

**GIS BASED GROUNDWATER VULNERABILITY ASSESSMENT IN
AKAKI RIVER CATCHMENT, ADDIS ABABA (CENTRAL
ETHIOPIA)**

By

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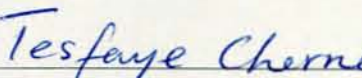
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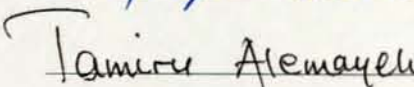
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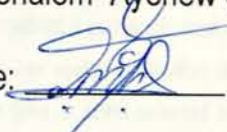
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APPROVAL FOR EXAMINATION

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ABSTRACT

The studied area, Akaki River Catchment, is located at the headwaters of the Awash River Basin. The Intoto Mountain Ranges formed by Ambo-Kassam regional fault form the hydrographic divide between Awash and Blue Nile Rivers. The Akaki River Catchment has an approximate surface area of about 1464 km² and perimeter of 216 km, and approximately bounded between 8° 46' 57" and 9° 13' 00" N and 38° 35' 00" and 39° 05' 00" E. It has an elevation range of less than 2040 to 3,200 m above mean sea level (amsl).

The studied area is made up of different volcanic rocks ranging in age from Quaternary to Miocene, including recent alluvial/residual deposits. There are also regional and local faults. Different type of clay soil and lacustrine deposits formed from the weathering of volcanic rocks are the dominant soil type that characterizes the area. At some localities these clay soil are either thin or totally absent.

The mean yearly rainfall depth of the Akaki River Catchment was 1150 mm (from 1964- 1998). The arithmetic mean monthly rainfall ranges from 6 mm (in December) to 276mm (in August) for the three stations (see chapter 2) in the catchment for 35 years. The highest and lowest mean monthly maximum temperature occurs in months of March (25 °C) and the lowest is in the month of August (20 °C), while the minimum mean monthly values were 8 °C (in December) and 12 °C (in March) for Addis Ababa Observatory from 1951- 1998 respectively. The calculated mean annual temperature was 16 °C.

Studies show both surface and groundwater pollution in the Akaki River Catchment; and associated it to the following major sources: industrial activities, agricultural practices, municipal/ domestic/ wastes, fuel stations, garages, and health centers and also to graveyard (cemeteries), quarry mining, and market areas (see chapter 4). In this chapter an account was made on possible potential pollution sources. The over view include general potential pollution/contamination sources and existing potential groundwater polluting sources identified by earlier works in the studied area. To see spatial distribution of groundwater contamination situation in the catchment the discussion was supported by groundwater quality analysis data at some selected sites in the catchment extracted from recent study. For these purpose three important groundwater quality indicators (Cl, NO₃, and TDS) was selected.

The population density of Addis Ababa and its environs vary from more than 400 persons per hectare to less than 25 persons per hectare. The existing land use patterns in the catchment were broadly divided into four groups as: agriculture/open area (69%), forest land (15%), urban area & its associated uses (15%) and water body and wetland covers (0.98%) of the total land use/cover.

The general objective of the study is to identify and map the *aquifer vulnerability to pollution* in the Akaki River Catchment by using an empirical model/system known as **DRASTIC** (Aller et. al, 1987; Evans and Meyers, 1990) to assess relative groundwater pollution susceptibility using hydrogeologic factors (intrinsic rather than specific or integrated approach) was adopted, with **GIS** there by to prepare vulnerability index maps. One of the specific objectives of this thesis was the application or use for the first time in Ethiopia of an index method of aquifer vulnerability assessment with Geographic Information System (GIS).

Practically and academically, the research is of interest since there was no earlier comprehensive study concerned with *groundwater contamination protection*. Thus, to supplement the policy makers on *groundwater resource management and protection* in this catchment, there must be *map-based information* that indicates spatial distribution of relatively vulnerable areas that is useful in major aspects of planning (chapter 1). Where as, previous researchers dealt with general hydrogeology, hydrochemistry, pollution condition, etc. in this catchment.

Basic concepts and over views/definitions of groundwater aquifer vulnerability mapping was given in chapter 5 as it is necessary to make clear how we carry out such vulnerability mapping or assessment. After we have seen concepts of vulnerability mapping, we need to decide and define which method of vulnerability analysis will be used (chapter 6). Hence, DRASTIC model was selected as tool for vulnerability analysis and mapping. DRASTIC factors use a numerical ranking system to assess groundwater pollution potential in hydrogeologic settings. The system consists of three parts, which are designated as: *ranges, ratings and weights*. Review of experiences with the model, its inherent assumptions and ambiguities, and why it was particularly selected and its potential uses especially, with GIS was outlined. Data base was designed and constructed for attribute inputs for spatially distributed geographic data to make use of GIS as it is described in chapter 7. After data base was designed and constructed, attributes were extracted and modelled to get the different DRASTIC parameters or layers to work within the GIS latter on (chapter 8).. Furthermore Chapter 8 gives the description/definition of each DRASTIC parameter and how each of them contributes to groundwater aquifers contamination or protection. Rating and weighing was made according to the predefined ranges or values given for the seven factors (Aller et al., 1987). The land use/cover of Addis Ababa/Finfinne city was rated to indicate the potential risks from the land use in the city.

The ultimate goal of this vulnerability mapping is the subdivision of an area into several units showing the differential potential for pollution or for a specified purpose and use based on an index map. The results of vulnerability assessment are portrayed on a map showing various homogeneous areas, sometimes called cells, which have different levels of vulnerability. Accordingly, using a cell size of 30m subjectively defined in this thesis, and is believed to provide sufficient resolution; the catchment was divided into 1708 rows and 1807 columns. After the seven DRASTIC layers were made read the following results were obtained by employing an overlay operation/analysis: the minimum normal/general DRASTIC index is 73 and the maximum normal/general DRASTIC index is 249; whereas, the minimum pesticide DRASTIC index is 78, and the maximum pesticide DRASTIC index is 260. Both types of the above DRASTIC index maps show that the northern part of the study area is relatively more vulnerable to pollution than other areas except some localized areas showing higher index values as well (Chapter 9).

Furthermore, the environmental impact assessment (EIA), and an environmental police, legislation, etc. of Ethiopia was pin pointed (Annex 8).

This research work was ambitious in the sense that aquifer vulnerability assessment was planned & conducted under serious constraints of resources. Even though this might affect the quality of the research result, all possible endeavors and necessary scarifications have been made to organize data found in archives of different organizations and field surveys for the model input to tackle these problems. Finally, as this work is the first application of the groundwater aquifer vulnerability assessment method; I recommended further detail research work (chapter 10) to fill the knowledge gap and provide detailed data for future aquifer vulnerability mapping and groundwater protection using various methods.

Key words/phrases: Akaki River, alluvial, aquifers, attributes, contamination/pollution, DRASTIC, fault, GIS, groundwater, hydrogeology, intrinsic/specific/integrated vulnerability, spatial, volcanic

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CONTENTS

ABSTRACT	IV
ACKNOWLEDGEMENTS	VI
PART ONE	0
GENERAL INTRODUCTION	0
CHAPTER ONE	1
INTRODUCTION	1
1.1 Background	1
1.2 Location	8
1.3 Objective(s)	10
1.4 Methodology	11
1.5 Scope of the Study	15
1.6 Previous Works	16
PART TWO	19
GENERAL BACKGROUND OF THE STUDY AREA	19
CHAPTER TWO	20
PHYSICO-CLIMATIC CHARACTERISTICS	20
2.1 Climate	20
2.2 Population Density	21
2.3 Physiography, Drainage and Land use	23
CHAPTER THREE	32
GEOLOGICAL SETTINGS	32
3.1 Regional Geology	32
3.2 Geology of Akaki River Catchment	34
3.3 Geological Structures	40
CHAPTER FOUR	43
HYDROGEOLOGY AND GROUNDWATER QUALITY: AN OVERVIEW	43
4.1 General Characteristics of Volcanic Rocks	43
4.2 Overview of the Hydrogeology of the Studied Area	47
4.3 Potential Sources of Pollution and Groundwater Quality: Synopsis of Existing Situation	52

PART THREE	64
THEORITICAL BACKGROUND OF GROUNDWATER VULNERABILITY MAPPING AND DRASTIC MODEL	64
CHAPTER FIVE	65
GROUNDWATER VULNERABILITY MAPPING AND ASSESSMENT CONCEPT	65
5.1 Historical Overview	65
5.2 Concept of Groundwater Vulnerability to Pollution	66
5.3 Approaches to Vulnerability Mapping and Assessment	69
CHAPTER SIX	70
GROUNDWATER VULNERABILITY ASSESSMENT METHOD: DRASTIC MODEL	70
6.1 Model Description	70
6.2 Review of Experiences with DRASTIC Model	74
6.3 Definition and Significances of the DRASTIC Parameters	80
PART FOUR	84
MODELING AND APPLICATION OF DRASTIC WITH GIS ON THE AKAKI RIVER CATCHMENT	84
CHAPTER SEVEN	85
GIS DATABASE DESIGN AND CONSTRUCTION: DATA CAPTURE AND INPUT	85
7.1 DRASTIC System and GIS	86
7.2 Data Sources	87
7.3 Database Constructions and Structure for Attribute Data	89
CHAPTER EIGHT	93
DATA ANALYSIS AND PREDICTIVE MODELING	93
8.1 Predictive Modeling	94
8.2 IMPACT OF LAND USE ON GROUNDWATER	112
CHAPTER NINE	116
RESULTS AND DISCUSSION	116
CHAPTER TEN	126
CONCLUSIONS AND RECOMMENDATIONS	126
REFERENCES	130
ANNEXES	136

LIST OF TABLES

Table 3.1 Lithostratigraphic divisions and correlation of the Miocene-Pleistocene volcanic succession in the Addis-Debre Zeit	34
Table 4.1 Major pollutants discharged by some small-scale industrial facilities and their character	58
Table 4.2 Summary of water quality parameters detected in groundwater Samples	60
Table 6.1 Assigned ranges, ratings and weights for the DRASTIC factors	73
Table 7.1 Constructed GIS layers for Akaki River Catchment	88

LIST OF FIGURES

Figure 1.1 Location Map of Akaki River Catchment	9
Figure 1.2 Data integration and procedures followed in vulnerability mapping	12
Figure 1.3 GIS Data Base Construction step	13
Figure 1.4 Conceptual layers Illustration of additive overlay process for the computation of the DRASTIC index maps	15
Figure 2.1 Population Density Map of Akaki River Catchment	22
Figure 2.2 Hill shade Map of Akaki River Catchment	25
Figure 2.3 Relief Map of Akaki River Catchment	27
Figure 2.4 Land use/cover Map of Akaki River Catchment	30
Figure 2.5 Soil-Land use/cover Intersection Map of Akaki River Catchment.....	31
Figure 3.1 Geological Map of Akaki River Catchment	41
Figure 4.1a North- South well log correlations	49
Figure 4.1b East- West well log Correlations	50
Figure 4.2 Schematic representations of general potential pollution sources	54
Figure 4.3 Nitrate concentrations in groundwater at selected sites in the Akaki River Catchment	61
Figure 4.4 Chloride concentrations in groundwater at selected sites in the Akaki River Catchment	62

Figure 4.5 TDS concentrations in groundwater at selected sites in the Akaki River Catchment	63
Figure 8.1 Depths to Water Table Map of Akaki River Catchment	96
Figure 8.2 Net Recharge Map of Akaki River Catchment	100
Figure 8.3 Aquifer media Map of Akaki River Catchment	104
Figure 8.4 Soil Media Map of Akaki River Catchment	106
Figure 8.5 Slope Map of Akaki River Catchment	108
Figure 8.6 Impact of the Vadose Zone Media Map of Akaki River Catchment	111
Figure 8.7 Hydraulic Conductivity Map of Akaki River Catchment	113
Figure 8.8 Simplified Land use/cover Rating Map Showing Levels of Potential Danger to Groundwater pollution	115
Figure 9.1 Normal/ general DRASTIC Index Map of Akaki River Catchment	124
Figure 9.2 Agricultural/ Pesticide DRASTIC Index Map of Akaki River Catchment	125

LIST OF ANNEXES

Annex 1. Some general results of different studies on most frequent values of permeability of volcanic material	136
Annex 2. Grain size Distribution and textural classification of soil according to U.S. SCS	137
Annex 3. Main Industries in Addis Ababa metropolitan area	141
Annex 4. Groundwater quality indicators for selected wells	146
Annex 5. U.S. SCS (1951) Triangle for textural classification of soil media	148
Annex 6. Hydraulic Conductivity Ranges used to classify aquifer media in to Conductivity ranges	149
Annex 7 Water level data used for the interpolation of depth to water.....	150
Annex 8 EIA of Ethiopia: Constitution, Policy and legislations	159

1.3 Background

Over the last 20 years or so there has been a growing awareness of environmental problems and hence it becomes a major national and international (political) issue (Pattar, 1994; Larson, 1987). Environmental Planning has, therefore, become part of the normal planning process to ensure the specific consideration of environmental matters.

PART ONE GENERAL INTRODUCTION

effects of water use (Dawson, 1983; World Resource Institute, 1987).

The quality of groundwater can affect not only our health, but also society and the economy. Groundwater contamination can adversely affect property values, the safety of a community, economic development, and overall quality of life we all share. Once groundwater has been contaminated, it is usually very difficult and costly to clean. Even small contamination does not often easily clean up. For many years, it was thought that groundwater was protected from contamination by the layers of rock and soil that sat on top, but contaminants do move down into the groundwater and affect its quality.

To be more specific, water pollution has been consistently reported in the Athabasca River

CHAPTER ONE

INTRODUCTION

1.1 Background

Over the last 20 years or so there has been a growing awareness of environmental problems and hence it becomes a major national and international (political) issue (Foster, 1991; Leeson, 1995). Environmental Planning has, therefore, become part of the normal planning processes to include the specific consideration of environmental matters.

Environmental problems are mainly caused by /recognized to be arisen by/ man's action under the conditions of poverty and lack of awareness or economic growth. These include resources mismanagement and (indicated by) rapid population growth, water pollution, deforestation, etc. On the other hand, those associated with economic growth are the results of use of fertilizers and pesticides, urbanization, mineral extraction, industrial development and associated effluents/wastes, etc. (Doornkamp, 1985; World Resource Institute, 1996).

The quality of groundwater can affect not only our health, but also society and the economy. Groundwater contamination can adversely affect property values, the image of a community, economic development, and overall quality of life we all share. Once groundwater has been contaminated, it is usually very difficult and costly to clean. Even small contamination sites often costly to clean up. For many years, it was thought that groundwater was protected from contamination by the layers of rock and soil that act as filters, but contaminants do make their way into the groundwater and affect its quality.

To be more specific, water pollution has been consistently reported in the Akaki River

Catchment since 1974 (Komolrite and Firdu, 1974). Recent studies show both surface and groundwater pollution in the Akaki River Catchment; and associated it to the following major sources: industrial activities, agricultural practices, municipal/ domestic/ wastes, fuel stations, garages, and health centers and also to graveyard (cemeteries), quarry mining, and market areas (BCEOM-GKW, 1993; AAWSA, 1983 in: BCEOM-GKW, 1993; Adane Bekele, 1999; BCEOM-Seureca, 2000; Solomon Tale, 2000 etc.).

BCEOM-Seureca (2000) carried out groundwater quality analysis and concluded that high chloride and nitrate values that were found in groundwater are associated with waste disposal and pit latrines. BCEOM-GKW (1993) also took water samples from 45 wells in 1992 and out of the surveyed wells 19 of them was found to contain high nitrate. Similarly, AAWSA (1983) (as cited in BCEOM-GKW, 1993) sampled 14 boreholes and were reported as polluted by nitrate (NO₃), sulphate (SO₄) or showed high concentrations of chloride (Cl) and total dissolved solids (TDS).

Leaving aside the formal and informal urban development activity at the outskirts of the capital city (Addis Ababa); Addis Ababa Proper alone, was increased in size to about 540 km² and in the year between 1984 and 1994, the area of the city increased more than two folds (Solomon Tale, 2000). Solomon Tale (2000) and Adane Bekele (1999) also mentioned that the processes of industrial development are not controlled at all and industries discharge their wastes to the nearby rivers. More than 1082 formally registered industrial development/ establishments exist in the capital city up to 1998 (Addis Ababa Trades, Industry and Tourism Bureau Cited in Solomon Tale, 2000). Adane Bekele (1999) identified only six industries in the city with some form of waste treatment facility, while the rest discharge their waste directly to Little Akaki

River. Little Akaki is highly polluted and Big Akaki is polluted.

Despite all these prevailing conditions in the area, the demand for pure water is top issue in the catchment due mainly to increase in population and industrial activity. To meet this anguish demand there has been several exploration works to tap groundwater in the study area. Of more than four sites selected as groundwater promising areas, the Akaki well field has been successful. It was estimated that groundwater from the well field might meet more than 30 per cent of the water supply of the capital city.

Pressure on the development of the concept of groundwater vulnerability has been generated by the worldwide concern about the problems of groundwater contamination. Hydrologists were involved in the *protection of groundwater* against contamination in industrialized countries, especially with respect to drinking water since 1900 in France (Zaporozec et al., 2002). Groundwater quality issues are receiving widespread attention, and hydrogeologic information is essential for the effective *protection and management of groundwater* quality, which aimed at improving resource and waste management. Effective protection should be primarily aimed at the prevention of problems and requires a sound information base to determine, on a continuous basis, the groundwater quality problems that exist and those that may develop in the future (Center for Natural Resources, 2001).

Therefore, it is crystal clear that there should be a *protection of the groundwater resource* from any pollution threat. To supplement the policy makers on *groundwater resource management* in this catchment, there must be *map-based information* that indicates spatial distribution of

relatively vulnerable areas. Hence, this study is initiated to make available this information for the decision/policy makers and professionals who are interested to work on related issues.

1.1.1 Statement of the Problem

With increasing demand and reliance on groundwater from a growing population comes the need to increase efforts to protect and manage the resource. Incidences of water quality problems in aquifers are becoming documented in the catchment as described above. However, the information available to groundwater resource managers, planners, and stakeholders is primarily in raw data form (i.e. well records, water chemistry, etc.), or localized studies in specific areas in the catchment targeting to water supply quantity and quality. There is a need to compile the groundwater data into information to enable more effective management decision-making regarding the resource. As well, a method of identifying and prioritizing aquifers for different types of management attention is becoming essential in an era of limiting budget resources.

This work is, therefore, planned to address and cater groundwater degradation by *anthropogenic* sources of pollutants which is critical problem to the society's resource and which is consistently facing development planners with regard to *groundwater management*. Furthermore, in order to conduct development in harmony with groundwater regime in particular, and the environment in general, the concerned development needs to have such comprehensive groundwater vulnerability map, which is used easily by other professionals.

To pin point some of the current situation of groundwater pollution condition in the Akaki River Catchment, (also described in chapter 7) it is very important to see the works of Adane Bekele (1999), Solomon Tale (2000), BECEOM-Seureca (2000), and others. There is a general

consensus that pollution of groundwater is caused by infiltration of polluted water (the sources of which is different).

Adinew et al. (2001) described and associated aquifers vulnerability to dense human settlement and intensive industrial development in the catchment.

Depth to groundwater varies from flow artesian (above ground surface) to as deep as 120 meters. The aquifers are primarily volcanic rocks characterized by double porosity type (Vernier et al, 1985; Tesfaye Chernet, 1993; Solomon Tale, 2000; BCEOM-Seureca, 2000).

1.1.2 Significance of the Problem

"By the time subsurface pollution is conclusively identified, it is too late to apply remedial measures.... Degradation of groundwater often requires long periods of time before the true extent of the problem is readily detectable. Long periods of groundwater flow are often required for pollutants to be flushed from contaminated aquifers. Groundwater pollution often results in aquifers or parts of aquifers being damaged beyond repair." (Freeze and Cherry, 1979).

Groundwater pollution in the Akaki River Catchment has been getting concern recently. The problem might be, however, started to persist more than a century ago when polluting human activities come into existence. Both for the capital city and other small towns like Akaki, earlier urban plans for these populated areas did not take seriously the issue of water pollution problem and water management in the catchment as a whole. Previous researchers also dealt with general hydrogeology, hydro-chemistry, pollution condition, etc of the particular part of this catchment.

Currently, the studied catchment could be compared to one of the highly populated and moderately industrialized areas of the world having low provision of sanitation and/or waste management services and water supply. The capacity of the municipalities to provide different services, regulate urban development and their reluctance to enforce the treatment of effluents and control over illegal housing development further complicated the problem.

"...the problem facing scientists and engineers in the protection of groundwater resources is to identify the areas ... pollutants can enter groundwater flow systems ..." (Freeze and Cherry, 1979).

Groundwater has proved to have a number of (quality, quantity, and economic) advantages over surface water. It represents more than 98% of the available planet's fresh water is groundwater, which far exceeds the volume of surface water (Fetter, 1988). It also has the following advantages: it supplies more than 1.5 billion urban dwellers with water, is also extensively used for low-cost rural water supply, is increasingly developed for both large- and small-scale irrigation, is generally reliable in periods of drought because of its large storage capacity, and is cheap to develop because of its wide spread occurrence and its generally good natural quality (Zaporozec et al., 2002). Thus it is very important and necessary to protect this resource from pollution threat/risk. So far, there is no comprehensive (map based) information that could serve the purpose of *ground water protection*, and can be used to identify areas/aquifers that are vulnerable to pollution due to the inherent static nature of the given hydro-geological settings of the aquifers.

The demonstration poster of the project for *managing water for African cities* (Dakar, Abidjan,

Accra, Addis Ababa, Nairobi, Lusaka and Johannes Burg) prepared by Addis Ababa Water and Sewerage Authority (AAWSA) and Habitat (2000), of which Addis Ababa is one, has planned three broad *water management* aspects. Out of these three aspects, the following key management issue was highlighted under *pollution mitigation and sound aquifer management* for Akaki well field found in the studied area as follows: “*environmental monitoring of water sources in and around Addis Ababa is a high priority. Special focus will be placed in collaboration with Agence Francais de Development (AFD), World Bank and International Atomic Energy Agency (IAEA) on developing a management plan for the fragile and vulnerable groundwater aquifers of the Akaki well field.*”

Therefore, the results of this study will prove useful to policy makers, land use or development planners and researchers and academicians concerned with *groundwater pollution protection and its management* in the catchment. Furthermore, the study provides the user with a measure of relative *groundwater aquifers vulnerability to pollution* and it also help in the following particular major aspects of planning:

- used as one phase of the actual site selection in the catchment;
- used for preventive purposes through the prioritization of areas where *groundwater protection* is critical;
- used to identify areas where special attention, or protection efforts are warranted;
- assist in resource allocation and prioritization of many types of groundwater related activities,
- used for selection of well sites and waste disposal sites as preliminary screening tool, and land use planning for *groundwater protection* as basic data.

1.2 Location

The Akaki River catchment is located on the western margin of the Main Ethiopian Rift (MER). The capital city, Addis Ababa/Finfinne/, is found in the northern central heart of the catchment. The following prominent landmarks bound it: the Intoto Mountain Range forms the northern boundary; volcanic mountains (Mt Yerer, Mt. Furi and Mt. Wechecha) form the eastern and southeastern, southwestern and western drainage boundaries respectively.

The Akaki River Catchment has an approximate surface area of around 1464 km² and perimeter of 216 km, and bounded between 8° 46' 57'' and 9° 13' 00'' N and 38° 35' 00'' and 39° 05' 00''E. It is accessible from Addis Ababa in five main directions by the highways stretching to Wallaga, Gojjam, Wallo, Harar and Sidamo, and Jimma. Many other secondary roads are available for inter-site movements/traverses (Figure1.1).

Figure 1.1a. Inset Map Showing Major River Basins of Ethiopia



Figure 1.1b



LEGEND

- Air Port
- All Weather Road
- Addis Ababa & Sendafa town Boundary
- + + + + Railway
- Rivers/streams
- Wet land/ swamp
- Water body/ Reservoir



LOCATION MAP OF AKAKI RIVER CATCHMENT

PROJECTION UTM ZONE 37

1.3 Objective(s)

The general objective of the study is to identify and map the groundwater aquifers vulnerability to pollution in the Akaki River catchment by using the system known as DRASTIC with GIS (Arc View GIS) there by to prepare vulnerability index maps. One of the specific objectives of this thesis was the application or use of an index method of aquifer vulnerability assessment with Geographic Information System (GIS) for the first time in Ethiopia. This index method called “DRASTIC” could serve as a non-subjective mathematical tool for the assessment of groundwater vulnerability to pollution. The hydrogeological factors defined in the DRASTIC system are:

- D=** Depth to water,
- R=** Net Recharge,
- A=** Aquifer media,
- S=** Soil media,
- T=** Topography/slope,
- I=** Impact of vadose zone media,
- C=** Hydraulic Conductivity.

Given the stated general objectives and problems, this study is particularly concerned and will systematically attempt to achieve the following goals:

- Produce dynamic GIS spatial database for the present analysis and future groundwater management or another subsequent DRASTIC analysis or integrated vulnerability mapping of the catchment;
- Describe and map DRASTIC parameters that controls groundwater aquifers vulnerability to pollution;
- Provide comprehensive map based information on hydrogeological aspects of the catchment for

optimum *groundwater management* and land use (since the study area has big plan like different constructions and regional development programs in accordance with the revised master plan of the capital city);

- The application or use of an index method of aquifer vulnerability assessment for the first time in Ethiopia;
- Assist decision and policy markers, (land use) planners and researchers to direct and prioritize resource for *conservation of groundwater* aquifers that are more vulnerable to pollution, and;
- Recommend possible future sustainable utilization of the groundwater resource in the catchment from pollution/environmental point of view.

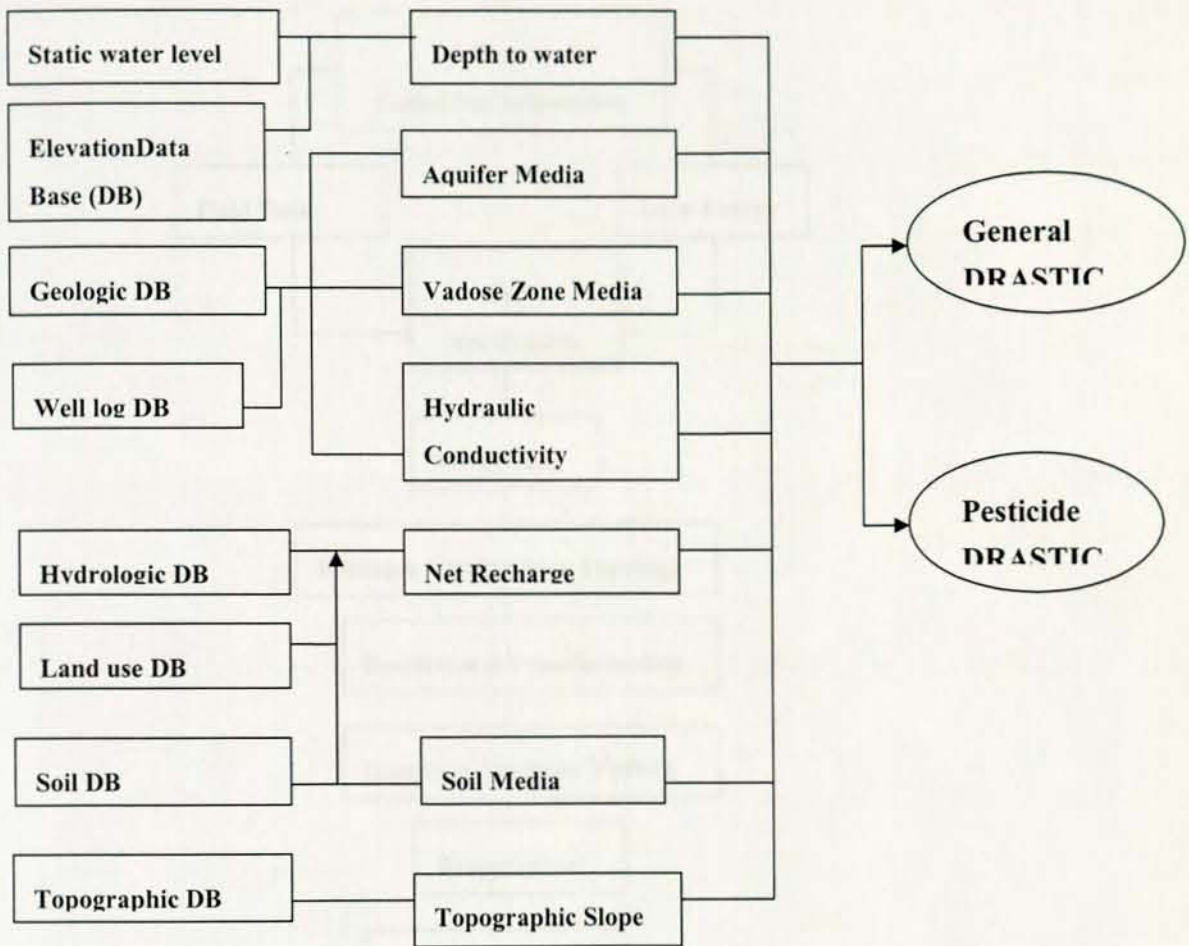
1.4 Methodology

To meet the above-specified objectives of the research project, the empirical model known as the **DRASTIC** Model developed by the National Water Well Association under a cooperative agreement with the United States Environmental Protection Agency (Aller et. al, 1987; Evans and Meyers, 1990) to assess relative groundwater pollution susceptibility using hydrogeologic factors with **GIS** was adopted. Figure 1.2 and 1.3, and equation 1.1 shows the particular methodology that was followed during an evaluation of pollution potential, the data collection and thesis work.

1.4.1 Data Integration

The following Figure 1.2 shows data flow and procedures followed to prepare the seven DRASTIC base maps for the final aquifer vulnerability analysis.

Figure 1.2 Data integration and procedures followed for groundwater vulnerability mapping.



In this thesis GIS is used as a tool for aquifer vulnerability mapping and the procedures of data base construction using this tool is as shown in Figure1.3. Groundwater vulnerability is determined by assigning point ratings to the individual data layers and then adding the point ratings together as shown in equation 1.1 below when those layers are planned to be combined into a vulnerability map as in this work.

