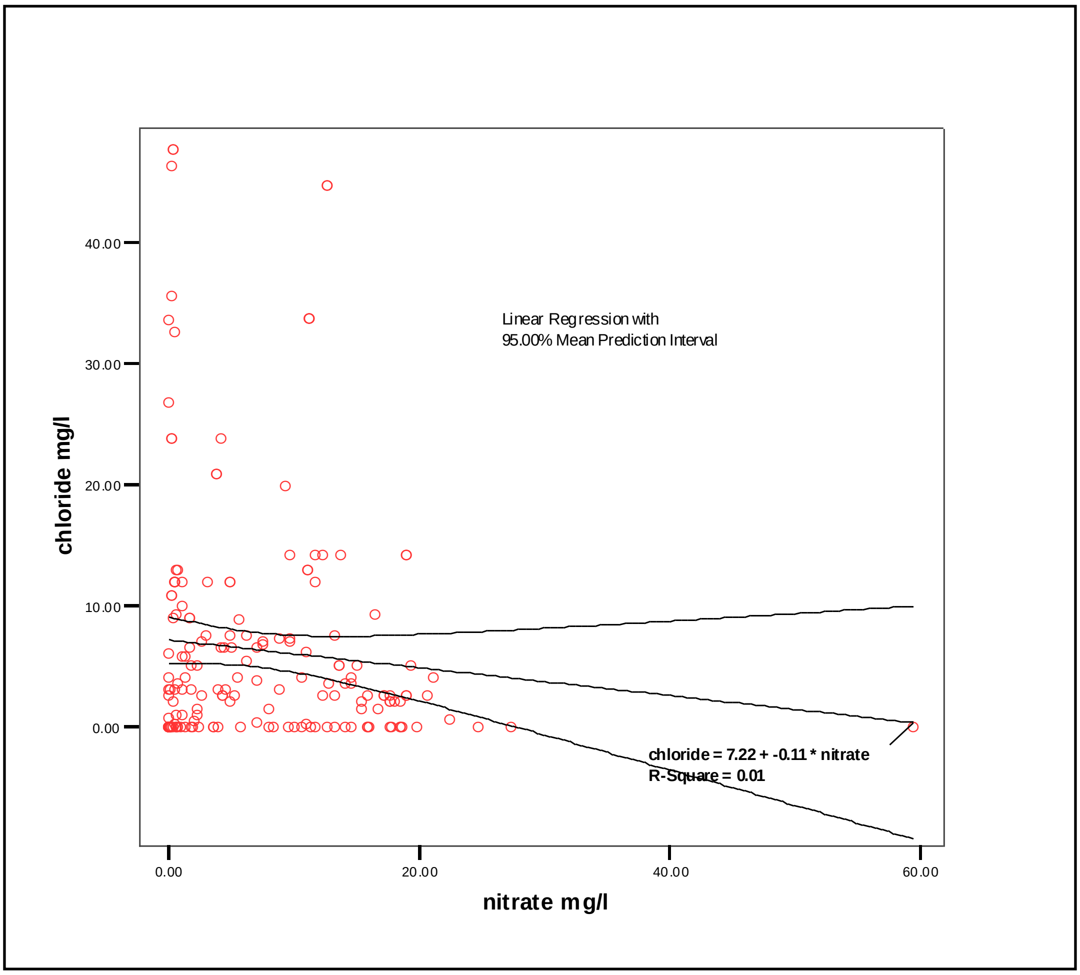


Fig. 6.15 Nitrate and chloride correlation in 189 wells and springs in the major aquifer area in 2008

Table 6.2 provides a summary of the results obtained for the correlation between chloride and nitrate levels for major aquifers for the period 1978 to 2008.

Table 6.2 Summary of results obtained for the period 1978 to 2008 in the major aquifer area

Year	No. of wells/ springs	Correlation coeff. (r)	Level of significance	Significant relationship
1978	9	0.24	>5%	no
1989	10	0.43	>5%	no
1999 (wells only)	31	0.12	>5%	no
1999 (springs only)	21	0.45	5%	yes
1999 (springs and wells)	52	0.21	>5%	no
2000	230	0.03	>5%	no
2008	31	0.10	>5%	no
2008	190	0.10	>5%	no

Comparison of Tables 6.1 and 6.2 indicates that there is a higher correlation of the two chemicals in the minor aquifers in the center of the city. There is no evidence of such contamination in wells obtaining water from the major aquifers. However, the quality of water from springs in the latter area appear to be affected by poor sanitation.

The results of the analyses also indicates that the shallow minor aquifers close to the city center were most contamination-prone. This corresponds well with the built-up area of the city, where the wells may be exposed to anthropogenic sourced contaminants. As there is little agricultural activity in the minor aquifer area, it is possible that the contaminants may have been sourced from human waste origins.

6.3 Temporal patterns of Nitrate and Chloride in aquifers

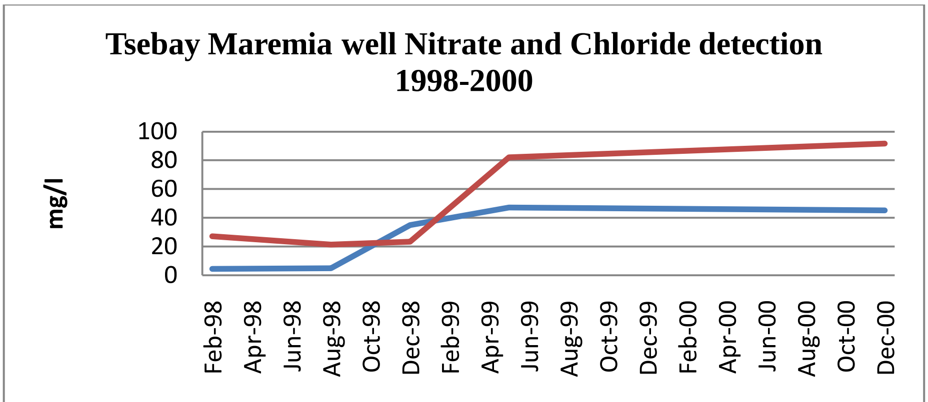
In general, nitrate and chloride levels within the minor and major aquifers has increased over the last decade. As chapter 5 demonstrated a high concentration of pit latrines was associated with the central areas of the minor aquifer. Outlying areas, on the other hand displayed a lower value. Although, nitrate and chloride levels in some cases were lower than the WHO guideline values, a steady temporal increase was observed.

The analysis of grouped well data, whilst useful in rendering a wider perspective, may not give a clear insight into the degree of temporal variation of contaminants in individual wells. The following assessment attempts to analyze temporal contamination levels in individual wells in both major and minor aquifers.

6.3.1 Individual Minor Aquifers wells

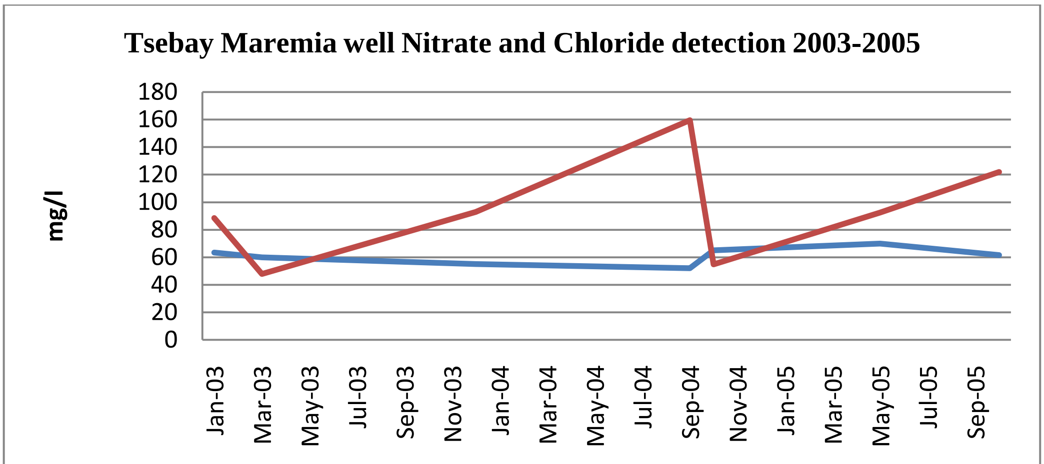
One of the wells which has consistently shown a high level of nitrate is the *Tsebay Maremia* well. This well is located in the minor aquifer area. Aside from the small seasonal variation, the well shows an increase in nitrate concentrations over time, well above the WHO recommended maximum limit of 50 mg/L. The high value of 159.48 mg/L observed in September 2004, at the end of the rainy season, suggests a possible contaminant input from the surface (Fig. 6.16).

The well also exhibited a corresponding temporal increase in chloride levels. Unfortunately the 2008 Chloride content was not recorded. However, compared with other boreholes the level of chloride in the *Tsebay Maremia* well is relatively high.



	Feb-98	Aug-98	Dec-98	May-99	Dec-00
Chloride	4.5	5	35	47.16	45.14
Nitrate	27.2	21.4	23.45	82.04	91.68

Fig. 6.16 Temporal Variation of nitrate and chloride in the Tsebay Maremia well 1998-2000



	Jan-03	Mar-03	Dec-03	Sep-04	Oct-04	May-05	Oct-05
Chloride	63.5	60	55	52	65	70	61.5
Nitrate	88.4	48	93.03	159.48	54.93	92.4	121.83

Fig. 6.17 Temporal Variation of nitrate and chloride in the Tsebay Maremia well 2003-2005

The temporal variation of nitrate and chloride in the wells for the 1998-2000 and 2003–2005 periods are shown in Fig. 6.16 and 6.17, respectively. Comparison of these two figures and the corresponding chloride and nitrate levels, clearly indicates a considerable rise in both chemicals over the 7 year period. Moreover, both chemicals seem to have the same temporal pattern of rising and falling values. This is confirmed by the correlation coefficient of 0.6 (statistically significant at the 5% level) and suggests human waste to be the origin of the contaminants (Fig. 6.18).

There is some evidence of a seasonal pattern in the contamination levels. The peaks during April and May 1998 (Fig. 6.16) and again in August 2004 (Fig. 6.17) may be due to human waste contaminated runoff during the rainy months of March and August. However, the limited amount of temporal data precludes further investigation of seasonality.

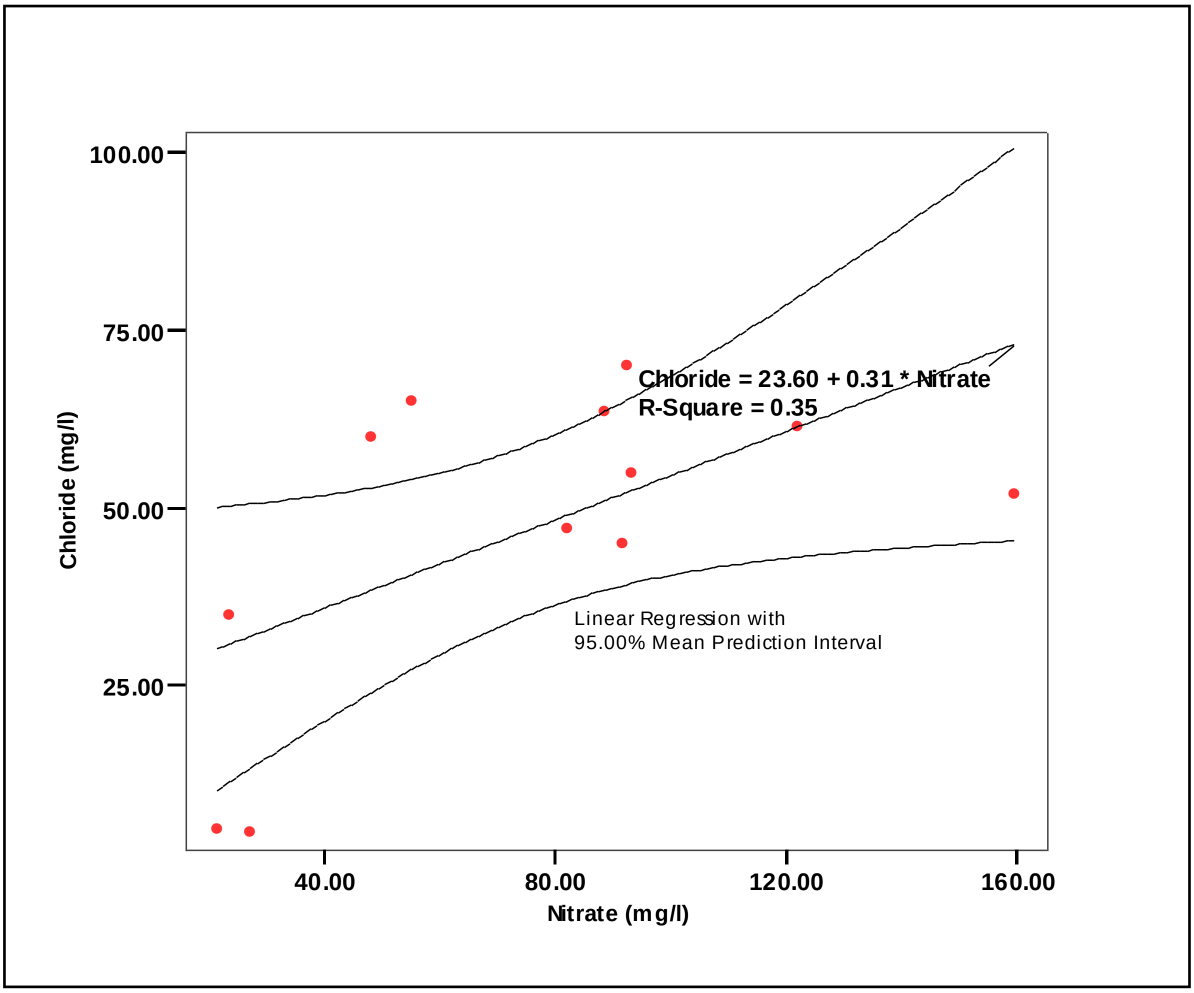


Fig. 6.18 Nitrate and chloride correlation in the Tsebay Maremia well 1997-2009

Other wells located in the city centre have also exhibited elevated nitrate content. Wells utilized by beverage factories and hotels appear to display elevated nitrate content as compared to other wells. Table 6.3 shows data for some of these wells.

Table 6.3 Nitrate level in minor aquifer wells

Factory Name	Date of Observation	Depth (m)	Chloride levels mg/L	Nitrate levels mg/L
Coca Cola Factory	Jun 77	44	35.4	50.7
East African Bottling (Coca Cola Factory)	Sept 00	112	87	43.2
Meher Fiber Factory 2	Jan 78	179.4	60.3	45.7
Meskerem Soft Drinks factory	1993		253	176
Pilsner Brewery (St George. Brewery)	Jan 68		28.36	6.26
Pilsner Brewery 8 (St George. Brewery)	Aug 82	40	62.4	75.3
Pilsner Brewery 2 (St George. Brewery)	Mar 84	34	0	115
AA Brewery BH 9	Jan 00	88	78	97.5
AA Brewery BH 1	Feb 00	36.4	60	74.4
Abay Mesk Soft Drinks Factory W1	1983	121	260	94
Abay Mesk Soft Drink Factory W1	Mar 84	121		311
Akaki Ethio Fiber	Feb 00	96	60.3	45.7
Akaki Ethio Fiber	Sep 1979	96	60.3	45.7
Awash Winery	Jan 67	67.1	248	7
Awash Winery W3	Mar 84	67.1		170
Ras Hotel	Jul 75	41	39	9
Ras Hotel	Mar 84			61
Ras Hotel	Jun 99		41.8	55.3
Africa Hotel	Jun 99	120	59.4	89.9
Africa Hotel	Jan 00	120	67.5	75

The level of nitrate in the St. George Brewery shows a steady temporal increase (Fig 6.19) while the Ras Hotel well shows fluctuation in levels (Fig 6.20). These two wells are located about 5 kms apart in the minor aquifer zone of the city. The elevated nitrate content, may have originated from the effluent in the factory or the hotel itself. In addition the Abay Mesk soft drink factory well 1, with a depth of 121 meters, shows elevated nitrate content. Considering the well depth, this elevated content suggests a direct input from the factory waste water or sewage. It is possible therefore that contaminants sourced from the untreated effluents of the industries as wells as the polluted rivers flowing close by may be finding their way back into the aquifer. Other wells in the vicinity of these wells have also exhibited a steady rise.

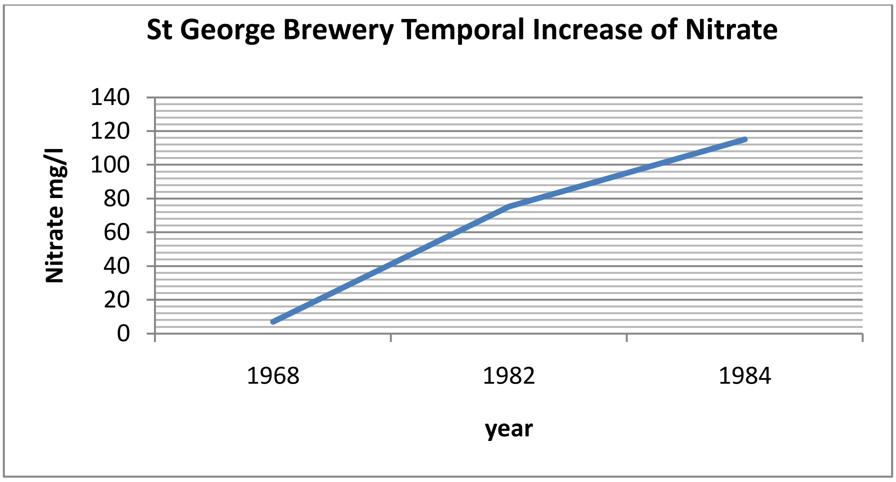


Fig. 6.19 Temporal increase of nitrate in St. George Brewery well 1968-1995

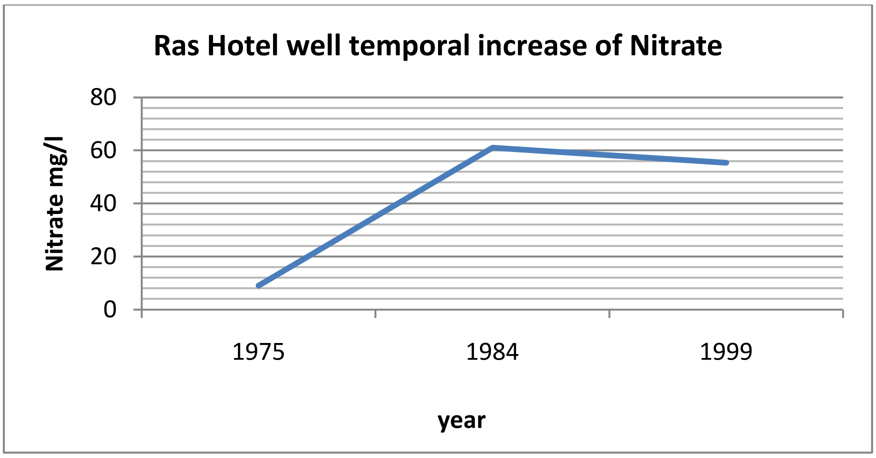
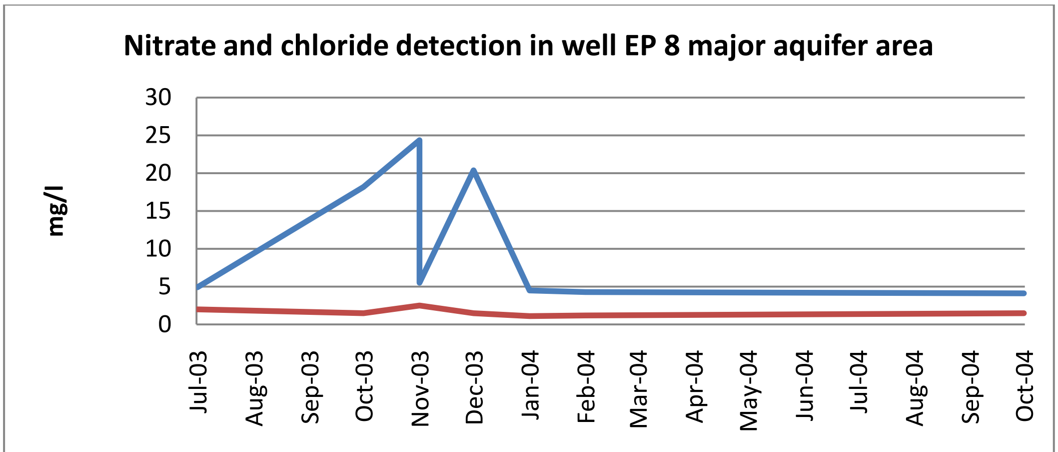


Fig. 6.20 Temporal increase of nitrate in Ras Hotel well 1975-1999

6.3.2 Individual Major Aquifers wells

Individual wells in the major aquifer area located to the south of the minor aquifer, have also shown varying levels of nitrate and chloride. Well EP 8 located in the Akaki well field, showed a nitrate level of 18.16 mg/L in July 2003 which increased to 24.37 mg/L in October 2003 (after the major rainy season) and then decreased to 4.92 mg/L in December 2003 (Fig. 6.21). The fluctuations within that period suggest that the well may have been exposed to an external nitrate input. A sharp fluctuation is observed in the nitrate content for one year's duration during 2003-04 (Fig. 6.21). After January 2004 the observed values appear to remain low at about 4.5 mg/L. In 2008 however, observed values have been noted to increase to 16.4 mg/L.



	Jul-03	Oct-03	Nov-03	Nov-03	Dec-03	Jan-04	Feb-04	Oct-04
Nitrate	18.16	24.37	5.5	20.38	4.92	4.1	4.5	4.3
Chloride	1.5	2.5	2.5	1.5	2	1.5	1.1	1.2

Fig. 6.21 Temporal variation of nitrate in well EP 8 Major aquifer area (2003-04)

As shown in Fig. 6.22 the nitrate and chloride correlation in well EP 8 is very low at 0.17. No linear relationship is evident between the two chemicals, suggesting the chemicals could have originated from anthropogenic sources other than human waste.