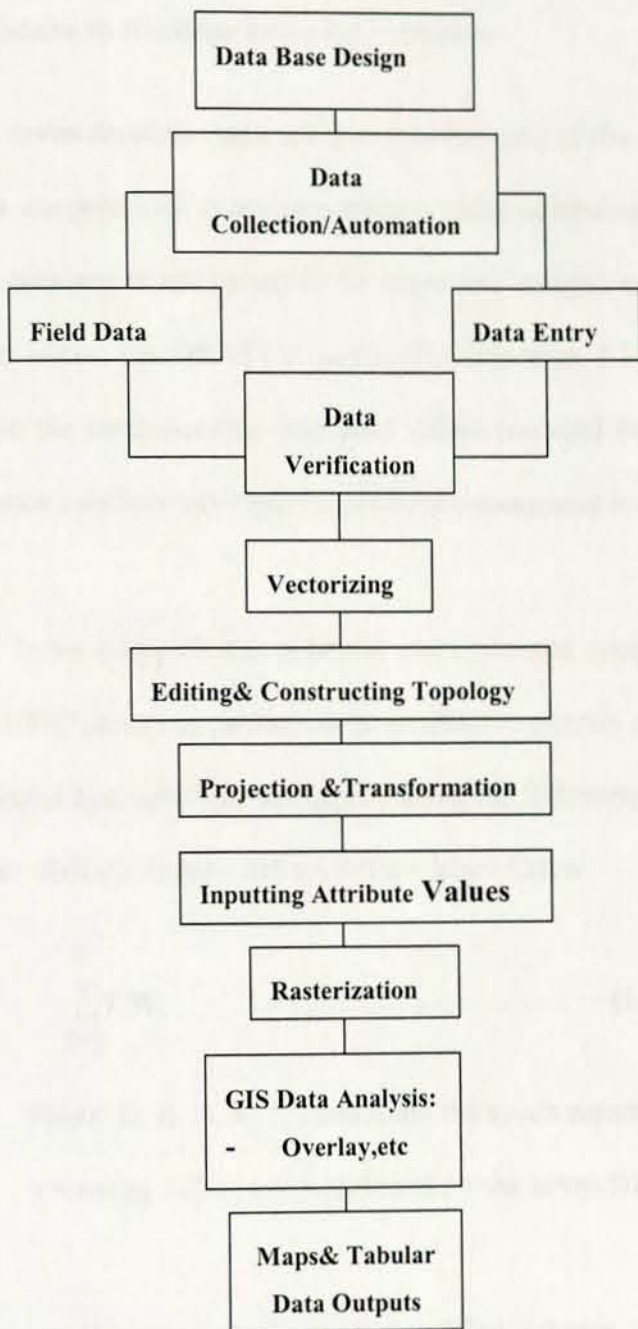


Figure 1.3 GIS database construction procedures

1.4.2 Procedure to Evaluate Potential Pollution

First of all seven thematic maps are produced for each of the seven DRASTIC factors, and seven other maps are produced to assign a relative value according to the ratings shown in Table 6.1. The value obtained is multiplied by its respective weight, and the seven layers or products are summed to obtain the DRASTIC Index (D_i) (equation 1.1). That means the additive-overlay processes in the corresponding data layer values (ratings) for a particular cell are multiplied by an importance coefficient (weight) to produce a composite score called vulnerability index.

➤ DRASTIC Index (D_i)/pollution potential was computed using the assigned rates and weights for each DRASTIC factors or parameters as an additive overlay model resulting in a numerical value for the mapped hydrogeologic settings by using the following equation as follows:

$$D_i = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$$

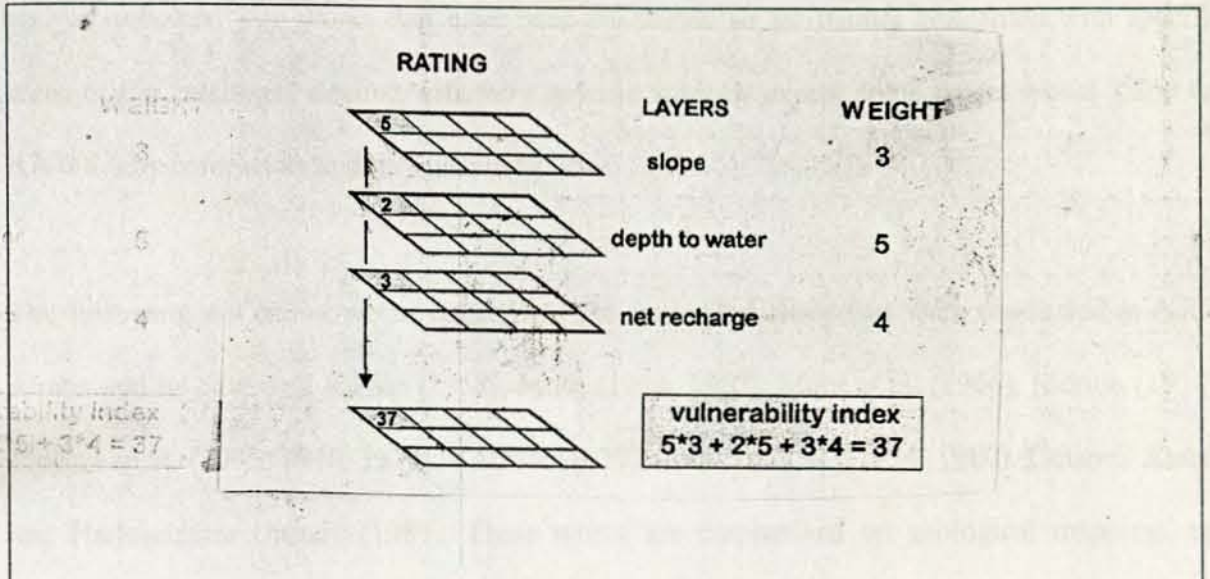
$$= \sum_{i=1}^7 r_i w_i \dots\dots\dots (1.1)$$

Where: D, R, A, S, T, I and C are the seven parameters stated before, and

r = rating value, w = weight and i = the seven DRASTIC factors too.

The following (Figure 1.4) shows a simplified scheme that uses only three parameters to illustrate how the DRASTIC index is computed for one pixel.

Figure 1.4 Conceptual layers illustration of additive overlay process for the computation of the DRASTIC Index Maps (three layers for selected three parameters) (Napolitano, 1995; in: ILWIS Department, 1997).



Once a DRASTIC index has been computed, it is possible to identify areas, which are more likely to be susceptible to groundwater contamination relative to one another. That means using the constructed databases and the DRASTIC system with GIS, regional groundwater pollution susceptibility of the study area was assessed and results were compiled on DRASTIC index map. The higher the DRASTIC index the greater the groundwater contamination potential.

1.5 Scope of the Study

The study was conducted within the Akaki River Catchment and bounded by the hydrographic basin of the catchment upstream of the Akaki Lake. Apart from area scope, the extent of the problem to be dealt with is limited to the *intrinsic aquifer vulnerability mapping of the top most aquifer* using DRASTIC system with GIS.

1.6 Previous Works

Different geological, hydrogeological (surface and groundwater potentiality), engineering geological, pollution/water quality/ study, drilling, etc. have been made by different institutions and/ or scholars. The works that have been conducted so far mainly concerned with specific areas of the catchment dealing with very specific subjects except some recent works made for AAWSA by contractors and/ or consulting firms.

The following are earlier works concerning the geological study that were conducted at Addis Ababa and its environs: Kundo (1958), Mohr (1964, 1967), Mohr et al. (1966), Morton (1974), Morton et al. (1975, 1976, 1979), Kazmin (1979), Zanettin et al. (1974, 1980), Getaneh Assefa and Haileselassie Girmay (1989). These works are emphasized on geological mapping, age dating, and reconstruction of the litho-stratigraphic sequences of volcanic rocks in the area.

Kebede Tsehayu and Tadesse Hailemariam (1990) conducted geological and engineering geological mapping of the central Addis Ababa. Lulseged Ayalew (1990) also carried out engineering geological characterization of the clay soils of Bole area. The former Building Design Enterprise (BDE) now called Building Construction Share Company has conducted site-specific foundation investigation at different corners of the city since long time. The Department of Mineral Development and Regulations of the Ex-Oromia Water, Mineral and Energy Resources Development Bureau now called Oromia Mines and Energy Bureau made geological mapping, and rock and soil sampling at Lega Tafo area. In 2002 Saba Engineering PLC conducted foundation investigation for Addis Ababa Ring Road at the footbridges crossing the ring road at different sites. BCEOM/GKW (1993) conducted soil grain size analysis and falling

head permeability test at ten selected sites in their effort to prepare wastewater master plan preparation for Addis Ababa.

The following are some of the works that contributed to the hydrogeological and pollution of the catchment or part of it: Vernier et al. (1985) conducted preliminary hydrogeological investigation and identified four different aquifers in Addis Ababa; Anteneh Girma (1994) made groundwater potential assessment for Great Akaki river particularly in north east of the Akaki town; under the supervision of AAWSA there are many surface and groundwater study conducted over half of the last century. Some of the recent and most important works are that of AESL (1984) in which well inventory data of more than 175 wells documented. Seureca (1990; 1991) made well inventories of 257 wells and identified potential groundwater areas at four sites based on test drilling; TAHAL (1992); and TAHAL and SHAWEL (1992) assessed groundwater for Akaki town by drilling test production boreholes, AESL (1993) made groundwater development proposal for the Akaki Well Field and its southern extension and proposed Sululta as the fifth groundwater investigation area. In 1991, AAWSA made an inventory of 271 boreholes in the catchment for the purpose of isotopic and hydrochemical sampling together with IAEA. The most important data for this research was partly produced by drilling contractors and BCEOM- Seureca (2000). BCEOM-Seureca (2000) conducted comprehensive geo-hydrological study as part of their effort of modeling the Akaki well field.

Berhane Melaku made general hydrogeology of the Upper Awash Valley in 1982. Adane Bekele (1999) studied pollution of surface and groundwater in the upper Awash Valley in which Akaki River Catchment is located. Ayinalem Ali (1999) assessed water quality and groundwater/river

interaction in Sekelo stream in great Akaki River sub-basin. The extent of surface and groundwater pollution in central part of Addis Ababa was dealt with Solomon Tale (2000). Trufat H/Mariam (2001) carried out geotechnical and engineering geological investigation of Sibilu Dam Site, Reservoir and Catchment area.

CHAPTER TWO

PHYSICO-CLIMATIC CHARACTERISTICS

PART TWO

GENERAL BACKGROUND OF THE STUDY AREA

summer rains. The ITCZ moves back southwards during September and October, reversing a flow, westerly air streams that prevail until the ITCZ resumes its northward migration in March. Accordingly, the area is characterized by two distinct rainfall seasons.

precipitation was recorded in the catchment since 1960 at Addis Ababa observatory. The mean annual rainfall at Addis Ababa Observatory (at an elevation of 2305m amsl) was 1257mm for 91 years (from 1909-1999), and 1076mm at Addis Ababa Dole (elevation of 2154m amsl) for 27 years (from 1964-1990). At Akaki Mission (elevation of 2125m amsl) the mean annual value is 1177mm for 40 years (from 1951-1990) with frequent interruptions in the records (TAMALE-MSISWAL, 1992). Therefore, the mean yearly rainfall of the Akaki River catchment as calculated by Solomon Tulu (2000) for 25 years (from 1964-1990) was 1150mm. The willowbelt zone monthly rainfall ranges from 5mm (in December) to 276mm (in August) for the three

CHAPTER TWO

PHYSICO-CLIMATIC CHARACTERISTICS

2.1 Climate

The studied area experiences both cool temperate and warm climate. There is seasonal variation of precipitation in the Akaki River Catchment. The seasonal variation of rainfall distribution within the study area can be explained by the annual migration of the ITCZ (a zone of low pressure marking the convergence of dry tropical easterlies and moist equatorial westerlies) across the catchment (HALCROW, 1989). The ITCZ starts its advance from the south in March bringing the small or spring rains. It reaches its most northerly location beyond the Awash River Basin, where the studied catchment is located, in June and July, which brings the heavy or summer rains. The ITCZ moves back southwards during September and October, restoring a drier, easterly air stream that prevails until the ITCZ resumes its northward migration in March. Accordingly, the area is characterized by two distinct rainfall season.

2.1.1 Population Density

Precipitation was recorded in the catchment since 1900 at Addis Ababa observatory. The mean annual rainfall at Addis Ababa Observatory (at an elevation of 2408m amsl) was 1257mm for 91 years (from 1900- 1990), and 1074mm at Addis Ababa Bole (elevation of 2354m amsl) for 27 years (from 1964-1990). At Akaki Mission (elevation of 2120m amsl) the mean annual value is 1157mm for 40 years (from 1951-1990) with frequent interruptions in the records (TAHALSHAWAL, 1992). Therefore, the mean yearly rainfall of the Akaki River catchment as calculated by Solomon Tale (2000) for 35 years (from 1964- 1998) was 1150mm. The arithmetic mean monthly rainfall ranges from 6mm (in December) to 276mm (in August) for the three

stations in the catchment for 35 years. Depending on altitudinal variations the catchment experiences mainly sub-tropical climatic condition. Temperature records are available at different stations in the catchment. The highest and lowest mean monthly maximum temperature occurs in months of March (25 °c) and the lowest is in the month of August (20 °c), while the minimum mean monthly values were 8 °c (in December) and 12 °c (in March) for Addis Ababa Observatory from 1951- 1998 respectively. The calculated mean annual temperature was 16.32 °c (Solomon Tale, 2000). The monthly means for other climatic elements such as relative humidity, wind speed at 2m height, sun shine hours recorded at Addis Ababa Bole as it was calculated by (TAHAL-SHAWAL, 1992) is given as follows: the lowest relative humidity was 53 % recorded for the month of December and the highest was 78% recorded for July and August (from 1964-1989), and the lowest sunshine, 3.0 hours per day, was recorded in July and the highest 9.5 hours per day was recorded for December for the period (1965-1985). Similarly, maximum wind speeds, 1.2 m/s, were recorded for October, while the minimum value, 0.5 m/s, was recorded for August.

2.2 Population Density

The capital city with a population of over 2.64 million (BCEOM-Seureca, 2000) and other small towns such as Akaki, Sendafa, Burayu, and small peasant association villages are found in this catchment.

According to NEDECO (2001) the population density of Addis Ababa varies from more than 400 persons per hectare to less than 25 persons per hectare (Figure2.1).

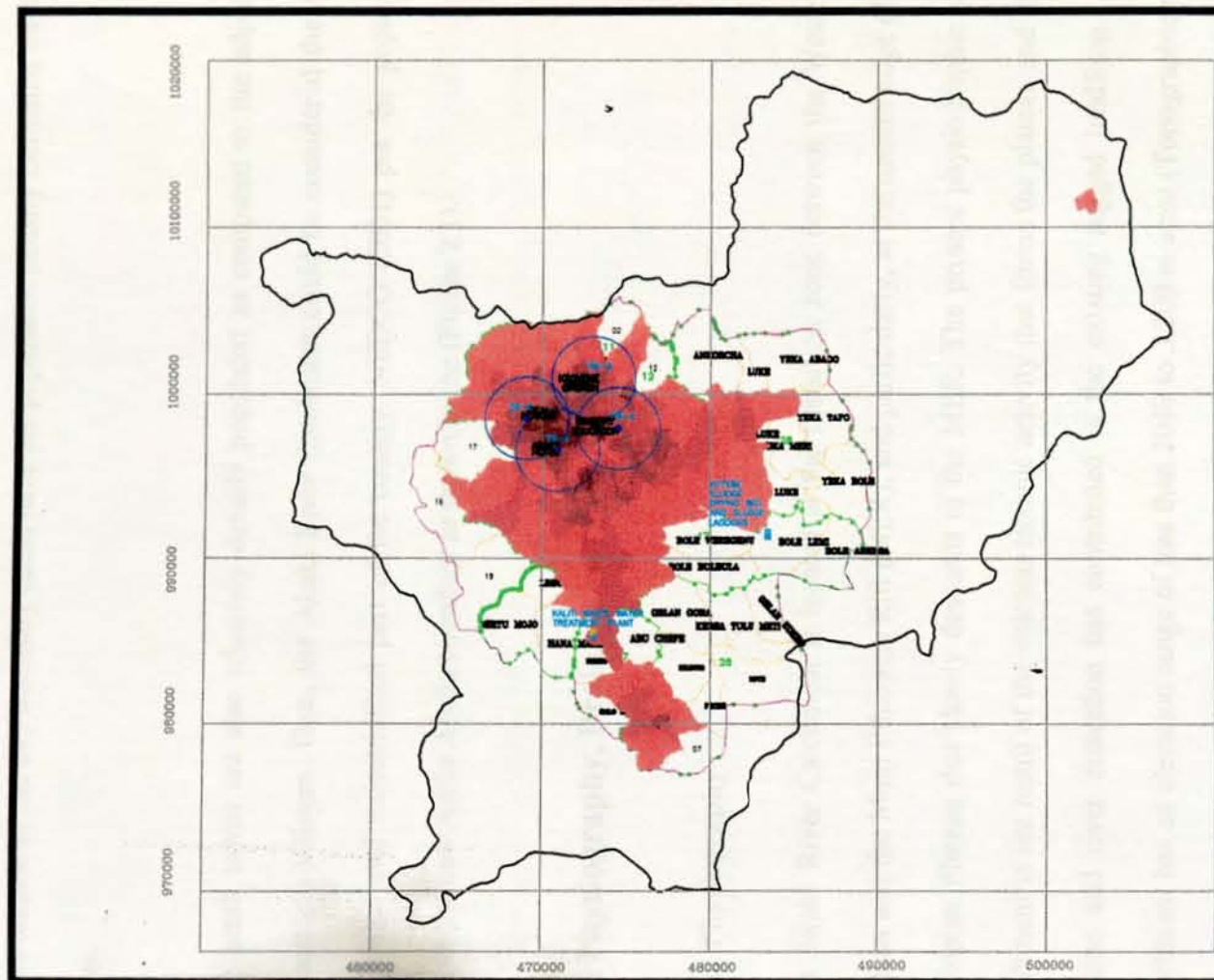


FIGURE 1.2: POPULATION DENSITY OF AKAKI CATCHMENT

Legend

- Population Density >400Pers.Ha.
- Population Density 300-400Pers.Ha.
- Population Density 100-300Pers.Ha.
- Population Density 50-100Pers.Ha.
- Population Density 25-50Pers.Ha.
- Population Density <25Pers.Ha.

- Existing Sewage Transfer Stations
- Existing Treatment Works
- WOREDA BOUNDARY
- KEBELE BOUNDARY
- CITY BOUNDARY
- MAIN ROADS
- KERBLES NUMBER
- KERBLES NAME



Scale : 1/300,000

The old city centers and Merkato area are the densest with greater than 400 persons per hectare while the peripheral areas are less than 25 persons per hectare. It was assumed that the other areas outside of the city boundary could have the population density estimated for the peripheral areas.

The small towns are also relatively densely populated as compared to the adjoining peasant association villages. Thus, the Akaki River Catchment could be considered the most densely populated and industrialized part of the country. NEDCO (2001) put the population density within the new Addis Ababa boundary as shown in the (Figure 2.1).

2.3 Physiography, Drainage and Land use

2.3.1 Physiography

The Akaki River Catchment is located at the transition zone between the Western Ethiopian Plateau and the Main Ethiopian Rift (MER); and particularly, at the eastern edge of the Western Ethiopian Plateau that slowly descends to the MER. The present physiographic setting of the catchment is the result of the volcano-tectonic activity that forms the plateau and the rift. Latter erosion and river dissection has contributed to the existing rugged landform. Akaki River Catchment has an elevation range of less than 2040 to 3,200 m amsl (Topographic map of Scale 1:50,000, EMA, 1973-1986) outlined in chapter 7. Ridges and/or mountain ranges and individual volcanic centers bound the catchment. The central part of the catchment resembles a wide caldera and is characterized by rolling topography that generally decreases to the south in the direction of river outlet or flow. The southeastern tip of this catchment is relatively flat with

recent Quaternary sediments and northeast southwest aligned scoria cone hills standing above the ground surface. It can be observed from the Hill Shade Map (Figure 2.2) and Relief Map (Figure 2.3) that the northeastern part of the catchment is also flat. The landform is thus complex and changes with in small distance.

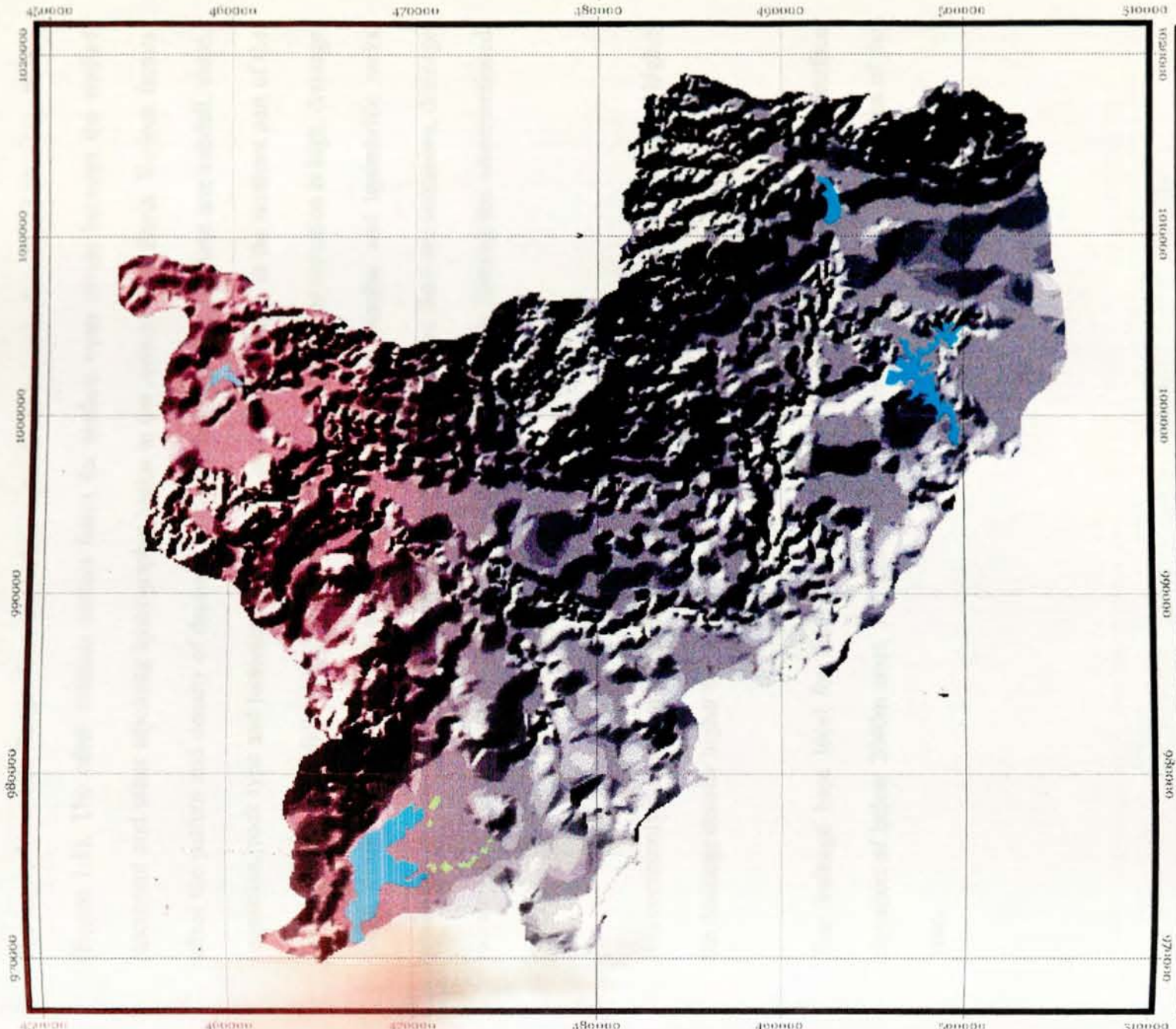
Vernier et al. (1985) tried to characterize the Intoto Mountain Range as remnant edge of an old volcanic caldera, which has been collapsed southward by means of a wide system of step faults. These authors observed that the landscape is the result of complex geological structures, which has been modified by the erosional processes. This assumption seems reasonable as we can see from the cross - section/ well correlations/ made by BCEOM–Seureca (2000), Figure 4.1a and 4.1b.

The maximum elevation is found in the north (eastern) extreme of the catchment (Intoto Range, 3100m; Mt Bari/Bereh/, 3200m) while the minimum elevation is found to the south of the studied area (around Akaki/ Abba Samuel/ Lake elevation less than 2040m). There are several volcanic centers, including: Mt. Wechecha (3385m), Mt. Furi (2839m) and Mt. Yerer (3100m) amsl. The Ambo-Kassam regional fault that forms the Intoto Range is another important structural feature that can be mentioned in connection to the development of the present landform.

2.3.2 Drainage

Two major rivers form Akaki River catchment: Little- and Big- Akaki Rivers, and their tributaries. The two jointly form one of the biggest tributaries of the Awash River called Akaki River.

Figure 2.2



LEGEND

- 0 - 149
- 150 - 166
- 167 - 173
- 174 - 178
- 179
- 180
- 181 - 184
- 185 - 192
- 193 - 254
- Water body/ lakes
- Wetland/swampy



HILLSHADE IMAGE OF AKAKI RIVER CATCHMENT

PROJECTION UTM ZONE 37

The Intoto Mountain Ranges form the surface water divide between Awash and Blue Nile Rivers (Figure 1.1). The other volcanic centers forms the surface water divide between the studied catchment and other adjoining hydrographic basins in the Awash River Basin. Various factors affect the pattern and density of drainage in the studied area. Among these are: rainfall, slope, vegetation, rock type and tectonics are important ones. Accordingly, in the northern part of the catchment where rainfall is high, vegetation is dense, and topographic elevation is high, drainage forms steep narrow gorges. In addition to these tectonized basaltic and ignimbritic rocks produced fine, parallel and/or dendritic drainage patterns. Where there are volcanoes, drainage radiates in all directions from the central volcanic centers finally forming the aforementioned patterns.

It is commonly known that the higher the permeability the lower the drainage density, and higher the drainage density higher the surface runoff.

The drainage base level for the catchment is the Akaki Lake having approximate surface elevation of below 2040m amsl. The Lake is seasonal one that dries during dry months of the year.

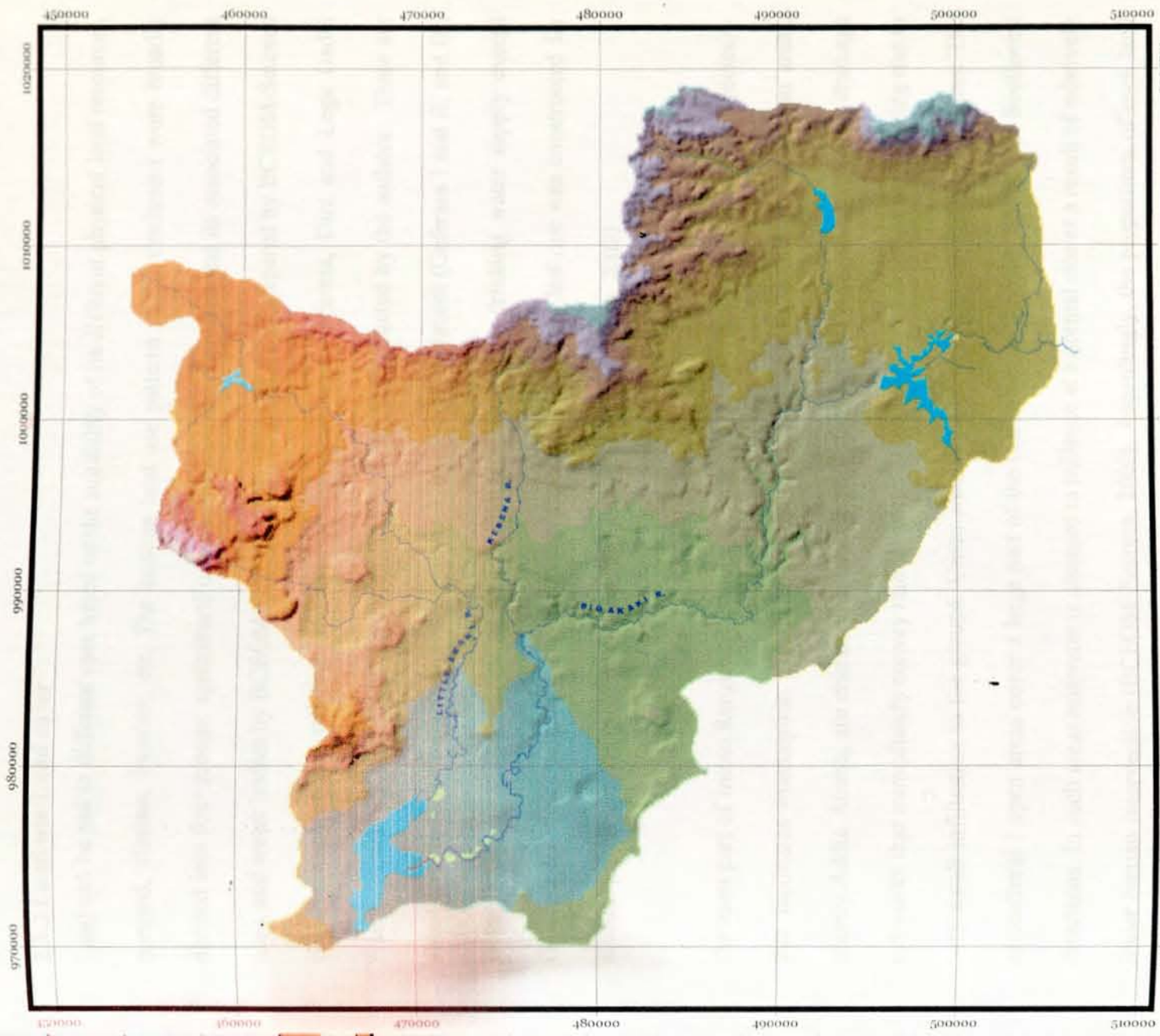


Figure 2.3

LEGEND

- 2992.295 - 3226.713
- 3226.713 - 3461.13
- 3461.13 - 3695.547
- 3695.547 - 3929.965
- 3929.965 - 4164.382
- 4164.382 - 4398.799
- 4398.799 - 4633.217
- 4633.217 - 4867.634
- 4867.634 - 5102.051
- No Data
- Reservoirs
- Wetland/swamp
- Rivers



**RELIEF MAP OF
AKAKI RIVER CATCHMENT**

PROJECTION UTM ZONE 37

2.3.3 Land use/Land cover

Land can be put to different uses based on the suitability of its different physical land resources, demand, climate, location, etc. The existing land use patterns in the catchment were broadly divided into four groups: agricultural or open area, forest, urban area and its associated different uses, and water bodies by BCEOM-Seureca (2000). Figure 2.4 was prepared by BCEOM-Seureca (2000) based on the existing land uses of the urban area, Geferssa, Dire and Lega Dadhi reservoirs and aerial photo interpretation and field checks conducted by the authors. There are about five man-made reservoirs/ dams in the Akaki River Catchment (Geferssa I and II, and III, Lega Dadhi, Dire and Akaki). The first four are serving for drinking water supply except Geferssa III which is mainly serving as a sediment trap while the last one was constructed for electric power generation (Yewendson Mengistu and Dereje Nigussa, 2002).

The most part of Intoto Range and its slope is covered by forest (dominantly eucalyptus species) that facilitates interception and faster infiltration of rainwater into the ground. Urban areas, mainly Addis Ababa, are characterized by paved surfaces and/or built-up areas, storm drainage net works that immediately convey rainfall as run off to the near-by drainage paths giving rise to very small infiltration to the ground. Urban areas are also characterized by some gardens. The agricultural / open areas cover a large part of the catchment in the East, South, and Southwest directions. In such areas rainwater is assumed to infiltrate at a normal rate as a result of relatively lesser human intervention (BCEOM-Seureca, 2000). Accordingly, the proportions of each land use type were recalculated as follows: agriculture/open (69%), forest land (15%), urban (15%) and water body/reservoirs and wetland covers (0.98%) of the total land use/cover.

An effort has been made to see the distribution of land use/cover over the major soil types of the catchment by overlaying in ArcView GIS the land use /cover map of the catchment over/with/ the soil map (Figure 8. 4) resulting in the out put shown in Figure 2.5.



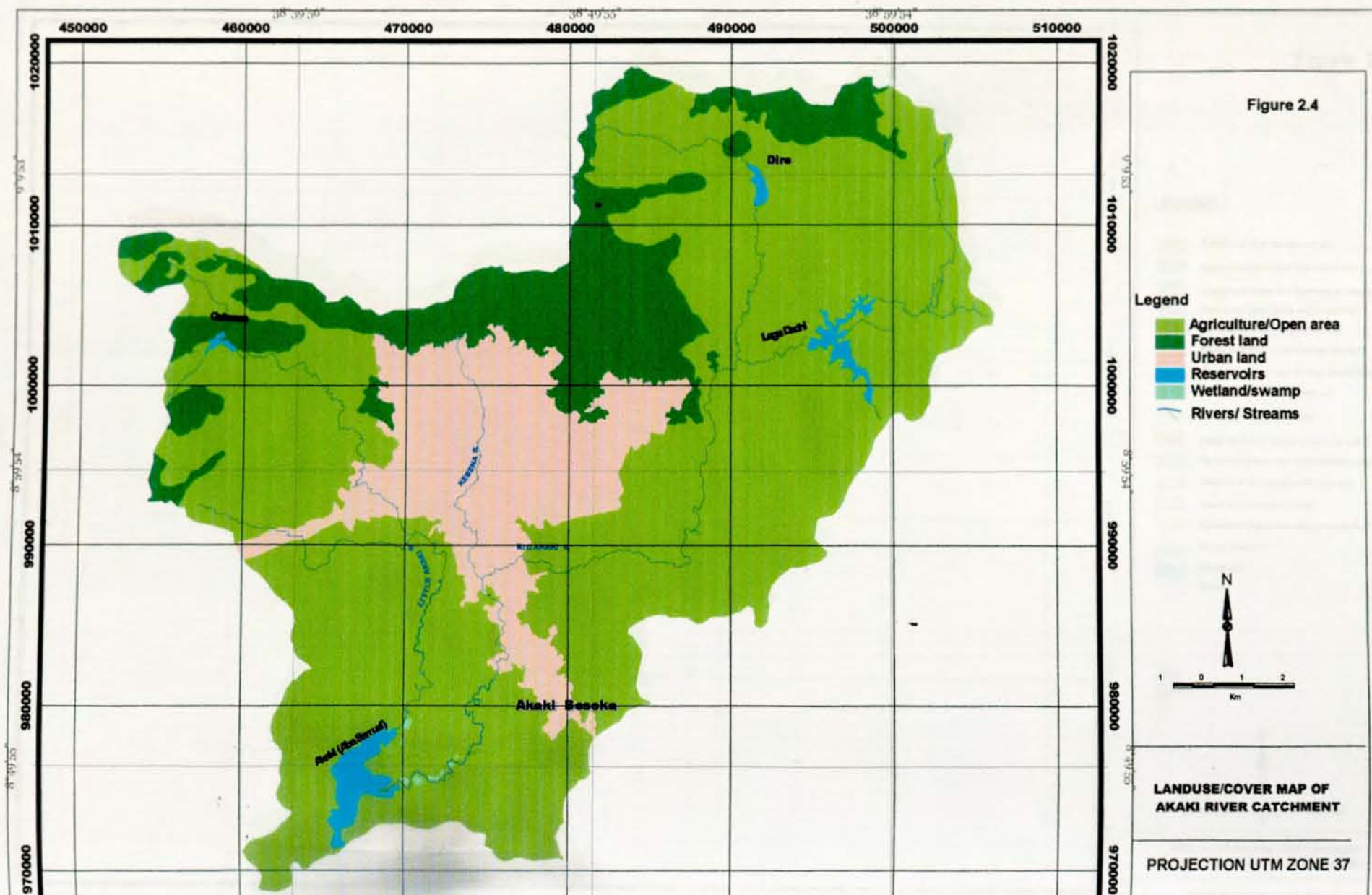


Figure 2.4

Legend

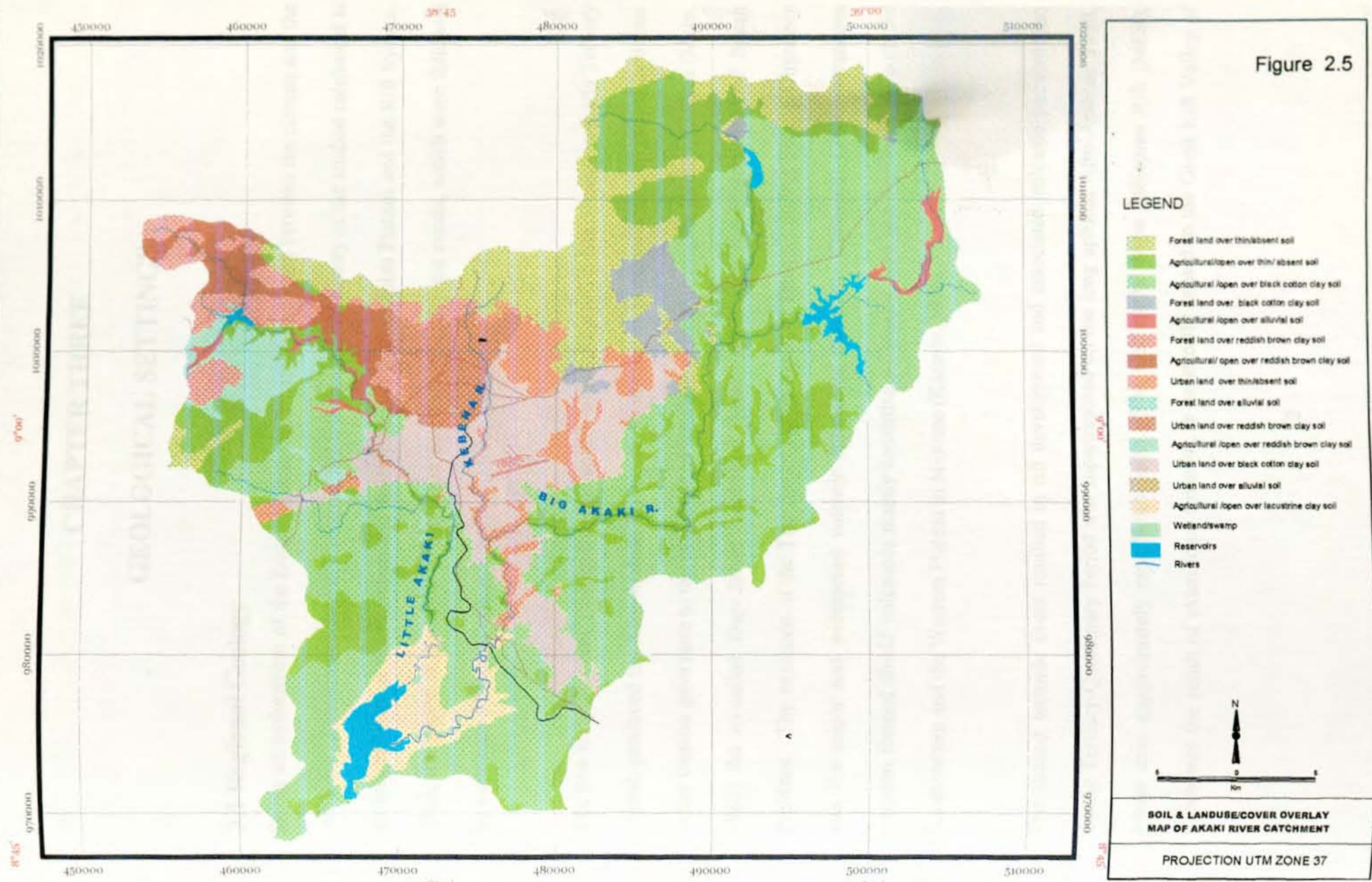
- Agriculture/Open area
- Forest land
- Urban land
- Reservoirs
- Wetland/swamp
- Rivers/ Streams



LANDUSE/COVER MAP OF
AKAKI RIVER CATCHMENT

PROJECTION UTM ZONE 37

Figure 2.5



CHAPTER THREE

GEOLOGICAL SETTINGS

3.1 Regional Geology

Being an embayment of the Ethiopian Rift (Mohr, 1967) and lying between the plateau and the rift-floor (Zanettin and Justin-Visentine, 1974) the geological history of the studied catchment is an integral part of the evolution and development of the Ethiopian Plateau and the Rift System. Thus, the region is the result of two major post-Paleozoic tectonic events, which were followed by important phases of volcanic activity (Mohr, 1964).

The first tectonic event, (the epirogenic uplift), which occurred in late Mesozoic -Early Tertiary Period, produced the Afro-Arabian Dome. As an immediate consequence of up arched landmass under tension gave raise to the extrusions of voluminous basaltic magma through fissures (Mohr, 1983) the so-called *Trap Series Succession* (Mohr, 1967) form the Ethiopian Flood Basalt Province. The extrusion of the Trap Series fissure basalt of Ethiopia during Eocene-Oligocene was the major and widespread volcanic episode of the whole Cenozoic. Contemporaneous eruption formed shield volcanoes mainly consisting of basaltic lava and developed on both the Southeastern and the Western Plateau in Miocene (Kazmin, 1975).

The second tectonic event resulted in rift development and associated volcanic phenomenon during Tertiary-Quaternary Period was superimposed on the long uplifted Afro-Arabian Swell, whose axis approximately runs North-South. The Continental Main Ethiopian Rift (MER), which was the result of extensional tectonics, is genetically related to the Great Rift Valley of

East Africa. It trends in NNE-SSW direction and started to develop in the Miocene. Rift related volcanic rocks were outpoured when fissural volcanism in the adjacent plateau had died out (Zanettin et al., 1980).

According to Kazmin et al. (1980), initial sagging of the MER started about 14 to 15 MY and was followed by major episodes of rifting at 10, 5, 4 and 1.8 to 1.6 MY. Each stage of rifting and down faulting was accompanied by a *bimodal* (silicic-mafic) volcanism in the rift and formation of basaltic and trachytic shield volcanoes on the rift shoulders and margins.

Contemporaneously with the emplacement of peralkaline rhyolites and trachyte lavas and ignimbrites (Mohr, 1964), there were wide spread basaltic cinder cones eruptions as well as restricted local flows of olivine basalt and olivine trachy-basalt in Akaki-Debre Zeit areas. This was later followed by the formation of explosion craters.

Haileselassie Girmay and Getaneh Assefa (1989) suggested the following litho-stratigraphic divisions and the correlation of the Miocene-Pleistocene Volcanic Succession in the Addis Ababa - Debre Zeit area based on previous studies from the youngest to the oldest as shown in Table 3.1.

Table 3.1 Litho-stratigraphic divisions and correlation of the Miocene-Pleistocene Volcanic Succession in the Addis Baba- Debre Zeit area (Haileselassie Girmay and Getaneh Assefa, 1989)

Stratigraphic Unit	Representative Lithologies	Age (MY)	Correlative to
Wonji Group	Aphanitic basalt		
	Weakly welded tuff	0.51	Wonji Series
	Porphyritic plagioclase basalt	0.61	Wonji Group
	Strongly welded tuff	1.7	
Bofa Basalts	Olivine basalt	2.8	Bishoftu Basalts
		2.9	Bofa Basalts
Nazareth Group	Upper welded tuff	3.2	Balchi Rhyolites
	Aphanitic basalt	3.5 & 3.9	Pliocene Silicics
	Lower welded tuff	3.6, 5.1 and 5.4	Nazareth Series Nazareth Group
Addis Ababa Basalts	Plagioclase Basalt	6.4	
	Olivine Basalt	6.9, 7.1 and 7.3	

3.2 Geology of Akaki River Catchment

Different workers or authorities were contributed to the study of the geology and volcanic stratigraphic sequences or age dating of the studied catchment or part of it. Based on radiometric dating Morton et al. (1979) have showed rift ward younging of surfacial volcanic units along a 100 kms wide swathe, Southeast wards from Blue Nile area on the plateau via Addis Ababa-Debre Zeit area on the rift margin to the rift floor axis at Wolenchiti. Haileselassie Girmay and Getaneh Assefa (1989) redefined the lithostratigraphic units and modified the existing stratigraphic sequences based on Morton's work and proposed the stratigraphy of the area between Sululta and Nazareth. The geology of the catchment compiled by BCEOM - Seureca (2000) that conforms to these earlier works is adopted. Therefore, the following are the lithostratigraphic units from the bottom (oldest) to top (youngest).

3.2.1 Alaji Series

As it can be seen from the geological map (Figure3.1) the series includes rhyolites, trachytes, tuff and agglomerate, and aphanitic basalt. These units are found in the Northern and Central part of the catchment. Earlier works further subdivided this series into Alaji rhyolites and Intoto Silicics. The Alaji rhyolites and basalts were outpoured from the end of Oligocene until Middle Miocene (Zanettin et al., 1974). These units extend from Intoto to the North across the Sululta Plain (Haileselassie Girmay and Getaneh Assefa, 1989). According to Mohr (1967) the Intoto trachytes overlies the Alaji basalt. Morton et al. (1979) dated a sample from North of Addis Ababa and assigned an apparent age of 22.8 MY (Miocene time).

The Intoto Silicics are localized terminal episodes to massive Oligocene fissure-basalt activity in the Addis Ababa area (Morton et. al., 1979). They make up a thick pile of flows, which accumulated along east-west fissures (east-west fault running from Kassam River to Ambo), and downthrown to southwards. It becomes thin away from this east-west running fault in both directions (Zanettin and Justin-Visentin, 1974). The Intoto Silicics are composed of rhyolites and trachytes with minor amount of welded tuff and obsidian (Haileselassie Girmay and Getaneh Assefa, 1989). The rhyolitic lava flow outcrop on the top and the foothills of the Intoto Ridge (Figure3.1). This rhyolite is overlain by feldspar porphyritic trachyte and underlain by a sequence of tuffs and ignimbrites (Solomon Tale, 2000).

From the general stratigraphy established by Zanettin et al. (1979), both rhyolite and trachyte of the Intoto Silicics belong to the "Miocene Alaji Rhyolite and Basalt" sequences. Morton (1974) and Morton et al. (1979) dated the Intoto Silicics as 21.5 MY and 22 MY respectively.

Some undifferentiated volcanic rocks cover large part of the studied area in the northeast, north, northwest and southwest and east of the catchment (Figure3.1).

3.2.2 Addis Ababa Basalts

These are younger basalts that overlie the Intoto Silicics and cover the central and Southern part of Addis Ababa. Compositionally, they can be porphyritic olivine basalt, porphyritic feldspar basalt and aphanitic basalt, and welded glassy and fiamme ignimbrites and trachy-basalt. Individual flows are usually easily observed and paleosols and scoriaceous horizons are found at the bottom of flows in many places (Kebede Teshayu and Tadesse Hailemariam, 1990).

Basalt Group

Olivine porphyritic basalt outcrop in the central part of the town such as: Merkato, Teklehaymanot and Sidist Kilo. The distribution of plagioclase porphyritic basalt is little more northwards around Sidist Kilo, General Winget School and French Embassy (Solomon Tale, 2000). The thickness of the olivine porphyritic basalt varies from 1m or less in the foothills of Intoto, Lideta Air field and Filwoha to greater than 130 meters at Ketchene Stream (Morton, 1974; Vernier et al., 1985).

The basalt flows are interbedded with welded glassy and fiamme ignimbrite outcrops in the areas of Filwoha, Ginfle and Lideta Air Field. At many outcrops it is overlain by aphanitic basalt flow and underlain by olivine porphyritic basalt flow (Anteneh Girma, 1994).

Morton et al. (1974) argues that Addis Ababa basalt have no time/compositional equivalent. Whereas, Morton et al. (1979) dated Addis Ababa Alkali olivine basalts which yield ages clustering around 7 MY (6.9 MY at Arat Killo, 7.3 MY few kilometers from St. George Church and 5 MY near Kebana Bridge).

3.2.3. Younger Volcanics

These groups of younger volcanic rocks include: Nazareth Group and Bofa Basalts. The Nazareth Group rocks out crop dominantly south of Filwoha Fault and extends towards Nazareth (Haileselassie Girmay and Getaneh Assefa, 1989) and Bofa basalts are found southward from Akaki River, Southeast part of Addis Ababa (Figure3.1).

3.2.3a) Nazareth Group

This group is composed of aphanitic basalts, welded tuffs, ignimbrites, trachytes and rhyolites.

Lower welded tuff out crops as a small discontinuous body in Filwoha, western parts of Addis Ababa and Sululta. It is glassy with abundant fiamme and has columnar joints. It is generally overlain by aphanitic basalt and underlain by the olivine and plagioclase porphyritic basalt (Haileselassie Girmay and Getaneh Assefa, 1989). The age of this rock according to Morton et al. (1979) at Addis Ababa and Sululta is 5.1 and 5.4 MY respectively. This age overlap with the period of the activity of Wechecha trachyte volcanoes, dated 4.6 MY. Wechecha is thus most probably the sources of the lower welded tuff at both localities, i.e. Addis Ababa and Sululta (Morton et al., 1979).

Aphanitic basalt flows cover the southern portion of Addis Ababa south of Asmara Road, especially the areas of Bole and Lideta. The flows show vertical and curved columnar jointing together with sub-horizontal sheet jointing (Anteneh Girma, 1994). According to Morton (1974) the age of this basalt ranges from 3.4 to 3.6 MY similar to Mt.Yerer Volcano with 3.5 MY (Morton, 1975). Trachy-basalt outcrops are found around Repi area and General Winget School, and associated with undifferentiated volcanics (BCEOM-Seureca, 2000) Figure3.1. It is underlain by the plagioclase and olivine porphyritic basalt, and overlain by the younger ignimbrite from which it is separated by tuffs and agglomerates (Haileselassie Girmay, 1985).

An ignimbrite sheet of Anteneh Girma (1994) that Solomon Tale (2000) described as upper welded tuff outcrops in most part of southern Addis Ababa, central part of the catchment, including areas of Bole, Nefas Silik and Railway station; and also is present in the central and northern part of the city. It is gray colored, vertically and horizontally jointed (Haileselassie Girmay and Getaneh Assefa, 1989). This unit is underlain by aphanitic basalts and overlain by young olivine basalts (Haileselassie Girmay, 1985). According to Anteneh Girma (1994) it is underlain by tuff deposits and overlain by olivine porphyritic basalt flow southeast of Addis Ababa, and by trachyte in the southwest part of the city. Morton et al. (1979) gave an age of 3.2 MY for a sample taken from nearby Asmara road that overlap with the activity of Mt. Yerer trachytic volcanoes.

As can be seen from the geological map (Figure 3.1), trachyte flow covers extensive areas in the west and southwest part of the catchment, i.e. from Mt. Furi Hana Mariam, Tullu Iyoo to Repi and Wechecha Range. The trachyte flow is underlain by tuff and overlain by alternating flows of plagioclase basalt and rhyolite at the Repi (Anteneh Girma, 1994).

Rhyolite flows belonging to this group outcrop at the top and southern flanks of Mt. Yerer. The exposed thickness of the lava sequence is about 500m (Anteneh Girma, 1994). Morton (1975) determined the age of Mt. Yerer rhyolite to be 3.3 MY, and may be correlated to the Balchi rhyolite of Zanettin et al. (1974).

3.2.3b) Bofa Basalts

This unit consists of olivine porphyritic basalt, scoria, vesicular and scoriaceous basalt, and trachy-basalt lava flows. They extend into the south from Akaki River. They appear to have upper thick basalt of 20-40 ms, over the Akaki well field but thinner to absent in places. AE-HBT AGRA JV (1998) in BCEOM- Seureca (2000) described it as overlain in places by scoria, tuff, sand and gravel. The underlying beds are sequences of relatively thin basalt flows alternating and complexly inter-fingered with scoria, scoriaceous and vesicular basalt. They have well preserved shape of cones and maars.

The basalt flow unit was dated 2.8 MY at Asmara road by the by Morton et al. (1979). It correlates to Bishofitu basalts (Zanettin et al., 1974).

3.2.4 Lacustrine, Alluvial and Residual Deposits

Lacustrine sediments occur around Bole, Lideta, and Mekanissa, between Akaki Lake and Akaki town and Little Akaki River. The thickness of this deposit varies between 5m and 50m (BCEOM-Seureca, 2000). It is overlain by dark younger clayey soil and this clayey soil was formed during transition from the wet pluvial phase to dry climate period, the Maskalian (Karstaedt, 1986).

Alluvial deposits are found in some places along Little- and Big-Akaki Rivers particularly south and southwest of the capital city. Thick alluvial deposit occurs in the area between Akaki Town and the Akaki Lake. Some deposits occur along the Kebana River northwest of Bole area. Soils, which are developed *in situ* by the decomposition of rocks on which they lie, are located in the central, southeast, and northeast part of the catchment and Gullele and Kolfe Regions.

3.3 Geological Structures

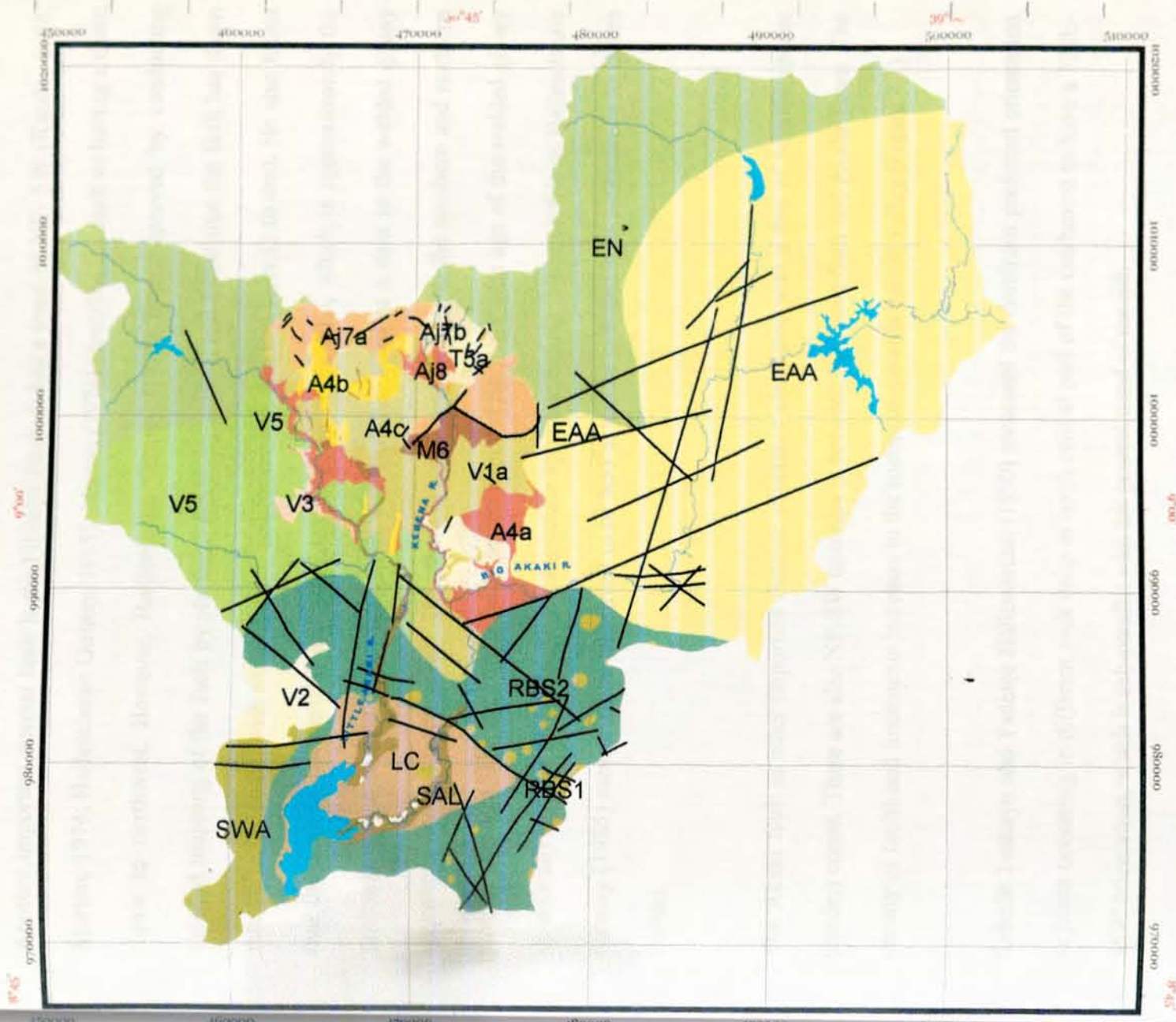
As the catchment is located at the shoulder of the Main Ethiopian Rift (MER), the studied area has been subjected to volcano-tectonic activity that formed the rift. The geological structures shown in Figure 3.1 were compiled by BCEOM-Seureca (2000). Though general trend of most of these faults follow the rift system (NE-SW) orientation, there are faults with orientation of east-west, northwest and northeast- southwest.

The largest regional fault that goes east-west from Kassam River via north of Addis Ababa to Ambo, cut across the Western Rift Escarpment and uplifted its northern block (Zanettin et al., 1978) at about 8 MY ago. The Intoto Silicics are confined along this fault and form a ridge. This ridge forms the surface water divide between Awash and Blue Nile Rivers and it is the northern boundary of the studied area (Figure 1.1). The fault has a down-throw to the south in the studied catchment.

Figure 3.1

LEGEND

- QUATERNARY SEDIMENTS
 - SAL ALLUVIAL SOIL
 - LC LAQUESTRINE CLAYS AND SILTS GENERALLY THICK 5 TO 50 M
- YOUNG VOLCANICS (PLIOCENE - QUATERNARY)
 - RBS1 SCORIA
 - RBS2 BASALT PREDOMINANTLY SCORACEOUS AND VESICULAR
 - V1a FINE GRAINED IGNI MBRITE
 - V1b TUFF
 - V2 TRACHYTE
 - V3 TRACHY BASALT
- ADDIS ABABA BASALT (UPPER MIOCENE TO PIOCEN)
 - A4a APHANITIC BASALT
 - A4b PORPHYRITIC BASALT
 - A4c PORPHYRITIC OLIVIE BASALT
- TARAMBER BASALT (25 MA TO 5 MA)
 - T5a PORPHYRITIC BASALT
- MIDDLE MIOCENE ACID VOLCANICS
 - M6 COARSE GRAINED IGNI MBRITE
- ALAJI SERIES (LOWER MIOCENE)
 - Aj7a RHYOLITE
 - Aj7b TRACHYTE
 - Aj8 TUFF AND AGGLOMERATE
 - Aj9 APHANITIC BASALT
- UNDIFFERENTIATED VOLCANICS
 - EN PREDOMINANTLY TRACHYTES, TRACHYBASALT AND RHYOLITES WITH SUBORDINATE IGNI MBRITE & TUFFS
 - EAA IGNI MBrites TUFFS AND RHYOLITES WITH SUBORDINATE TRACHYTES & BASALTS
 - SWA INCLUDES TRACHYTES, RHYOLITES & BASALT
- FAULTS WITH DOWN THROW SIDE
- LINEAMENTS CERTAIN
- LINEAMENTS PROBABLE
- River/wetland
- Reservoirs
- Wetland/swamp



GEOLOGICAL MAP OF AKAKI RIVER CATCHMENT

PROJECTION UTM ZONE 37

Another important normal fault is the Filwoha Fault. It has a trend of NE- SW (Kundo, 1958; Morton, 1974; Haileselassie Girmay, 1985). Morton (1974) identified the fault as having a down throw to northwest. However, Haileselassie Girmay (1985) later disproved by conducting detailed mapping of the fault by electrical resistivity survey, and found that the fault has down thrown to the south, with shallow depth and covered by thin soil layer (1 to 4m). He also found that the fault is not vertical and estimated its throw to be 40m, which is approximately the thickness of the welded glassy ignimbrite. The fault has acted as a dam to the welded glassy ignimbrite and not to the basalt. Thus there is a different geology in the southern and northern parts of the area. The age of the fault may be bounded by 5 MY (the age of the welded glassy ignimbrite) and 6.4 MY (the age of plagioclase aphanitic basalt). Mohr (1964) in Haileselassie Girmay (1985) measured the fault trend to be $N55^{\circ}E$ and he assumed it to continue up to Debre Birhan.

The Akaki fault is other important tectonic structures associated with a line of basaltic spatter (cinder) cones. There are also NE-SW tectonics in between the above fault and Akaki Town. The density of faults and lineaments increases to the southeast towards the rift valley (Figure 3.1)

Kebede Teshayu and Tadesse Hailemariam (1990) measured the dominant preferred orientation of joints occurring in different rock units in north central part of the catchment to have a NNE-SSW orientation, which is sub-parallel with the general trend of the rift.