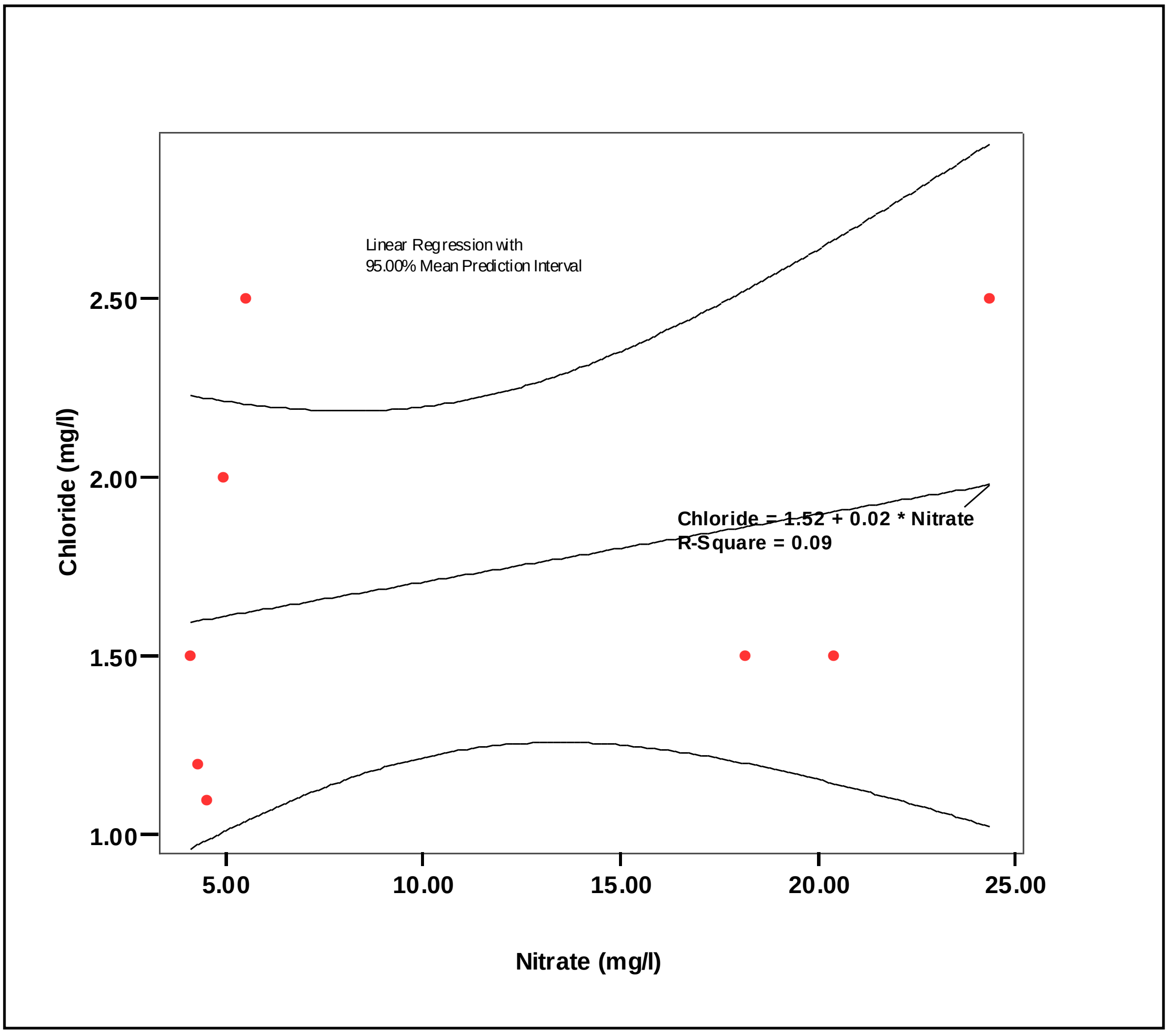
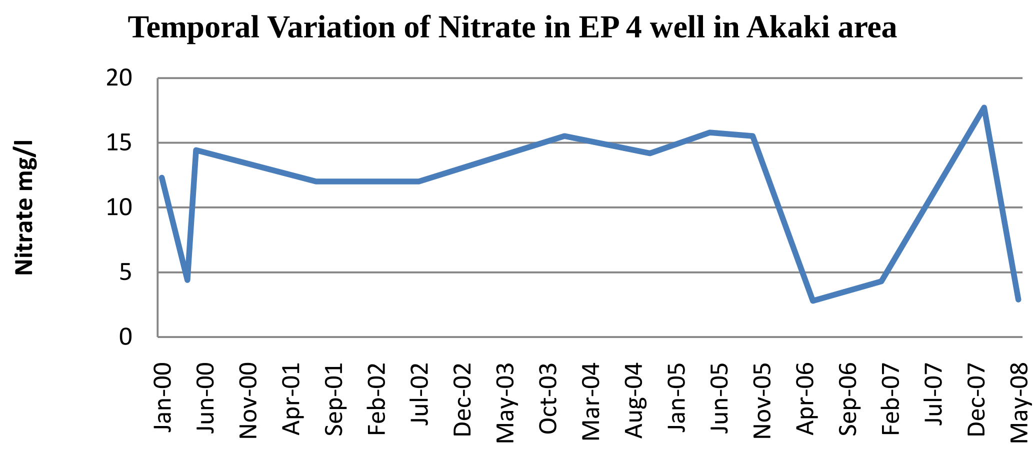


Fig. 6.22 Nitrate and chloride correlation in well EP 8 major aquifer area

Borehole EP 4 in the same area also exhibits a similar fluctuation in nitrate content (Fig. 6.23). The change in nitrate content exhibits no predictable trend. The sharp fluctuations could possibly be due to external sources.



	Jan-00	Apr-00	May-00	Jul-01	Jul-02	Dec-03	Oct-04	May-05	Oct-05	May-06	Jan-07	Jan-08	May-08
Nitrate	12.3	4.4	14.42	12	12	15.51	14.18	15.8	15.51	2.8	4.3	17.72	2.88

Fig. 6.23 Temporal variation of nitrate in borehole EP 4 Major aquifer area

6.4 3 Major Aquifer Springs

Springs in the city have also shown high nitrate levels. Some of the springs, including the Lideta and Gebriel Abo springs, are found in the vicinity of churches and are considered as medicinal, '*Tsebels'* 'holy waters'. These springs show elevated nitrate content, the continual consumption of which may threaten human health. The following table (Table 6.4) summarizes observed data in some selected springs.

Table 6.4 1990–2004 nitrate and chloride levels in springs in minor aquifer area,

Spring Name	Date of Observation	Chloride levels mg/L	Nitrate levels mg/L
Chefe Spring	Aug 90	2	88
Fanta Spring	Jan 91	5	11.75
Fanta Spring	Oct 96	8.5	10.12
Fanta Spring	Nov 99	10	17.16
Fanta Spring	Dec 03	2	10.63
Fanta Spring	Jun 04	9	18.61
Ayat Spring	Oct 97	6	21.38
Spring 8	Dec 99	2.5	14.08
Asco Spring	May 99	4.34	26.4
Addisu Gebeya Spring	Jun 99	0	184.6
Gabriel Abo Spring	May 99	0	116.07
Saris Spring	May 99	146.44	66.61
Lideta Spring	Jun 99	194	728.21
Lideta Spring	May 03	130	27.9
Lideta Spring	Jul 03	105	12.5
Lideta Spring	Aug 03	125	22
Lideta Spring	Nov 03	65	13
Lideta Spring	Dec 03	125	21.6
Ras Mekonnen Bridge Spring	Jun 99	56.5	481.41
Yeka North Spring	Jun 99	2.2	55.34

The linear correlation of nitrate and chloride values in 20 springs in the minor aquifer area show a correlation coefficient of 0.42 (Fig. 6.24) which falls just outside the 5% level of significance. It is thus possible that the springs were contaminated from a variety of anthropogenic sources, some of which may have been human excreta.

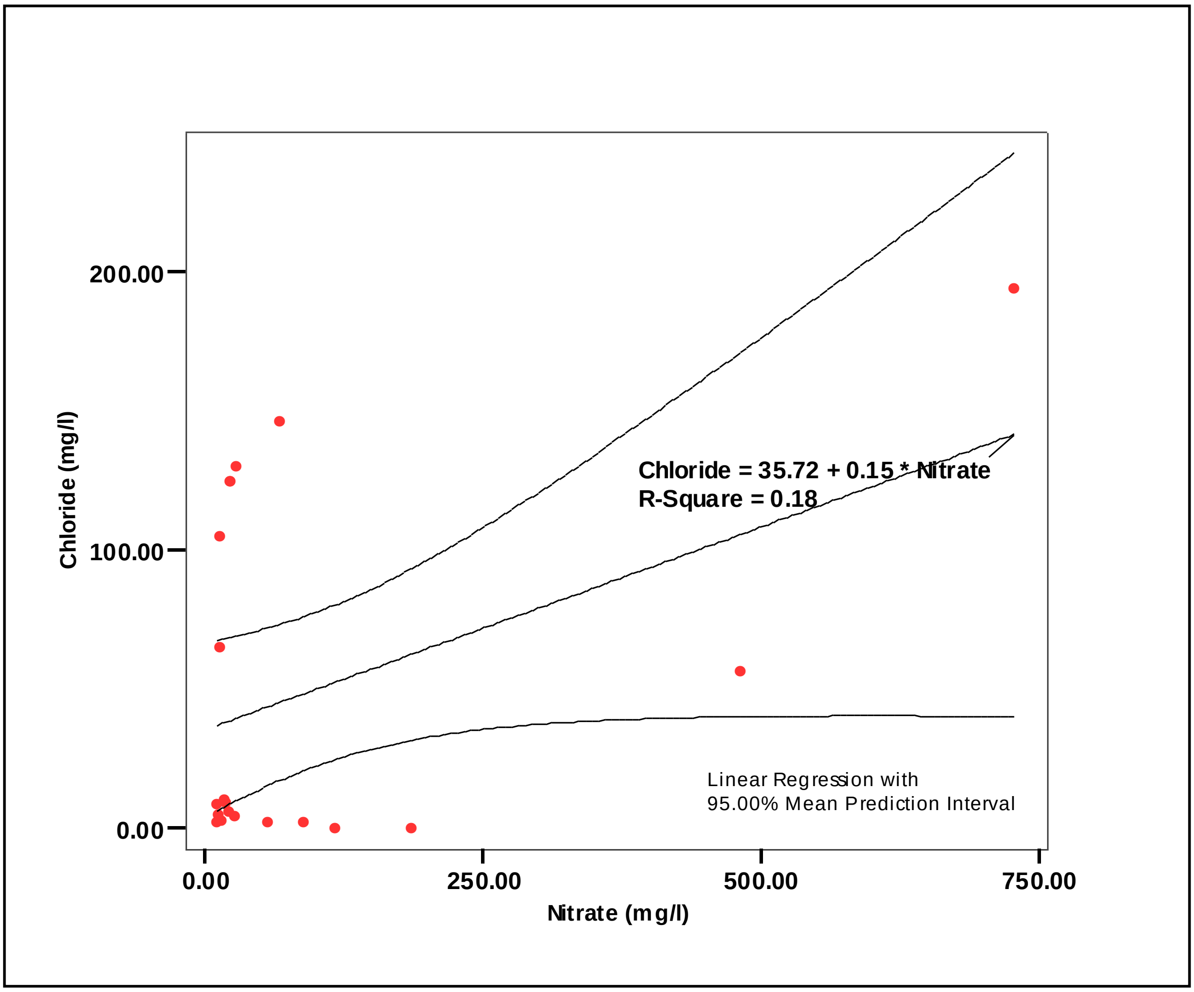
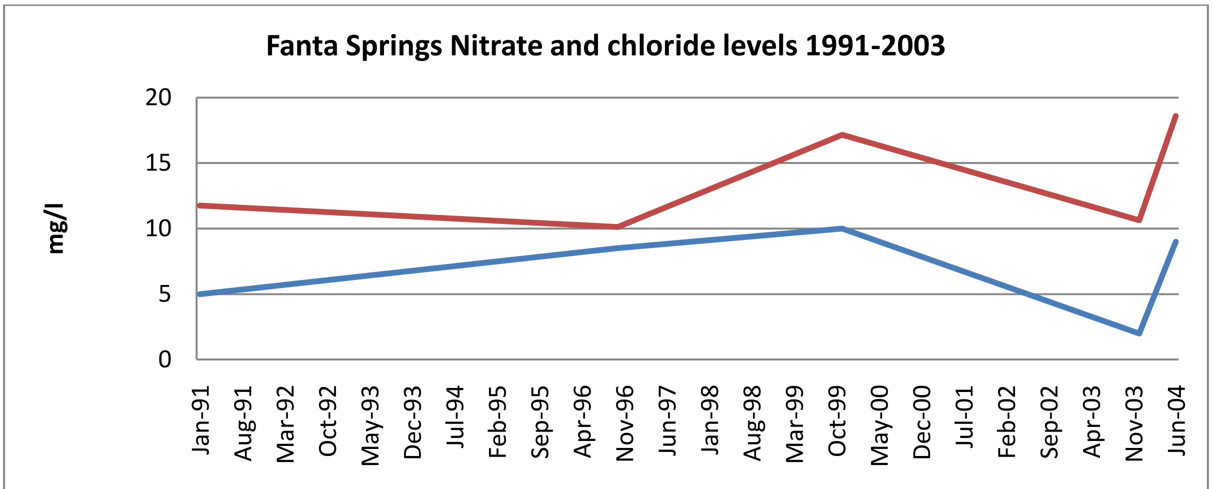


Fig. 6.24 Nitrate and chloride correlation in 20 springs in the minor aquifer area

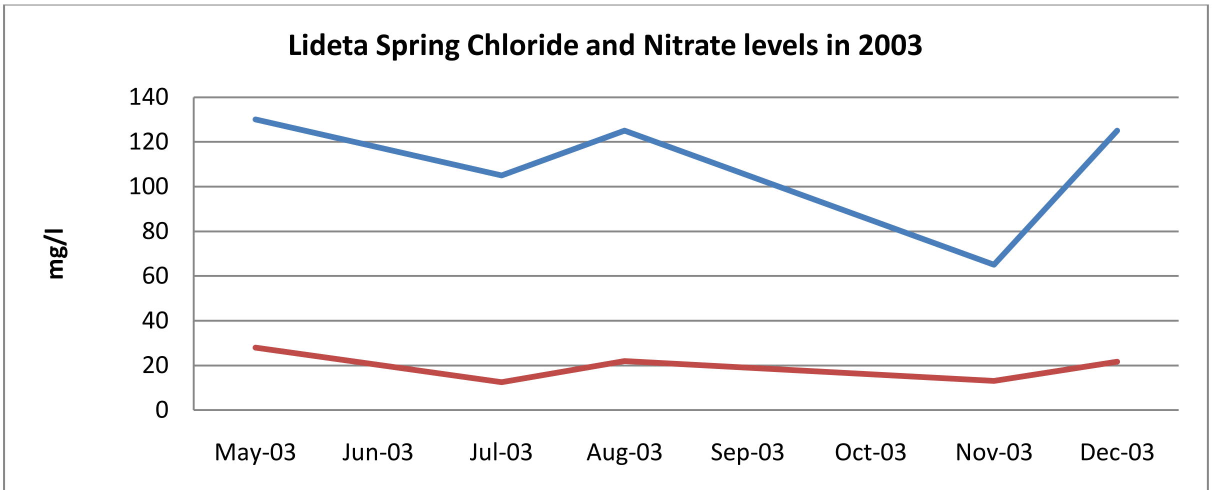
When analyzing chloride and nitrate levels in individual springs, an interesting picture emerges (Fig. 6.25). Although low, the correlation coefficient between nitrate and chloride in the Fanta springs appears to suggest no linear relationship between the two chemicals, both values peak during October 1999 and reach a minimum in November 2003. In view of the small number of data points available for Fanta springs, it was decided to use Spearman's Rank Correlation Coefficient (r_s) to indicate possible linear relationships. The r_s was found to be 0.94, indicating a highly significant relationship between chloride and nitrate levels. This finding indicates that, at least some of the contamination, could be due to human waste. The difference in r and r_s, values might be due to a combination of various sources of waste.



	Jan-91	Oct-96	Nov-99	Dec-03	Jun-04
Chloride	5	8.5	10	2	9
Nitrate	11.75	10.12	17.16	10.63	18.61

Fig. 6.25 Temporal variation of nitrate and chloride in the Fanta springs area (Major aquifer area)

Analysis of the Lideta spring data showed a high nitrate level at 728.21 mg/L and chloride at 194 mg/L in June 1999. Both contaminants decrease over time. It is noticeable that the high value corresponds with the beginning of the rainy season. Excluding this high value, which may possibly have originated from direct human waste contact, or direct sewage flow, and evaluating 2003 levels shows the following trend (Fig. 6.26).



	May-03	Jul-03	Aug-03	Nov-03	Dec-03
chloride	130	105	125	65	125
nitrate	27.9	12.5	22	13	21.6

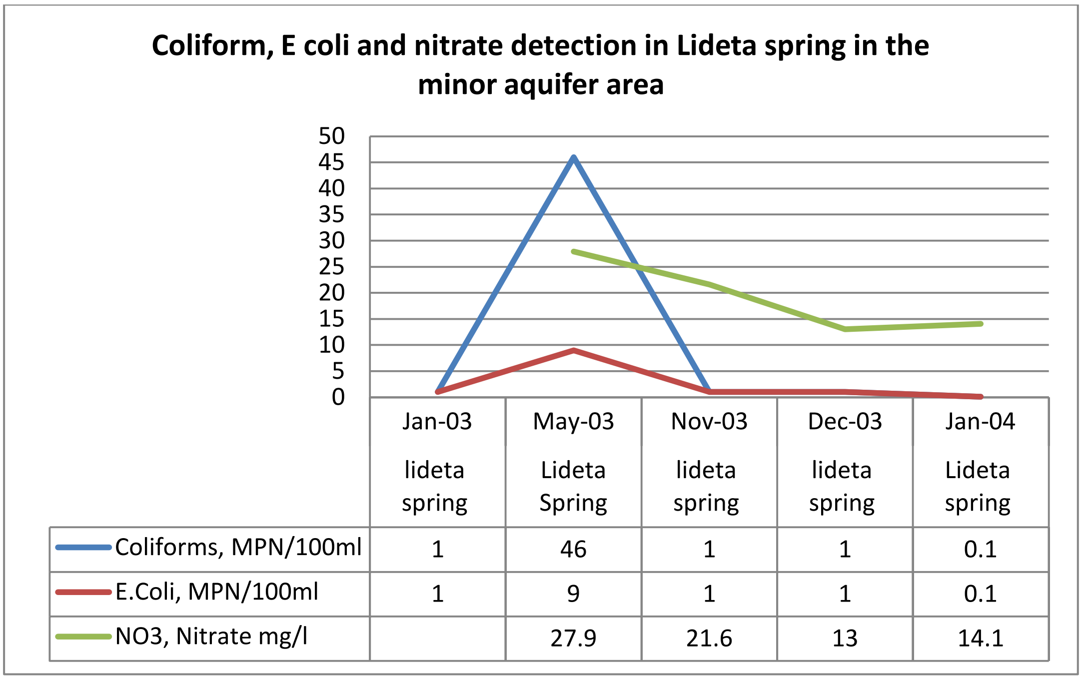
Fig. 6.26 Temporal variation of nitrate and chloride in the Lideta spring (minor aquifer area)

Again, although levels are comparatively low, the simultaneous variation suggests a possible seasonal variation. This may have been due to springs located in shallower aquifers being exposed to a higher contamination risk from anthropogenic activities. This is confirmed by an r_s value of 0.95.

The Lideta spring is also located in highly populated areas, as compared to the Fanta springs which are located at the peripheries of the city. This may have been one reason why comparatively elevated nitrate content is observed in the Lideta spring.

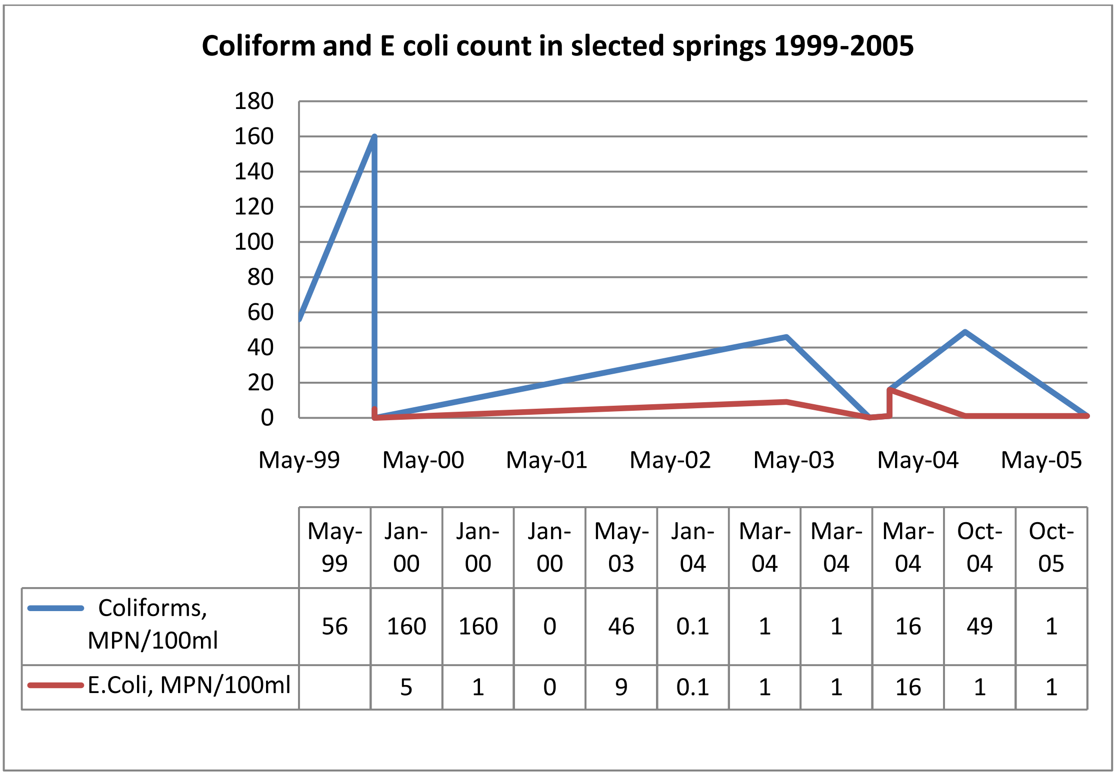
6.5 Faecal Contamination Indicators

A review of historical water quality test data has shown that the primary focus of analyses was on testing physio-chemical parameters only. Compared with these data, the bacteriological test data were not as plentiful; nevertheless, all available data on coliform concentrations has been analyzed. Fig. 6.27 to 6.32 show coliform and E-coli contamination in various wells and springs.