CHAPTER FOUR

HYDROGEOLOGY AND GROUNDWATER QUALITY: AN OVERVIEW

Here, general introductions on the hydrogeology of volcanic rocks are provided before directly going to the modeling approach with particular emphasis on the catchment under discussion. Potential sources of pollution and general groundwater quality are also briefly outlined.

Custodio (1989; in: IAEA, 1989) presented a comprehensive and general description on the hydrogeology of volcanic rocks, and their nature in a very good way as follows.

4.1 General Characteristics of Volcanic Rocks

Groundwater flow and storage in volcanic formations are affected by the type of volcanism, distance from the source of emission, age, alteration processes and tectonics. Accordingly, lava, which is not highly explosive, spreads and produces huge piles of sheet like deposits when attaining lands of gentle to moderate slope. The material is compact and not very porous, although tight cooling joints form. Acidic and mainly intermediate lavas (phonolites) also produce thick and extensive massifs, with steeper individual flows. Highly explosive volcanism tends to throw large quantities of material into the air, which accumulates, near the source of emission. Thus, steep sloped piles of material accumulate that are held together by lava flows and dikes. Explosive volcanism may give rise to flows as solid and semi-molten materials. These are fluidized in hot gaseous masses, which spread out rapidly over the territory, adapting themselves to the topographical relief. The ash flows leave ash flow tuffs or ignimbrites that are regular, compact and remarkably porous, although poorly pervious as a whole. Within one volcanic area, the type of volcanism can vary in the course of time as a consequence of the

tectonic evolution of the area and differentiations in magmatic chambers. Acid, intermediate and basic, emission can exist at one and the same time. The emission of large quantities of pyroclastic material and violence of eruptions, particularly when large quantities of water is involved (such as lakes), can give rise to flows of cold or warm solid materials lubricated by water (lahars) that are capable of producing local accumulations of geo-hydrological importance. Close to the source of emission dykes contribute to the heterogeneous nature of the materials, other forms of intrusion are sills or horizontal dykes, nakes that are usually very compact and of very low permeability are commonly found. Also materials have been altered in varying degrees by effect of high temperature gases or steam, metamorphosing into material that is less permeable.

Tectonic process effect volcanic material owing to seismicity associated with the effusions themselves, the collapse of magmatic chambers and compaction of materials as deposits build up.

Volcanic material is made up of glass and mineral associations that are unstable in the conditions prevailing on the Earth's surface and subject to the effect of groundwater flow. All kinds of alteration occur, such as filling of vacuoles with minerals, intera-clast precipitation of minerals, filling of cracks, hydration and expansion of minerals and formation of clays (Custidio, 1989; in: IAEA, 1989). The most frequent effect is the progressive reduction in initial permeability. Generally, other circumstances being equal, age correlates with a decrease in permeability. Thus, young volcanic rocks are the most permeable formations known, for example, coarse lapilli's, loose scoria, etc; they can, however, be weathered into semi-homogeneous, almost impermeable, clay rich masses.

Effects of non-volcanic interlayering are evident since the generally effusive activity of volcanism is not continuous. Between effusions there are long periods of inactivity, sometimes hundreds or thousands of years. These conditions give rise to possibly intense erosion and the climatic weathering of surface volcanic materials with the formation of soils and subaerial vegetation, or to the deposition of materials of different origin (alluvial, colluvial, marine, etc) or even deposits of volcanic ash from eruptions in other places. When new effusions cover these deposits they may be thermally metamorphosed, giving rise to the “*almagres*” or *red layers* characteristically found in Chile, the Canary Islands and the French Massif Central (Custodio, 1989). These materials may impede water flow if they are not very permeable (clayey soil) or may facilitate flow, as in the case of alluvial or sand deposits.

4.1.1 Hydraulic Characteristics of Volcanic Materials

Custodio (1989) contend that the total porosity of volcanic materials is often high, even in compact lavas, but connected porosity, useful for water flow movement, is normally much lower. Many pores are sealed and contain gas given off by magma once the environmental pressure drops; this is true of lavas, ignimbritic deposits and agglomerates. In the case of accumulation of scoria, pyroclasts, ash fall tuff and breccias, however, connected porosity can be very high, similar to a classical porous medium, but the clasts still conserve a rather high non-connected internal porosity. Connected porosity in compact zones, blocks and clasts increases as alteration increases, although associated permeability is low and may even drop as weathering progresses. Permeability may vary over more than six orders of magnitude, from values at times in excess of 1000 m/d (10^{-2} m/s) in recent scoria, to values below 0.001m/d (10^{-8} m/s) in altered pyroclastic accumulations, massive zones of lava and ignimbrite, etc. (Annex 1).

Distribution of permeability in volcanic rock is generally usually heterogeneous. The accumulation of successive layers of material horizontally layered in differentiated zones (top, interior and base), with possible inter-layering of sub-aerial alterations or more or less continuous diverse deposits, makes it justifiable to expect marked anisotropy.

4.1.2 Groundwater Flow in Volcanic Formations

Volcanic formations may generally be considered to form a whole, with three-dimensional connected permeability, within a single aquifer system, even though the degree of internal heterogeneity may be very marked. Extreme cases of contrasts in permeability exist. In these cases it would be correct to consider different aquifers, but with a certain degree of connection along their boundaries. Heterogeneities can play a predominant role in flow distribution. They condition piezometry and appearance of springs. The existence of an old volcanic core overlain for example by much more permeable modern material along a steep slope causes most of the recharge water to circulate through the contact between the two formations. Greater concentrations exist in palaeo-reliefs and buried forms (Custodio, 1989).

In tabular deposits with low permeable inter-layering and high relief, perched aquifers may commonly be found. The presence of inter-layered sediments can give rise to well-defined situations where confined or semi-confined aquifers can occur. There is tendency to classify volcanic terrains as permeable material due to fissuration, this concept is, however, valid for lava flows and large intrusions, it may not be advisable in other cases where conditions come close to those of a porous medium (Custodio, 1989).

4.2 Overview of the Hydrogeology of the Studied Area

The Akaki River Catchment is made up of multi-layer aquifers having different hydro-geological characteristics (BCEOM- Seureca, 2000). The existing data shows that the catchment is composed of both inter-granular and fracture porosity type aquifers. The inter-granular porosity aquifers are alluvial sediments and pyroclastic rocks. The fractured aquifers are composed of different volcanic materials such as weathered and/or fractured basalts, ignimbrites, trachytes, rhyolites, and welded tuffs. Basalts and ignimbrites found in the upper Awash Basin are mostly tectonized and fractured; and therefore have good permeabilities (Berhane Melaku, 1982). Accordingly, he classified scoriaceous and vesicular basalts of Pleistocene age as very good aquifers (with yield $1296 \text{ m}^3/\text{day}$). Faulted ignimbrites and basalts make good aquifers while less fractured and less jointed basalts including alkaline flood basalts of the Addis Ababa region are moderate aquifers with yields of up to $432 \text{ m}^3/\text{day}$, $260 \text{ m}^3/\text{day}$ respectively. Poor aquifers are fine-grained alluvial deposits intercalated with ash material, and well-compacted lacustrine deposits. In contrast to this general observation the alluvial deposits of sand and gravel types have very good yield in the studied catchment.

Based on analysis of existing well data as well as those gathered for this research, all types of aquifers are found in the catchment (unconfined, semi-confined and confined) BCEOM- Seureca (2000) including *perched aquifers*. The data for the classification of aquifers requires intensive data collection on: lithologic and resistivity logs, static and dynamic water levels, water-strike, screen position, (total) draw down, etc. For the confined and semi-confined aquifers the confining layers are clays and fresh and/or massive and/ or aphanitic basalts and welded tuffs/ ignimbrites. Solid basalt layers contain water in narrow cooling joints/fissures or fractures and

therefore at some places act as semi-pervious confining beds. The confining clays are dark brown /chocolate/, gray or light-gray, and reddish-brown paleosol layers generally known as *baked soil*. The depositions of alluvial materials between basaltic materials result in a large and extremely complex geological structure with a variable and unpredictable lithology (Figure 4.1) difficult to correlate. The water level surface in these wells are not also smooth, and this abruptness can be attributed to either topography or both vertical and horizontal change in lithology.

Perched aquifer conditions were recognized by the position of the water-strike and the recorded static water level. The static water level is below the water-strike position.

In an effort made to gather all available data for the characterization of the aquifer media and the vadose zone, different well data were obtained. Most of the wells in the study area were drilled for different purposes /demands at different times. Thus, pumping test and other data were not to the standard field hydrogeological test of a carefully monitored pumping test with observation wells and in most of the cases recovery data measurement have been stopped after a short period before full recovery of the well (Ayinalam Ali, 1999). Different aquifer types/systems were drilled through and the pumping tests were also conducted for the whole multi-layer aquifer system. Therefore the hydraulic data derived for the aquifer system were not directly used for the characterization of the aquifer. Also the aquifer thicknesses were commonly evaluated or approximated by using screen length for the calculation of transmissivity, hydraulic conductivity, etc. this does not tell the actual condition.

Figure 4.1a NORTH-SOUTH WELL LOG CORRELATION

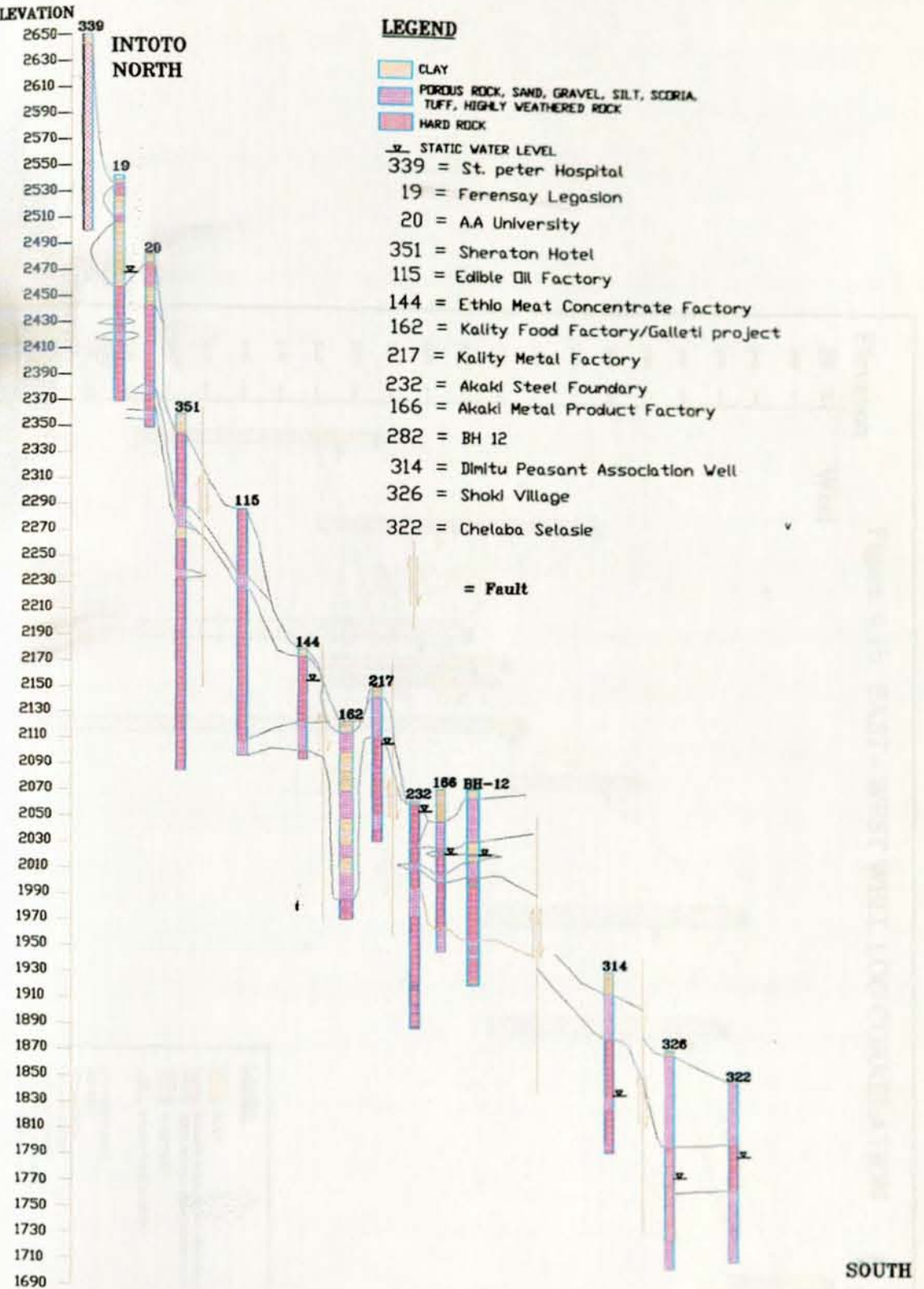
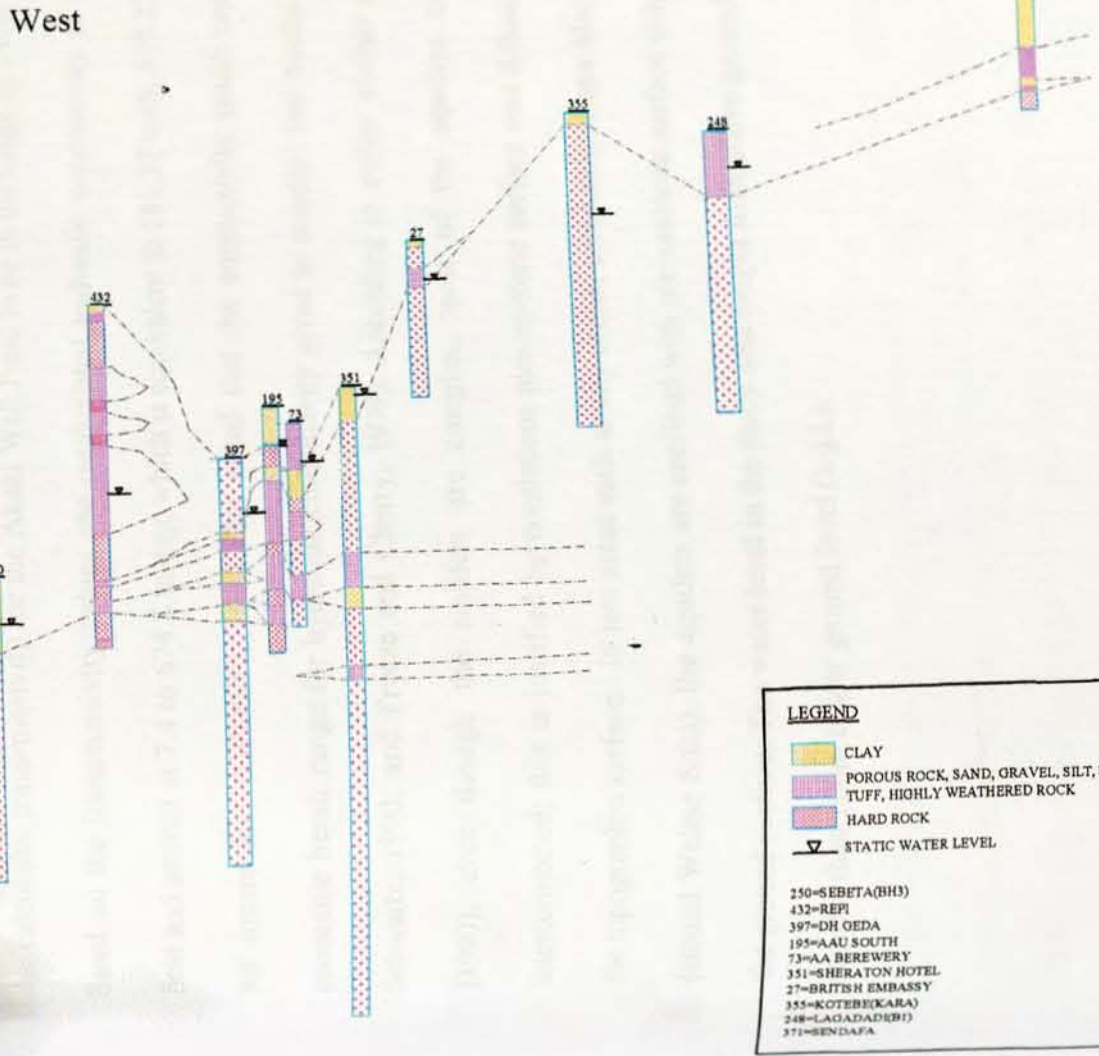
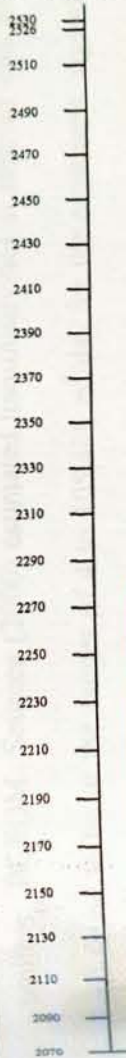


Figure 4.1b EAST - WEST WELL LOG CORRELATION

Elevation

West

East



LEGEND

- CLAY
- POROUS ROCK, SAND, GRAVEL, SILT, SCORIA, TUFF, HIGHLY WEATHERED ROCK
- HARD ROCK
- STATIC WATER LEVEL

- 250=SEBETA(BH3)
- 432=REPI
- 397=DH OEDA
- 195=AAU SOUTH
- 73=AA BEREWERY
- 351=SHERATON HOTEL
- 27=BRITISH EMBASSY
- 355=KOTEBE(KARA)
- 248=LACADADE(BI)
- 371=SENDAFA

According to Neven Kresic (1997) the hydraulic conductivity calculated using the pumping well data is only approximate since the measured draw-down includes an undetermined well loss. These were the problems faced to use either transmissivity or pumping test data to calculate the hydraulic conductivity, one of the seven DRASTIC base maps.

Under the above conditions, however, different authorities have estimated transmissivities of the aquifers. BCEOM- Seureca (2000) estimated transmissivities at selected sites in the catchment and found to be in the ranges of 4 to 105,408 m²/day for the catchment. Ayinalem Ali (1999) also calculated transmissivity for the Akaki Well Field to be in the range of 1440- 21,600m²/day. Based on the transmissivity values she recalculated hydraulic conductivity of the Akaki well field and arrived at 7.4 to 674.8 m/day, which is equivalent to 181.37 to16, 539.22 gallon per day per square feet (GPD/Ft²). She also noted that the conductivity could correspond to the permeable basalt range for hydraulic conductivity given in standard text books (Domenico and Schwartz, 1990; and Freeze and Cherry, 1979). According to earlier studies such as Seureca (1990), even though the aquifers are complex, most of the aquifers are hydraulically interconnected; this is justified by continuous piezometric surface that follows approximately the topographic surface. In low areas such as city center, east Kality, Hana Mariam, Jimma road (around Welete Suki), the aquifers are confined with piezometric surface either above or near the ground surface. The water level in the study area ranges from above ground surface/artesian/ to more than 100m below ground level (b.g.l.).

4.3 Potential Sources of Pollution and Groundwater Quality: Synopsis of Existing Situation

"Obviously no one personally chooses to have contaminated drinking water. Nearly every one, however, willingly uses and benefits from the products that contaminate drinking water". Anonymous

Under this topic the following themes were discussed: potential groundwater contamination sources (general and specific), groundwater quality from the point of view of pollution.

4.3.1 Potential Contamination Sources: General

Natural processes and human activities cause changes in groundwater quality directly or indirectly. Groundwater is degraded when its quality parameters are changed beyond their natural variation ranges by the introduction or removal of certain substances (Vrba and Zaporozec, 1994).

Most of the contaminants are anthropogenic sources that commonly cause concern and originate above ground, often as a result of different human activities. Thus, intrinsic groundwater aquifer vulnerability mapping is appropriate to assess potential pollution from these surface sources.

Potential contaminants include *non-point sources* such as agricultural pesticides, fertilizers, and feedlot runoff as well as *point sources* such as automotive service garage floor drains and shallow septic systems (Figure 4.3). In addition, oven cleaners, furniture polishes, bathroom

drain openers, paint and paint thinners, paper and ink, and countless other products contain chemicals that can turn up in drinking water if the products are not properly manufactured, used, and disposed (University of Wyoming, 2002). The principal contaminants in groundwater include heavy metals, organic chemicals, and others (bacteria and virus). Organic matter and soluble salts in manures (dung and liquid manure) are also potential contaminants

The sources of heavy metals can be natural processes (weathering and soil leaching) and human activities (industrial products or catalyst and pesticides or fertilizers, solid waste dumps and residue from mining, ore processing and smelting operations) (Mathess, 1974; in Vrba and Zaporozec, 1994). These are mostly found in industrial and domestic fuel gases and continental dusts, municipal sewage and industrial liquid wastes, etc. (Vrba and Zaporozec, 1994).

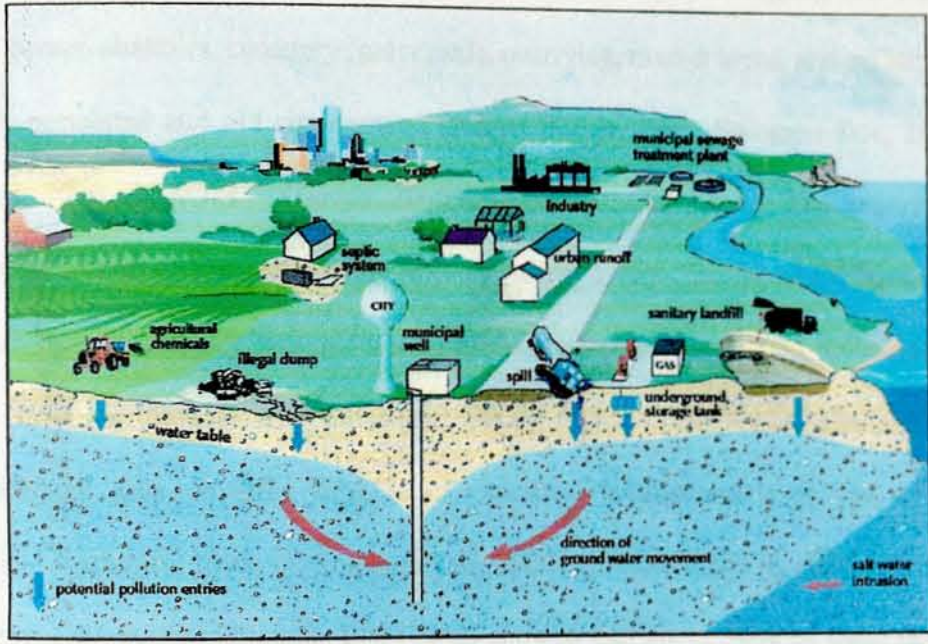
Either heavier and lighter immiscible organic compounds or fluids are common contaminants. The other solubilization of contaminants is mobilization of industrial flue gases in rainwater that allows introduction into groundwater.

Domestic and industrial liquid wastes discharged into surface waters, infiltrated from septic tanks, spread as fertilizers, applied at land application sites (spray irrigation), or injected into deep hydrogeological structures (Miller, 1975; Miller et al., 1977; Van Duijvenbooden et al., 1987 in: Vrba and Zaporozec, 1994) cause groundwater contamination (Figure 4.2).

Out breaks of waterborne diseases due to pathogenic bacteria and viruses occur where downward moving contaminated water by-passed the unsaturated zone by means of hydraulic shortcuts

(Althaus et al., 1982; in: Vrba and Zaporozec, 1994). The common short cuts are improperly constructed or sited wells and fractures. The main contamination sources are nearby septic tanks, leaky sewer lines, sanitary landfills, waste oxidation ponds, and land application of wastewater (Figure 4.2).

Figure 4.2 Schematic representation of major potential groundwater contaminating sources (Zaporozec et al., 2002)



The soil as will be described later under chapter 6 act as a first defense line for all pollutants placed on the surface of the ground. In addition, plants and soil microorganisms use some potential pollutants, such as nitrogen, as nutrients for growth, thereby depleting the amount that reaches the groundwater. However, as any man made filtering device is overloaded, so can the natural filtering capacity of soil. Large amounts of potential pollutants concentrated in a small area can cause localized groundwater contamination depending on the depth and type of soil above the water table (University of Wyoming, 2002).

4.3.2 Existing Situation in the Studied Area

In Ethiopia, as in most of the developing countries, where the issue of environmental pollution is not seriously considered and environmentally oriented legislation is lacking (Annex 8), activities that generate potential pollutants are threatening the quality of water resources. In the capital city and its environs the sources of pollution can be many, and the major ones are: industrial effluents, agricultural activities, municipal wastes (both solid and liquid), fuel stations, garages, health center, abattoirs, cemetery (graveyard), quarrying, market areas, and pit latrines (mostly in heavily populated and old city corners) (Adane Bekele, 1999; Solomon Tale, 2000; BCEOM–Seureca, 2000, BCEOM – Seureca, 2000 (EIA); NEDECO, 2001). The majority of industrial establishments discharge their waste into the nearby rivers. Addis Ababa Trade, Industry and Tourism Bureau and Ministry of Industry (1998) registered about 1082 industrial establishment up to 1998 in the city (Solomon Tale, 2000). This made Addis Ababa to be the most industrialized area covering 65.32% of industrial establishments in the country (Central Statistical Authority, 1998; in: Solomon Tale, 2000). Studies made in 1999 by Zeyakobe Belete and Zeru Girmay; in: Solomon Tale (2000) showed that about 96% of them do not have any wastewater treatment plant resulting in the pollution of streams and rivers.

Municipal wastes (both solid and liquid) are the most important potential sources of pollution. NOR Consultants (1982) in Solomon Tale (2000) estimated solid wastes generated by source as domestic waste (76%), street sweepings (6%), commercial wastes (9%), industrial effluents (5%), hotels (3%) and hospitals (1%). Solid wastes generated by and collected from the above sources are disposed into the so-called Kore landfill (southwest of the studied catchment), which is not actually a landfill, but rather an open dump site. From this site there is a possibility of leachate pollution.

Liquid wastewater (sewage) is another potential source of pollution and health risk as leaking sewer lines contaminate soil and water. Either due to inaccessibility or complete absence of the sewerage line many liquid waste generating sources in Addis Ababa are directing their wastes into nearby storm water drains that end up in the adjoining streams or they directly discharge into rivers or streams. These main sources include: toilets, petrol stations, industries, garages, etc. (Solomon Tale, 2000; Adane Bekele 1999). As a result it is common to see dark colored stream- or river- water. These watercourses are acting as an open sewer. BCEOM – Seureca (2000) (EIA) considered the clay soil of the area to have the filtering capacity for the pathogenic organisms. This implies that the chance of these organisms to reach the groundwater is minimal where the thickness of clay soil is significant.

One of the most suspected severe environmental problems in groundwater contamination not well known so far is non-aqueous phase liquids (NAPLs). They are usually considered as a long-term pollution sources in groundwater due to the low water solubility and low mobility (Biazen Setarge et al., 1999). The possible sources for these pollutants in the studied area can be garage, stationary vehicles, truck check points, used oils and detergents, leaking gasoline tank and oil spillage. These compounds have the ability to kill the living biota in the soil and water.

In addition to the above-mentioned sources, the application of agricultural inputs, poultry development and animal rearing might have some contribution to the general pollution of water. At the moment there is no as such intensive fertilizer and pesticide application in the catchment. According to BCEOM-Seureca (2000)(EIA) the annual rate of urea [$\text{CO}(\text{NH}_2)_2$]; and Di-

ammonium phosphate (DAP) $[(\text{NH}_4)_2 \text{HPO}_4]$ used in the project area was 100kg/ha. Urea contains 46% Nitrogen (as N) and DAP, 18% of Nitrogen and 46% phosphorous (as P_2O_5). Nitrogen in the form of nitrate (after nitrification of urea) is the most mobile element while phosphorus is not very mobile due to adsorption. According to Solomon Tale (2000) about 4441 kg of urea; 91,225 kg of DAP, and 395 liters of different types of pesticides were used in 1998/99 in Addis Ababa and its environs.

The rate of pesticide application in the area was very low; mainly, insecticides were spread on crops. The herbicide 2, 4 D also known as [2-(2, 4-dichlorophenoxy) ethyl] phosphate (=2, 4-DEP) is the most commonly used, and represented by the following formula $\text{C}_{24}\text{H}_{21}\text{Cl}_2\text{O}_6\text{P}$. It is very mobile in soil.

In Lake Akaki, there is an eutrophication process due to excess level of nutrients that stimulate plant growth of rooted vegetation and floating algae continuously supplied by Akaki River and its tributaries from different sources. Such nutrients principally come from agricultural activities, municipal and industrial sources (Tenalem Ayenew, 1998).

The following table shows major pollutants discharged by some small-scale industrial facilities (BCEOM-Seureca, 2000; EIA) around the Akaki well field in the catchment.

Table 4.1 Major Pollutants discharged by some small-scale industrial facilities and their character (BCEOM-Seureca, 2000; EIA).

Activity/Sector	Major Polluting agents discharged in the effluents
Tannery	Organic matter (1), suspended solid (1), chromium III (1,2,3), Phenol (1,3), Sulfides (1), salts (1), greases (1)
Textile	Organic matters (1), suspended solid (1), dyers (1), solvent (1,3)
Metal(galvanization, chrome plating, etc.)	Chromium VI (1,2,3,4), Zinc (1,2,3), copper (1,2,3) Nickel (1,2,3,4), cadmium (1,2,3,4), Cyanides (1,3), detergents (1), acids (1), oil and greases (1,3)
Food and beverage	Organic matters (1), suspended solids (1), detergents (1), acids (1), oil and greases (1,3)
Wastewater treatment plant	Organic matters (1), suspended solid (1) Pathogens (1,3)

1= harmful for aquatic life,

2= non-biodegradable,

3= of peoples health significance

4= carcinogen

4.3.3 Groundwater Quality

Different water chemistry data are available for the catchment, which were sampled and analyzed at different times. From these data, however, the most recent one was selected to see the general groundwater quality condition in the studied area. The data used for groundwater quality analysis are presented in Annex 4.

Chloride, Nitrate and total dissolved solids (TDS) values are commonly used as groundwater quality indicators of potential contamination due to human activity. Especially, chloride and nitrate levels are good indicators of potential contamination of groundwater (NEDECO, 2001). As has been expected and seen from Figures 4.4 and 4.5 the concentration of nitrate and chloride are relatively high in densely populated areas of Addis Ababa (Figure 2.1) and particularly at Merkato area. High nitrate concentration levels indicate contamination from municipal wastes. Whereas high chloride concentrations in groundwater show contamination from pit latrines, waste disposals and from city water supply (treated with chlorine).

Nitrate concentrations of greater than 50 mg/l were detected for the densely populated Merkato area. For same reason, at Akaki Town, nitrate levels of 20 mg/l and higher were reported. Similarly, comparative high chloride content was also detected for Merkato area. High TDS values were reported for central areas of the Addis Ababa Region. The detected values exceed 1000mg/l (at Filwoha area) and west of the city (Figure 4.5). These localized high TDS values are believed to be associated with thermal water effects. Table 4.2 and Figures 4.3 to 4.5 show summary of physico-chemical results detected in groundwater that could give a clue to the general overview of the groundwater quality of the catchment from the point of view of tested parameters.

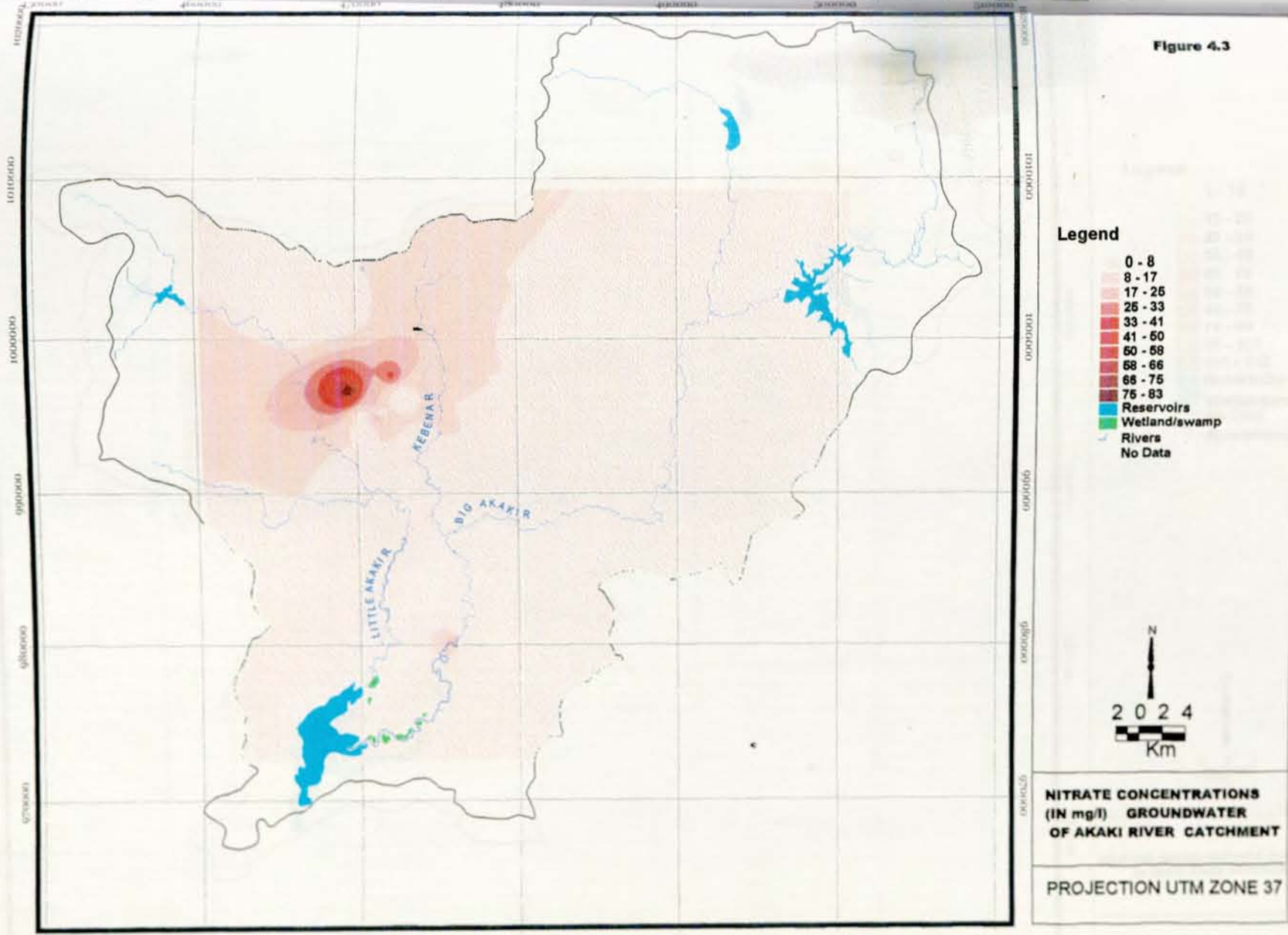
From Table 4.2 it can be observed that there is trend of groundwater quality deterioration as it is especially indicated by maximum values of some tested parameters, such as alkalinity, hardness, nutrients, and some trace elements. Higher values than the WHO standards prove this trend. Therefore, there is the potential of groundwater contamination in the catchment especially for the analyzed parameters from limited sample points. Therefore, this is a precautionary cursor in locating well and waste /generating/disposal sites in the catchment.

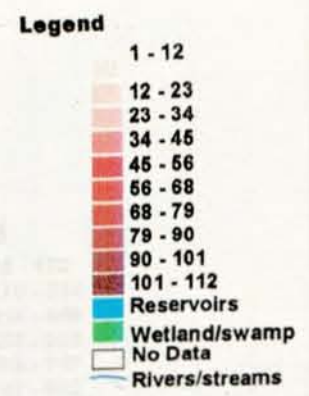
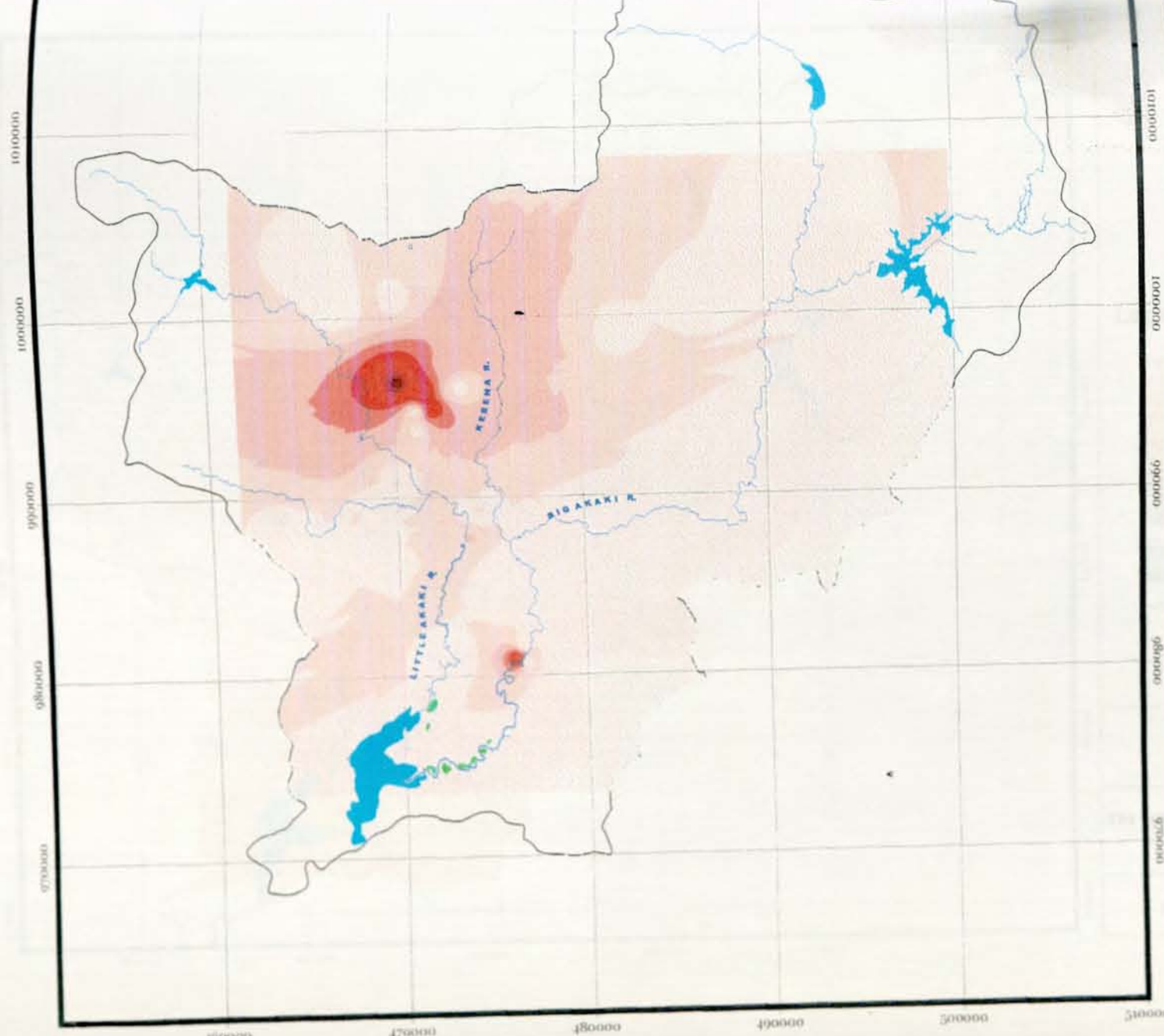
Out of 64 wells having recent water quality data 56 wells were used to prepare the above three maps using Arc View GIS.

Table 4.2 Summary of water quality parameters detected in groundwater samples (BCEOM-Seureca, 2000)

Physico-Chemical parameters	No. Of Wells Analyzed	Minimum Value	Mean Value	Maximum Value	WHO Standard
<u>Physical properties</u>					
PH	64	6.600	7.67	8.60	6.5 - 8.5
TDS (mg/l)	64	24.600	286.18	1470.00	1000
<u>Major Inorganic Compounds</u>					
Calcium hardness as CaCO ₃ (mg/l)	64	1.800	143.93	314.00	500
Chloride as Cl (mg/l)	64	0.700	13.87	112.50	250
Fluoride as F (mg/l)	64	0.000	0.76	19.70	1.6
Magnesium hardness as CaCO ₃ (mg/l)	64	1.000	70.68	226.00	500
Sulphate as SO ₄ (mg/l)	64	0.000	21.95	106.60	400
Total Alkalinity as CaCO ₃ (mg/l)	64	9.000	235.47	1340.00	500
Total hardness as CaCO ₃ (mg/l)	64	6.000	217.11	540.00	500
<u>Nutrients</u>					
Ammonia as NH ₃ -N, (mg/l)	64	0.000	0.30	1.56	-
Nitrate as NO ₃ -N (mg/l)	64	0.130	5.48	82.50	50
Nitrite as NO ₂ -N (mg/l)	64	0.008	0.01	0.11	-
Phosphate as PO ₄ (mg/l)	64	0.045	0.45	1.42	-
<u>Trace elements</u>					
Hexavalent Chromium as Cr (mg/l)	64	0.001	0.00	0.03	1.04-3.00
Iron as Fe (mg/l)	64	0.000	0.01	0.03	0.05
Silica as SiO ₂ (mg/l)	64	0.003	0.42	8.27	0.3
Manganese as Mn (mg/l)	64	0.005	0.07	1.01	0.1
Copper as Cu (mg/l)	64	10.300	52.81	683.00	-

Figure 4.3

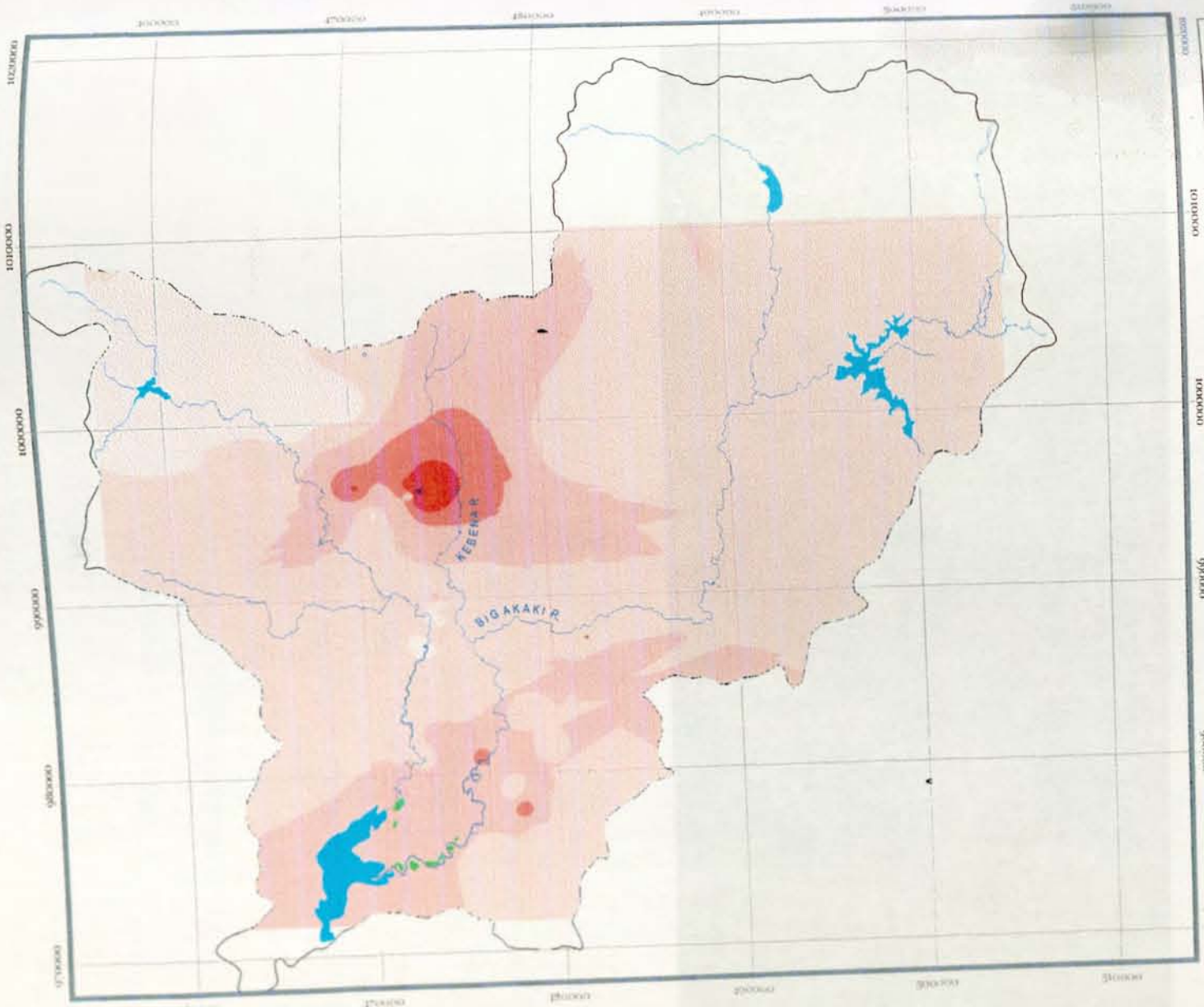




CHLORIDE CONCENTRATIONS MAP (IN mg/l)
IN ARAKI RIVER CATCHMENT

PROJECTION UTM ZONE 37

Figure 4.5



Legend

- 25 - 170
- 170 - 314
- 314 - 459
- 459 - 603
- 603 - 747
- 747 - 892
- 892 - 1036
- 1036 - 1180
- 1180 - 1325
- 1325 - 1469
- No Data
- Reservoirs
- Wetland /Swamp
- River



**TDS CONCENTRATION (In mg/l) MAP OF
AKAKI RIVER CATCHMENT**

PROJECTION UTM ZONE 37

GROUNDWATER VULNERABILITY MAPPING AND ASSESSMENT CONCEPT

A picture is worth more than a thousand words and a map more than a thousand pictures

Pro and Zepherus (1994)

PART THREE

THEORETICAL BACKGROUND OF
VULNERABILITY MAPPING

The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against human and natural inputs, especially with regard to contaminants entering the subsurface environment. The degree of protection provided by the natural environment may vary from site to site. The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against human and natural inputs, especially with regard to contaminants entering the subsurface environment. The degree of protection provided by the natural environment may vary from site to site. The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against human and natural inputs, especially with regard to contaminants entering the subsurface environment. The degree of protection provided by the natural environment may vary from site to site.

CHAPTER FIVE

GROUNDWATER VULNERABILITY MAPPING AND ASSESSMENT CONCEPT

"A picture speaks more than a thousand words and a map more than a thousand pictures."

Vrba and Zaporozec (1994)

5.1 Historical Overview

Groundwater vulnerability mapping was started during the 1960's and 1970's as a part of an effort made in the field of hydrological mapping. The first concept of groundwater vulnerability was introduced by a French hydrogeologist, Jean Margat, in the late 1960's with the original idea of vulnerability of groundwater to contamination that is mainly from water quality aspects (Margat, 1968; in: Vrba & Zaporozec, 1994). The idea of describing the degrees of vulnerability of groundwater to contaminants as a function of hydrogeological conditions by means of maps was conceived in an effort to create awareness of danger of groundwater contamination (Albinet and Margat, 1970; Margat, 1968, in: Vrba & Zaporozec, 1994).

The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against human and natural impacts, especially with regard to contaminants entering the subsurface environment. That means the soil-rock-groundwater system may provide a degree of protection against contamination of groundwater by 'self-purification' or 'natural attenuation' (Zaporozec, 2001). Thus, the (intrinsic) groundwater vulnerability could be described as the 'relative inability' of the soil-rock-groundwater system to protect its water against contamination. As a

result some land areas are more vulnerable to groundwater contamination than others. This situation is due to the potential for contaminant attenuation possessed by earth materials. The “purification capacity” of the environment is called “attenuation capacity” and it expresses the intrinsic/ natural/ ability of the earth materials above and within the groundwater system to absorb, disperse, or retard contaminants by a number of physical, chemical, and biological processes acting in the soil-rock- groundwater system (Vrba & Zaporozec, 1994). Hence, the potential for natural protection is limited and extremely variable. Different parts of the physical environment have varying capacities for attenuating contaminants. Therefore, mapping the vulnerability or sensitivity of the physical environment enables us to identify areas that are more (and less) sensitive to contamination because of the materials overlying the groundwater.

Different authors defined groundwater vulnerability differently until the International Association of Hydrogeologists (IAH) defined it as: “Vulnerability is an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and /or natural impacts” (Vrba & Zaporozec, 1994). A generally recognized and accepted definition of vulnerability has, however, not been given yet.

5.2 Concept of Groundwater Vulnerability to Pollution

Almost all groundwater resources are vulnerable to various degrees (Center for Natural Resources, 2001). As it was described earlier, the fundamental concept of groundwater vulnerability is that some land areas are more vulnerable to groundwater contamination than others. That is, the original concept of groundwater vulnerability was based on the assumption that the physical environment may provide some degree of protection (*referred to as the barrier*

zone) with regard to contaminants (*the threat*) entering the subsurface water (*groundwater resource*).

The term vulnerability has been defined and used before in the area of water resources, but within the context of the evaluation of system performance. Hashimoto et al. (1982) in Lobo-Ferreira and Oliveira (1997) present an analysis of system performance, which focuses on system failure as follows. They define three concepts that provide useful measures of system performance:

- how likely the system is to fail is measured by its *reliability*,
- how quickly the system returns to a satisfactory state once a failure has occurred is expressed by its *resilience*, and
- how severe the likely consequences of failure may be is measured by its *vulnerability*.

This concept of vulnerability defined in the context of system performance may also be used in the context of groundwater pollution if we replace "system failure" by "pollutant loading" Lobo-Ferreira and Oliveira (1997). The severity of the consequences is measured in terms of water quality deterioration, regardless of its value as a resource.

Lobo-Ferreira and Oliveira (1997) believe that among the ambiguous definition of vulnerability from the context of groundwater pollution the one that refers to the *intrinsic* characteristics of the aquifer, which are relatively *static* and beyond human control is useful; and defined it as: "*the sensitivity of groundwater quality to an imposed contaminant load, which is determined by the intrinsic characteristics of the aquifer.*"

These authors also argue that the term "*vulnerability to pollution*" is used with a composite

meaning that would perhaps be better described by *risk of pollution*. Based on the above concept they have the opinion that vulnerability and pollution risk shall be defined differently. Accordingly, *pollution risk* depends not only on vulnerability but also on the existence of significant pollutant loading entering the subsurface environment. From this concept it is possible to have high aquifer vulnerability but no risk of pollution, if there is no significant pollutant loading. To have high pollution risk in spite of low vulnerability the pollutant loading shall be exceptional. Thus, it is important to make clear the distinction between *vulnerability* and *risk*, because risk of pollution is determined not only by the *intrinsic characteristics* of the aquifer, which are relatively *static*, but also on the existence of potentially polluting activities, which are *dynamic* factors that can in principle be changed and controlled. From this definition vulnerability of an aquifer will be different for different pollutants. Furthermore, they also suggests that it is scientifically more sound to evaluate vulnerability to pollution in relation to a particular class of pollutant, such as nutrients, organics, heavy metals, pathogens, etc., i.e. to create *specific vulnerability* maps. Foster (1987) in Lobo-Ferreira and Olveria (1997) contend that vulnerability mapping could be performed in relation to groups of polluting activities; such as sewage/waste disposal, agriculture, and particular groups of industries.

Specific vulnerability mapping requires specific and costly data set to prepare. Hence a relatively less costly assessment method, intrinsic vulnerability mapping, that could utilize an input data from existing data archives was applied as a first application of index method of vulnerability mapping in this thesis.

5.3 Approaches to Vulnerability Mapping and Assessment

Two basic approaches exist to vulnerability mapping: general and specific. The *general* or *intrinsic* vulnerability maps are used to evaluate the natural vulnerability of groundwater without context to a specific contaminant or a specific contamination source. *Specific* or *integrated* vulnerability maps sometimes called land suitability maps are used to evaluate the impact of a particular land use or a contamination source on groundwater.

Margat (1991) in Vrba & Zaporozec (1994) suggested that general vulnerability maps are useful for sensitizing planners to groundwater protection issues at the beginning of a regional planning process.

Vulnerability map is time-dependent and constantly requires updating to portray changes in both the characteristics of a groundwater system and the location and nature of potential contamination sources. Vulnerability map is commonly constructed to evaluate the *upper most aquifer*, and assessment of deeper aquifers is less frequent (Vrba and Zaporozec, 1994). Vulnerability is often assessed in terms of water quality.

In this study, intrinsic groundwater vulnerability is adopted. The principal attributes of intrinsic groundwater vulnerability are recharge, soil properties, and the characteristics of the unsaturated zone. In the case of *specific groundwater vulnerability*, however, the attenuation capacities of the soil, of the unsaturated zone, and of the aquifer with respect to the properties of individual contaminants are important parameters. Land use (human impact) and population density are also major attributes (Vrba and Zaporozec, 1994).

CHAPTER SIX

GROUNDWATER VULNERABILITY ASSESSMENT METHOD: DRASTIC MODEL

"It is often unrealistic to talk about a "cure" for groundwater contamination. Prevention is the key and prevention includes...learning to control them." Anonymous

During the last 30 years a number of techniques were developed to assess groundwater vulnerability. This study, however, adopted one of the *parametric system methods* (PSMs) or *point count system models* (PCSMs) called DRASTIC Model developed by the U.S. Environmental Protection Agency in 1985 by Aller et al. (1987). It is one of the first PCSMs (Vrba and Zaporozec, 1994) and one of the most successful and commonly used methods (Lee, 2001, 2002; Gogu, 2002; Lobo-Ferreira & Olveria, 1997; Napolitano, 1995). It is a standardized index, which has been widely used in USA and Canada, and adopted in many other countries too. The adoption of an index method has the advantage of, in principle, eliminating or minimizing subjectivity in the ranking process (Lobo-Ferreira & Olveria, 1997) of vulnerability classes.

6.1 Model Description

The DRASTIC vulnerability mapping technique can generally be referred to as a composite description of all the major geologic and hydrogeologic factors that affect and control groundwater movement, into, through, and out of an area (Center for Natural Resources, 2001). From this concept, areas with similar hydrogeologic parameters therefore could have similar vulnerability.

The DRASTIC Model, which is used by many countries, was first designed to permit systematic evaluation of pollution potential in any hydrogeological setting in the United States. The word *hydrogeologic setting* was defined by Aller et al. (1987) as: "a composite description of all the major geologic and hydrologic factors which affect and control groundwater movement into, through, and out of an area. It is defined as a mappable unit with common hydrogeologic characteristics, and as a consequence, common vulnerability to contamination by introduced pollutants. ...the area of a hydrogeologic setting should be larger than 100 acres in size, thereby limiting the system to use as a screening tool and not as a site specific assessment methodology."

The DRASTIC System was developed to help planners, managers and administrators in the evaluation of groundwater pollution from various sources of contamination. It provides on a general, broad assessment to be used to evaluate sites for potential pollution (Aller et al., 1987).

The DRASTIC System is standardized system of groundwater pollution susceptibility assessment by analyzing hydrogeologic factors. The acronym DRASTIC as described under the methodology section is taken from the initial letters of the seven parameters used to evaluate *intrinsic* vulnerability of aquifers; i.e. groundwater contamination potential (Vrba and Zaporozec, 1994).

The choice of the factors was based both on consideration of the physical and chemical characteristics which affect groundwater and the availability of mappable data. These factors represent measurable parameters for which data are available from a variety of sources or detailed reconnaissance (Napolitano, 1995).

6.1.1 Ranges, Ratings and Weights in DRASTIC Model

DRASTIC factors use a numerical ranking system to assess groundwater pollution potential in hydrogeologic settings. The system consists of three parts, which are designated as: *ranges, ratings and weights*. Each DRASTIC factor has been divided into either ranges or significant media types, which have a significant impact on pollution potential. Ranges for each DRASTIC factor have been evaluated with respect to the other factors in order to determine the relative significance of each range with respect to pollution potential (Napolitano, 1995). The range for DRASTIC factor has been assigned a subjective rating, which varies between 1 and 10 (Table 6.1). From these factors, D, R, S, T, and C, have been assigned one value per range, while the other two, A and I, have been assigned a “*typical*” rating and a “*variable*” rating. The variable rating permits the user to choose either a typical value or to adjust the value based on more specific knowledge. In this thesis the typical rating was applied.

Two relative *weight strings* (varying from 1 to 5) have been assigned to each DRASTIC factor in order to determine the relative importance of each factor. The most significant factors assigned weights of 5 and a weight of 1 for the least significant factors. The two strings as shown in Table 6.1 are weights for the “general or normal” DRASTIC and “Agricultural or pesticide” DRASTIC. Agricultural DRASTIC was developed to reflect the effect of herbicides and pesticides. According to the authors Aller et al. (1987) both ratings and weights are *constant* and *cannot be changed*. However, modified DRASTIC approach is followed by the users of the model based on local condition.

Table 6.1 Assigned ranges, ratings and weights for DRASTIC factors (Aller et al., 1987).

Factors	Weight		Range (cm)	Rating	Typical Rating
	General (Normal)	Agricultural (Pesticide)			
*Depth to Water (m)	5	5	0 – 1.524 1.524 – 4.572 4.572 – 9.144 9.144 – 15.24 15.24 – 22.86 22.86 – 30.48 30.48+	10 9 7 5 3 2 1	
Net Recharge (mm)	4	4	0 – 50.8 50.8 – 101.6 101.6 – 177.8 177.8 – 254.0 254+	1 3 6 8 9	
Aquifer Media	3	3	Massive shale Metamorphic/Igneous Weathered Metamorphic/Igneous Glacial Till Bedded sandstone, limestone, shale sequences Massive sandstone Massive limestone Sand and gravel Basalt Karsts limestone	1-3 2-5 3-5 4-6 5-9 4-9 4-9 4-9 2-10 9-10	2 3 4 5 6 6 6 6 8 9 10
Soil media	2	5	Thin or Absent Gravel Sand Peat Shrinking and/or aggregated clay Sandy loam Loam Silty loam	10 10 9 8 7 6 5 4	

			Clay loam	3	
			Muck	2	
			Nonshrinking and nonaggregated clay	1	
Topography (%)	1	3	0-2	10	
			2-6	9	
			6-12	5	
			12-18	3	
			18+	1	
Impact of the Vadose Zone media	5	4	Confining layer	1	1
			Silt/Clay	2-6	3
			Shale	2-5	3
			Limestone	2-7	6
			Sandstone	4-8	6
			Bedded limestone, sandstone, shale	4-8	6
			Sand and gravel with significant silt and clay	4-8	6
			Metamorphic/ igneous	2-8	4
			Sand and gravel	6-9	8
			Basalt	2-10	9
			Karst limestone	8-10	10
Hydraulic Conductivity (GPD/Ft ²)	3	2	1-100	1	
			100-300	2	
			300-700	4	
			700-1000	6	
			1000-2000	8	
			2000+	10	

* Modified DRASTIC approach was followed to rate depth to water (see chapter 8).

6.2 Review of Experiences with DRASTIC Model

6.2.1 Inherent Assumptions and Ambiguities

This methodology, DRASTIC Model, is based on the following important assumptions that one has to know before using it for assessment of the potential pollution problem:

- The contaminant is introduced at the ground surface; DRASTIC, therefore, does not consider the situation in which the pollutants are introduced directly in to the aquifer;

- The contaminant is flushed in to the groundwater by precipitation and it has the mobility of water. The hydraulic conductivity of the aquifer, therefore, is expression of the velocity of the contaminant in aquifer;
- There is no interaction between chemical pollutants and the physical environment: attenuation phenomena such as dilution, dispersion, mechanical filtration, volatilization, biological assimilation and decomposition, precipitation, etc. are not considered;
- The variables included in the model are critically related to groundwater vulnerability;
- Data are available and possess sufficient precision, resolution and accuracy for assignments of ratings;
- The ratings, weights and mathematical relationships between variables are adequately set forth in the DRASTIC procedure;
- The area evaluated, i.e. the hydrogeologic setting, should be 100 acres or larger

The following are assumptions forwarded by the key contributors to the model (Napolitano, 1995). As part of her master's thesis work, Napolitano (1995), assessed the critics made by the previous workers on DRASTIC System, and summarized the most unclear points as follows:

- Ambiguity with regard to scale at which the model should be used. The authors, who constructed DRASTIC, did not provide arguments in support of particular scales for its application. On one hand the ratings are to be assigned to "geological settings" and it is recommended to not use sites smaller than 100 acres for the hydrogeological setting. Such a recommendation could be interpreted to imply a small-scale application. On the other hand, the ranges established for some factors let imagine that detailed information is required.
- Insufficient representation of available data to analyze the behavior of natural systems. In particular, only few lithologic types are represented for assigning rates to Aquifer media and

Impact of the vadose zone media.