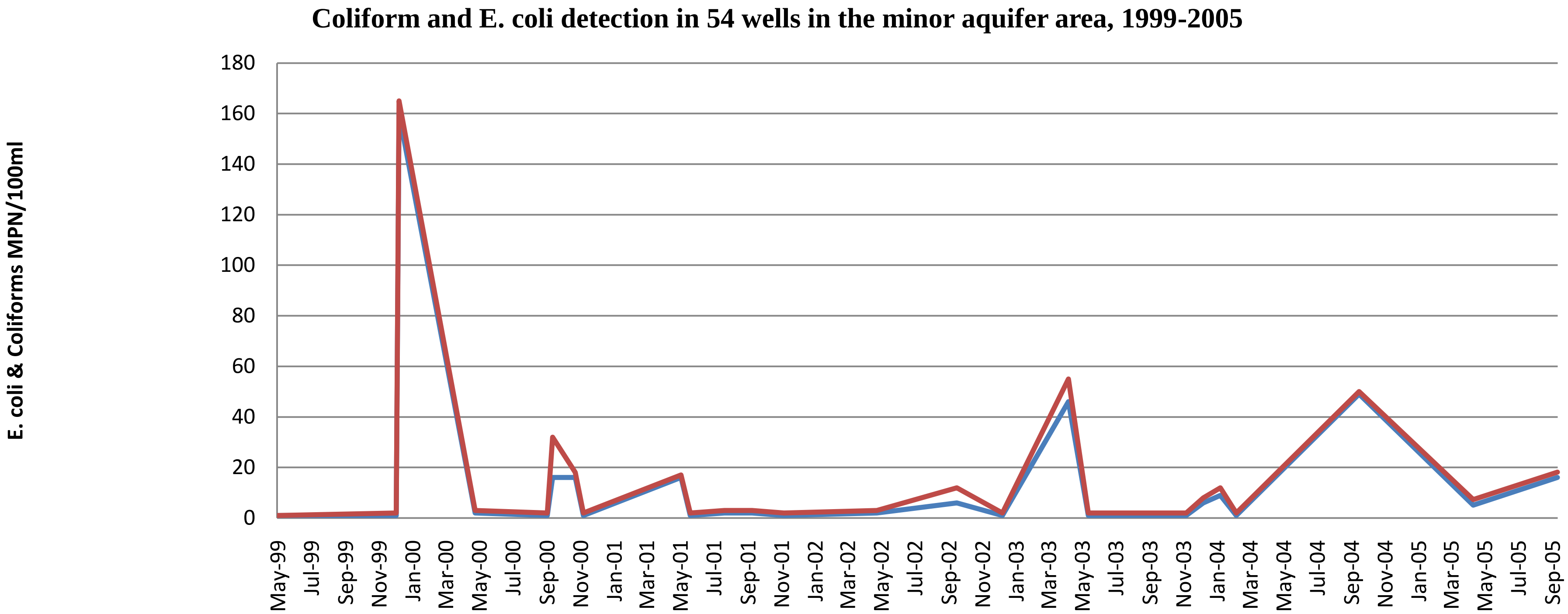
	Jan-03 lideta spring	May-03 Lideta Spring	Nov-03 lideta spring	Dec-03 lideta spring	Jan-04 Lideta spring
Coliforms, MPN/100ml	1	46	1	1	0.1
E.Coli, MPN/100ml	1	9	1	1	0.1
NO3, Nitrate mg/l		27.9	21.6	13	14.1

Fig. 6.27 Coliform and E. coli concentrations in the Lideta spring in minor aquifer area 2003-2004



	May-99	Jan-00	Jan-00	Jan-00	May-03	Jan-04	Mar-04	Mar-04	Mar-04	Oct-04	Oct-05
Coliforms, MPN/100ml	56	160	160	0	46	0.1	1	1	16	49	1
E.Coli, MPN/100ml		5	1	0	9	0.1	1	1	16	1	1

Fig. 6.28 Temporal variation of coliform and E. coli in selected springs 1999-2005



	May-99	Dec-99	Jan-00	May-00	Sep-00	Oct-00	Nov-00	Dec-00	May-01	Jun-01	Aug-01	Oct-01	Nov-01	May-02	Oct-02	Jan-03	May-03	Jun-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Oct-04	May-05	Oct-05
E.Coli, MPN/100ml		1	5	1	1	16	2	1	1	1	1	1	1	1	6	1	9	1	1	1	2	3	1	1	2.2	2.2
Coliforms, MPN/100ml	1	1	160	2	1	16	16	1	16	1	2	2	1	2	6	1	46	1	1	1	6	9	1	49	5.1	16

Fig. 6.29 Coliform and E. coli concentration in 54 wells in minor aquifer area 1999-2005

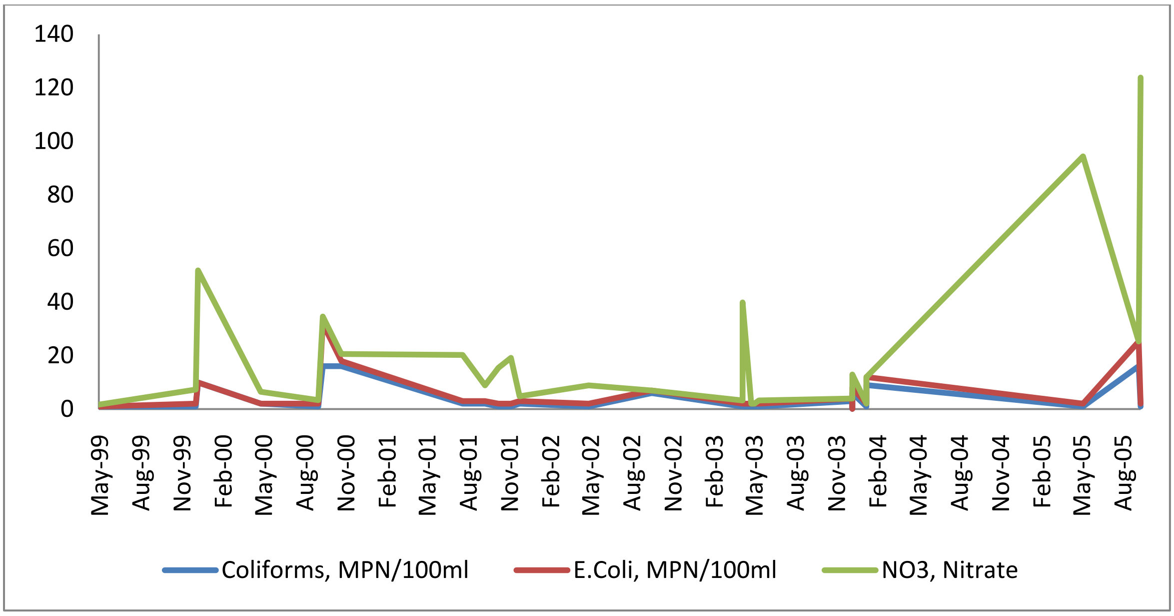


Fig. 6.30 Coliform, E. coli and nitrate concentrations in 15 wells in minor aquifer area 1999-2005

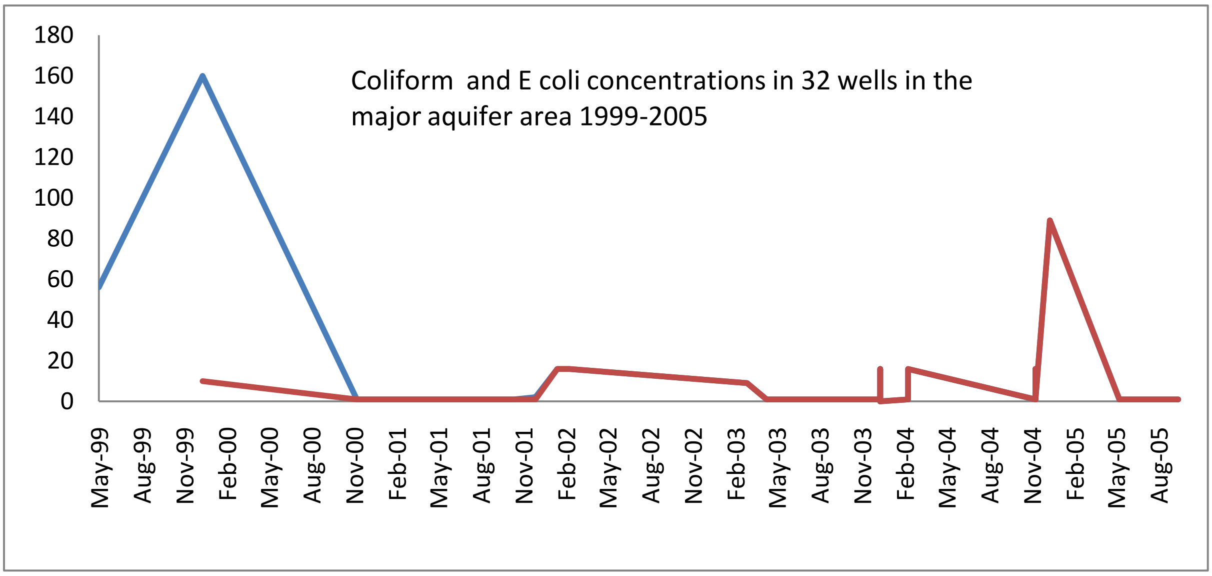


Fig. 6.31 Coliform and E. coli concentration in 32 wells in major aquifer area 1999-2005

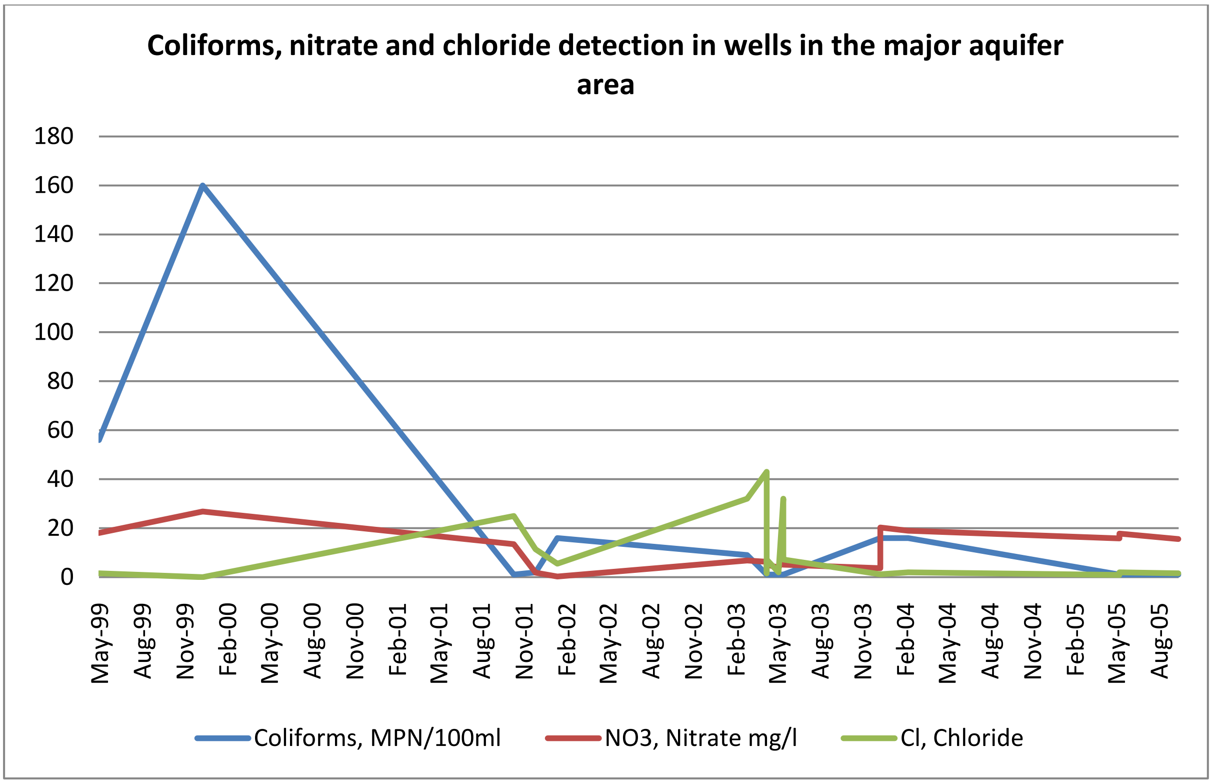


Fig. 6.32 Coliform, E coli and nitrate concentration in 12 wells in major aquifer area 1999-2005

The WHO recommends that drinking water should not contain any E. Coli (WHO, 2006). It is thus assumed that the presence of E. coli in water indicate contamination by human excreta. The Ayat spring located on the periphery of the minor aquifer area has shown a coliform count of 1400 MPN/100 ml and E. coli count of 140 MPN/100 ml in 1997. In 2004 E. coli count decreased to 16 MPN/100 ml. In other wells and springs the level has been comparatively lower. Nevertheless elevated levels correspond with high nitrate contamination areas.

The higher levels also appear to correspond with the rainy season. Comparatively elevated numbers of coliforms have been detected in March or August both periods of elevated rainfall.

These figures indicate that the springs and wells in minor aquifers have been contaminated with human waste for a considerable period. The level of contamination varies over time, and in some cases such as springs at Lideta, has improved in quality over the last few years. Of the two, minor aquifers are relatively more contaminated than water from major aquifers. This accords well with the results obtained previously. It is also interesting to note that nitrate concentrations alone are not good predictors of faecal contamination.

6.6 Variation of Nitrate and Chloride with Depth of Wells

Table 6.5 and 6.6 show the nitrate content in shallow and deep wells, respectively. Comparison of these tables suggest that shallow wells have higher nitrate content than deeper wells.

Table 6.5 Nitrate levels in shallow wells

Well name	x	y	Depth	Nitrate levels mg/L	Date observed
Korean Embassy	468425	996350	68	283	01/12/1996
Awash Winery	469900	996000	67.1	40.5	
Tikur Abay Shoe Factory	466200	1001008	53	22	
Coca Cola factory 2	470000	996400	44	50.68	20/06/1977
Minilik school	474009	998554	41	41.8	01/02/2000
Ras Hotel	472675	996208	41	55.3	03/06/1999
Abay Mesk Soft Drinks Factory	473100	992600	40	94	01/08/1983
Addis Ababa Brewery-1	471600	995800	36.4	74.4	
Addis Ababa Brewery	471600	995800	34	74.4	01/02/2000
Mean			47.2		

Table 6.6 Nitrate content and depth variation in selected deep wells

Well name	X Coordinate	Y Coordinate	Depth m	Nitrate levels mg/L	Date observed
Summit SMV 14	485290	994522	290	12.6	11/03/2008
SMV 14			270	12.4	2008
Abo church Ferensay			250	7.84	2008
Alem bank Kidanemihret			250	6.8	2008
Kolfe Keranyo	468268	996584	240	17.9	03/09/2008
Test well 3			220	9.7	2008
Test well 5			220	11	2008
Test Well No. 5	485798	968308	217	11	01/03/2000
Summit Medhanealem			210	11.2	2008
Meher Fiber Factory (Akaki) 2	475336	980717	179.4	45.7	01/01/1978
Water III test well	481200	980000	173	11.7	01/02/2000
Kaliti Food Share Co.	475300	985080	170.76	14.52	26/06/1989
Bassefa Trading Kaliti Shell Depot			166	14.1	01/02/2005
Misrak Flour Mills factory	473500	992900	162	13.2	01/02/2000
Akaki WOW international Plc			161	12.5	22/05/2005
Satcon, Bisrate Gabriel area	469750	993850	150	14.96	28/02/2001
Water III Borehole BH19	478019	977985	150	13.13	13/05/1997
Water III Borehole	479246	977104	146	25.7	01/02/2000
Akaki Water well EP 8	478998	977937	130	16.4	03/01/2000
Abay Mesk Soft Drinks factory (Pepsi Cola)	473000	992700	121	26.4	
Chereka Leprosy Patients Multi Purpose Asso. Alert area			100.7	18.25	01/01/2006
Africa Hotel	471700	996300	96	75	
Mean			185.1		

The relationship between nitrate and depth in shallow wells is illustrated in Fig. 6.34.

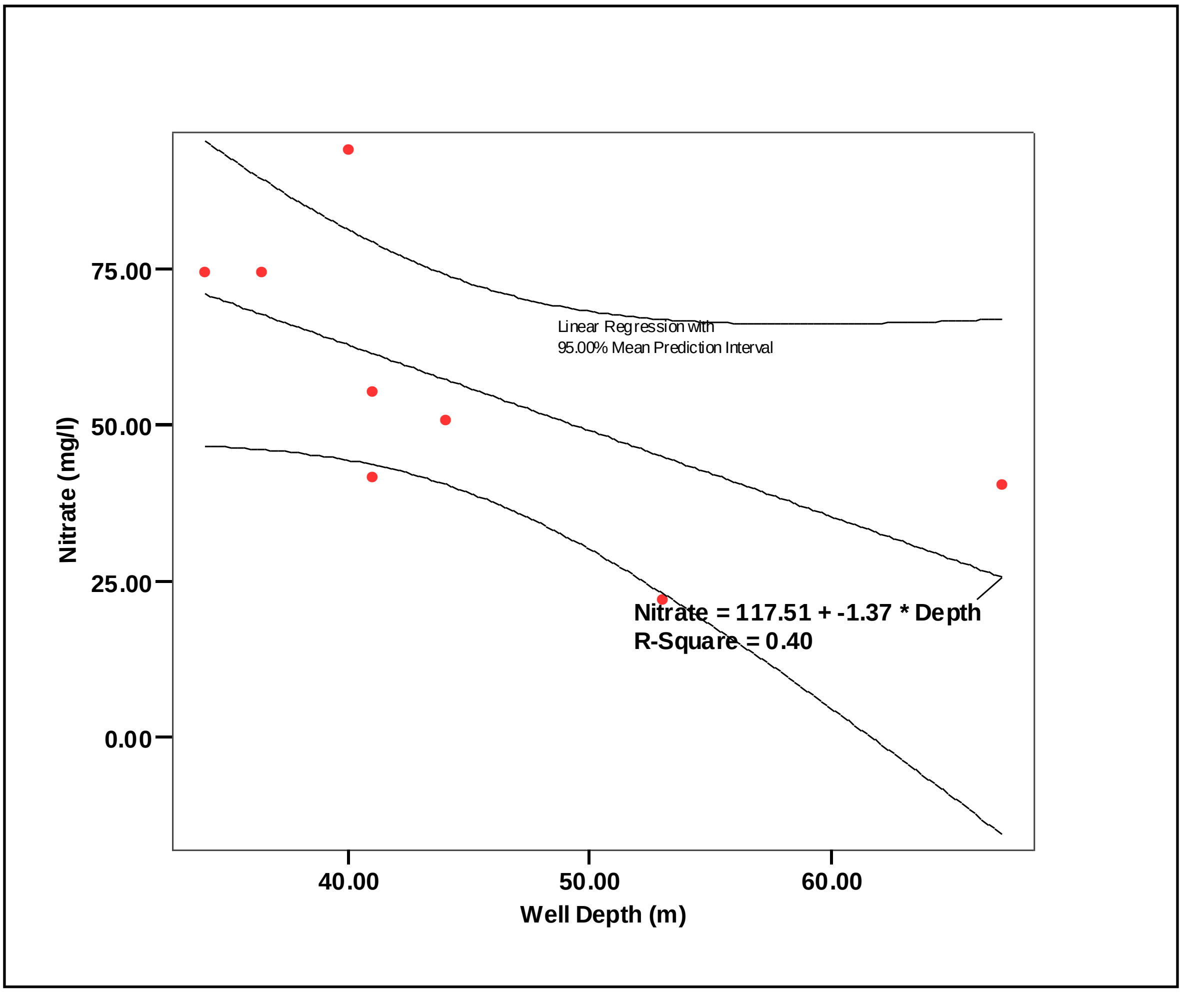


Fig 6.33 Nitrate levels in shallow wells

Excluding the abnormally high value of nitrate detected in the Korean Embassy well, which may have been due to a direct contamination from anthropogenic sources, Fig. 6.33 shows a strong negative correlation between nitrate content and depth ($r = 0.63$; $r_s = -0.083$). The nitrate content thus decreases with depth. This seems to be logical since the water in shallow wells is closer to surface sources of contamination. This accords well with findings reported by Lilly *et al*. (2001) for Scotland.

However, deep wells are also showing signs of nitrate contamination (Table 6.6), suggesting that deeper aquifers may also be vulnerable. An analysis of the relationship between nitrate levels and depth in deep wells indicates an inverse relationship with r = -0.50 (significance level = 5%) (Fig. 6.34).