- Definition of variables, functions, and weights are subjective and based on an incomplete knowledge of the physical processes involved. Several authors, indeed, found that the ratings and the weights proposed by Aller et al. (1987) did not vary appreciably in their study areas or are not expression of the real pollution potential (Civita et al., 1990; Civita, 1994).
- Little importance has given to the soil attenuation action.
- Absence of a valid methodology in evaluation of net Recharge and in the evaluation of water inter-change between aquifer and subsurface water, i.e. rivers and lakes.

Following this, the application and suggestions made on DRASTIC Model are summarized and presented based on the original contributors employing the model.

6.2.2 Suggestions on the Applicability of the Model

The following are suggestions forwarded by the key contributors to the model (Napolitano, 1995).

Evans and Meyers (1990) presented a GIS-based approach to evaluating regional groundwater potential using DRASTIC System. The authors computed the vulnerability index using only four DRASTIC factors, i.e. Depth to water, Soil media, Topography, and hydraulic conductivity, assuming that the other parameters did not vary appreciably in their study area.

Civita (1990), Civita et al. (1990), and Civita (1994) suggested a method, named SINTACS, partially derived from DRASTIC, that uses the same seven parameters or factors. SINTACS derived partially from DRASTIC (Napolitano, 1995) was developed by Civita (1990), Civita et

al. (1990) and Civita (1994) is the acronym derived from the initials (in Italian) of the seven principal factors which essentially are those used in DRASTIC (Soggiacenza as Depth to water, Infiltrazione as net Recharge, Non-saturo as Impact of the vadose zone media, Tipologia copertura as Soil media, Caratteristiche Acquifero as Aquifer media, Acclivita Superficie Topografica as Slope). The weight strings used in SINTACS are not fixed in number unlike that of DRASTIC. Thus, four different weight strings used in different situations (Normal, Agricultural, Drainage and Karstic) can be applied. Also the range of parameters and hence the corresponding ratings are wider.

Rundquist et al. (1991) summarized a technique for implementing DRASTIC within the context of an automated raster-based GIS. The authors identified the areas of Nebraska considered vulnerable to groundwater pollution. The same area was the object of analysis by Kalinski et al. (1994), who tested the correlation between the vulnerability index, computed with DRASTIC and incidence of volatile organic chemical (VOC) contamination. The authors observed that significant positive correlations exist between the two indices, providing a validation to the usefulness of the DRASTIC method.

Barber et al. (1993), in a view of several methods for assessing groundwater vulnerability to pollution, argued that DRASTIC, as well as other empirical methods, runs the risk of being subjective mainly when assessing ratings for soil and rocks. The authors suggested that, because the method was developed for a broad relative vulnerability assessment, the result of the application of this method could be used for localizing the sites that need a more detailed assessment.

Rosen (1994), in a study on the application of DRASTIC in some sites of Sweden, considered both favorable and unfavorable properties of the system. The author analyzed the statistical properties of the interrelations between the DRASTIC parameters to evaluate if the parameters are correlated and to estimate their individual usefulness. Then he arrived at the conclusion that in the study area the seven parameters are quite independent and, therefore, representative enough to assess pollution vulnerability. On the other hand, the author argued that the rating tables were constructed so that the system tends to *overestimate* the vulnerability of *porous aquifers* compared to aquifers in *fractured media*.

Merchant (1994) provided a critical review of the DRASTIC model. After a detailed analysis of the problems related to data quality, model formulation and model validation, the author concluded that the model seems relatively robust, and he suggested that additional research should be focused on:

- ☞ Determination of the relative importance of the parameters and of possible interdependencies among them;
- ☞ Incorporation of other factors, e.g. land use, in the model, and linkage of DRASTIC with complementary models that evaluate the influence of point sources of contamination;
- ☞ Investigation of scaling issues;
- ☞ Expansion of DRASTIC through GIS-based 3D, finite-element, solute transport and temporal modeling;
- ☞ Validation and verification of the model;
- ☞ Means to assist decision-makers in using model results.

6.2.3 Selection and Potential Uses of DRASTIC Model

There are different techniques/ models that can be used for aquifer vulnerability assessment. The selection of the DRASTIC model (or any other model for that matter) depends on the availability of input data, resource and technology, time, and popularity of the model and knowledge.

DRASTIC represent classic approaches in vulnerability assessment (Gogu, 2002) and has been widely used with more frequency in many countries (Napolitano, 1995; Lobo-Ferreira & Olveria, 1997; Lee, 2001 and 2002; Gogu, 2002). The reason of its "success" can be due to the fact that data inputs required for its application are usually available or easily obtainable from several agencies, and that it can be implemented using geographic information systems (GISs). Few and inhomogeneous distributed point data that could not used in other complex models can be applied by such models that give a global idea of pollution vulnerability in large areas. Therefore, given the broader management objectives of the system and the operational and data constraints, this model can be considered both acceptable and appropriate.

6.3.2 No Recharge

According to Vrba and Zaporozec (1994) DRASTIC provides/has potential as:

- ✗ a measure of relative groundwater vulnerability to pollution;
- ✗ one of the actual site selection phase;
- ✗ to identify areas where specific attention, or protection efforts are warranted;
- ✗ in the prioritization of areas for monitoring purposes, etc.

6.3 Definition and Significances of the DRASTIC Parameters

In the following paragraphs definition of each DRASTIC layer will be given together with their significances in pollution potential assessment.

6.3.1 Depth to water

Depth to water represents the depth of the water table from the topographic surface and it gives an idea of the minimum distance that a pollutant has to travel to reach the saturated zone. In other words, it is the depth or thickness of the material through which a contaminant travels before reaching the aquifer. The presence of low permeability layers, which confine aquifers, will also limit the travel of contaminants into an aquifer. Where an aquifer is confined, depth to water should be redefined as the depth to the top of the aquifer. Depth to water is important because it provides the maximum opportunity for oxidation of the contaminant by atmospheric oxygen. As the depth to water increases generally, there is a greater chance for attenuation to occur because deeper water levels imply longer travel times.

6.3.2 Net Recharge

Net recharge is the amount of water, which infiltrates from the ground surface to the aquifer on annual basis. This recharge water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. The net recharge is the difference between total precipitation and the cumulative loss by direct runoff and effective evapotranspiration.

The vulnerability potential of an aquifer to groundwater contamination is in large part a function of the susceptibility of its recharge area to infiltration. Areas that are replenished at a high rate are generally more vulnerable to pollution than those replenished at a slower rate. In addition, it

controls the volume of water available for dispersion and dilution of the contaminant in the vadose and saturated zones.

6.3.3 Aquifer media

An aquifer is defined as a subsurface rock unit that will yield sufficient quantities of water for use. Aquifer media is based on lithology and refers to consolidated or unconsolidated rock, which serves as an aquifer. Aquifer medium governs the route and path length (groundwater flow system) within the aquifer. Textural and formation features of the saturated zone control the pollutant diffusion when it reached the aquifer. That is the route that the contaminant will take can be strongly influenced by fracturing, porosity, or by an interconnected series of openings which may provide preferential pathways for groundwater flow. The effect of fracturing of the aquifer on the pollutant migration considered in the rating of depth to water, described above. The contaminant flow system within the aquifer is also affected by the aquifer medium.

6.3.4 Soil media

Soil is the portion of the unsaturated zone characterized by significant biological activity. Soil is developed via the physical, chemical, and biologic alterations of the bottom litho types and of the organic matter they made up of. It provides the primary protection against groundwater pollution (University of Wyoming, 2002) and is considered as the first defense-line of the hydrogeologic system (Civita and De Maio, 2000). The characteristics of the soil influence the amount of recharge infiltrating the ground surface, the amount of potential dispersion, the purifying process of contaminants, the ability of a contaminant to move vertically into the vadose zone. Bacteria, sediment and other insoluble forms of contamination become trapped within the soil pores. Some

chemicals are absorbed or react chemically with various soil constituents, thereby preventing or slowing the migration of these pollutants in to groundwater. The presence of fine-textured materials such as silts and clays can decrease relative soil permeabilities and restrict contaminant migration.

6.3.5 Topographic slope

The topographic slope is an important factor in vulnerability assessment as it rules the amount of surface runoff produced, the precipitation rate and displacement velocity of the water (or a fluid and/or hydro-vectorable contaminant) Civita and De Maio (2000). It also refers to the slope variability of the land surface. Furthermore, the slope may be a genetic factor of the soil type and thickness that indirectly rules the attenuation potential of the hydrogeologic system. It also determines the extent of runoff of the pollutant and the degree of settling sufficient for infiltration. Areas with steep slopes, having large amounts of runoff and smaller amounts of infiltration, are less vulnerable to groundwater contamination. Contrary to this, topography influences soil development and therefore have an effect on contaminant attenuation. Slope was then classified and ranked for use in the topography component map.

6.3.6 Impact of the vadose zone media

Vadose zone is defined as the unsaturated zone from the ground surface to the top of the aquifer (for unconfined aquifer); and for confined aquifer the vadose zone is defined as all unsaturated and saturated zones between the ground surface and the top of the confined aquifer (Napolitano, 1995). The type of vadose zone media determines the attenuation characteristics of the material including the typical soil horizon and rock above the water table. The media also controls the path length and routing, thus affecting

the time available for attenuation and the quantity of material. In short, it is defined as the zone above the water table that is unsaturated or discontinuously saturated (Lee, 2002). The type of vadose zone media determines the attenuation characteristics of the material below the typical soil horizon and above the water table. Biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization and dispersion are all processes that may occur within the vadose zone.

6.3.7 Hydraulic Conductivity

This DRASTIC factor refers to the ability of the aquifer materials to transmit water, which in turn controls the rate at which groundwater will flow under a given hydraulic gradient. Hydraulic conductivity measures the rate at which a contaminant moves away from a point at which it enters the aquifer (Aller et al., 1987). It also controls the rate of groundwater movement in the saturated zone, thereby controlling the degree and fate of the contaminants. Therefore, high hydraulic conductivity is associated with higher pollution potential.

PART FOUR

MODELING

AND

**APPLICATION OF DRASTIC WITH GIS ON THE
AKAKI RIVER CATCHMENT**

CHAPTER SEVEN

GIS DATABASE DESIGN AND CONSTRUCTION: DATA CAPTURE AND INPUT

Data capture refers to the sources while data input refers to the database construction. Database structure was constructed for attributes used to define and to be linked with spatially distributed data. Attribute data were organized in such way that the information necessary for vulnerability assessment could be easily extracted and exported to a geographic information system. Attribute tables are used to reclassify the original map into a new field and hence commonly called lookup table. The output map is a reclassified version of the input map. Reclassification is the process of changing the assignment of objects from one classification system to another commonly based on a lookup table that relates the class of the output map to the class of the input map (Bonham-Carter, 1994).

For the purposes of data input, modeling and analysis in this thesis work a geographic information system (GIS) was used. A GIS is designed to store, process, retrieve, and display spatially referenced data. GIS is suitable for the combination and evaluation of disparate data layers for the purpose of providing "new" information (Evans and Myers, 1990). The geographic information system software known as ArcView GIS developed by ESRI was used in this research for data analysis and overlay operations, and there by to evaluate these layers of spatially referenced data to assess the groundwater contamination potential within the study area.

7.1 DRASTIC System and GIS

Geographic Information System (GIS) is used with DRASTIC in this work. GIS is a tool for storing, manipulating, retrieving and presenting both spatial and non-spatial data in a quick, efficient and organized way. The term "geographic", refers to the locational attributes, which define the spatial positioning of the piece of information on the face of the Earth (Das, 2002).

When DRASTIC was proposed for the first time, its formulation did not take the advantage of advanced GIS techniques (Napolitano, 1995). The method was primarily developed for manual overlay of semi-quantitative data layers (Vrba and Zaporozec, 1994). According to the earlier works in Napolitano (1995) many authors (Evans and Meyers, 1990; Cavallin and Giullano, 1992; Rundquist et al., 1991) used DRASTIC with raster-based GISs because the vulnerability index defined as an equation of a linear combination equation (1.1) given in chapter 1 can be calculated with the overlay operations available in GIS.

Many researchers agree why the use of GIS for aquifer vulnerability assessment is recommended:

- ☛ storage of a large amount of georeferenced data and of the attributes;
- ☛ data processing with interpolation of spatial data, rating of variables with appropriate weighting and calculation of a final vulnerability index by digital overlaying of raster data layers;
- ☛ out put of large data sets;
- ☛ frequent update of time-dependent data sets in a flexible and comfortable way;
- ☛ use of several techniques of parameter coding to apply and compare different scenarios or strategies.

7.2 Data Sources

Different data inputs pertaining to the seven DRASTIC maps must be available for data base construction. For this study, some of the data such as water level, well log, land use/cover, geological and structural map were collected during the summer of 2002 (July and August). Then the rest of the data used like soil, ground truthing of geological map were conducted during the main periods allotted for the thesis work. The author lately realized in the course of data analysis and modeling that the project was ambitious to use DRASTIC Model in the short time available inline with the lack of resources where there is no as such well organized and detail data for the model input. Thus, time, effort and money has been spent to gather the data and to overcome some obstacles such as data confidentiality, proprietorship and the bureaucratic red tape of some public offices. At the outset some data (such as soil and water) proposed to be collected and analyzed in the laboratory. But, this proposal was ruledout and rejected due to lack of financial resource. The data collected had different formats, scales, levels of spatial coverage, temporal resolutions, etc.

Though it is not always possible to get direct information on data quality for all data acquired from different sources an effort has been made to check data quality used for the modeling.

Table 7.1 Constructed GIS Layers for Akaki River Catchment

Data	Data Source	Data Format	Scale
Contour lines	Topographic Map (EMA)	Map Coverage/Vector data	1:50,000
Drainage	Topographic Map (EMA)	Map (Coverage)	1:50,000
DEM(Digital Elevation Model)	Contour of Topographic Map (EMA)	Grid (Raster) map	1:50,000
Slope	Elevation contours (generated from hill shaded image)	Grid	1:50,000
Hill shaded Image	DEM (generated)	Image (Bil-format raster data types)	1:50,000
Geology	Geological Map (BCEOM Seureca, 2000)	Map (coverage)	1:50,000
Fault	Structural Map (BCEM-Seureca, 2000).	Map (coverage)	1:50,000
Soil*	From this research	Map (coverage)	1:50,000
Land use	Land use map (BCEOM-Seureca, 2000)	Map (coverage)	1:50,000
Well data (Drill-holes)	AAWSA, Drilling companies, BCEOM-Seureca	Tables and reports	
Piezometric level	BCEOM-Seureca (2000)	Tables	
Depth to water	This research (using the above data)	Raster/grid map	300 000
Net recharge	This research (using earlier data)	Raster/grid map	"
Aquifer media	This research (using drill hole & geology)	Raster/grid map	"
Vadose zone media	This research (using drill hole & geology)	Raster/grid map	"
Hydraulic conductivity	This research (using drill hole & geology)	Raster/grid map	"
Normal DRASTIC	Overlay operation (this thesis)	Raster/grid map	"
Agricultural DRASTIC	Overlay operation (this thesis)	Raster/grid map	"
Land use/cover-soil	Intersection of land use-soil	Raster/grid map	"

*Soil textural analysis of relatively referenced point data was also obtained from (BCEOM/GKW, 1990; Lulseged Ayalew (1990), Kebede T. and Tadesse H/M (1990); Construction Design Share Company /BDE/ well data and from this research.

7.3 Database Constructions and Structure for Attribute Data

To build a database for the purpose of this research work, much time has been spent to decide on how to store and use data. Attribute data were stored in a spreadsheet using Microsoft Excel while spatial data have been directly digitized into a GIS using ArcInfo, and imported into Arc View GIS 3.2 for modeling and analysis. Digital data in AutoCAD format was obtained and after necessary editing and transformation the data was exported to ArcView GIS.

7.3.1 Topographic Data and Hydrography

The topographic base maps of 1:50,000 Scale produced by Ethiopian Mapping Agency (EMA) were used to digitize contours and drainage. The base maps used for the production of topographic data and hydrographic network of the area are:

Name	Index	Issued /Produced/
Addis Ababa NW	0938-D3	1982
Addis Ababa SW	0838-B1	1973
Addis Ababa NE	0938-D4	1982 (Reprinted 1999)
Addis Ababa SE	0838-B2	1975
Sendafa	0939-C3	1986

The topographic base maps were used for the construction of the digital elevation model, and hence good resolution was obtained. The topographic base maps used have a contour interval of 20m. The morphology of the study area is mostly covered by rugged and undulating topography. The contours are very dense on hills and mountains. Therefore, to facilitate the digitization process contour lines were digitized at 40m intervals. After that interpolation of contours were done with in ArcView using the Spatial Analyst extension.

Drainage networks were digitized from the same base maps. The characteristics of the drainage are described in Chapter 2. Contour lines and drainage consist of line features and have length and height attribute value. Data qualities regarding the base maps were not indicated by EMA.

Digital Elevation Model (DEM) or Digital Terrain Model (DTM) was calculated from the contour line at a resolution of 30m. The DEM is of GRID type and has height value. Hill shaded Image, relief map, and slopes were extracted from the DEM at the same resolution; and slope is calculated in per cent. The spatial resolution of 30 m was set for the grid cell size by subjective decision of the author, and was believed that it is sufficient to represent the details required by the work.

7.3.2 Drill-hole Database

Drill hole data were collected from different drilling companies (Water Wells, Hydro-Constriction, Pile Foundation and Water Wells, AAWSA, Oromia Water Wells Construction Enterprise/OWWCE/). The drill-hole database was used to classify aquifer media and types of vadose zone and to some extent depth and type of soil. Based on the drill-hole database the hydraulic conductivity of the aquifers was estimated using the ranges presented in standard text books such as Freeze and Cherry (1979). Under the drill hole database, the aquifer media has attributes of location (Coordinate), depth to top of the aquifer media types, type of aquifer, confining unit (if any) and finally rating value of the upper aquifer media.

The vadose zone media has attributes of location and coordinate, significant media type, total vadose zone thickness and average rating for the materials constituting the vadose zone.

Similarly, soil media was derived from drill-holes data to reinforce the grain size distribution analysis conducted by different authorities and/or organizations. It has attributes of qualitative description of (soil type) genetic origin, thickness of overburden and rating. The thickness of overburden is simply to indicate the depth of the soil with similar color and texture up to the bedrock or soil of another color and/or texture according to the lithologic log description.

Hydraulic conductivity data was not obtained for this work. However, based on the aquifer material and the associated description given for the material in the lithologic log in each of the specific drill hole and geologic data, and using the hydraulic conductivity ranges given in Freeze and Cherry (1979), an effort has been made to classify aquifer materials in to hydraulic conductivity ranges based on the ranges given in the DRASTIC model (Table 6.1). The drill hole hydraulic conductivity database has attributes of relative location/owner and coordinate, aquifer material, range of hydraulic conductivity and corresponding rating value.

The drill-hole database was stored in the table DRILL using Microsoft Excel spread sheet. The table DRILL provides data used in the classification of aquifer, vadose zone, and hydraulic conductivity.

7.3.3. Others

The estimation of net recharge was done based on earlier works (Anteneh, 1994; and Trufat, 2001) in the catchment and adjoining region and on going research (Tenalem, unpublished) see chapter 8.

The estimation of depth to water was made based on the existing well inventory data corrected by avoiding confined aquifers using drill hole data stored in the table DRILL as we are concerned with the shallow and non confined aquifers. Soil map (Figure 8.5) was prepared by this research, by using the textural analysis data gathered from the archives of different organization.

CHAPTER EIGHT

DATA ANALYSIS AND PREDICTIVE MODELING

It seems important to explain the words: “*data analysis*” and “*modeling*” at the out set. Data analysis can be defined as the extraction of significant facts embodied in a dataset. The word *spatial data analysis* therefore means the extraction of useful information from data that are distributed over space. The word modeling is used to mean many things, but from the context of this study modeling in GIS environment means basically an ideal schema for organizing data about the real world. Thus, the word model means the symbolic representation of the relationships between spatial objects and their attributes (Bonham Carter, 1994). A model according to Anderson and Woessner (1992) is any device that represents an approximation of a field situation/the reality. The purpose of creating a model is therefore to help understand, describe, or predict how things work in the real world by exploring a simplified version of a feature or phenomenon. A spatial model consists of a collection of processes performed on spatial data that will produce information, usually in the form of a map. Thus, predictive modeling involved manipulating data in various ways to provide qualitative assessments of the potential of groundwater contamination for any given parcel of land, or cell. One can use such information for decision making, scientific study, and to produce general information.

Having these explanations in mind, this chapter describes the basic procedures followed to obtain the seven DRASTIC base maps.

8.1 Predictive Modeling

As described above, predictive modeling from the point of view of this study involved manipulating appropriate data in various ways to provide qualitative assessments of the potential for groundwater pollution/contamination. The data used as an input by this model are many and were not readily available. Therefore, it was necessary to derive the data sets from other existing "raw" data. The different data sets should be modeled first of all for the next spatial analysis in a GIS environment.

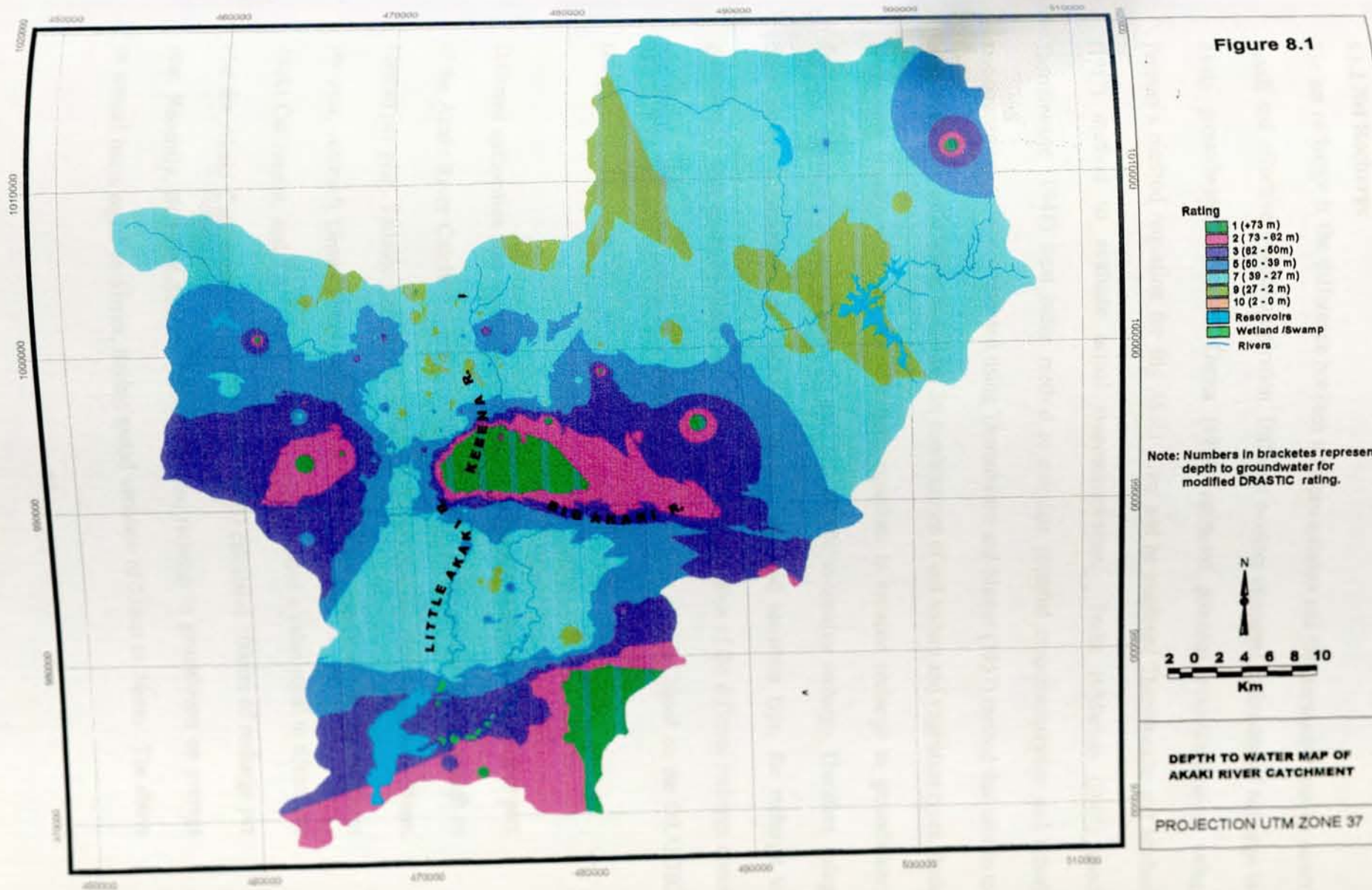
8.1.1 Depth to Water

The depth to water is an important factor since it determines the thickness of the material through which a contaminant must travel before reaching the aquifer. Depending on hydro-geological setting the depth to water not necessarily coincides with the SWL. Therefore, to evaluate such conditions, the depth to water is determined by the type of aquifer (confined or unconfined). Based on the SWL inventory and information extracted from well data depth to water strike were determined. Where confined aquifers were identified the corresponding SWL of that well was excluded from mapping depth to water.

After aquifer characterization and necessary corrections were made to the well inventory data, for those wells/areas/ where information on well data was obtained, and then point water level data were interpolated. Depth to water can be computed either by converting all water level observation data to water levels below land surface by using topographical base maps and draw isobaths or lines of equal depth to groundwater or by using computer we can subtract the SWL from the DEM. The water level map was obtained by interpolating water level data collected by BCEOM-Seureca (2000) and others. Then, depth to water level was obtained by subtracting the

ground surface elevation from the water level. The presence of fractured aquifer means the time required by the pollutant to reach the groundwater becomes shortened. Based on comments and consultation of relevant professionals on how to rate depth to water in fractured terrain a modified DRASTIC approach was applied. In this study, therefore, to account for the fractured nature the aquifer the ranges of depth to water were modified before rating the depth to water. Accordingly, almost double of the ranges provided by DRASTIC was used to rate depth to water. The depth to water (Figure 8.1) was obtained and range and rating distribution of depth to water are shown.

Figure 8.1



8.1.2 Net Recharge

The net recharge is the difference between total precipitation and the cumulative loss by direct runoff and effective evapotranspiration. Different workers attempted estimation of recharge to Akaki groundwater. Anteneh Girma (1994) estimated potential evapotranspiration using Penman's method /equation for Big Akaki River and he employed Thornthwaite and Mather (1957) method to evaluate actual evapotranspiration. Trufat H/Mariam (2001) used Thornthwaite (1948) heat index method to calculate potential evapotranspiration and actual evapotranspiration was computed using Thornthwaite and Mather (1957) method that take in to account the available water capacities for combinations of soil texture and vegetation types. Both researchers finally used the water balance equations to estimate recharge to groundwater. Tenalem Ayenew (on going research) used MODFLOW to simulate recharge. Therefore, using these earlier estimations and based on the soil and land use/cover type, the recharge to groundwater was spatially classified; and further reclassification of the different recharge zones into ranges with new zones as shown in (Figure 8.2) were obtained based on the DRASTIC rating.

Different authorities also attempted estimation of recharge available for the whole or part of the Akaki River Catchment groundwater. The values so far estimated were as high as 150mm per year. Tadesse Belachew (1975) in BCEOME-Seureca (2000) estimated 95mm per year. Anteneh Girma (1994) estimated a value of 106.7mm per year for the Great Akaki Catchment, and TAHAL-SHAWEL (1992) calculated a value equal to 65mm per year for Akaki Catchment. BCEOM-Seureca (1993) calculated 100mm of recharge per year. Recently, BCEOM-Seureca (2000) estimated recharge to groundwater on average on annual basis equal to 51mm, having spatial variation of 33mm to 74mm. The above

estimations agree with the global net recharge estimated for the whole country in which the catchment has net recharges in the range of 50-150mm per year (Tesfaye Chernet, 1988). Geology (soil and rock type), slope, land use/cover type are the dominant factors that govern the spatial distribution of recharge to groundwater. Therefore, based on the existing situations in the studied area the earlier estimates made by Anteneh Girma (1994), Trufat H/Mariam (2001), and Tenalem Ayenew (ongoing research) were utilized. From these studies the average for the catchment was assumed to be 128.35mm per year with the largest value being 150mm and the lowest 106.7 mm per year. Based on the aforementioned conditions, the spatial variations in recharge values were estimated as follows, and shown on Figure 8.2:

- The northern and northwestern Intoto and Wechecha ranges to have maximum recharge values as compared to other regions and assigned 150 mm per year. The reason is that these areas are covered with thin soil and/or only with fractured and deeply weathered volcanic rocks covered with forest and shrubs (Figures 2.4/2.5, and 8.4). Particularly in this the slope (Figure 8.5) and elevation favors higher precipitation and runoff. Runoff, however, counter balanced by the land use/cover and geology.
- The second regions that get larger recharge are areas covered with relatively thin clay cover and with land use/ cover of agriculture or open and at second higher elevation. These areas receive the average value /128.35 mm per year/.
- The third zone is where the elevation relatively drops at southern central part of the catchment and assumed to get 80 percent of the average recharge. At these areas the slope and distance favors the formation of relatively thick clay soil.
- The areas covered by urbanization are commonly assumed to have lower recharge values

as compared to other geologically and topographically similar areas. In most practical works urbanized areas are assumed to get less than 50 per cent of the average annual catchment recharge. Urbanization brings sealing of the ground by asphalt, and interception of precipitation by building roofs thus in favor of evaporation and runoff. Hence, the urbanized parts of the city get 64mm per year associated to open or garden areas. In addition to these areas the areas covered by thick clays of black cotton type (around Dire, Yerer and Bole) and lacustrine clays around Akaki Lake were assumed to have small recharge value similar to urban areas. Lerner et al. (1990) stated that the black cotton clay soil that developed on the basalt of the Deccan Trap of India has cracks as deep as 6m under perennial grass and shrub, and 1.5 to 2m under cultivated areas. Therefore, there is some initial recharge during the onset of rainfall. It is, however, known that the amount of recharge is very small for deeper aquifers. Lerner et al. (1990) contend that black cotton soils as in the case of the eastern part of the studied area for shallow soil sites of less than 1.5m forms one system with underlying weathered basalt for cultivated areas and greater under perennial grass/ shrubs.

➤ Where the urban area overlap with thick clay soil at Bole areas the recharge is assumed to reduce again by half from that of urban areas.

Finally, the original map was reclassified into a new map based on the ranges of recharge provided in DRASTIC Model as shown in Figure 8.2.

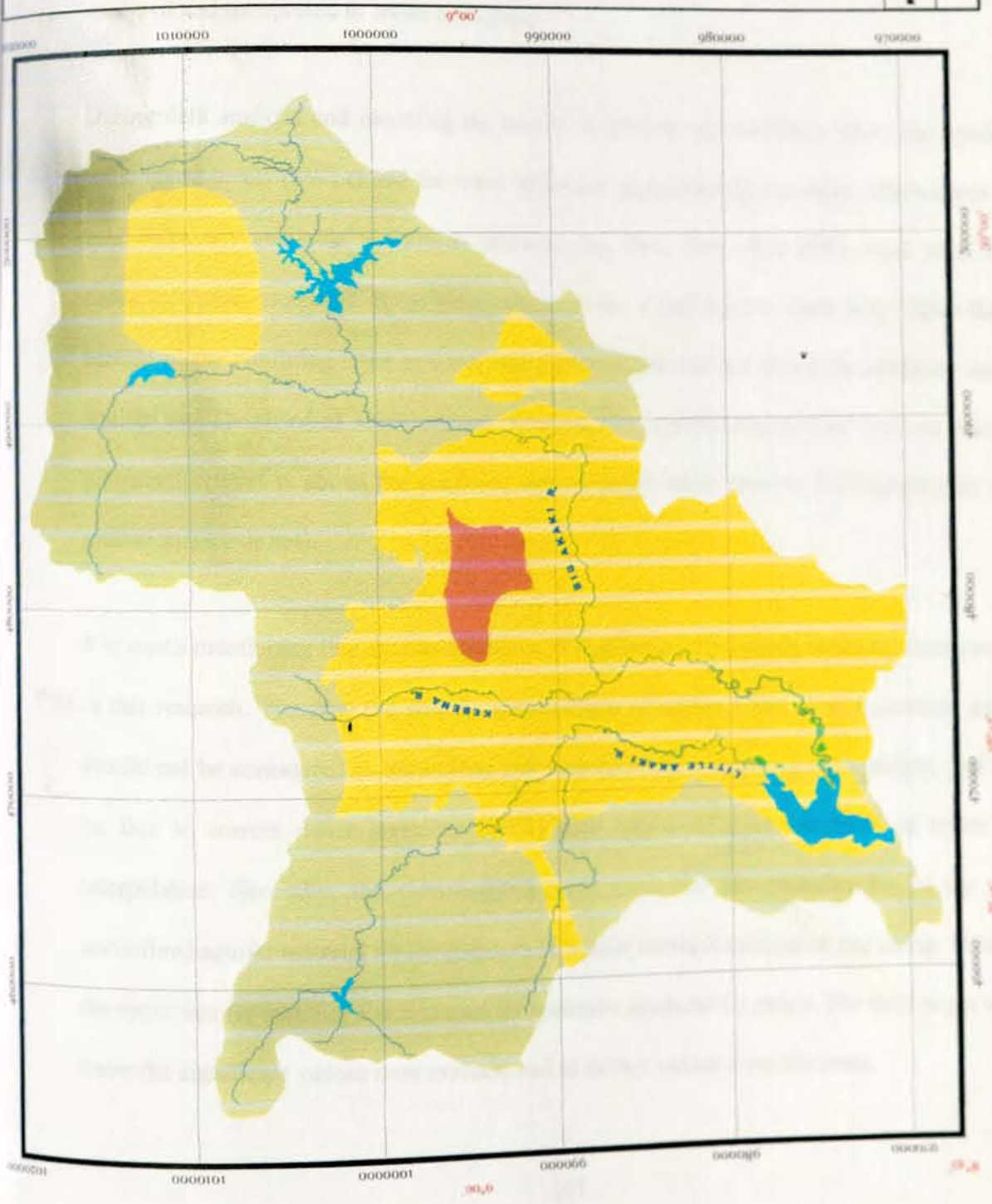
Figure 8.2



Note: Numbers in brackets are estimated recharge values



RECHARGE MAP OF AKAKI RIVER CATCHMENT
PROJECTION UTM ZONE 37



8.1.3 Characterization of the Aquifer and of the Vadose Zone

In an effort to characterize the aquifer and the vadose zone, first of all some problems such as the aquifer type and media, and vadose zone media and thickness should be resolved. Accordingly, to characterize the aquifer types in the studied catchment different, well data (such as: water strike, static and dynamic water level (DWL), screen position, lithologic, etc) were gathered, analyzed and interpreted to create a database.

During data analysis and modeling the aquifer is defined as *unconfined* where the position of static water levels (SWLs) and the water strike are approximately the same. When water strike data were not available the screen position, log data, SWL and DWL were used in the characterization processes. If the piezometric /static water/ level is some how higher than the bottom of the confining layer or water strike position but still not above the confining unit, the aquifer was classified as *semi-confined*. Whereas, the aquifer identified as *confined* where the piezometric level is above the confining unit (whether water head is flowing/artesian/ above ground surface or not).

It is worth mentioning that the classifications of aquifers were primarily made for three purposes in this research. The first one was for identification of aquifer types so that confined aquifers should not be considered as unconfined and vice-versa while mapping vulnerability, and based on this to correct water inventory (SWL) data before using it for depth to water level interpolation. Secondly, the classifications were made for the identification of the upper unconfined aquifer material for the purposes of aquifer media classification and rating. Similarly, the upper aquifer material was also used for hydraulic conductivity rating. The third target was to know the significant vadose zone media(s) and to extract vadose zone thickness.

For this purpose, a number of well logs and associated data were collected, analyzed and interpreted according to the input required in the DRASTIC Model. Many of the well logs were rejected since they do not meet the requirement for characterization process and modeling approach; i.e. they do not allow further extraction of information.

8.1.3a Aquifer media

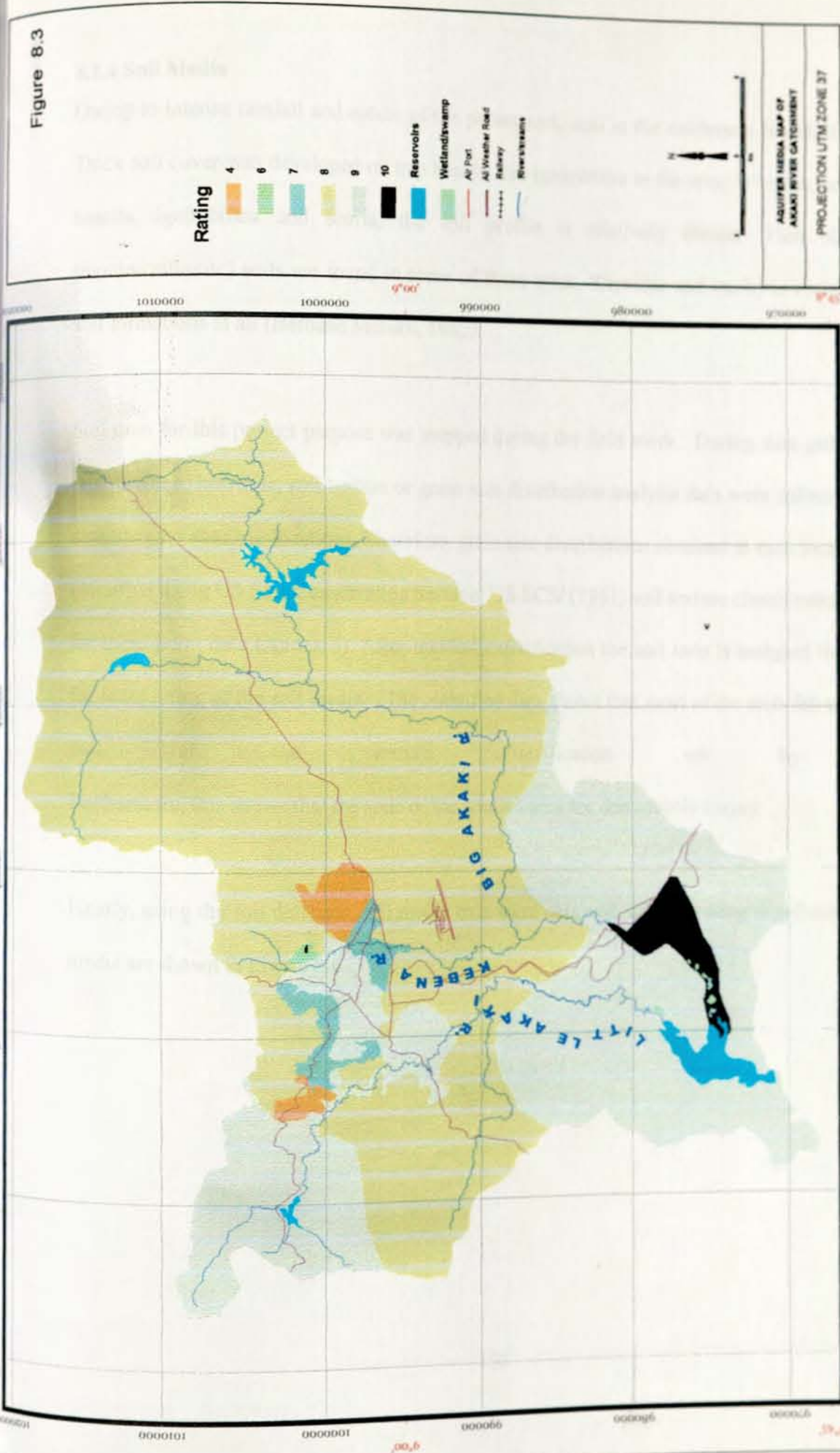
The characterization and rating procedures to be followed for aquifer media is one of the unclear concepts of DRASTIC Model as in the vadose zone media described below. Added to this was lack of earlier works on the methodology of information extraction used as an input for the model from crude hydrogeological/ well/ data found in archives of different organizations. The lack of reference materials or earlier research works conducted by using DRASTIC Model (or any aquifer vulnerability mapping methods for that matter) so far in the country was another chronic problem during data analysis and modeling process. Based on the experiences of Napolitano (1995) in Italy, a semi-quantitative procedure was adopted in the data analysis and modeling with some modifications based on the existing data in the studied area.

The general procedure is similar to that described below under vadose zone rating. Whether confined, semi-confined or unconfined, aquifer media was assigned a rating value according to Table 6.1. In the analysis of data there is a difference between this work and that of Napolitano (1995). She considered the whole aquifer system and calculated a weighted mean using thickness of each unit below the water level. Vrba and Zaporozec (1994) pointed out that; aquifer vulnerability analysis is conducted for the upper aquifer. Thus the upper aquifer material was used in rating of aquifer media, and hydraulic conductivity as will be described under hydraulic conductivity rating.

The rating of the aquifer media assigned based on point (well) data was transformed into polygon map of aquifer media by the same procedure described under vadose zone rating. Each polygon corresponding to a geological unit was assigned the mean value of the data points falling in it. Different neighboring polygons that were assigned the same (mean) value were reclassified based on the new field in the attribute table.

Using lithologic log and geologic database, the information on aquifer media was obtained, and the rating distribution of aquifer media are shown in Figure 8.3.

Figure 8.3



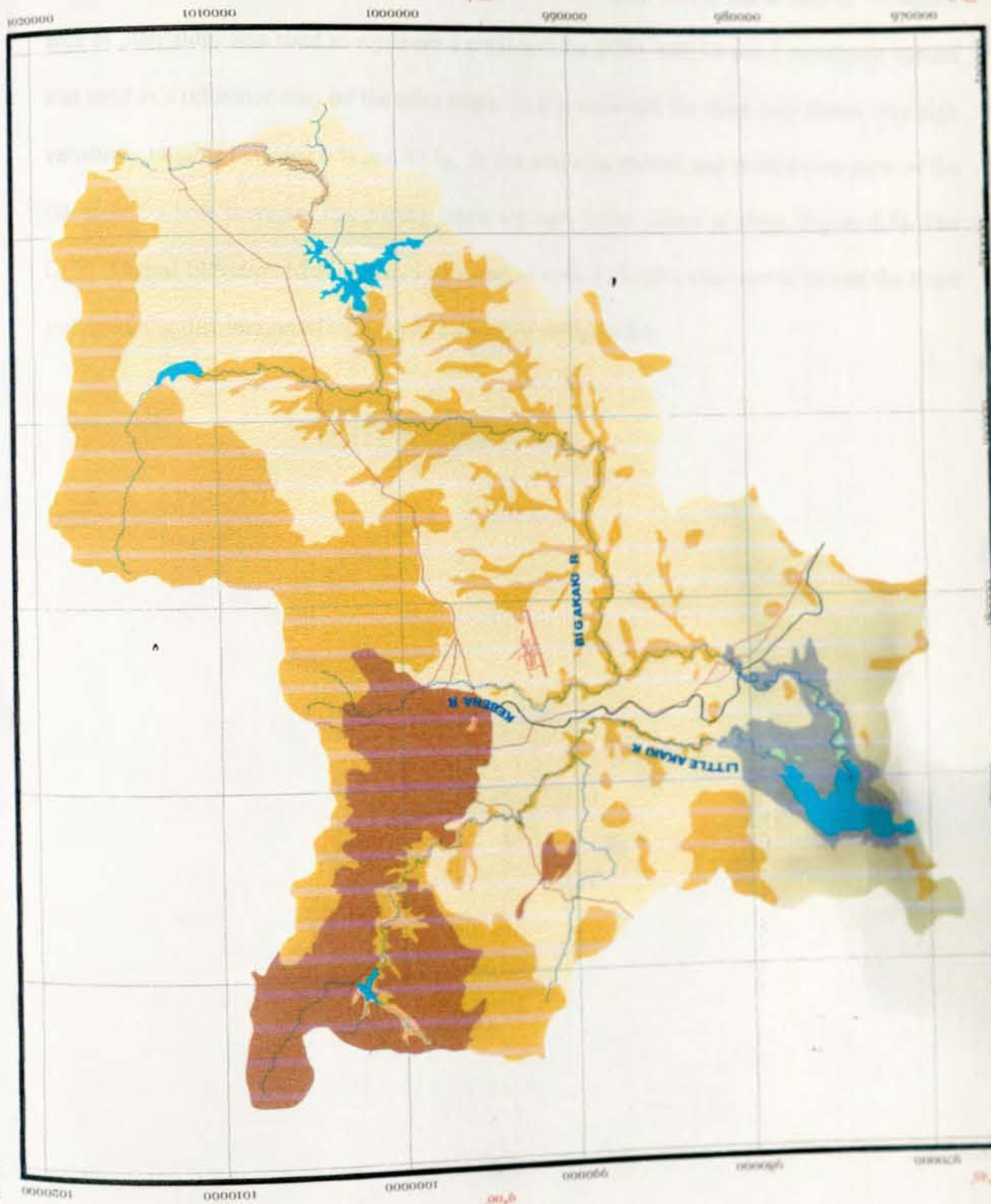
8.1.4 Soil Media

Owing to intense rainfall and nature of the parent rock, soil in the catchment is well developed. Thick soil cover was developed on trap basalts and ignimbrites in the area. Whereas, on younger basalts, ignimbrites and scoria, the soil profile is relatively thinner. Thin black clay (montmorillonite) soils are found in some of these areas. Rhyolitic and trachytic rocks have no soil formations at all (Berhane Melaku, 1982).

Soil map for this project purpose was mapped during the field work. During data gathering for this research, however, soil texture or grain size distribution analysis data were collected. These data have no absolute locations. Therefore, grain size distributions obtained at each location were classified using US Soil Conservation Service/ US SCS/ (1951) soil texture classification method for these point data (Annex 5). After textural classification the soil map is assigned this texture for latter rating of the soil media. The classified data shows that most of the soils fall in the clay part of the texture classification set by SCS. Furthermore, this shows that the soils of the studied area are dominantly clayey.

Finally, using the soil database, soil media data were obtained, and the rating distribution of soil media are shown in Figure 8.4.

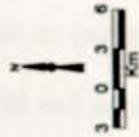
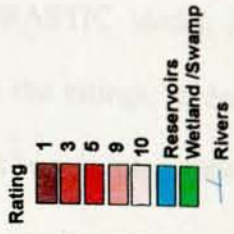
Figure 8.4



8.1.5 Slope

The Digital Elevation Model, DEM, was used for the construction of the slope map, one of the seven DRASTIC factors and for other computations where surfaces such as the piezometric level, have to be referred to the ground surface if the elevation data is not available. A square area of 30m sides was used to represent a pixel and the DEM with its pixel coordinate system was used as a reference map for the other maps. As it is expected, the slope map shows very high variability ranging between 0 % and 47 %. In the southern, central, and northeastern parts of the catchment, where there are flat/ rolling lands, we have lower values of slope (Figure 8.5). The DEM (Digital Elevation Model), based on a map of scale 1: 50,000, was used to extract the slope and the rating distribution of topography are shown in Figure 8.5.

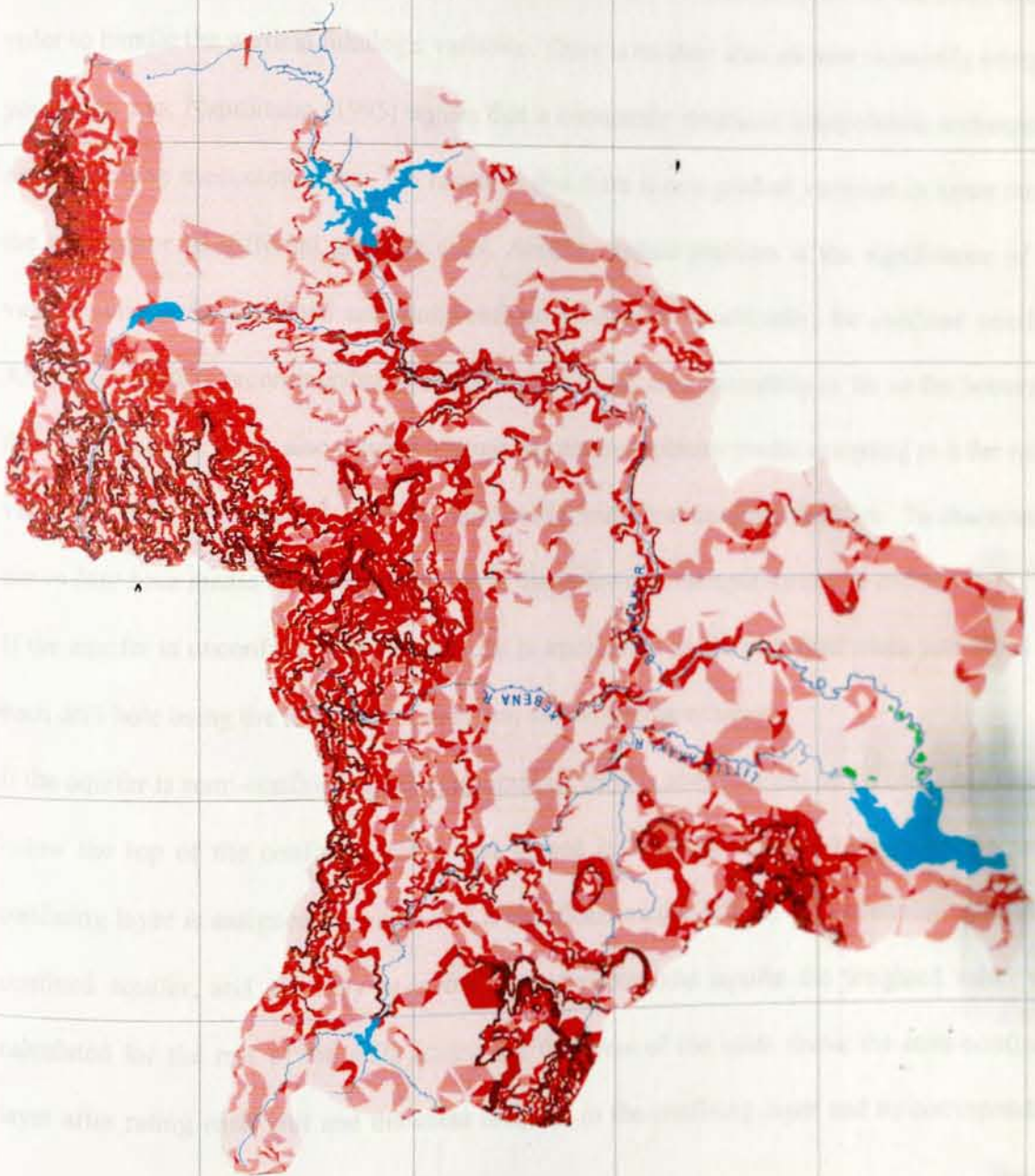
Figure 8.5



SLOPE MAP OF
AKAKI RIVER CATCHMENT

PROJECTION UTM ZONE 37

1020000 1010000 1000000 990000 980000 970000



1020000 1010000 1000000 990000 980000 970000

8.1.6 Impact of the Vadose Zone Media

The characterization of the vadose zone and of the aquifer media, however, is one of the unclear aspects of the DRASTIC Model. Aller et al. (1987) gave no idea or procedure on how to practically assign the ratings, to deal with problems such as vertical and horizontal lithologic variability, and on how to interpolate point (well) data to generate maps/ surfaces.

Civita (1994) in Napolitano (1995) suggested calculating the weighted mean for the point data in order to handle the vertical lithologic variation. There is no clear idea on how to aerially interpret point data too. Napolitano (1995) argues that a commonly practiced interpolation technique is not possible in most conditions. The reason is that there is non-gradual variation in space due to the occurrence of different geologic units. Another unclear problem is the significance of the vadose zone under confined and semi-confined conditions. Specifically, for confined aquifers, Aller et al. (1987) recommended to consider the vadose zone extending as far as the bottom of the confining bed. They also suggest treating this zone as silt/clay media assigning to it the rating value of 1. It is not specified, however, how to deal with semi-confined aquifers. To characterize the *vadose zone media* and assign rating to it, the following concepts should be defined.

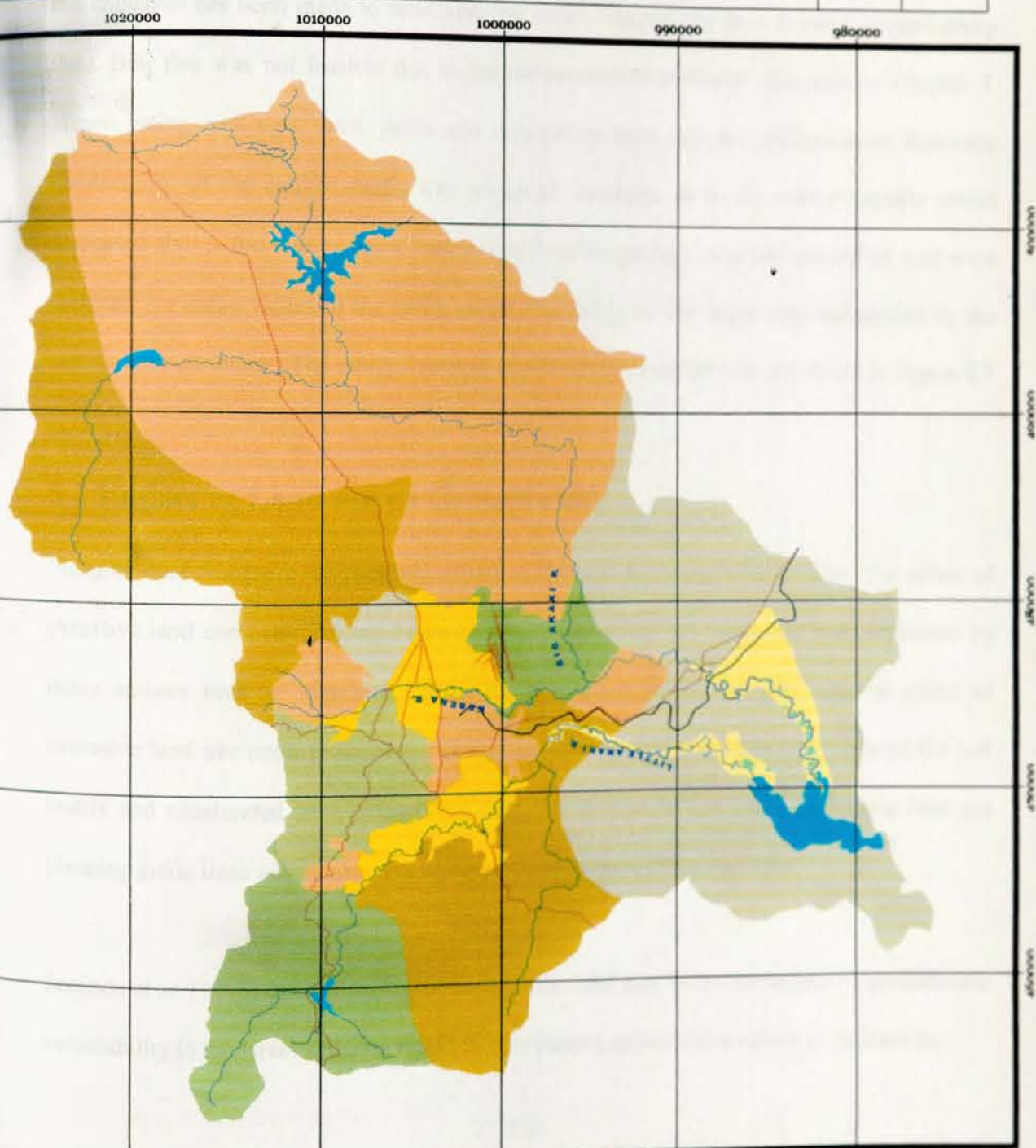
- a) If the aquifer is unconfined, the vadose zone is represented by the weighted mean calculated for each drill hole using the thickness of each unit as a weighting criterion.
- b) If the aquifer is semi-confined and the piezometric level is above the top of the confining unit or below the top of the confining unit it was treated in the same way. In both cases the semi-confining layer is assigned the value of 1 a significant media defined for the confining layer in confined aquifer, and similarly as in the case of unconfined aquifer the weighted mean was calculated for the rest of the units adding the thickness of the units above the semi-confining layer after rating each unit and thickness assigned to the confining layer and its corresponding

rating.

- c) Where the aquifer is confined, the vadose zone was assigned a value of 1 as suggested by Aller et al. (1987) irrespective of the other vadose zone media. The value 1 is a typical rating of clay media.

Finally, the point (well) data computed for each drill-hole were overlaid on the geology map and each geological unit was assigned a value according to the mean value of the point values falling in it. Similar procedures were employed as in the aquifer media rating. Napolitano (1995) used similar procedures but with some modifications (at the initial characterization of the vadose media) were followed in this work. Using geological and hydrogeological /well log/data the vadose zone map was prepared and the rating is shown in Figure 8.6.

Figure 6.6



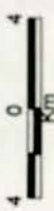
Rating

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Reservoirs

Wet land/swamp

- Air Port
- All Weather Road
- Railway
- Rivers/streams



VADOSE ZONE MEDIA MAP OF AKAKI RIVER CATCHMENT

PROJECTION UTM ZONE 37

1020000

1010000

1000000

990000

980000

9850000

9840000

9830000

9820000

9810000

9800000

8.1.7 Hydraulic Conductivity

In this study, hydraulic conductivity data are not sufficient for mapping. Thus, using the geologic database, hydraulic conductivity, which depends largely on the rock type and degree of weathering, was estimated according to the ranges given by Freeze and Cherry (1979) (Annex 6).

An endeavor has been made to recalculate hydraulic conductivity from existing transmissivity data. But, this was not feasible due to the aforementioned problems discussed in Chapter 7. Hence, using well data (well yields and information from relevant professionals) hydraulic conductivity of the aquifer media was estimated. Similarly, as in the case of aquifer media discussed above, the rating values were overlaid on the geology map and geological unit were assigned the mean values of the rating values that fall in it. The input map reclassified by the new field in attributes. The rating distributions of hydraulic conductivity are shown in Figure 8.7

8.2 Impact of Land use on Groundwater

Many authors recognize the potential impact of land use on groundwater quality. The effect of extensive land use over prolonged periods of time up on aquifer media has been explained by many authors such as Merchant (1994). These authors noticed that the potential effect of extensive land use upon groundwater quality is resulting from alteration over time of the soil matrix and unsaturated zone media. Thus, land use assessment can assist in drafting land use planning guide lines which take in to account hydrological realities and risks.