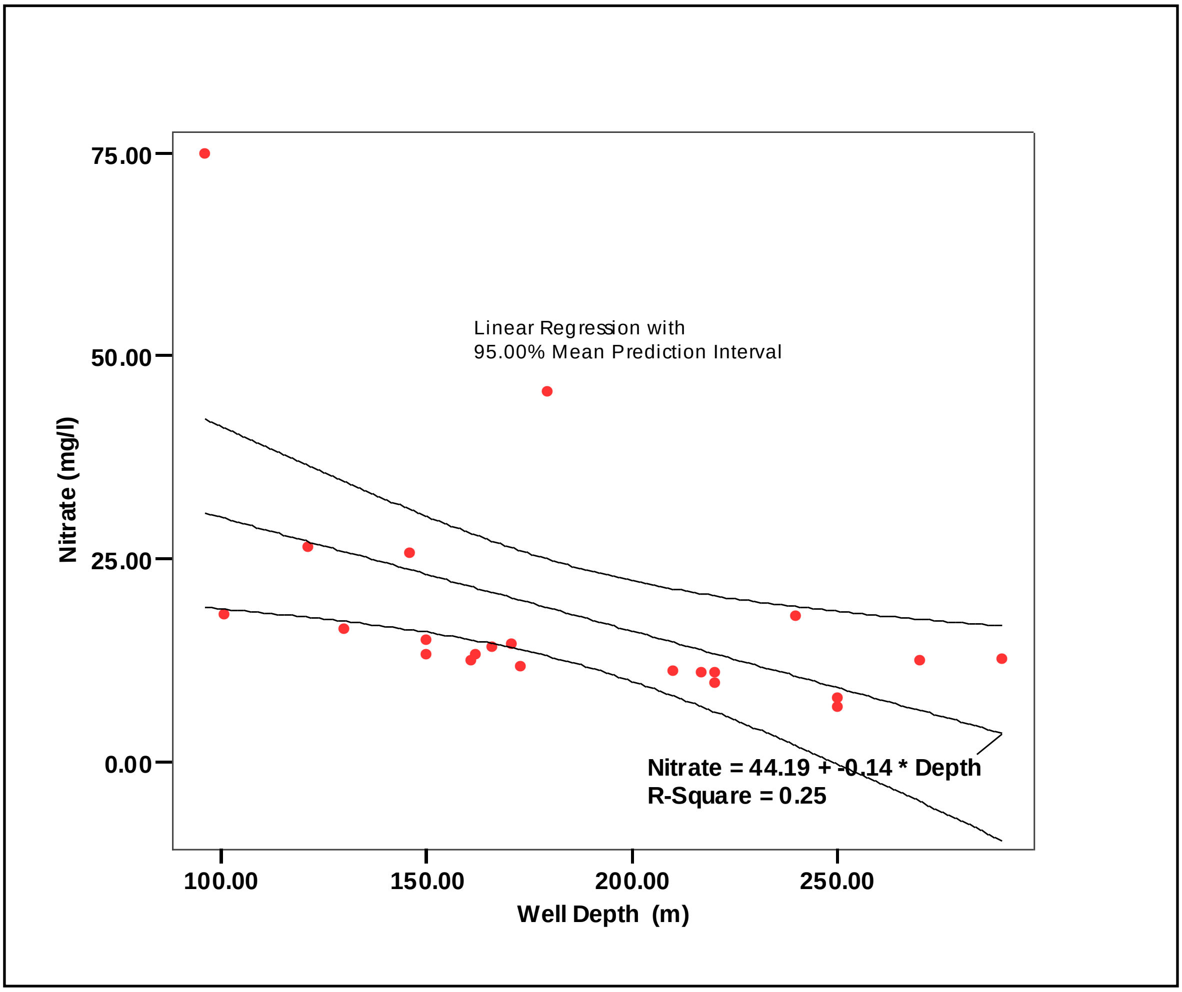


Fig. 6.34 Nitrate level and depth of wells

No conclusion can be drawn from these results concerning the origin of the nitrate contamination since Lilly *et al.* (2001) found that there is a poor relationship between the incidence of nitrate and coliform organisms. In addition, Goss *et al*. (1998) demonstrated that while nitrate concentration decreased with depth, the coliform levels did not. Decreases in nitrate could be due to the de-nitrification process, whereas bacteria multiply and increase number over time and hence with depth.

Recently drilled wells are also comparatively deeper than older wells. This may possibly be due to the utilization of modern drilling equipment, capable of deeper drilling. Alternatively it may be an effort to tap deeper aquifers with high yield. Observations of drilling in the city as well as discussions with drilling agencies have suggested, drilling is stopped once a sufficient yield is obtained. This implies that the intention may not be tapping deeper aquifers but mainly a search for water.

The increasingly deeper wells (over 200 meters deep) being drilled indicate that the groundwater table may be receding, possibly due to over-abstraction. The following graph indicates a steady increase in well depth over the years (Fig. 6.35).

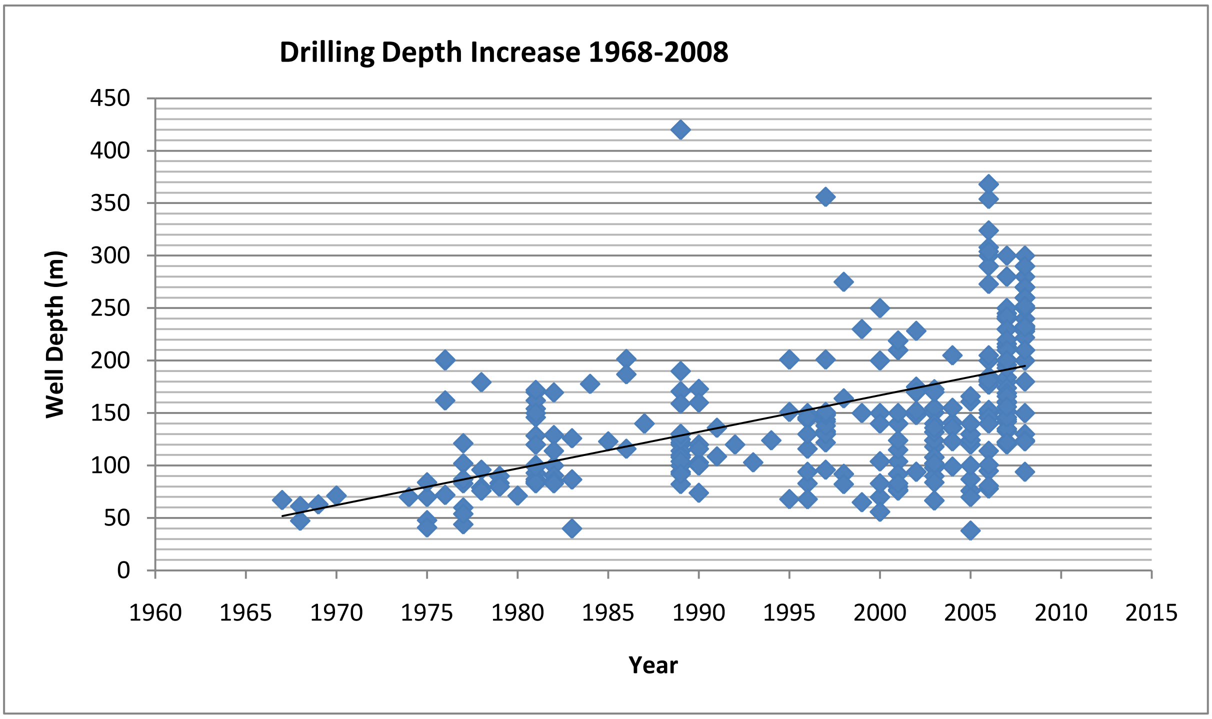


Fig 6.35 Temporal increase in well depth

The above analysis suggests that groundwater in the minor and major aquifer areas of the city have been exposed to contamination by nitrates and chlorides for quite some time. The increasing depth of newer wells also suggest that groundwater level may be receding.

In summary: the data analysis showed the presence of contaminants, primarily in the minor aquifer areas. This corresponds with the high population density in the same area. The southern areas and peripheries of the city, which are less densely populated, showed a low spatial increase of contaminants. The increase in contamination has been periodic rather than linear. This might correspond to periods of heavy rainfall where human waste is washed into wells or may percolate into shallow aquifers.

7 Spatial Extent of Groundwater Contamination

An assessment of the spatial extent of contamination was carried out on both the minor (central city areas) and major (south-western areas) aquifers. The assessment, as obtained from Arcview 3.2 software analysis revealed varying degrees of contamination in the aquifers. The extent of the contamination on the minor aquifer area is initially discussed below followed by review of the major aquifer areas.

7.1 Minor Aquifers, 2000 to 2008/09

The minor aquifer area covers a large part of the highly populated city center. It is located at a lower elevation, and has a high concentration of pit latrines. Contamination maps indicate that this minor aquifer area has elevated nitrate content. Superimposing the built-up area map of the city on the contamination contour maps also shows that the high nitrate and chloride levels coincides with this highly populated area located at lower elevations.

This suggests that contamination may have been enhanced by the higher number of pit latrines concentrated in the area. In addition to this, surface runoff from higher areas to lower elevation areas may also have contributed to the elevated nitrate detection. Hence the elevated nitrate and chloride levels may have been caused by proximity of polluted rivers to groundwater, high density of pit latrines in habited areas and low surface elevation. It appears that within aquifer contamination in the minor aquifer areas may not be as significant.

Observation of the maps shows that, in 2000, few boreholes in the minor aquifer area exhibited a nitrate content of 45.3 to 56.7 mg/L (Fig. 7.1). The rest of boreholes showed a nitrate content varying from 0 to 11 mg/L. In 2008/09 boreholes in this aquifer area showed a nitrate level of 99.8 to 112 mg/L, while the rest of boreholes showing 2 to 14.2 mg/L of nitrate (Fig. 7.7). This is a significant increase during the decade. The maps also indicate that the spatial extent of contamination in the city centre, the minor aquifer area, is increasing. Maps plotted for the years 2003 and 2007 on a comparatively smaller number of wells also show a similar pattern of elevated nitrate and chloride content in the minor aquifer area. The minor aquifers exhibit elevated levels while a lower level is observed on the major aquifer areas (Fig. 7.4 & Fig. 7.5).

In comparison chloride levels in the boreholes in the minor aquifer area increased from 46.7 mg/L to 58.9 mg/L in 2000 (Fig. 7.2) to 88.9 to 100 mg/L in 2008/09 (Fig. 7.8). In 2008/09, close to the city center, chloride levels tend to decrease to 22.2-33.3 mg/L with outliers on higher ground registering a chloride level of 0-11 mg/L. The areal extent of chloride levels is much larger than the 2000 levels. The maps also indicate that in the minor aquifers nitrate and chloride levels were higher with the values decreasing outward from the center.

In 2000 the same area outside the city center had registered a chloride level of 10 to 22 mg/L. the spatial extent of chloride level is nevertheless much smaller than that observed in 2008/09. Some wells on the eastern side of the city have, over the last decade shown a high chloride level, while the nitrate levels were low or nonexistent (Fig. 7.6 & Fig 7.8). This has been observed to be an anomaly. As the area has no settlement and has been a farming area, the high chloride levels could not be satisfactorily explained. On the other hand, the chloride may have been sourced from lacustrine sediments in nearby areas. This however needs further investigation. TDS maps plotted for the periods of 2000 and 2008/09 also show a higher content in the minor aquifer areas (Fig. 7.3 & Fig. 7.9).

7.2 *Major Aquifers, 2000 to 2008/09*

In 2000, wells located in the major aquifers, southwest of the city show nitrate levels varying from 0 to 22.7 mg/L while chloride levels were observed to range from 10 to 59 mg/L (Fig. 7.1). In 2008/09 nitrate levels in these wells has increased from 2 to 26.67 mg/L while chloride levels had increased to 11 to 45 mg/L (Fig. 7.7). The spatial extent of contamination in the major aquifer area is also observed to be increasing, although at a slower rate than the minor aquifer.

The less habited areas of the city, primarily on the peripheries, tend to exhibit lower nitrate and chloride levels. This is perhaps due to the reduced anthropogenic input. Hence the observed elevated nitrate and chloride values in the major aquifer area may have originated from sewage flow from the city centre towards the aquifer area. Additionally there may be a sewage input from the nearby Aba Samuel Lake, and possibly from the industries nearby. The apparent tandem increase with the minor aquifer in the city centre and the major aquifer area suggest a possible inter-aquifer contaminant transmission.

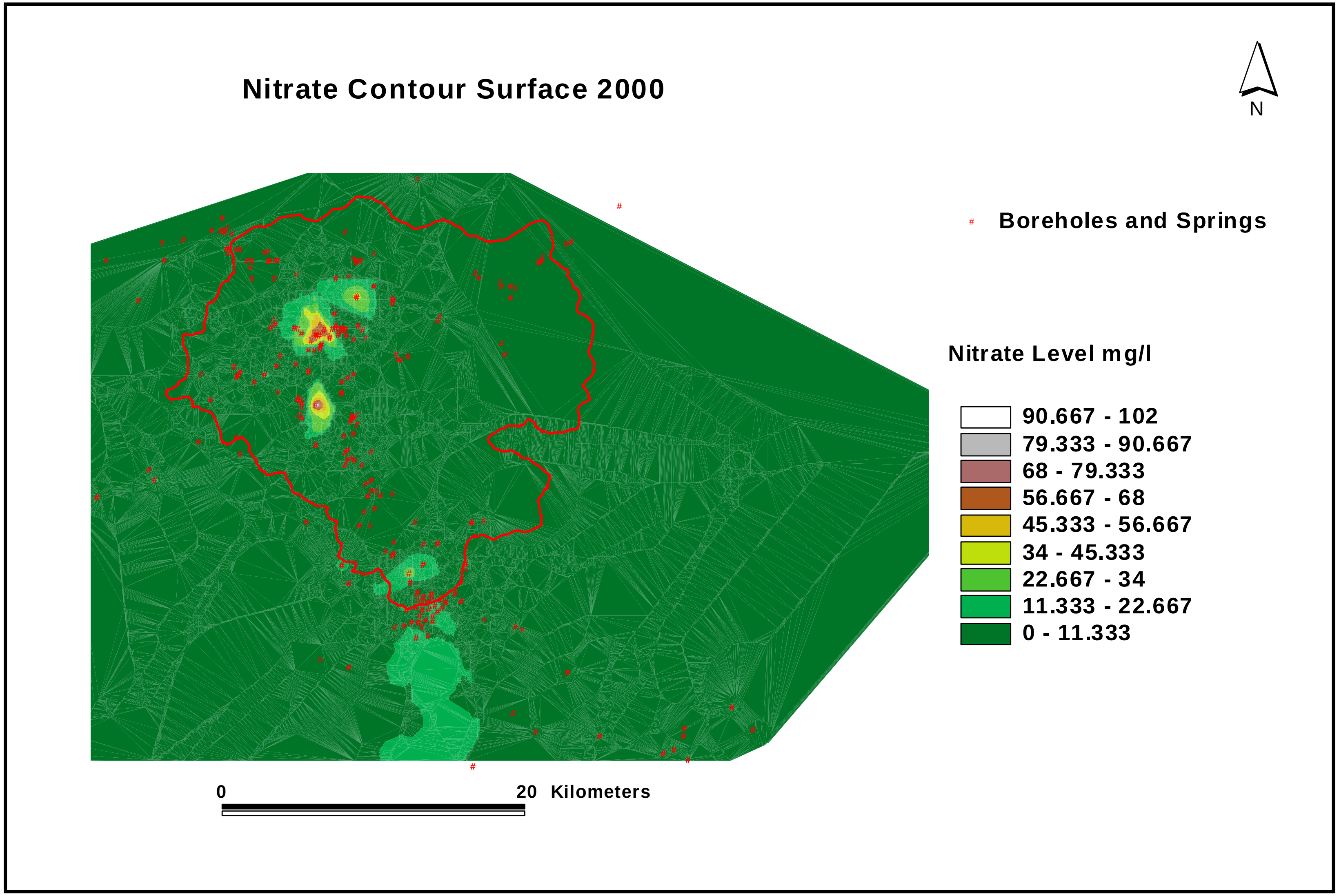


Fig. 7.1 Nitrate level in wells in the minor and major aquifers in 2000

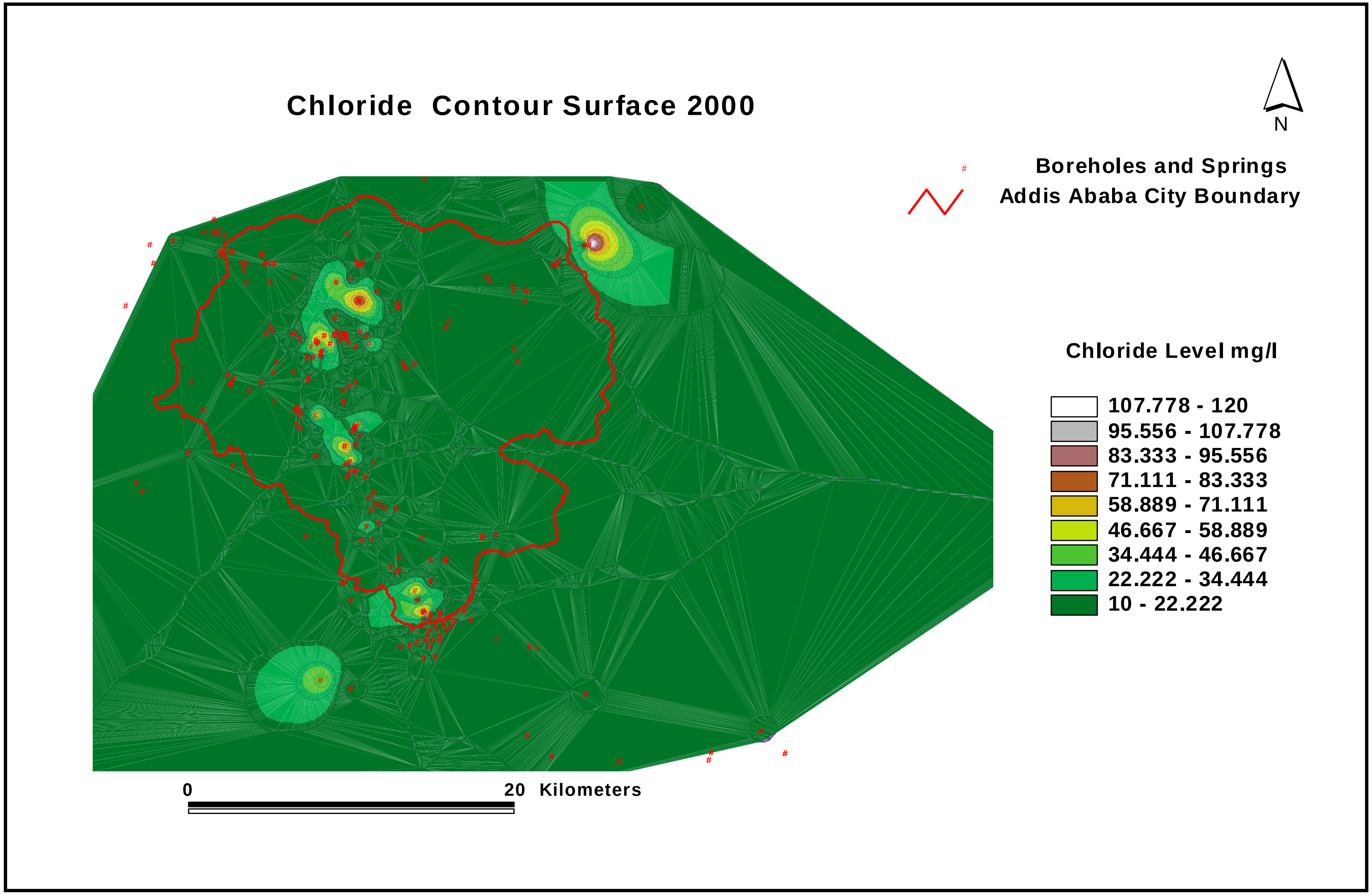


Fig. 7.2 Chloride level in wells in the minor and major aquifers 2000

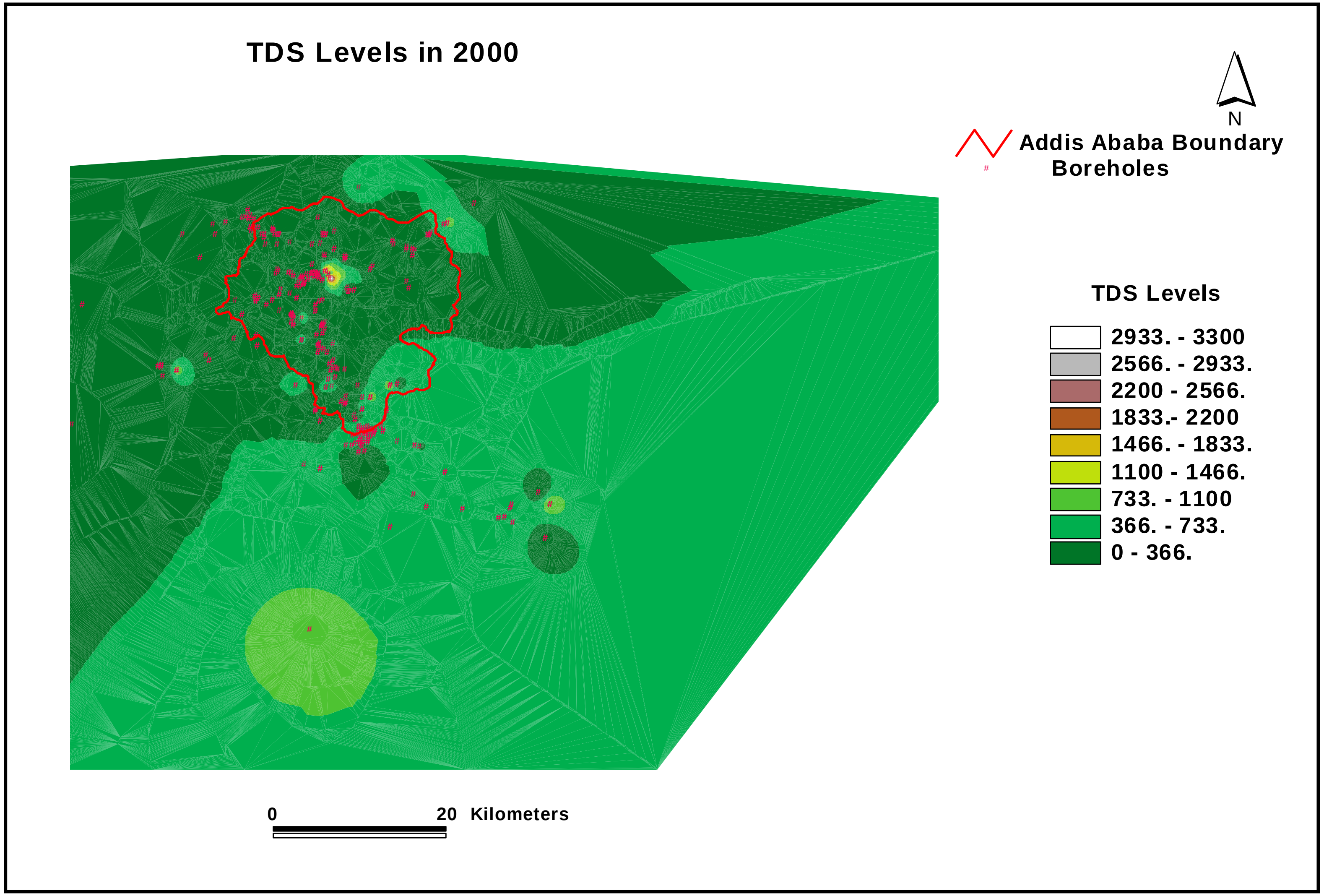


Fig. 7.3 TDS level in wells in the minor and major aquifers 2000

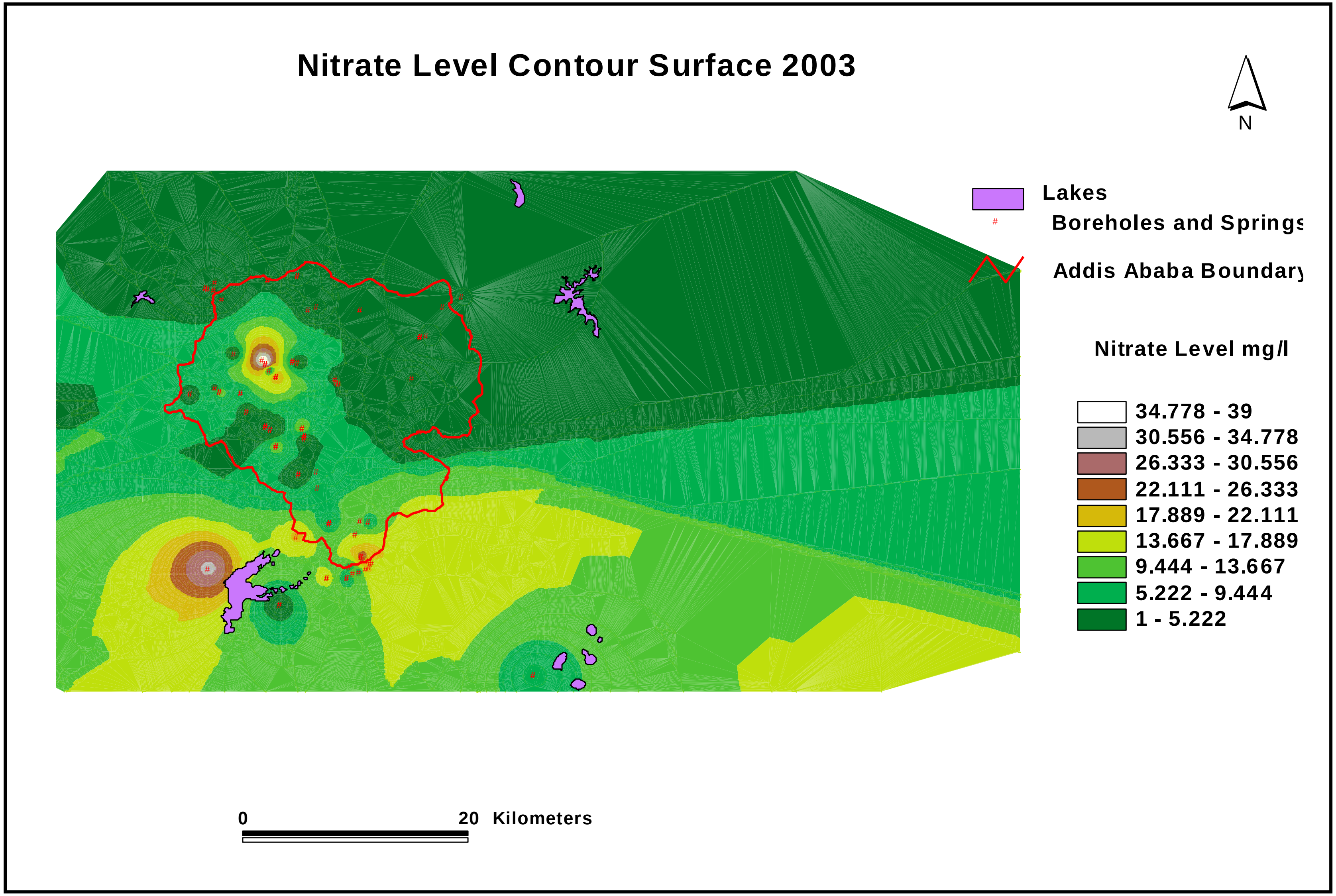


Fig. 7.4 Nitrate level in wells in the minor and major aquifers 2003

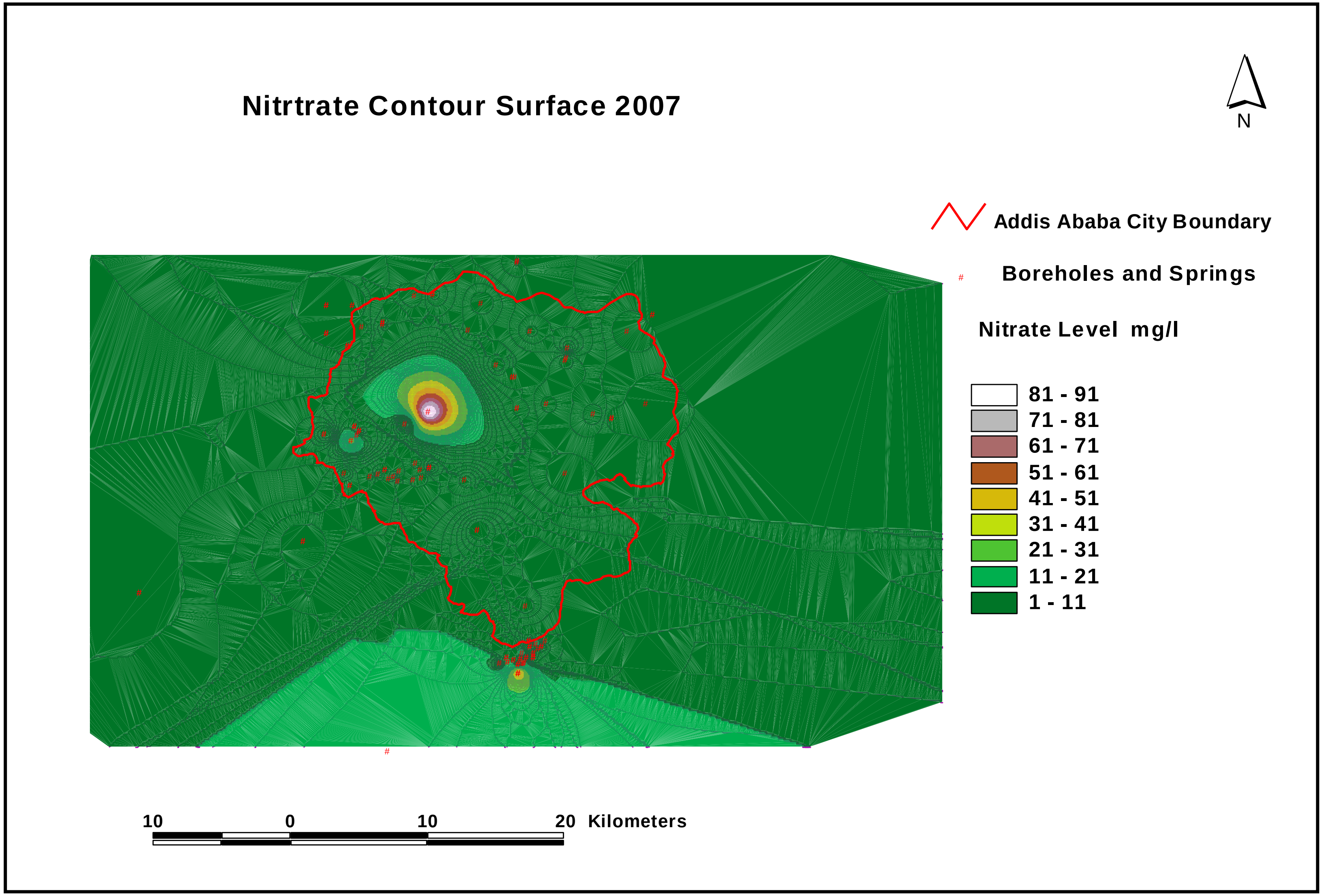


Fig. 7.5 Nitrate level in wells in the minor and major aquifers 2007

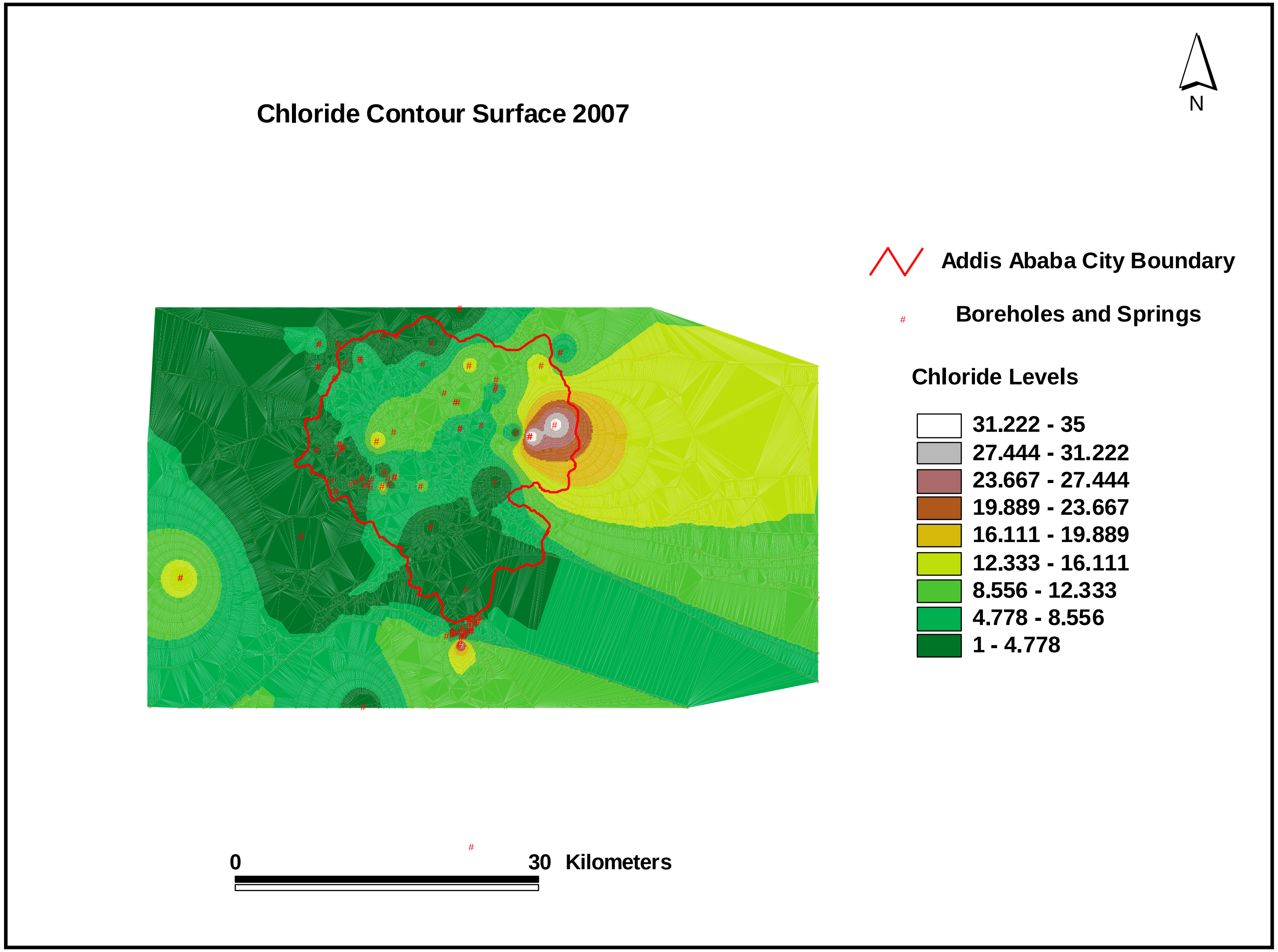


Fig. 7.6 Chloride level in wells in the minor and major aquifers 2007

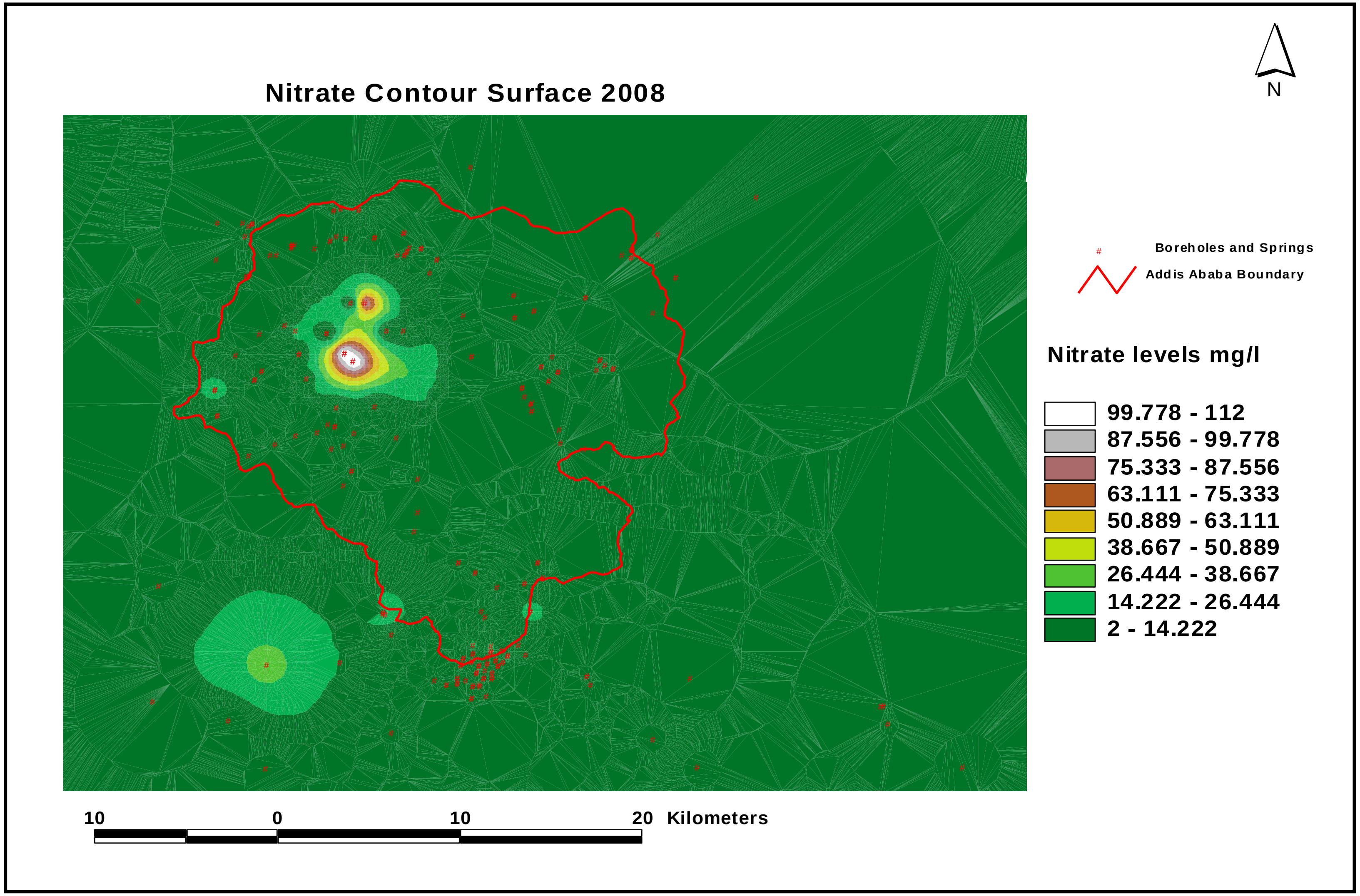


Fig. 7.7 Nitrate level in wells in the minor and major aquifers 2008/09

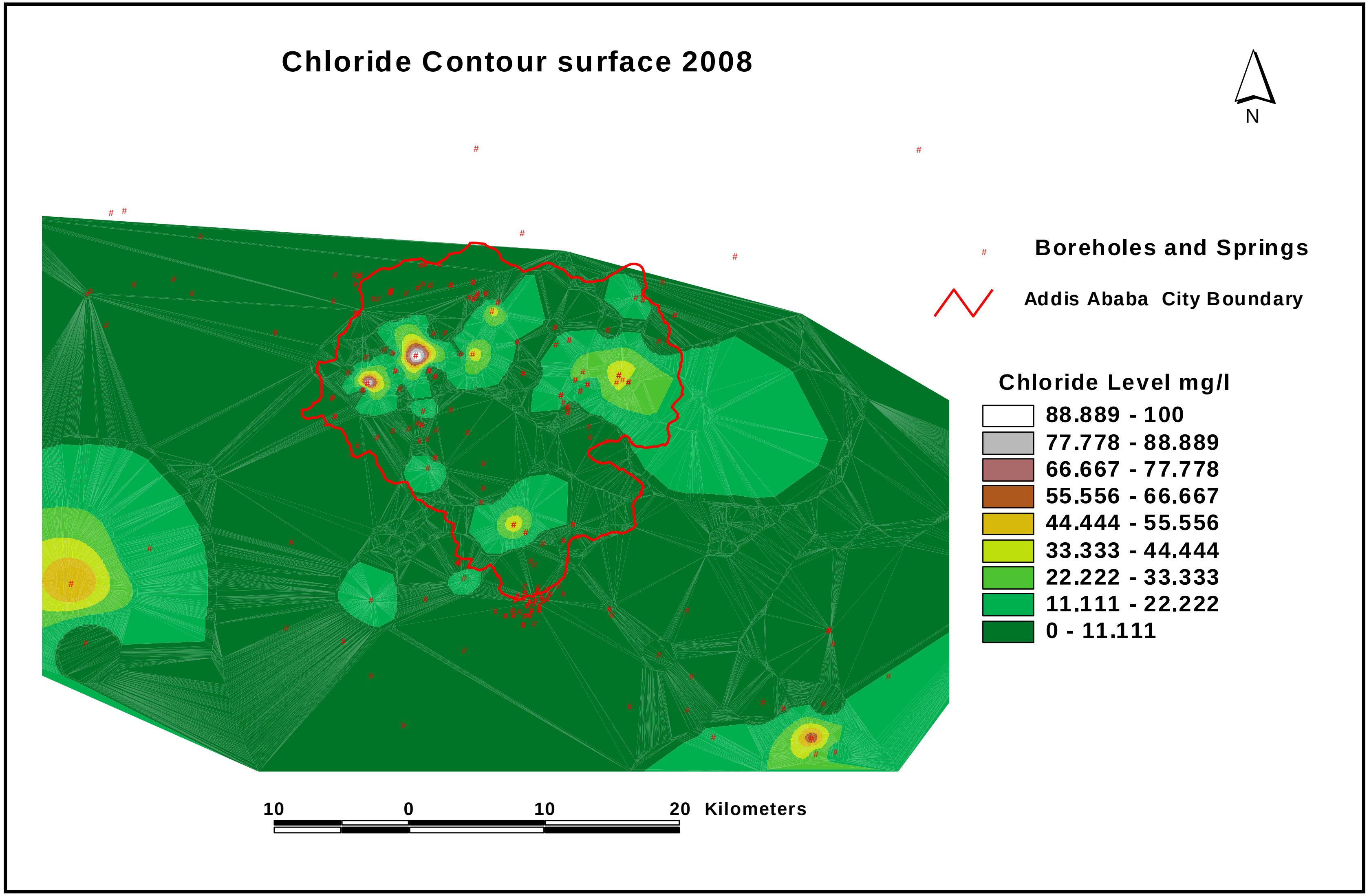


Fig. 7.8 Chloride level in wells in the minor and major aquifers 2008/09

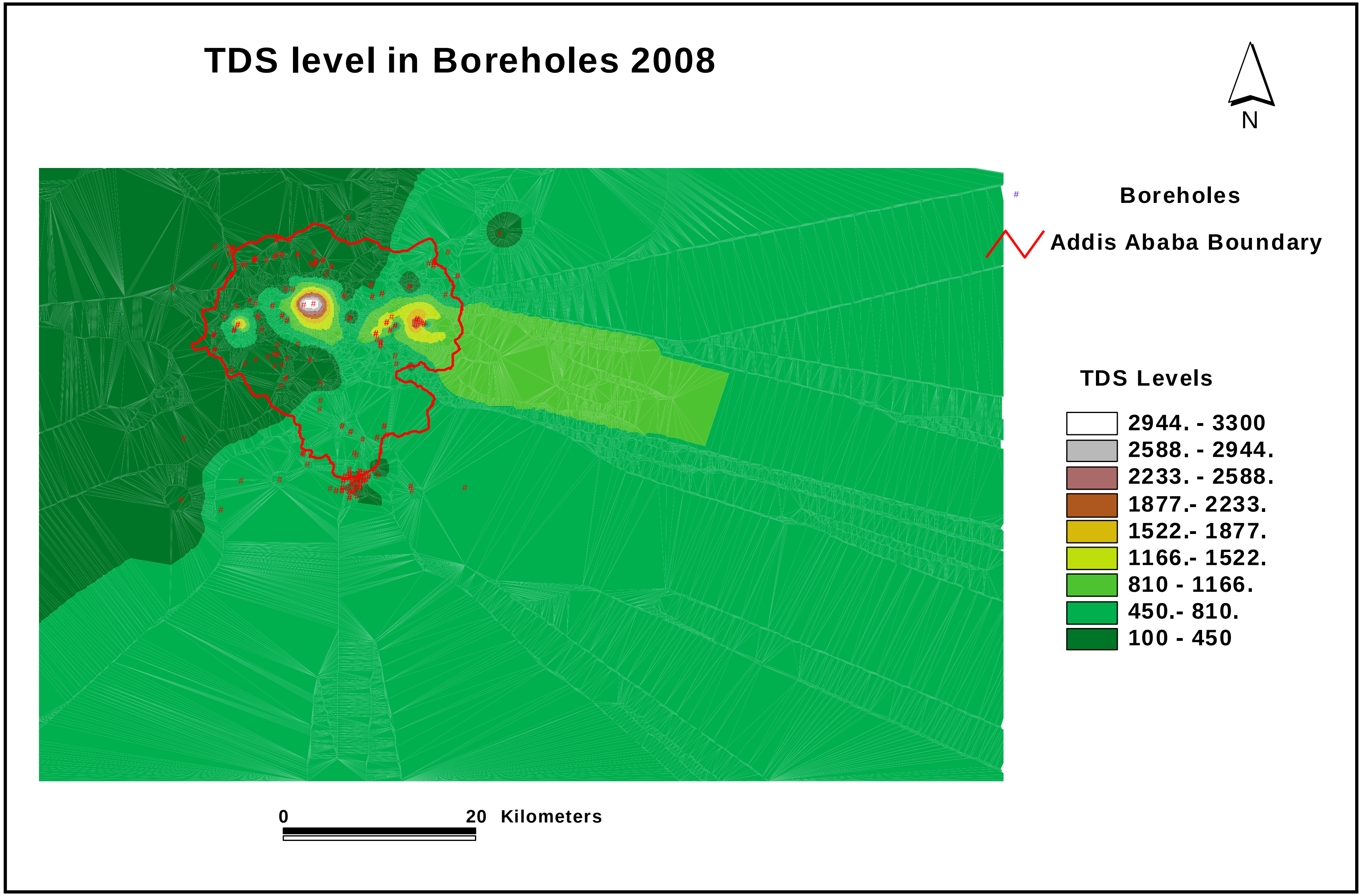


Fig. 7.9 TDS level in wells in the minor and major aquifers 2008/09

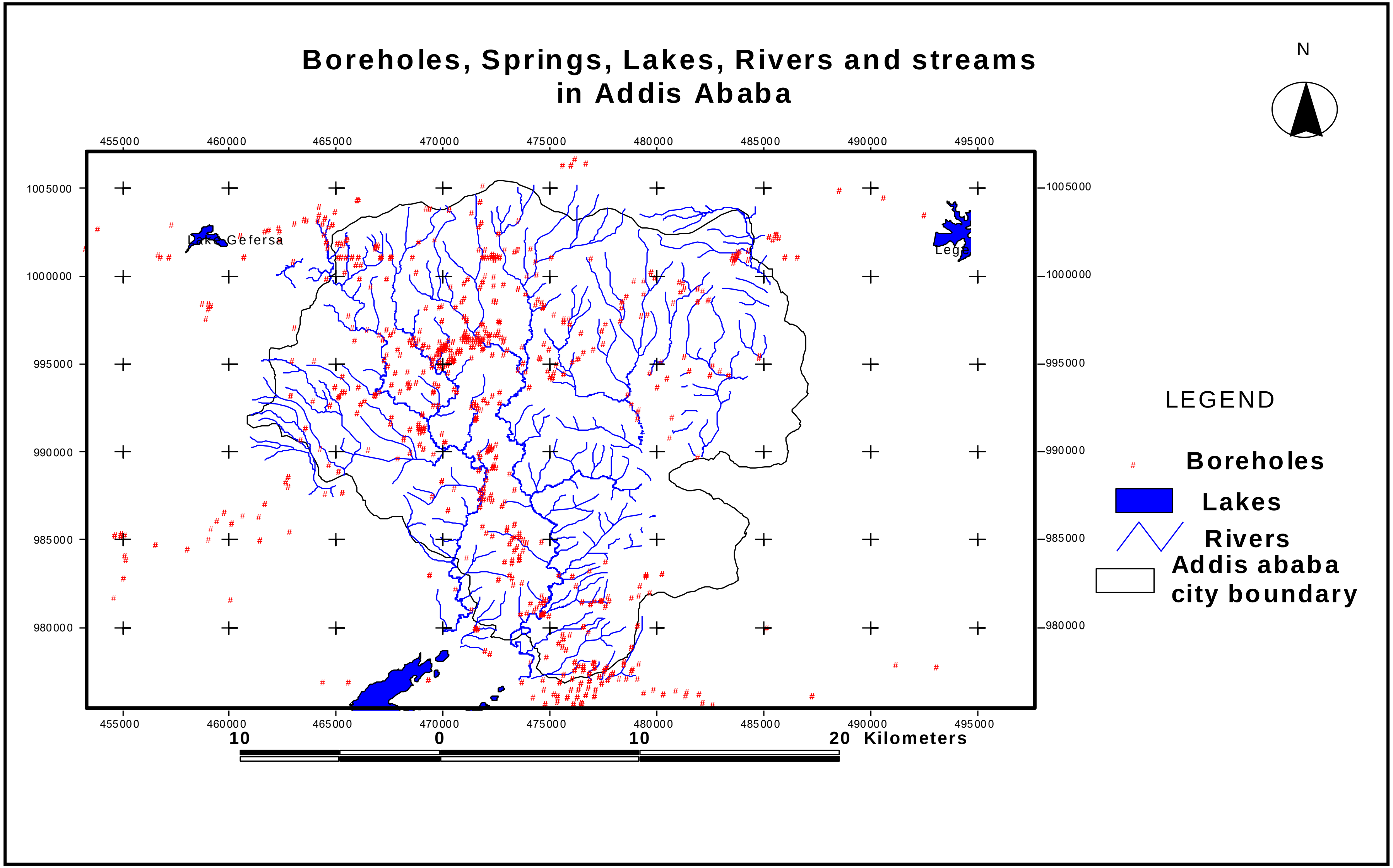


Fig. 7.10 Borehole and streams location in the city boundary (adapted from AAWSSA)

Additionally, over the years, the minimum nitrate level has risen in almost all wells in the city. This possibly suggests a steady increase in nitrate levels. Whilst the level of nitrate in most of the wells observed tends to be lower than permissible limits, the steady rise suggests a continual upward increase. Lower nitrate and chloride values were observed in wells located at higher elevations in the city, which are also less habited areas.

This appears to suggest that the anthropogenic input from the surface may be playing a significant role in groundwater contamination. Superimposing the city's built-up surface on nitrate contamination maps invariably indicated elevated nitrate levels coinciding with high population density areas.

It is possible therefore that a significant portion of the nitrate may have originated from anthropogenic sources. It is unlikely that the little agricultural activity in the city centre could have contributed to such high nitrate levels in wells. It has also been observed that the high nitrate concentration appears to be in wells that are located in close proximity to the rivers crossing the center of the city (Fig. 7.10). This increases the likelihood that nitrate contamination could be due to sewage infiltration from these polluted rivers.

The chloride contour maps also tend to show a similar pattern of spatial and temporal distribution. High nitrate areas tend to exhibit higher chloride levels. Again there appears to be a steady temporal increase of chloride content, covering the period 2000 to 2008/09. The maps also indicate a southward trend of increase in contamination. Higher contaminant concentration in the major aquifer area appears to occur, simultaneously, with a relatively elevated contamination in the minor aquifer area. This simultaneous rise is observed to occur in almost all of the contour maps analyzed. It may be possible that the minor aquifers in the city centre may be interconnected with the major aquifers, hence resulting in a speedy transport of contaminants. Elevated nitrate and chloride levels have also been detected in wells and springs adjacent to the Aba Samuel Lake. This indicates that the lake may be a cause of contamination in the major aquifer area. It further suggests that the soil cover may not be providing adequate attenuation of contaminant load on the aquifers.

In comparison a relatively elevated nitrate level is observed in the minor aquifer area, which has also shown an increasing spatial extent. The increase in nitrate content is observed to be high in the central areas of the minor aquifers, encompassing the Addis Ketema, Lideta, part of Kolfe-Keranyo and Nifas-Silk Lafto sub cities. The major aquifer area located in the Akaki-Kaliti sub city also displayed elevated nitrate content although lower than the central areas.

Comparing the nitrate levels of 2000 and 2008 it is observed that there is a marked spatial extent variation in these periods. The areal extent of contamination, in the central minor aquifer areas is observed to be much smaller in 2000, as compared with that of 2008. The 2008 contamination extent covers a larger area, suggesting that areal contamination has increased over this period. A similar increase in chloride levels over this period is also observed. The observed values of nitrate and chloride are also observed to have increased over this period. In general the maps suggest that the threat of nitrate contamination is present and that this threat may have been increasing temporally as well as spatially. The TDS levels also coincide with high contamination areas.

7.3 Low Cost Sanitation and its Impact on Groundwater Quality

Chemical and biological elements present in human waste, if discharged untreated or inappropriately, may affect the quality of groundwater. This threat is enhanced with high spatial density of low cost sanitation facilities such as pit latrines. Pit latrines, which discharge human waste into the ground untreated, increase the risk of contamination. Some of the chemicals found in human waste, including nitrates and chlorides, when exceeding permissible limits may threaten human welfare.

The analysis of data, spanning over the past few decades suggests that the increasing contamination of the groundwater resource in Addis Ababa may be related to other anthropogenic sources rather than from human waste. The increasingly elevated levels of these chemicals detected in the city groundwater, suggests that waste from anthropogenic sources such as industrial and agricultural activities may have impacted the overall quality of groundwater in the city.

7.4 Environmental Impact of Low Cost Sanitation on Groundwater

The previous analysis suggests that prolonged exposure of the groundwater resource in Addis Ababa, to industrial and domestic waste may have impacted its quality. The observed positive correlations between, nitrate and chloride, nitrate and TDS, TDS and chloride suggest that contamination may have already occurred. It is possible therefore that the groundwater quality is already affected by the increased levels of chemicals, mainly nitrate. The most significant effect of this impact on groundwater resource would be on its quality, or suitability for human consumption and industrial purposes.

The values of nitrate and chloride show a marked deviation from the background or levels observed decades ago. This suggests that the nitrate and chloride content is displaying a steady temporal increase. Besides, the sources of these chemicals may be possibly from human waste related contamination rather than geologic origins. As the city's built-up area is also increasing towards the major aquifer area, by annexing previously farmed areas, it is likely that agriculture could contribute significantly to the presence of these chemicals.

A direct relationship between the highly populated areas of Addis Ababa and higher level of nitrates and chloride also appears to be present. This areas classified as minor aquifers, are the most affected at present. It is also observed that there are numerous wells in the city center which are still being used. The quality deterioration of groundwater in these areas may therefore continue, and as a result impact the environment. In addition to this, consumption of groundwater with elevated nitrate content may pose a health concern such as Blue baby syndrome in children. And if corrective measures are not instituted, the quality deterioration and hence the impact may continue.

The correlation with highly populated areas and elevated levels of nitrate and chloride also suggest urbanization is possibly impacting groundwater quality. This is possibly linked to new housing development and the attendant anthropogenic activities.

7.5 Water Quality Impact on Minor Aquifers

Increasing levels of nitrate are now observed in almost all of the aquifers within the city environs. Some of the wells, located in the minor aquifer areas, show a higher concentration of nitrate than is permissible.

It is observed that the nitrate levels in some wells in the minor aquifers have exceeded the WHO recommend maximum permissible limit of 50 mg/L. This would render wells around the minor aquifer areas unsuitable for human consumption. It is also observed that the spatial extent of nitrate contamination appears to be increasing. This will have an impact on water quality in terms of quality deterioration, as well as suitability for consumption or industrial purposes. Some of the highly contaminated wells, showing elevated levels of nitrate are still in use. The impact on health of people using the contaminated water may not precisely be known at present.

7.6 Water Quality Impact on Major Aquifers

In wells around the major aquifer area nitrate levels of 2-14 mg/L and in some wells nitrate as high as 24 mg/L has been detected. The temporal increase trend of the nitrate and chloride content suggests the increase may continue. This will lead to the wells eventually reaching the WHO recommended maximum limit of 50 mg/L, beyond which, long term usage would be detrimental to human health.

Comparatively lower levels of nitrate and chloride are observed in the major aquifer area. Detected levels are generally below the permissible levels, but are increasing gradually. It is possible therefore that groundwater in this aquifer is becoming slowly impacted.

8 *Environmental Policy and Sanitation and Groundwater Resource Management*

The Federal Government has instituted an environmental policy framework. This has been given prime importance as it is enshrined in the Constitution. Therefore there is the political will to protect the environment and its resources.

The Constitution of the Federal Democratic Republic of Ethiopia in article 44.1 states 'All Persons have the right to a clean and healthy environment' and under this overarching principle the National and Regional environmental policies have come into effect.

Whilst the policy emphasizes the right to a clean environment, some parts of the policy may need to be revisited in view of this stipulation. One main area of concern is the emphasis that the policy renders on the use of pit latrines for human waste disposal. This is particularly of important in relation to protection of groundwater resource from human waste contamination. The potential of contamination of water resources that the profuse use of pit latrines may cause appears not to have been addressed. Therefore a policy review may be appropriate.

8.1 *Ethiopian Environmental Policy*

The Ethiopian Constitution provides a framework and important provisions and guidelines for the protection and management of the environment. Article 44 of the Constitution provides the right of all citizens to a clean and healthy environment, and further elaborates it in article 92:

- *The government shall endeavor to ensure that all Ethiopians live in a clean and healthy environment*

- *The design and implementation of programs and projects of development shall not damage or destroy the environment*
- *People have the right to full consultation and to the expression of views in the planning and implementation of environmental policies and projects that affect them directly*
- *Government and citizens shall have the duty to protect the environment*

Under the provisions of the Constitution, the Environmental Policy of Ethiopia (EPE) was approved by the council of ministers in April 1997 (Addis Ababa, 2002). This was established with an aim of rectifying previous deficiencies in policy as well as implementation. Along this line, the Conservation Strategy of Ethiopia was formulated in 1996 with a provision for integrating environmental planning into new and existing policies, programs and projects.

The Environmental Policy of Ethiopia is '*sought to guide all environmental related activities which are undertaken or must be undertaken by the environmental Protection Authority and other sectors*'. In Article 2.2 it defines as one of its specific policy objectives (MoED and C & EPA, 1997);

f) '*Prevent the pollution of Land, Air and Water in the most cost effective way so that the cost effective preventive intervention would not exceed the benefits*'

Under section 3.7 on its sectoral environmental policies, Human settlement, urban environmental and environmental health section it enumerates as its policies;

c) *To ensure that improved environmental sanitation be placed highest on the Federal and Regional agenda for achieving sustainable urban development,*

j) To construct shared Ventilated Improved Pit (VIP) Latrines in the low income and high density housing areas of Addis Ababa and the older towns with frequent emptying by *tankers integrated with programs on user education, health and hygiene, with follow-up maintenance and cleaning, all implemented as a component of a broader urban environmental upgrading program including storm water drainage'*

k) *to ensure the construction of family latrines in lower density and peri- urban areas as a conditionality of the house plot lease and to integrate this with health and hygiene awareness program*

The above stipulations suggest the continual emphasis on the provision of pit latrine services in all urban areas regardless of population density or their potential impact on the environment. On the other hand, the policy under section 3.7 (o) states;

o) *To promote the development of sewerage systems and sewerage treatment facilities in urban centres*.

The policy therefore appears under article (k), to suggest 'conditionality' or a mandatory enforcement of pit latrines construction, under article (o), it appears to suggest only 'promote'(ing) or a lesser emphasis on the provision of sewerage systems. Given the threat that pit latrines pose to groundwater particularly in urban areas, it appears there may be a need to recast this policy to reflect the current threat of contamination.

Since environmental issues are addressed at both the constitution and policy levels, there is the legal frame-work for further improvement. Specifically a number of issues may need to be addressed in order to deal with the immediate concern. There are now two issues of immediate concern, sanitation and groundwater protection.

Pit latrines have long been the main human waste disposal facility in Ethiopia. This has now caused serious contamination threat. A review of the environmental policy does not appear to show specific policy guidelines in regard to groundwater protection in cities. A review of the policy on issues of appropriate sanitation and protection of resources is therefore urgent.

With a number of case studies, including this research, showing contamination of groundwater resource in urban areas, the implementation of protection priorities need to be emphasized even more. It is imperative therefore that the overall policy framework be revitalized in view of enforcement capabilities, awareness creation, selection and implementation of environmentally friendly sanitation facilities.

In the short term, the focus has been on the mandatory, at least on legislation level, provision of sanitary facilities, or pit latrines. This objective viewed from a short term perspective is no doubt a positive step. But long term usage of pit latrines, is not beneficial to groundwater quality protection. Therefore immediate steps need to be taken to address this threat.

Failure to address this urgently will cause serious contamination threats. Remedial actions may also be difficult, perhaps without substantial financial investment. Therefore the environmental guidelines of the city as well as the nation may need to be streamlined taking into consideration the current situation.

Specific policy revisions and recommendations could include, an integrated policy review, environmental awareness campaign and policy enforcement, improved environmentally friendly sanitary facilities, communal sewers, appropriately designed and monitored sewage treatment facilities. These recommendations would also need to be buttressed by a robust enforcement capability in all Federal Regions.

8.2 Groundwater Management Strategy

The Ethiopian Civil Code stipulates that groundwater resources are public property and that prior authorization is required for abstraction below a hundred meter depth. This guideline issued more than 50 years ago shows the recognition of the potential of groundwater resources and their relevance to the public (Addis Ababa, 1960).

The environmental policy of Ethiopia builds upon that basic premise and further enumerates the protection and sustainable abstraction of water resources. On the other hand, current observations show that in many parts of Ethiopia groundwater abstraction is carried out, in an unregulated and unsustainable manner. To date no regulatory enforcements are in place in regard to abstraction, for private or industrial use, nor levying of charges for usage.

Location of groundwater abstraction wells is only decided on the potential capacity of aquifers and availability of water. In many cases sustainable abstraction has not been adequately reviewed. Besides no consideration appears to have been given towards protection of these resources from human interference, particularly in urban highly congested areas. In the case of Addis Ababa, the rapid horizontal expansion of the city, encroaching into areas of potential aquifers, is an increased threat to groundwater contamination.

Hence in order to minimize this, a groundwater protection strategy, inclined towards a sustainable usage coupled with contamination mitigation will need to be implemented. In addition to this maintaining a more focused balance between supply and demand, and the quality of available resources would then be of prime importance.

The environmental policy needs to be reviewed in light of these issues and the current abstraction scenario. Federal Regions would also need to be empowered to implement environmental policy regulations by delineating protected zones of groundwater sources, issue licenses for abstraction, levy charges as well as enforce a much more improved environmentally friendly adaptation of pit latrines.

For a start, the policy needs to be revisited to take into consideration the sustainable abstraction of water resources. Additionally, protection from contaminants originating from industries as well as domestic waste needs to be addressed. Industries could be obliged to treat effluents, pay for abstraction costs and possibly increased charges to cover cost of environmental rehabilitation.

Private users should also be encouraged to submit drilling data so that an accurate data base could be developed. This will assist in defining aquifer extent and potential. Besides charges for abstracted water as well as environmental concern need to be addresses by private or institutional users. Private drilling agencies also need to be accountable to provide drilling information and well data to the pertinent authority, so that an up-to-date data base could be built up.

Domestic waste could on the other hand be handled with newer designs of suitable toilet facilities, communal waste storage facilities; improved de-sluging services, a functioning treatment plant and environmental awareness of the community. To produce a sustainable impact, legislations need to be enforced. Therefore, the Federal as well as the Regional environmental authorities needs to be mandated with a more robust enforcement capability. Hence monitoring of resources, degree of contamination and mitigation targets could be possible.

A general integrated policy framework encompassing particularly issues in urban areas, a housing and industrial policy in tandem with water resource utilization and sanitation will reshape the current unsustainable utilization and contamination threat to water resources. It will also be vitally necessary to plan the development of urban areas in relation to groundwater resource usage as well as protection.

The policy framework will need to address this issue through incorporation of environmental parameters in any urban master planning work in the country. Urban areas are dependent for development on available water resources in their vicinity. These two factors are intertwined and hence it is critical to address both at the same time. The first step would therefore be revisiting the overall policy frame work in light of such observation as this research has shown. In terms of these observations an overall groundwater management strategy as well as recasting policy parameters would be necessary.

Lessons from other countries that have successfully addressed this challenge also needs to be learned from and appropriate and relevant solutions incorporated in the local context. The most critical issue would however be the creation of environmental awareness and monitoring enforcement in the policy formulating sector and the population at large. Due emphasis is therefore necessary in urban as well as rural areas. This will need to build upon the existing policy framework, revised to take into consideration current situations and strengthened with a more robust legislative enforcement capability. The delicate balance between available resources and human need and its effect on these valuable resources must also be maintained.

Ethiopian environmental policy would need to address this gap in order to maintain the limited available resources with a long term objective. Aquifers in urban areas need to be protected from contamination by human waste while those in rural areas, farming and fertilizer induced contamination need to be controlled to protect water resources. This is not necessarily to be carried out in selected sites, but even further out areas, which contribute towards recharge of aquifers.

The focus on food security or emphasis on developing farming potential through an integrated fertilizer usage would need to be revisited with a sustainable and environmentally conscious utilization and protection of water resources. An overarching policy addressing salient features of this sector is therefore, of paramount importance. Such a policy will assist in the management of water resources coupled with remedying issues of contamination. As a public property, water resources have to be protected for the public and by the public through the formulation of appropriate policy framework and general awareness.

9 *Discussions of Findings*

Groundwater continues to be a major source of potable water in Ethiopia. Many urban centers are increasingly relying on groundwater to address water supply demand. The steady increase in the number of boreholes in Addis Ababa appears to indicate a rise in the abstraction of groundwater resource. Currently there are about 800 deep wells within the city of Addis Ababa and more than 1200 within 100 km of the city.

Whilst groundwater in Addis Ababa is increasingly abstracted to meet demands, it is on the other hand being exposed to large-scale contamination. The main cause of groundwater contamination in the city of Addis Ababa may be considered to be anthropogenic activities including industrial activities, the high density of pit latrines, absence of sewerage services, rapid expansion of the city encroaching onto aquifer areas, lack of a general public awareness, and over-abstraction of groundwater resources and lack of enforcement of environmental policies.

It is estimated that there could be in excess of over 250,000 pit latrines in the city, with as many as 230,000 located in the minor aquifer area. This area is also habited by over 2.5 million people. By comparison the major aquifer area is home to mere 181,202 people only.

In general it is estimated that the nitrate loading into the minor aquifer area could amount to over 10,000 tonnes/year, while the major aquifer area is exposed to about 725 tonnes /year. It is therefore possible that the aquifers could be exposed to significant nitrate loading.

The contamination maps (Figs 7.1 to 7.10) indicate high contamination areas corresponding with high population density areas, hence suggesting contaminants may be sourced from anthropogenic activities. The main contaminated areas are observed to be the minor aquifers in and around the city centre, where some wells exhibit high nitrate values. The simultaneous presence and fluctuation of chloride with nitrate suggest that the contaminants may have been sourced from anthropogenic activities. The lack of strong correlation of the two chemicals however, suggests the nitrate may not have been sourced from human waste. In addition to the chemical parameters, the concentration of Coliform bacteria, and E. Coli in particular, as indicators of faecal contamination, further appear to confirm this may indeed be the case. It is also observed that the detection of nitrate and chloride as well as coliform bacteria in many instances appears to correspond with periods of rainy season. This suggests the possibility that an external waste input may be a factor in enhancing contamination of groundwater. In light of the presence of polluted streams and rivers in the city, it is possible that floods may enhance sewage input into wells and aquifers.

Additionally low lying areas of the city display a high value of nitrates compared with higher elevation areas of the minor aquifers. It is possible therefore that the flow of waste into low lying areas may be significant. Chemicals possibly sourced from detergent use, such as Boron, have also been detected in some wells. The Hilton hotel borehole is a case in point. The very high boron level possibly suggests an external waste input. It is very likely that in the absence of sewerage services, wells may be exposed to chemical originating from domestic waste.

On the other hand, wells on the eastern periphery of the city, on the minor aquifer areas have displayed high chloride content, with no corresponding elevated level of nitrate. As this area is sparsely populated, the chloride may not be sourced from human or industrial waste. The origin of the observed elevated chloride level could not be explained and is considered an anomaly.

The major aquifers on the periphery of the city have also shown comparatively elevated nitrate and chloride content, whilst these values are lower than permissible limits, the steady temporal increase suggest that contamination may be increasing. There also appears to be a simultaneous detection of elevated nitrate and chloride content for similar time spans in both the minor and major aquifers.

The simultaneous detection of elevated nitrate and chloride in similar time spans on both the minor and major aquifers also appears to suggest that the two aquifers may be interconnected. Given the porous nature of the underlying geology of the area, it is highly probable that inter-aquifer contaminant transport may have occurred. The closely located and highly contaminated Aba Samuel Lake may also be contributing to the elevated nitrate and chloride content of the wells in the vicinity. It is also possible that the overlying thick soil cover on the major aquifer area may not be providing the expected attenuation capacity.

Besides showing a temporal increase, the spatial extent of contamination in the aquifers is increasing steadily. The most significant increases in spatial extent are occurring in the minor aquifers located in the city center increasing southwards towards the major aquifers. This suggests that contaminant may be moving southwards following groundwater flow direction. It is noted that low lying areas of the aquifers appear to be more vulnerable to contamination than higher elevation areas.

The city of Addis Ababa does not have much agricultural activity, and hence nitrate from agricultural activities may be assumed to be minimal. The use of low cost pit latrines as human waste disposal mechanism may therefore be considered as the main cause in groundwater contamination in the city.

A comparison of the level of nitrate with depth of wells has also revealed an inverse relationship between level of chemicals and depth of wells. This suggests that shallow aquifers may be at an enhanced risk of contamination than deep aquifers. The detection of nitrate, (although of lower values) in deep wells also suggests that deeper aquifers may also be becoming increasingly vulnerable.

Depth of wells is observed to have increased in the past two decades. In 2008/09 the average depth of wells drilled in the city was about 250 meters. While this may be due to improved drilling equipment able to tap deeper aquifers, actual site visits of drilling activities suggest otherwise. Drilling is stopped once a sustainable yield is obtained, suggesting that the groundwater table may be fast receding.

New data have also shown that the extent of thermal waters in the minor aquifer areas may be larger than previously thought. New thermal wells have been drilled at the new Accor Hotel site in the vicinity of the St. Stephan's church and the Greek Community Club. Additional thermal springs have also been observed further to the southwest of the city center in the Mekanissa area. This suggests a larger spatial extent of thermal water. If this occurrence is due to a geological fault, it is highly probable that contaminant transport may also have a larger spatial impact.

An evaluation of recent changes in the concentration and spatial extent of contamination suggest that the trend may continue in the future. Should the degree of contamination continue to increase, it is very likely that it will become a major health threat. This hazard may become serious in the future as the population is continuously exposed to nitrate and other dangerous chemicals.

Additionally there appears to be a lack of coordinated monitoring of contaminated wells. Newer wells are directly connected with the supply system, without a detailed suitability assessment. The existing environmental policy also appears to have not considered the threat that may emanate from a large-scale use of inappropriate human waste disposal system. The policy is also constrained by the absence of any meaningful implementation empowerment.

The apparent gap in the policy may be attributed to different factors. Mainly the absence of a comprehensive contamination threat study on the city's groundwater resource may be partly to blame. This would have brought the issue to light and the urgency of instituting remedial actions. There has not, however, been a total absence of such studies. There have been a number of limited scale studies that have cautioned about the presence of contamination in wells. This appears to have not been considered in formulating the policy, as it does not address the risk of contamination of groundwater resource due to low cost sanitation.

It is vitally necessary therefore to address this issue through an integrated policy review, environmental awareness campaign and policy enforcement. As a major metropolitan area and home to millions, Addis Ababa is faced with a major environmental threat through contaminated water resources, and hence needs to take urgent measures to curb this pressing challenge.

The absence of sewerage services may also contribute to enhanced contamination of aquifers. Additionally the location of the treatment plants, with one discharging effluents directly into a stream that flows to the Aba Samuel Lake, may enhance contamination risk. Therefore a groundwater protection strategy needs to focus on the introduction of sewerage services in contamination-prone aquifers. This will then be followed by a large-scale mitigation strategy with a more focused approach.

The absence of comprehensive data on wells and sanitation facilities in the city has also been one constraint in this study. The data base for this study was compiled following an extensive search for groundwater resource related information. It has been noted that there appears to be no firm estimate of the groundwater resource potential in the city or in the country in general. This has been manifested in instances of aquifer depletion due to flawed estimation of yield capacity.

The discrepancy in estimating the groundwater potential both in Addis Ababa and that of Tigray region should be a wakeup call towards facilitating the common understanding of these scarce resources. More work is therefore needed to improve the degree of accuracy in evaluating aquifer capacity, necessitating that further detailed geological studies be carried out, particularly for urban areas, which are faced with the challenges of water shortages.

It is believed that the major aquifer areas in the city of Addis Ababa could be depleted in the near future. This would create a critical water shortage. Therefore, a reassessment of aquifer capacity as well as a search for potential alternative water sources needs to be carried out urgently. Together with this, the existing supply sources need to be protected from contamination.

Interviews with professionals actively engaged in the field of water supply and sanitation has also indicated that there may not be general consensus as to the potential areas of groundwater resources, in regard to the total capacity of aquifers, their recharge mechanism and their sources. Additionally, differing views are held concerning the level of contamination or the vulnerability of aquifers.

Generally it is thought that only shallow aquifers in the city are vulnerable to pollution, while deep aquifers are believed to be adequately protected. This conviction appears to be the driving force behind the choice of drilling new deeper boreholes close to the rivers in the city which have become open sewers for all practical purposes. This is observed from the maps that show locations of boreholes in the city and the locations of rivers. With underlying rocks thought to be largely porous the risk of contamination is increased if wells are located in proximity to any sources of pollution.

In order to effectively use these resources in a sustainable manner, it is of primary importance to establish a consensus among water resource professionals. Without this, these resource may be mismanaged and eventually be depleted, leaving the country in general and the city of Addis Ababa in particular, at a higher water shortage risk.

A strategy focused on a detailed inventory of water wells, springs, discharge capacities and water quality need to be comprehensively researched and documented. Future engagements would also need to be focused by enforcing abstraction regulations, to protect the scarce resources from over-abstraction or impact of human activity as well as increased number of monitoring wells. This is even more urgent in Addis Ababa.

Nationwide, a comprehensive management strategy, based on dialogue and in-depth assessment of water resources needs to be in place. This will no doubt assist in determining whether, in the long term, surface or groundwater resources are the most appropriate sources of water for various uses.

Obviously there will not be one solution for all urban centres or rural areas in general. It would need to be decide on an individual basis; however a shift from the focus on groundwater resources to surface water utilization is appropriate if long-term supply objectives are to be met. It is understandable that cost plays a significant role in the choice of water supply source. Nevertheless, this reflects a short term perspective, hence considering a long term perspective is appropriate.

The city of Addis Ababa has now focused on meeting water supply demand from groundwater sources, again for ease of abstraction and distribution as well as cost. This is however an 'emergency' solution and may not address the long term needs. In the mean time the boreholes supplying the city of Addis Ababa have to be protected from contamination and monitored continuously for increased signs of contamination. As failure to do so will have an impact on health and if drastic measures are not taken at this time, would put the city in a far more serious water shortage crisis than it is in now.

To date the emphasis in the city of Addis Ababa has been in the development/abstraction of groundwater and less on protection and monitoring of this scarce resource. The low number of monitoring wells in the city groundwater development venture as well as lack of a coordinated and standardized protection effort has no doubt contributed towards quality deterioration. Increased effort is therefore necessary in the monitoring of abstraction, as well as in the protection of these resources.

Effective protection of groundwater resources would depend on accurate knowledge of aquifers. This can be done through establishing a network of monitoring wells and a continuous assessment of relevant chemical, biological and physical parameters. At present a fair number of wells are accurately identified as to their location, status, yield and some data on physio-chemical properties. This is a good start for initiating a monitoring program, coupled with a protection scheme. Additionally a comprehensive engagement on the preparation of a hydrogeological map of the city, much more enhanced than the currently available maps is urgently required.

Once the monitoring wells are in place then it would be possible to continuously take steps to protect vulnerable resources through an empowered environmental policy program. This however would take a coordinated effort by all concerned. On the other hand, monitoring of the groundwater resources does not necessarily have to wait for the drilling of new boreholes. Rather, the wells that already exist in the city can be utilized to start a monitoring program. These can give an extensive spatial coverage and a good indication of contamination levels. The urgency of this cannot be overstated.

It will also be valuable to revisit the vulnerability concept with a view to re assessing whether the soils and rocks are providing the expected or assumed protection and attenuation of waste ingression into the groundwater systems. This is particularly relevant as the expansive soils predominantly covering the southern areas of the city, including the Akaki well field tend to exhibit deep cracks during dry seasons. This may aggravate further contamination with a potentially higher contamination risk than assumed before.

10 Conclusion and Recommendations

10.1 Summary and Conclusions

The provision of clean water to a population of a nation is one of the measures of welfare. In many parts of the world this remains a major challenge, especially in urban areas where a large number of people live in a relatively smaller area.

Addis Ababa is one example of this. With its population of nearly 3 million, efforts to provide clean water to the population has remained a challenge for the city's administration. Efforts to address this are however in progress. Whilst the investment in the water supply sector for the city is increasing, the provision of sanitation services has not been viewed with an equal urgency. This is evident when noting that only 0.6% of the population has access to sewerage services. The rest of the population uses pit latrines.

The main thrust of clean water supply has to date remained focused on groundwater abstraction. This appears to be carried out without the consideration of the impact the numerous pit latrines would have on groundwater quality. So far the number of pit latrines nor their distribution over the city is accurately known. In spite of this, groundwater abstraction to meet the city's water supply demand is on the increase, within the city and around its periphery.

This research was therefore focused on investigating whether the human waste originating from the pit latrines has impacted groundwater quality, and its temporal as well as spatial extent. Observation in this research suggest that aquifers in and around the city of Addis Ababa are showing signs of increasing contamination by chemicals such as nitrate. It is assumed that nitrates probably originate from anthropogenic sources.

The level of nitrate contamination in some areas, particularly the minor aquifers, is above permissible limits as defined by local and international standards. At the central parts of the minor aquifer, nitrate values are as high as 112 mg/L. This is more than twice the WHO recommended maximum limit of 50 mg/L. The highest nitrate levels correspond spatially to the most densely populated areas in the city centre, decreasing towards the periphery. A contamination plume extends southwards following the general topography of the area with levels around Akaki-Kality being elevated. The major aquifers exhibit lower nitrate values of around 24 mg/L. However, a rise in these levels has been observed in the area, particularly over the last two decades. It appears that as previously uninhabited areas are annexed into the city limits and residential and industrial areas are built over them, the spatial extent of contaminants is spreading over a large geographical area.

The spatial distribution of the contamination shows higher concentration of nitrate around the minor aquifer area around the city center. Following the general slope of the topography and possibly the groundwater flow direction, the contamination tends to increase southwards. The major aquifers located in the south of the city around Akaki-Kaliti areas have also shown elevated nitrate levels. The spatial extent also appears to increase outwards from the city center.

In terms of the temporal increase of the contaminants, it has been observed that the contamination levels have increased over the last two decades. As previously uninhabited areas are annexed into the city limits and residential and industrial areas are built over them the spatial extent of contaminants is spreading over a larger geographical area, from the city centre outwards.

The study also showed that the concentration of nitrates decreases with increasing depth of wells. Deeper wells are thus less prone to contamination than shallow wells. nevertheless deeper wells are also being affected.

The study has shown that the concentration of nitrates and chlorides are linearly correlated in the minor aquifer areas. This indicates that the contamination probably originates from sewage. By contrast, the major aquifer areas showed no significant linear relationship between these two chemicals and hence, these pollutants appear to be largely from other anthropogenic sources such as agriculture and industrial activities.

The study has thus indicated that the level of nitrates and chloride has increased spatially as well as temporally. Although current levels of these chemicals are lower than permissible values in many of the areas, particularly in the southern major aquifer areas, the increase will eventually impact groundwater resources in the city. Therefore the minor and major aquifers in the vicinity of Addis Ababa are at risk.

It appears that the environmental policy of Ethiopia has not incorporated mitigation measures against groundwater contamination threats. The absence of enforcement capability with regard to industrial effluents, waste disposal and sewerage is likely to aggravate the current contamination. On the other hand the recommendation by a new policy that the design of the pit latrines be modified so as to limit leakage of contaminants into aquifers and the building of pit latrines as a condition for housing construction will assist in alleviating the problem. Addressing the policy gaps will contribute to increased awareness in reducing this threat. At the moment public awareness of the link between anthropogenic activities including pit latrine construction and groundwater contamination appears to be limited.

10.2 Recommendations

In order to deal with these pressing problems, it will be necessary to implement a two-pronged approach. First anthropogenic waste input into the aquifers must be minimized and secondly, the water abstraction areas must be protected.

Minimizing of anthropogenic waste input into the aquifers could be addressed through the implementation of sewerage system in the city of Addis Ababa and other major urban centres. A new sewerage system can be incorporated in tandem with the current massive infrastructure work being carried out in the city. New real estate ventures should also be encouraged to introduce localized sewerage system. The southward sloping features of the city's landscape can also be put to effective use by designing gravity operated sewerage networks. This will reduce the massive non-point source of contamination.

Standard anthropogenic waste disposal facility designs should be made available, appropriate location of these facilities should be identified, more frequent septic collection services should be introduced and a continuous public awareness program needs to be initiated. The use of unsealed pit latrines should be actively discouraged and substituted with a more environmentally friendly system that takes geology, soil and groundwater table characteristics as well as population density of each area into account.

Since implementation of sewerage systems needs substantial finances, a staged approach would need to be implemented, so that all sections of the city can be assisted. Meanwhile, pit latrine designs could be improved by issuing standard designs. Modified sanitation systems could later be connected to sewerage systems. Industries should be required to treat their own waste, preferably on-site and to devise and implement a waste management strategy.

Considering current financial limitations, a short term community-based system such as a community septic storage facility could be introduced. In this arrangement each household would be encouraged to connect waste systems to this unit which will then be periodically desluged.

Addressing increasing demands for clean water in urban centres ought to focus not only on assessing new sustainable water supply sources, but also of managing existing sources. This will include the protection of abstraction areas as well as the control of effluent discharge from anthropogenic activities.

A major and immediate effort is required to limit water leakage from the city's water distribution network. This would not only contribute towards an improved management of the scarce resources, but would reduce abstraction demand, leading to the long term management of water resources. Even a small reduction in leakage would reduce water shortages and increase coverage significantly.

Contaminants in the open sewers in the city gradually find their way into the major recharge area of the Akaki-Kaliti groundwater abstraction area. This needs to be managed. Pollutant levels in these rivers must be reduced and aquifers must not be recharged by waste and polluted waters. Legislation that prohibits direct discharge of waste into streams and open sewers, supported by a general awareness drive, needs to be implemented.

Sewerage is not the only sources of groundwater contamination in urban or rural areas. With the increasing importation of nitrogen-based fertilizers into Ethiopia, the level of nitrate in groundwater from agriculture is expected to rise. This could pose a health risk in the long run.

Remediation process would entail a change in focus of current environmental policy, a more robust enforcement capability, empowerment of Regional Governments as well as the continuous centralized monitoring of wells and springs and the compilation of a data base of groundwater quality should be implemented. In addition to this, a speedier remediation strategy is required in cases where groundwater contamination has already occurred. Contaminated wells should be closed until remedial action has been implemented.

However, a prerequisite for the implementation of a successful remediation strategy is sound planning and thus an environmentally sensitive, pre-emptive, master-plan for urban areas needs to be put in place to integrate infrastructure development works with appropriate sewage disposal and treatment.

The above activities should be based on sound research of the hydro-geology of Ethiopia and the attenuation capacity of soils/rocks. Appropriate well siting should be determined ensuring that septic tanks, farms and factories do not contribute to groundwater contamination. Research is also required to define protected zones for groundwater resources.

Abstraction of wells needs to be monitored so that unauthorized private drilling is regulated. In tandem, issuing permits, as well registering operational wells for the purpose of monitoring resources as well as protecting vulnerable aquifers will have to be established. Requirements to incorporate treatment facilities for waste water generated from private/industrial institution will also have to be considered. This would require instituting guidelines where major industries would have to recycle used water particularly that extracted from their '*own'* sources.

In addition to this installing water meters in these wells and instituting charges for consumption will contribute towards covering the cost of water supply related infrastructure development in the city.

It is essential that remedial efforts should be accompanied by a general public awareness drive, addressing the social and economic and religious implications of water contamination. A current problem is the contamination of '*Tsebels'* or 'holy waters' inside churches, normally held sacred by a large part of the community. Consumption of this water could pose a serious health threat as it is used for medicinal purposes. Elevated nitrate levels have been observed in the Anwar Mosque well, which is still used for religious purposes. Convincing the population of the dangers of such consumption would involve the participation of religious and community leaders. This is a serious challenge and would have to be addressed with caution and extends beyond the social and political setting into the religious domain, the handling of which would require tact and wisdom.

Research activities and drafting of policies should extend beyond the confines of Addis Ababa. A nationwide assessment of groundwater resources, and setting limits on sustainable abstraction and protection for each aquifer and the monitoring of selected wells is essential. The establishment of nationwide quality standards and data base centre as well as central laboratory is recommended. Such standardization will contribute to a better understanding and monitoring of water resources as it encourages data compilation and research

In order to achieve the above, the participation of all involved in groundwater resources management such as governmental or non governmental agencies as well as private drillers is indispensible. A concerted effort by all will assist in the effort to reverse and eventually bring under control the increasing contamination threat. Drastic steps in addressing the multi faceted challenges of supplying of clean water to Ethiopians and immediate action is needed to ensure that 'Addis Ababa' meaning 'New Flower' lives up to its name.

10.3 Issues for Further Research

This Thesis focused primarily on observing the effect of human waste on groundwater quality. As such, the main direction has been on observing the correlation of two chemicals, nitrate and chloride, as indicators of human waste contamination. The analysis has not observed the effect of other chemicals, such as those sourced from industries, on the quality of groundwater in the city. This suggests that a number of issues may be further researched.

Health Impact of Nitrate Contamination of Potable Water on Selected Urban Population of the City of Addis Ababa

This research has shown that, elevated level of nitrate is observed in groundwater in the centre of Addis Ababa. This would suggest that the population utilizing groundwater in these areas may possibly be exposed to elevated nitrate concentrations. Whilst observed levels tend to be within permissible levels, it is not clear whether long term exposure to these levels would have an effect on human welfare. A possible further research area would therefore be the health impact of exposure to nitrate in the city's population.

Lithology and Groundwater Contamination in the city of Addis Ababa

This research indicates that there may be an inter-aquifer interaction that facilitates contaminant travel. The contamination maps suggest that contaminants may travel between the minor aquifers in the centre of the city towards the major aquifers in the southern peripheries, in a north-south direction. This may explain why a tandem elevation of nitrate and chloride appears to be observed in both aquifers. In order to accurately determine this mechanism, however, further research into the lithilogy of the area and the geological factors that influence this interaction will need to be explored. Hence a further research possibility will be the study of the effect of lithology on groundwater contamination in the city, and ways of mitigating it.

Industrial Waste Impact on Water Resources in the City of Addis Ababa

The correlation of nitrate and chloride has been observed to suggest that the chemicals may have been sourced from human waste. The groundwater in the city is not however, exposed to human waste sourced chemicals only. This research has shown that it may also be exposed to industrial sourced contaminants. A further research area would therefore be the observation of the impact industrial waste on groundwater resource in the city of Addis Ababa. This may include an assessment of chemical contamination of boreholes in the Akaki-Kaliti well field, in addition to heavy metals contamination of shallow aquifers in Addis Ababa

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11.1 Appendixes

A partial List of Boreholes Assessed in the Research Work

No.	Borehole name	Coordinates	
		X	Y
1	Akaki well	477500	979300
2	Leather & Leather Products Training Centre, Kaliti	473326	986813
3	Leather & Leather Products Training Centre, Kaliti	473326	986813
4	Piezo 4 well Water (AAWSSA/ IAEA)	482950	963800
5	AA Hilton hotel BH near tennis court	473800	996600
6	AA Hilton Hotel Old BH	473800	996600
7	AA Hilton New Well	473800	996600
8	AA Michael	481779	994444
9	AA-Abay Mesk Soft Drinks-2(Pepsi Cola)	473100	992600
10	AA-Addis Tyre factory-1	473900	989000
11	AA-Adey Abeba Cotton Mill-1	473800	990250
12	AA-Adwa flour mill	476000	980900
13	AA-Africa Hotel	471942	996209
14	AA-Alert-2Well	468100	993100
15	AA-American Embassy(Marine old)-1	473900	1001050
16	AA-American Embassy-3 Near Garage	474050	1000875
17	AA-American Embassy-4 New Marine	474000	1001000
18	AA-Anbessa Transport Garage	468400	1001016
19	AA-Apostlic, Tero, Kolfe	467250	999800
20	AA-Artificial Insemination	475300	983800
21	AA-Asco, Black Lion Shoe Factory	466175	1001800
22	AA-Asko-99	465578	999808
23	AA-Ato Tahas Burayo	465410	1002944
24	AA-Ato Zena Gessesse, Kotebe Gabriel	483550	999250
25	AA-Awas Tannery-1	473500	987900
26	AA-Batu Tannery	473466	987247
27	AA-Beverage CorpGasv& Crate factory	478462	977721
28	AA-Bingham Acadamy, kolfe	468650	999800

29	AA-Bole Medihanialem Church BH2	476800	994200
30	AA-Brewery-7	471500	995800
31	AA-brewery-9	471400	995900
32	AA-Brewey-1	471600	995800
33	AA-British Embassy-1	476500	998250
34	AA-British Embassy-2	476450	998100
35	AA-Building College	470500	996000
36	AA-Burayu Simachew mekonen Borehole	465161	1003103
37	AA-Burayu, Beles Soft Drinks Factory	461300	1002250
38	AA-Burayu, Ethio-brick Factory	465550	1003250
39	Aa-Burayu, ethio-Libya joint Venture PLC.	464600	1003075
40	AA-Burayu-1-99	463972	1000788
41	AA-Burayu-99	464031	1002909
42	AA-Busa-Areda Jawe	415715	976666
43	AA-Campo Asmare Gerage	471800	995200
44	AA-Cement Factory-1	473100	991800
45	AA-Cement Factory-2	473100	991900
46	AA-Cigarette Factory	471300	994800
47	AA-Coca Cola Factory-1	470000	996400
48	AA-Dire Tannery BH1, Gulele	468200	1001600
49	AA-DL.M.PLC, Kaliti	475050	985050
50	AA-Donbosco fathers, yared Church	473900	993100
51	AA-ECAFCO	473750	990050
52	AA-EELPA-1	472300	995700
53	AA-ETHARSO-1	470250	991500
54	AA-ETHARSO-2	470200	991300
55	AA-Ethio-Marble industry-1	468800	1001007
56	AA-Ethio-Marble Industry-2	468900	1001007
57	AA-Ethio-Meat Concentrete Factory	473326	986813
58	AA-Ethio-Metal meal-1	476400	980600
59	AA-Ethiopia Thread Factory	473800	990200
60	AA-Ethiopian Iron And Steel Faoundary BH-3	476520	980710
61	AA-Ethiopian iron and Steel faoundry BH-1	476426	980749

62	AA-Ethio-Spice extraction	473300	987700
63	AA-Filwooha Hotel-1	473100	996400
64	AA-Filwooha Hotel-2	473200	996300
65	AA-Filwuha new	473209	996728
66	AA-Former Golf Club	471700	994900
67	AA-French Embassay	474300	1001005
68	AA-Gandi Memorial Hospital	473000	996300
69	AA-Gebremariam School	472600	997400
70	AA-General Winget School	468300	1001003
71	AA-Ghion Hotel -2	473300	996200
72	AA-Ghion Hotel-1	473300	996100
73	AA-Ghion Hotel-3	473300	996300
74	AA-Glass and Bottle Factory	467200	1001017
75	AA-Glass Factory BH2,Asco	467100	1000550
76	AA-Gulele Glass-Factory-3	466900	1001005
77	AA-Gulele Misionery of Charity No.1	465651	1001575
78	AA-Gulele Misionery of Charity No.2	465600	1001855
79	AA-Hagbes PLC., Bisrate Gabriel area	468875	993750
80	AA-Hollow block Nifas Silk	474075	989600
81	AA-Hope Enterprise -1	466200	993000
82	AA-Kaliti Airforce-1	476400	984800
83	AA-Kaliti Metal products Factory	474225	982650
84	AA-Lafto-99	471500	990500
85	AA-Mekanissa Mekaneyesus House of Assembly	470275	990353
86	AA-Motor Engineering Company (MOENCO)	477463	994346
87	AA-Repi Enyi General Business Group	464538	991302
88	AA-SOS Childrens Home Bisrate Gabriel	470110	993850
89	AA-Tadele Gelecha Plastic Bags factory, Burayu	465243	1003930
90	AAU main campus	473400	999600
91	AAU Well	473560	999968
92	AA-Vatican Indonesian embassy	470950	993300
93	AA-Water lll Borehole BH19	478019	977985
94	AA-Water lll Borehole BH01	477972	974859

95	AA-Water lll Borehole BH02	478399	975589
96	AA-Water lll Borehole BH03a	480517	977974
97	AA-Water lll Borehole BH05b	476574	975607
98	AA-Water lll Borehole BH06	479696	976936
99	AA-Water lll Borehole Bh07	479405	976735
100	AA-Water lll Borehole BH08	479061	976370
101	AA-Water lll Borehole BH09	479246	977104
102	AA-Water lll Borehole BH10	479058	976020
103	AA-Water lll Borehole BH11	478780	977307
104	AA-Water lll Borehole BH12	478808	976867
105	AA-Water lll Borehole BH14	478580	976051
106	AA-Water lll Borehole BH16	478347	976752
107	AA-Water lll Borehole BH17	478199	976361
108	AA-Water lll Borehole Bh18	478154	975966
109	AA-Water lll Borehole BH20	477945	976985
110	AA-Water lll Borehole BH24	477330	976793
111	AA-Water lll Borehole BH26	477181	975680
112	AA-Water lll Borehole BH3b	478713	974977
113	AA-Water lll Testwekk-B14	480900	978800
114	AA-Water lll Testwekk-T2	479400	981400
115	AA-Water lll Testwell-B10	461500	1001023
116	AA-Water lll Testwell-B11	466200	988800
117	AA-Water lll Testwell-B12	466400	987600
118	AA-Water lll Testwell-B13	479400	981400
119	AA-water lll Testwell-B15	473069	979881
120	AA-Water lll Testwell-B3	463700	988500
121	AA-Water lll Testwell-B4	486200	1001042
122	AA-Water lll Testwell-B5	481200	980000
123	AA-Water lll Testwell-B6	470800	982900
124	AA-Water lll testwell-B7	473566	978610
125	AA-Water lll Testwell-B9	481600	982900
126	AA-Water lll Testwell-T1	481200	980000
127	AA-Water lll Testwell-T5	481600	982900

128	AA-Watet lll Testwell-T4	473108	979851
129	AA-Watter lll Borehole BH22	477651	975923
130	AA-Woreda 17 Kebele 23	476963	994106
131	AAWSA Asko Borehole	465507	1002285
132	AAWSA Ayer Tena near kidanemeheret	466425	993308
133	AAWSA F1 at Fanta	479000	981400
134	AAWSA F3 at Fanta	479700	981700
135	AAWSA F7 at Koye	481337	982304
136	AAWSA Kaliti Well	475000	985800
137	AAWSA Kaliti Well	476500	981300
138	AAWSA Kaliti Well Kaliti	475000	985800
139	AAWSA Keraniyo No.1	467000	996300
140	AAWSA Keraniyo No.2	463908	995127
141	AAWSA LAFTO Hana Mariam	471400	988250
142	AAWSA Mekanissa	470450	990125
143	AAWSA Mekanissa No.2	469817	989866
144	AAWSA Mekanissa No.3	470316	991064
145	AAWSA Near Cigarette Factory	470900	994800
146	AAWSA Ras Kassa Sefer/Ferensay	475000	1001300
147	AAWSA Shegole	468100	1001625
148	AAWSA(IAEA) well water Piez 1	478347	976752
149	AAWSA, Ayer Tena, near Kidanemeheret	466425	993308
150	AAWSA, Kotebe Kara	484190	998500
151	AAWSA, Kotebe Kara	476963	994106
152	AAWSA, Kuskuam	472900	1003550
153	AAWSA, Lafto Hana Mariam	471400	988250
154	AAWSA, Mekanissa	470450	990125
155	AAWSA, Repi behind Roll Soap Factory	463850	993100
156	AAWSA, Shegole	468100	1001625
157	AAWSA,near Kotebe EELPA	480395	998100
158	AAWSA/IAEA Piezometer No.1	478347	976752
159	AAWSA/IAEA Piezometer No.2 (P2) Aba Samuel	470228	972214
160	AAWSA/IAEA Piezometer No.3 (P3)	475402	976807

161	AA-Yekamichael-99	477515	997474
162	AA-Yekamichael-99	477515	997474
163	Aba Samuel	473200	979800
164	Abay Mesk Soft Drinks Factory	473100	992600
165	Abay Mesk Soft Drinks Factory 1	473100	992600
166	Abay Mesk Soft Drinks Factory 2	473100	992600
167	Abay Mesk Soft Drinks Factory well A 5	473100	992600
168	Abay Mesk Soft Drinks-1	473000	992700
169	Abay Mesk Soft Drinks-1(Pepsi Cola)	473000	992700
170	Abay Mesk Soft Drinks-2	473100	992600
171	Abay Mesk Soft Drinks-2 (pepsi Cola)	473100	992600
172	Abay Mesk Soft Drinks-3/pepsi cola factory	473000	992700
173	Abay Mesk Soft Drinks-4/pepsi cola factory	473000	992700
174	Abo Bridge	475638	999991
175	Abo Church Ferensay	476078	1000763
176	Abo Spring	478048	1006634
177	Abo Spring, Awash	472400	953500
178	Abo Spring, Awash	472400	953500
179	Abo Tsebel Spring	478048	1006634
180	Abraham Zeleke, Kaliti	475300	985325
181	Abuloya Deep Well Akaki	478772	958888
182	Abune Yosef School, Alert	467150	992150
183	Abyssinia Flowers PLC (Dire Dam)	494571	1011834
184	Addis Ababa Kera	472150	993300
185	Addis Ababa University	473400	999600
186	Addis Ababa Winary	469900	996000
187	Addis Ababa Brewery-1	471600	995800
188	Addis Ababa Brewery-2	471500	995900
189	Addis Ababa Brewery-3	471400	995800
190	Addis Ababa Brewery-4	471400	996000
191	Addis Ababa Brewery-5	471500	996000
192	Addis Ababa Brewery-6	471550	995950
193	Addis Ababa Brewery-7	471500	995800

194	Addis Ababa Brewery-8	471300	995800
195	Addis Alem TWS	434015	1000129
196	Addis Alem-Amaro#1	430267	987498
197	Addis Beer-9	471400	995900
198	Addis Cement Well Water	473100	991800
199	Addis Tyre	473900	989000
200	Addis Tyre Factory 2	473900	989000
201	Addis Tyre Factory BH4	473700	988850
202	Addis Tyre Factory well	473900	989000
203	Addis Tyre Factory well	473970	989171
204	Addis Tyre Factory-1	473900	989000
205	Addis Tyre Factory-2	473900	989000
206	Adey Abeba Cotton Factory	473700	990000
207	Adey Abeba Cotton Mill	473800	990250
208	Adey Abebe Cotton Mill-2	473848	990072
209	Adventist Mission School near Akaki Minucipality	476762	980541
210	Adwa Flour Mill	476000	980900
211	Africa Hotel	471942	996209
212	Akaki	477500	979300
213	Akaki	477400	979500
214	Akaki	476521	980711
215	Akaki	477446	978851
216	Akaki	478463	977506
217	Akaki	477609	978690
218	AKAKI	478256	977722
219	Akaki	477233	979000
220	Akaki Air force - 1 Koye East Akaki	482400	983000
221	Akaki Air force - 1 Koye East Akaki	482400	983000
222	Akaki Air force - 1 KoyeEast Akaki	482400	983000
223	Akaki , Lesperance School	478425	981350
224	Akaki , Lesperance School	478425	981350
226	Akaki AKV-2	477248	982879
227	Akaki Barguba G.T Well Water	474648	985501

228	Akaki Barguba G.T.	474648	985501
229	Akaki Beverly Internation	480895	977403
230	Akaki BH 27		
231	Akaki BH 6		
232	Akaki BH 7		
233	Akaki Borehole BH- 56		
234	Akaki Borehole BH-27		
235	Akaki Borehole BH-64		
236	Akaki Borehole BH-67		
237	Akaki Borehole BH-92		
238	Akaki Borehole W 46		
239	Akaki Borehole W 50		
240	Akaki Borehole W 58		
241	Akaki Borehole, BH 56		
242	Akaki Borehole, BH 61		
243	Akaki Borehole, BH 64		
244	Akaki Borehole, BH 67		
245	Akaki Borehole, BH 79		
246	Akaki Borehole, BH 90		
247	Akaki Borehole, BH 92		
248	Akaki EP5 W	478707	979650
249	Akaki EP7 W	479495	977350
250	Akaki Ethio-Fiber - 1 Akaki	477500	979300
251	Akaki Ethio-Fiber - 1 Akaki	477500	979300
252	Akaki Ethio-Fiber - 1Akaki	477500	979300
253	Akaki Ethio-fiber-1	477400	979500
254	Akaki Ethio-fiber-2	477500	979300
255	Akaki Ethio-Fiber-2 Akaki	477400	979500
256	Akaki Ethio-Fiber-2Akaki	477400	979500
257	Akaki Fanta Spring	478849	981223
258	Akaki Garment Factory	477800	979500
259	Akaki Indo-Europian Textiles-1	477446.27	978851.17
260	Akaki Indo-Europian Textiles-2	476600	981500

261	Akaki Indo-Europian Textiles-3	476369.03	981717.33
262	Akaki kebele 06 Kilento	477900	982875
263	Akaki Kebele 06 Kilento	477900	982875
264	Akaki Klint Prison site	478130	982300
265	Akaki Koye Air defence -1	482400	983000
266	Akaki Koye Defence Gulele	465600	1001855
267	Akaki Lesperance school	478425	981350
268	Akaki Lesperance school	478425	981350
269	Akaki Mesfin Zelwlew Dairy Farm	481507.4	976220.97
270	Akaki Meta Sab Utility Factory-6	476500	981500
271	Akaki Metal Fac	477446.3	978851.2
272	Akaki Metal Products Factory - 1 Akaki	477446.27	978851.17
273	Akaki Metal Products Factory - 2Akaki	477232.61	978999.84
274	Akaki Metal Products/Sabean Utility Factory-1	477232.61	978999.84
275	Akaki Metal Products/Sabean Utility Factory-3	476500	981500
276	Akaki Metal Products/Sabean Utility Factory-4	477446.27	978851.17
277	Akaki OCFA	475400	982500
278	Akaki Prison	471700	994400
279	Akaki S A W	480252	976967
280	Akaki Telecommunications	476600	978200
281	Akaki Textile Mill	476350	981300
282	Akaki Textile Well	476161	981056
283	Akaki Textiles New Borehole (KK Plc)	475800	981300
284	Akaki Textiles New Borehole (KK Plc)	475800	981300
285	Akaki Water Supply Test Well EP-1 Akaki well field	479340	981400
286	Akaki Water Supply Test Well EP-1 Koye	479340	981400
287	Akaki Water Supply Test Well EP-1Akaki Well	479340	981400
288	Akaki Water Supply Test Well EP-1Akaki Well	479340	981400
289	Akaki Water Supply Test Well EP-1Koye	479340	981400
290	Akaki Water Supply Test Well EP-2	481600	982850
291	Akaki Water Supply Test Well EP-2 Akaki well field	481600	982850
292	Akaki Water Supply Test Well EP-2 Koye	481600	982850
293	Akaki Water Supply Test Well EP-2Akaki Well	481600	982850

294	Akaki Water Supply Test Well EP-3	479740	981400
295	Akaki Water Supply Test Well EP-5 Akaki well field	478450	979950
296	Akaki Water Supply WAkaki well field ell EP-4	479942	977322
297	Akaki Water Supply Well EP-4Akaki Well-field	479942	977322
298	Akaki Water Supply Well EP-5	478450	979950
299	Akaki Water Supply Well EP-5Akaki well field	478450	979950
300	Akaki Water Supply Well EP-6Akaki Well-field	479526	977468
301	Akaki Water Supply Well EP-8Akaki Well-field	478999	977938
302	Akaki Well	479340	981400
303	Akaki Well	479942	977322
304	Akaki Well	478695	976491
305	Akaki Well	481600	982850
306	Akaki Well	479942	977322
307	Akaki Well	478581	976052
308	Akaki Well	478450	979950
309	Akaki Well	479942	977322
310	Akaki Well	479340	981400

Sample Well Data

Well No.		1	2	3	4	5	6	7	8	9	10	11		12	13
Location/Owner		Patients Multi Purpose Asso.. Alert area	Bassefa Trading Kality Shell Depot	near Gedera Hotel	Kotebe Ato Demeke	Medhanialem Church	Marble tile Factory Akaki Dukem Area	AA Hilton hotel BH near tennis court	AA Hilton New Well	AA Hilton hotel old BH	AA Hilton Hotel Old BH	AA Hilton Hotel Old BH	AA Hilton Hotel Old BH	AA Hilton Hotel Old BH	Kharafi/Accor hotel deep well at maskal square
Grid Reference															
Data Obtained from															
Depth M		100.7	166		77		184	205					400		300
Static Wl		35.12	40.55		19.2		145.9	40					9.75		13.13
Dynamic WL		51.6	80.71		57.1		146.1								86.15
Discharge Avg.		5.5	1.5		5.1		7.7						3.15		10.5
Date of Sampling		Jan-06	Feb-05	Sep-04	Feb-01	Feb-08	Aug-00		1998	1998	Oct-95	Oct-96	Jan-67	Jan-82	Jun-08
Date of Analysis															
Laboratory													WATENCO	EIGS	wwd&SELS
Temperature	^{o}C												47	48	50
Turbidity	FTU						_	5							5
Color	Pt.Co.units						_	25							_
Taste															
P^H		6.83	7.76		6.94		7.6	8.65	7.48	7.7	8.65	7.59	8.3		7.51
Total Solids 105 oC mg/L															2462

TDS	mg/L	216	300			404.8	284	281.2			2812	513	3298	3021	2440
Conductivity	μS/cm	351	462		432		435	4.04			4.04	549			3760
Dissolved O_2	mg/L							0.75			0.75				
Dissolved CO_2	mg/L							42.5	104		42.5	11			
Silica, SiO_2	mg/L							19	75	75	19	16	49	100	
Hydrogen Sulphide, H_2S	mg/L														
Total hardness as $CaCO_3$	mg/L	164.9	155.4			21.9	205.8	46			46				61.6
Calcium hardness as $CaCO_3$	mg/L										32				
Magnesium hardness as $CaCO_3$	mg/L										14				
Total Alkalinity as $CaCO_3$	mg/L	140.8	161.8			210	230.4				2090				1860
Bicarbonate Alkalinity as $CaCO_3$	mg/L														
Carbonate Alkalinity as $CaCO_3$	mg/L							2090							
Hydroxide Alkalinity as $CaCO_3$	mg/L														
NH_3, Ammonia	mg/L	_					_	nil							0.07
Na, Sodium	mg/L	11	43.5		30	102	26		240	808		116	864	800	1000
K, Potassium	mg/L	3.1	4.2		4.6	8.2	5.5		15	17.2		3	64.8	18	17

Ca, Calcium	mg/L	49.59	41.8		44	5.4	71.4	32	6	6.4		13	16	5	13.2
Mg, Magnesium	mg/L	9.31	12.4		10	2.04	6.63	14	2	1		3	3.9	1	6.96
Fe, Iron	mg/L	0.02	0.021			0.12	0.06	0.03	0.4	0.14	0.03				0.11
Mn, Manganese	mg/L	_				0.02	_	0.13			0.13				
Al, Aluminium	mg/L														
Cu, Copper	mg/L														
Cr, Chromium (hexavalent)	mg/L														
MajorAnions															
Cl, Chloride	mg/L	9.5	25.8		9	23.83	6.72	1	43	42.5	1	15	0.053	48	55.6
NO_2, Nitrite	mg/L	_					_	0.018			0.018				trace
NO_3, Nitrate	mg/L	18.25	14.1		<0.04		10.5	0.1	0.04	24.3	0.1	6	NIL	2	0.023
F, Fluoride	mg/L	1.1	0.35		2.2	3.02	0.14	1.9	21.1	26	1.9	2		25	22.1
HCO_3, Bicarbonate	mg/L	171.7	197.4		240	256.2	281.09		2198	1952		317	2000.8	1070	2269.2
CO_3, Carbonate	mg/L	Trace	trace				trace					0.96	144		trace
SO_4, Sulphate	mg/L	0.28	20.2		20	3.5	1.58	60	55	48.2	60	10	156	48	52
PO_4, Phosphate	mg/L	_						0.5			0.5				0.64
Boron					<0.15				0.13					401	
Coliforms, MPN/100ml					92										
E.Coli, MPN/100ml					present										
Total Coliform					Non potable										

Total Coliform					Non potable										
Faecal Coliform															
COD															
BOD															
Heavy Metals															
Cadmium (Cd)															
Lead (Pb)															
Cobalt (Co)															
Nickel (Ni)															
Zinc (Zn)															

Declaration

I declare that "The *Impact of Low Cost Sanitation On Groundwater Contamination in The City of Addis Ababa*" is my own work, and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

Girmay Kahssay

Signature ____

Date ____