Secunda et al. (1998) gave rating values for different land uses in the assessment of groundwater vulnerability in the Israel's Sharon region. In this thesis I applied these values to indicate the

Figure 8.7

Rating

4

6

8

10

Reservoirs

Wetland/swamp

Road



HYDRAULIC CONDUCTIVITY MAP OF
ARABA RIVER CATCHMENT

PROJECTION UTM ZONE 3F

1010000

1000000

990000

980000

970000

500000

400000

400000

470000

600000

1010000

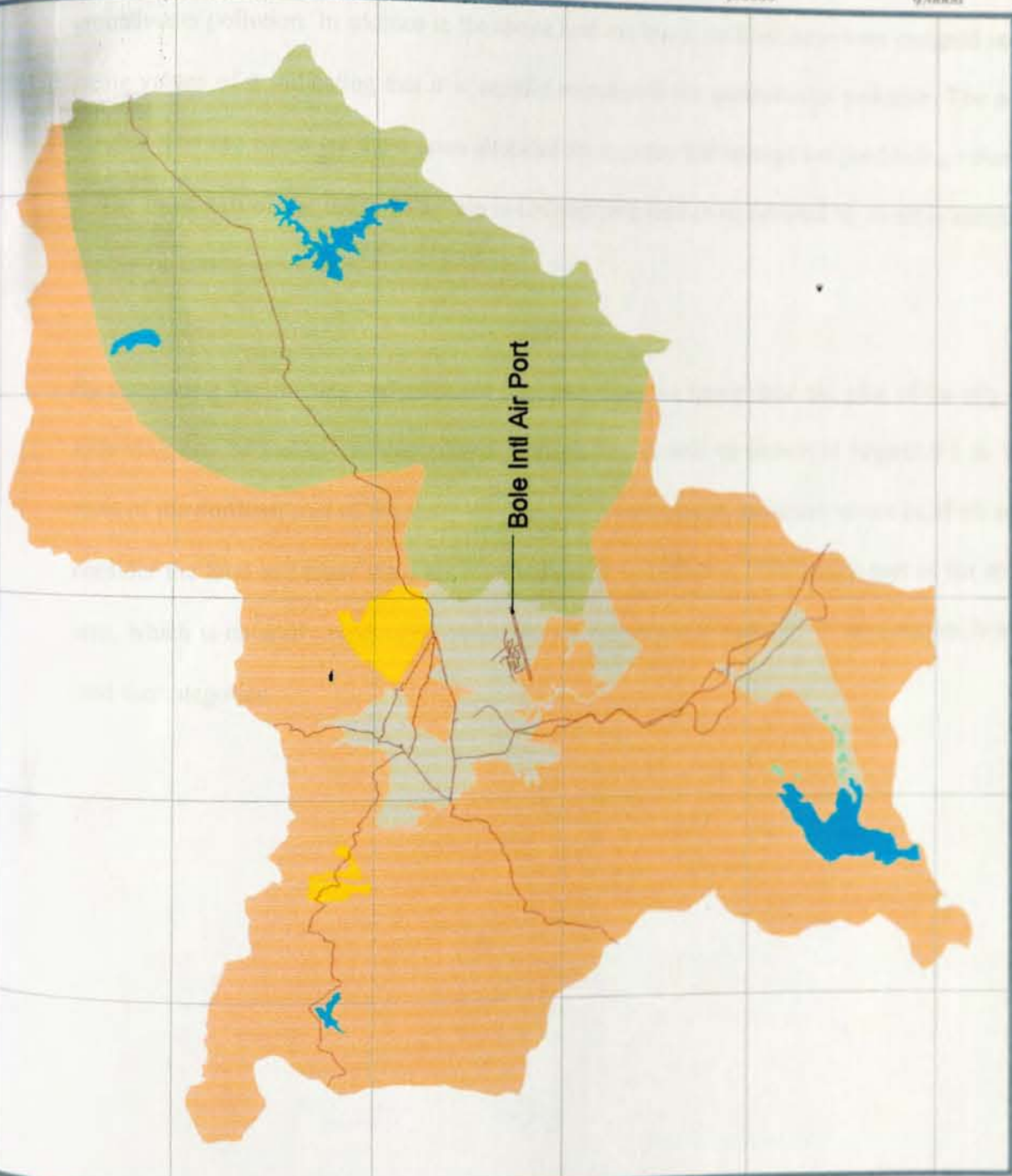
1000000

990000

980000

970000

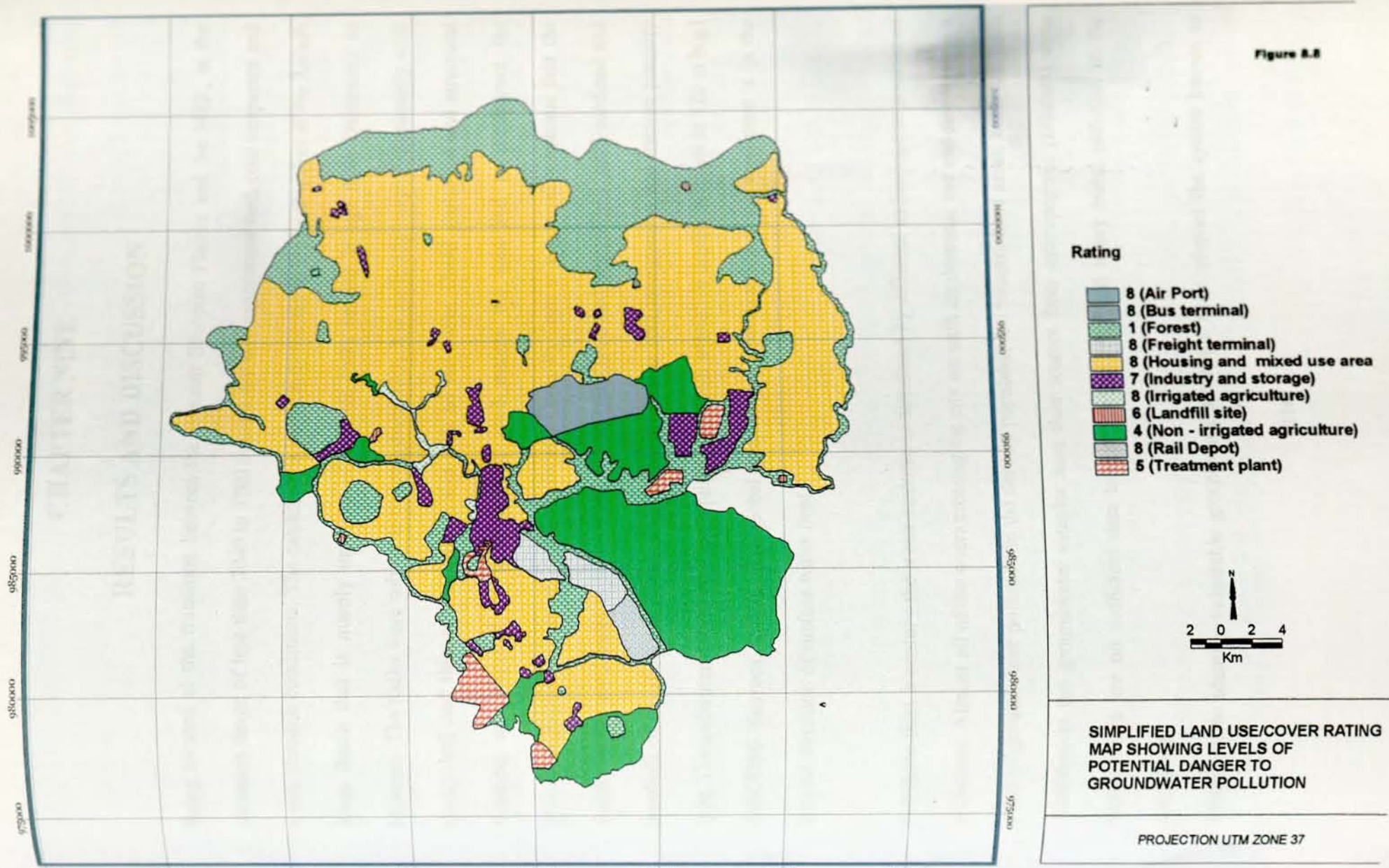
Bole Intl Air Port



potential risks of pollution to groundwater in the capital city, located at the north central part of the study area. Accordingly, the rating map for the simplified land use is shown in Figure 8.8. Overlay operation as would be expected not possible as the boundary of the two do not match. Based on the rating values proposed by Secunda et al. (1998) the bus and freight terminals and rail depot as well as some irrigation activities along river courses are expected potential risks of groundwater pollution. In addition to the above land use types, built up areas were assigned same rating values of 8 indicating that it is equally responsible for groundwater pollution. The next dangers land use zones are those areas allocated for industry and storage assigned rating value of 7. The most part of the Intoto Mountain is covered/proposed to be covered by forest is assigned the lowest rating value of 1.

By comparing the existing and proposed land uses from the recent land use plan of the city the following can be tentatively generalized. Intrinsically, as will be shown in Figures 9.1 & 9.2, most of the northern part of the study area is highly vulnerable to pollution; where as, if we only consider the land use these areas are least vulnerable to pollution. The central part of the study area, which is naturally moderately vulnerable, is vulnerable to pollution if we compare it with land use categories.

Figure 8.8



CHAPTER NINE

RESULTS AND DISCUSSION

Being located at the transition between the Western Ethiopian Plateau and the MER, at the elevation range of less than 2040 to 3200 m amsl, the area experiences both cool temperate and warm climatic conditions. The catchment is particularly located in the head waters of the Awash River Basin that is mainly made up of volcanic rocks ranging in age from Quaternary to Miocene. The rocks were subject to tectonic dislocation. It is superficially covered dominantly with clayey soil and thin soil at some places with no soil cover. Detail geological and structural mapping are required to understand in good manner the area and to reconstruct the hydrostratigraphic sequence in the catchment. Currently there is a general consensus that the aquifer in the catchment is multi-layer, and all types (confined, unconfined, semi-confined and perched) of aquifers are found. The aquifer material is both intergranular and fracture porosity type. Groundwater depths in these aquifers vary from artesian to depths as much as 126 m b.g.l (BECOM- Seureca, 2000). The global groundwater flow direction in the catchment is in the general direction of surface water flow.

For more than a century the water resource is threatened by different anthropogenic sources of pollutants. Almost all of the rivers crossing the city are unfit for domestic use and also there is a trend of groundwater pollution in the densely populated and industrialized areas. Most nutrients identified in the groundwater samples have their sources from anthropogenic pollutants even though there are no sufficient data to comment on trace and heavy metal pollution in the catchment.

Therefore, to identify vulnerable groundwater areas this work adopted the system known as

DRASTIC Model. In this study the intrinsic nature of the hydrogeologic setting of the area which is static and beyond human control is considered. Groundwater vulnerability maps do not consider the chemical nature of the pollutant in assessing vulnerability. They are concerned only with the hydrogeologic setting, which makes the groundwater susceptible to contamination from a surface source. When a development application is being prepared, or considered, it is important that the impact of the development, on both surface and groundwater resources is assessed. It is also important to know who uses these resources (beneficial use) and current groundwater quality. Within this context, this helps to determine the suitability of various developments in the area in a spatial context. In order to achieve this, a number of spatial attributes were mapped. These are then weighted, and ranked, and are combined to produce a final ranking value, which defines the groundwater vulnerability.

To make available the individual DRASTIC layer maps the following steps were followed (that is data extraction and integration procedure is shown in Figure 1.2) and these were: (1) data collection on the study area, (2) database construction using the collected data, (3) extraction of hydrogeologic factors from the database, and (4) overlay analysis of the factors. The discussions and the results obtained by mapping each input layers by rating and overlaying are presented in the following paragraphs.

To map depth to water, existing water point inventory data of about 470 drilled wells, 28 hand-dug wells and 19 springs were collected. From these only about 300 water points (annex 7) were used to produce depth to water map of the catchment. Some of the water points lack absolute location or SWL/water strike position while some of the drilled wells were rejected since they

are classified as confined aquifers. It is worth to note that there is a limitation of well information to classify all well inventory data into aquifer types so that confined aquifers are not considered as unconfined. The other limitation in connection with this DRASTIC factor is that the depth to water inventory data used were measured at different seasons or even hydrological years. For example in the the Akaki well field BCEOM-Seureca (2000) observed peizometric level differences of upto 2 meters.

In this study a modified DRASTIC approach is followed to map depth to groundwater in the catchment. This is due to the fractured nature of the volcanic aquifer. Therefore, to account for the fractured nature of the aquifer existing in the study area the depth to water map was subjectively classified in to 55 equal class intervals. The classification resulted in almost double of the depth to groundwater level given by Aller et al. (1987) (Table 6.1). This means that contaminant attenuation in fractured rocks need longer travel times before reaching the groundwater. Thus, in this case the rating of 1 is assigned for depth to groundwater greater than 70 meters as compared to 30meters given by the authors who developed DRASTIC system. Very shallow groundwater is mostly found in the northern part of the catchment where groundwater is discharged as springs. Areas with groundwater depth greater than 70 meters need further verification as to its aquifer type.

Recharge estimated by different workers for Akaki River Catchment or part of it and its immediate environs were used to prepare net recharge map. The values are almost in the ranges (50-150mm) estimated by the authors cited in chapter 8. As most of the methods used in their estimation of input parameters for final recharge estimation are similar empirical equations, this

also requires further checking by using different methods (if possible with necessary field controls) to get the values of recharge that average the field condition. The recharge boundaries applied in this thesis is derived mainly based on the amount of annual net recharge available, land use/land cover and soil type, and to some extent on topographic slope. Thus, to understand the effect of thick clay cover and urbanization on recharge pilot project test result is required to verify the amount (and depth) of infiltration.

Highest average rating values of 10 was assigned for scoria and scoraceous (aquifer media) and, highly fractured volcanic rocks, particularly basalts. Alluvial aquifers especially sands and gravel found in some of the central part of the catchment has got an average rating value of 9. The lowest value of 4 was assigned for highly weathered and decomposed volcanic rocks. The extent of the final rating values in terms of area is affected by the coverage of the geology polygons in which they fall while the exactness of the average rating value is subject to data density and correctness of information attached with lithologic logs. The facts embodied in this latter sentence also apply to impact of the vadose zone media and the hydraulic conductivity values derived by this research.

Impact of the vadose media rating was significantly affected by the presence of thick clayey sediments and massive volcanic rocks. Paleosol is also another important unit that could affect rating as it is mostly found inter-bedded within the volcanic rocks. These media are commonly assigned lower rating value implying lower pollution potential. When the above materials are acting as the confining unit the value becomes 1, which is the least value in DRASTIC rating. As it is seen from Figure 8.6, the central and southern areas are assigned a low rating value since

there are thick sediments, dominantly clayey in nature. Brownish black clays and massive basalts are two common confining units in the studied area. In some places there are also paleosol layers acting as confining unit. The average rating value used to map vadose zone media is affected by higher rating values given for the basalts, and sand and gravel. Relatively higher values are assigned where there are thin soil covers and thick unsaturated zone media with high rating or where there are basalt, and sand and gravel units. In the southern and central part of the catchment, the resultant mean values are outshined by the high rating values assigned by DRASTIC system for these two units, even though there are clay layers. Thickness and type of geologic materials are, therefore, the two most important factors that affect the average rating value assigned for vadose zone.

Soil is another DRASTIC factor commonly considered as the upper weathered part of the earth that exists up to an average depth of about 2 meters (Aller et al., 1987). In the studied catchment the black cotton soil, which is texturally classified as clay, cover the most part and it is followed by thin/ absent (less than 0.25 meters thick) soil which is mostly associated with hills, mountains and river banks and /or beds. The areas covered with the last soil type have got higher rating and is considered as the most vulnerable area if we only take soil into account. The areas covered by reddish brown soil, which is mostly found at the western part of the catchment, is classified as clay loam texture and assigned a lower rating value of 3. The impact of thin/absent soil is clearly seen in the result of the vulnerability assessment as it also affects the vadose zone rating described. It is also observed that soil development in the catchment is controlled by slope and lithologic type.

The weight or importance assigned for soil in the evaluation of normal DRASTIC is relatively

small and its effect on the final normal DRASTIC index computation becomes less important.

Slope is highly variable in the catchment and is the result of volcano-tectonic effect which is also aggravated by latter modification by erosion dissection. The mountains and hills are steep sloped areas with the slopes being greater than 47% in some places. There are also flat areas with a slope as low as 0%. Because of the least weight assigned for its assessment, this DRASTIC layer is also less important in the final computation of the normal index values.

For the same reason as in the case of the aquifer media, hydraulic conductivity rating was higher for the fractured volcanic rocks, especially basalts, and for sand and gravel units. Accordingly, the central part of the area is attributed the highest average rating value of 10, assigned for the most conductive layer such as fractured basalt, and sand and gravel. The southern part of the area (including the Akaki well field) the scoria and sand and gravel aquifers were also assigned high average rating values.

Starting from data storage, rating, analysis and final presentation GIS is used as another very important tool for vulnerability mapping together with DRASTIC Model. It facilitated the storage, retrieval, analysis and presentation of large data. The final vulnerability mapping was easily performed using GIS that might not be so easy or possible by manual overlaying of the DRASTIC layer.

After all DRASTIC layer is ready by rating and weighting, vulnerability mapping is performed. The ultimate goal of the vulnerability map is the subdivision of an area into several units

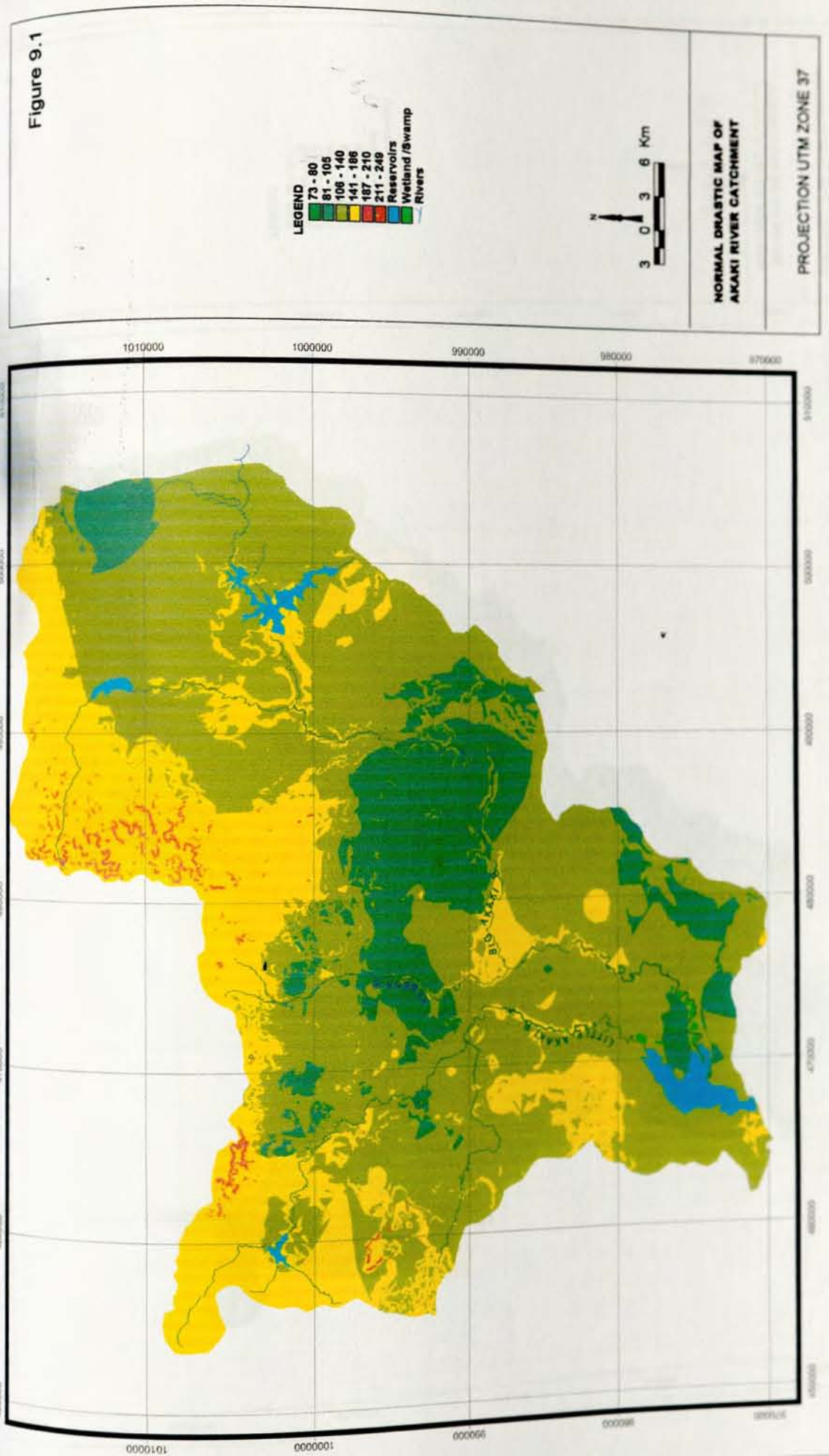
showing the differential potential for pollution for a specified purpose and use. Results of vulnerability assessment are portrayed on a map showing various homogeneous areas, sometimes called cells or polygons, which have different levels of vulnerability. Vulnerability maps show only the relative vulnerability of areas within the same map, and do not represent absolute values that can be compared between maps (Center for Natural Resource, 2001). Then, normal DRASTIC and pesticide DRASTIC systems were applied to the Akaki River Catchment. This method of evaluating regional aquifer pollution potential was used to assess the pollution potential of a region and can generate information that is readily usable by agencies that are involved in *groundwater protection* and evaluation at a level of detail that has not been achieved before. From the above data layers general/normal and pesticide DRASTIC maps were produced (Figures 9.1 and 9.2). As the name “general/normal” DRASTIC indicates it is designed to assess the general pollution potential of a region, and it differs from the “pesticide” DRASTIC in that the importance/ weight assigned for some DRASTIC factors are different. For instance, the weight given for soil media in the assessment of “pesticide” DRASTIC is higher than the same soil media during “general/normal” DRASTIC assessment (Table 6.1). Pesticide DRASTIC mapping is applied when the user wants to evaluate pollution potential from agricultural input. Otherwise the two have similar assignment of rating values.

The resultant DRASTIC index values from Equation 1.1 by employing overlay analysis are as follows: the minimum normal/general DRASTIC index is 73 and the maximum normal/general DRASTIC index is 249; whereas, the minimum pesticide DRASTIC index is 78, and the maximum pesticide DRASTIC index is 260.

The final DRASTIC values have been grouped together into very low, low, moderate, high, and very high pollution potential classes. These classes only represent the relative pollution potential within the study area. In terms of normal DRASTIC index extent, 73 to 80 is classified as indicating a very low pollution potential, 81 to 105 is classified as indicating a low pollution potential, 106 to 140 is classified as having a moderate pollution potential, 141 to 186 is classified as having a high pollution potential, and 187 to 210 and 211 to 249 are classified as indicating a very high pollution potential (Figure 9.1). The pesticide DRASTIC map is similar to the general DRASTIC map except for the range of the indexes, 78 to 111, 111 to 144, 144 to 177, 177 to 210, 210 to 244 and 244 to 260 for very low, low, moderate, high and very high respectively which were divided in to equal intervals (Figure 9.2).

Generally, the (recharge) areas mostly located at northern part of the study area have very high index values because of the relatively high rating values for recharge, soil- and impact of the vadose zone media, hydraulic conductivity and others. That means these areas with high index values are characterized with relatively higher pollution potential. Only very small areas found in east central parts were mapped as very low vulnerability degree in general DRASTIC assessment. This is due to very low recharge rate (as a result of thick soil cover overlapping with urbanization) and relatively deep groundwater. Areas with moderate pollution potential cover significant part of the catchment.

Figure 9.1



**NORMAL DRASTIC MAP OF
AKAKI RIVER CATCHMENT**

PROJECTION UTM ZONE 37

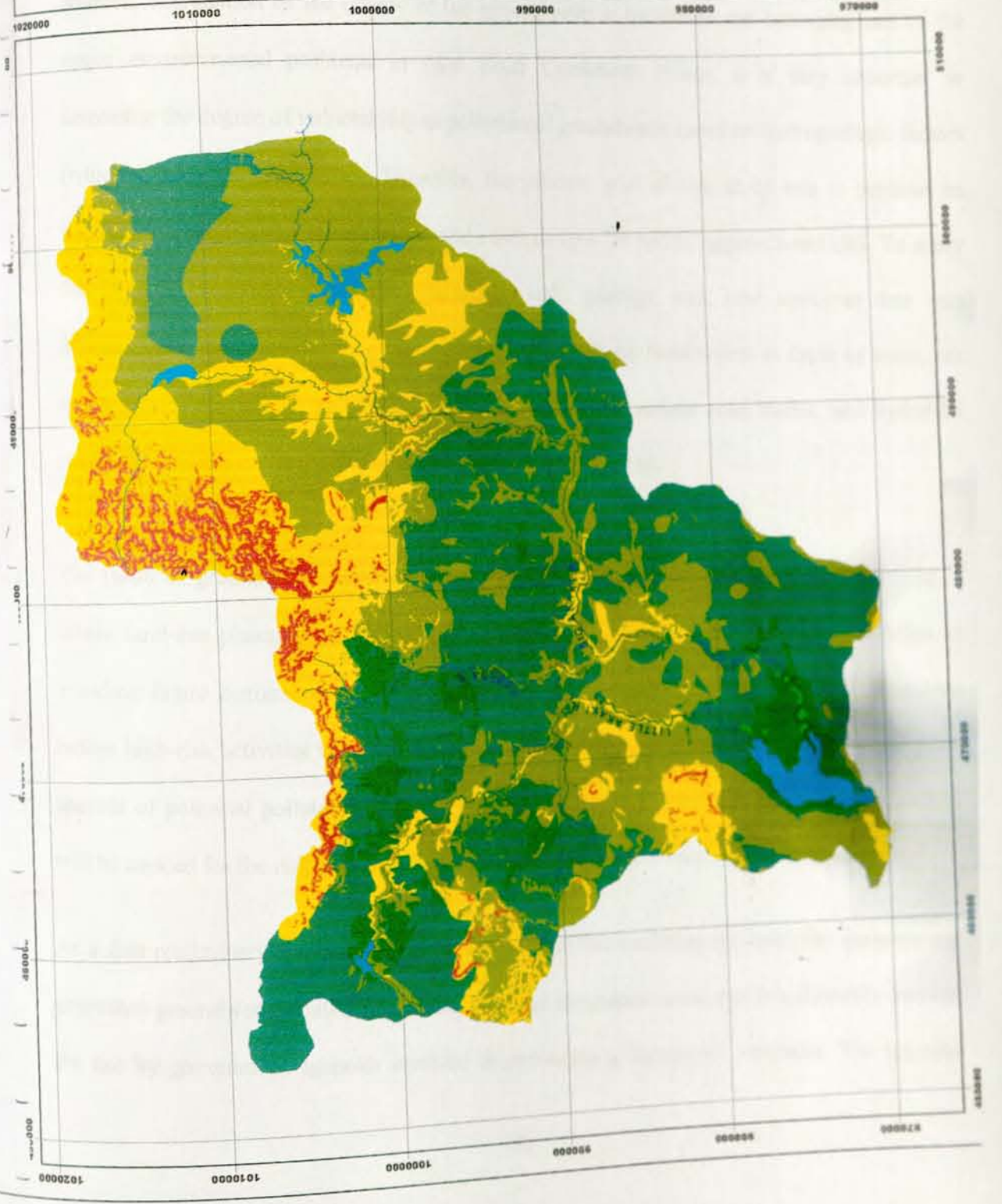
Figure 9.2

- LEGEND**
- 79 - 111
 - 111 - 144
 - 144 - 177
 - 177 - 210
 - 210 - 244
 - 244 - 280
 - Reservoirs
 - Wetland /Swamp
 - Rivers



**PESTICIDE DRASTIC MAP OF
AKAKI RIVER CATCHMENT**

PROJECTION UTM ZONE 37



CHAPTER TEN

CONCLUSIONS AND RECOMMENDATIONS

Because of the proliferation of the urban centers and associated potential pollutant generating sources, degradation of the quality of the groundwater is inevitable and becoming one of the major environmental problems in Akai River Catchment. Hence, it is very important to determine the degree of vulnerability to pollution of groundwater based on hydrogeologic factors (which is *intrinsic* and *static*). Therefore, the primary goal of this study was to perform an aquifer vulnerability assessment of the study area using a DRASTIC approach and GIS. To apply the DRASTIC system, topography, drainage, well, geology, soil, land use/cover data was designed and constructed. Using the database, hydrogeologic factors such as depth to water, net recharge, aquifer media, soil media, slope, impact of the vadose zone media, and hydraulic conductivity were extracted and made for index overlay analysis.

The result of groundwater pollution vulnerability map prepared by this work could be used in future land-use planning studies, where potential contamination may occur. It also helps in avoiding future contamination of the groundwater by considering the vulnerability of an area before high-risk activities were allowed to take place. Thus, information of non-point and point sources of potential pollutants, including population, livestock, pesticide usage, and industries, will be needed for the risk analysis of groundwater pollution and take necessary adjustment.

As a first preliminary findings, this study suggest that this modeling approach can generate and generated groundwater related information for large geographic areas that is sufficiently detailed for use by government agencies involved in *protecting groundwater* resources. The regional

perspective and parcel-size data resolution afforded by a GIS appears to be compatible with information requirements of various planning (and regulatory) activities.

From the above result of this study, it is possible to conclude that the recharge areas are more vulnerable to groundwater pollution as compared to other areas in the catchment. The high index values also indicate the precautions that should be taken for *well head protection* and general *groundwater resource management* in the catchment. Furthermore, this study proves that the general understanding of the conservation of a well filed for groundwater protection should not be considered as an end by itself as the conservation of the recharge areas are critical for groundwater protection and appropriate management of the resource. Generally, in order not to have polluted groundwater in the catchment, and especially, in the potential well field areas, land use planners and/or developers should be aware of the danger of groundwater contamination if vulnerable areas are not conserved. At these areas the soil is either thin or absent, the vadose zone is mainly fractured/weathered volcanic rocks, the recharge is relatively high, and it is also where groundwater outcrops as springs, etc. Thus, further detailed studies are requested in vulnerable areas before we plan any development activities that have the potential to pollute groundwater.

The central part of the catchment is characterized by thick sediment and is relatively less vulnerable to pollution. Generally, from the above index (Figures 9.1 and 9.2) it can be observed that vulnerability of groundwater increases from the central part to the preferential areas.

This study provides information on groundwater resource, and also indicates that apart from its resource value, groundwater could be considered as a constraint for development activity within the catchment when it is very near to the surface/shallow. The chemical constituent of

groundwater is also important parameter to be considered in connection with this problem.

The following recommendations were given based on the fore going results and conclusion.

- Based on the vulnerability index maps values produced by this thesis it is important to review existing potential contamination sources, and carefully plan future land use/development/activities located in the relatively sensitive/vulnerable zones of the catchment. Further conservation strategies should be planned to protect these vulnerable zones. Otherwise, through time we are going to have polluted groundwater in the catchment as a result of high loading of pollutant at even naturally less vulnerable zones.
- Groundwater level measurements in boreholes for critical periods during which the water table is highly recharged with rainfall should be made.
- To understand very well the hydro-/litho-/stratigraphic sequence of the multi-layer aquifers and estimate the hydraulic parameters for each aquifer systems an objective oriented project of core-barrel drilling and pump testing of the multi-layer aquifers separately is required. Geophysical and structural study is also important to extrapolate point data obtained from above observation.
- Detailed net recharge estimation will be required by using different methodologies, as this is one of the basic *hydrogeological parameters* affecting pollutant transport, and amount of safely and economically available exploitable groundwater resource in the catchment.
- Integrated land use planning, *groundwater protection*, and soil and groundwater remediation are only possible after a through inventory of potential contamination sources and the assessment of groundwater vulnerability have been made. Thus, it is recommended that *groundwater contamination sources inventory* are crucial for above-mentioned objectives and for the purpose of *groundwater quality monitoring* and/or sampling.

- The pollutant/contaminant transport modeling with particular emphasis on its rate and path length is important in order to visualize the general scenarios of pollution movement from a certain source to a particular area.
- *Groundwater protection* requires a number of restrictions on land use and human activities. Hence, integrated area-planning approach commonly known, as *land use planning* is most appropriate to solve conflicts between *land use* and *groundwater protection*, as it takes, from the beginning, all relevant aspects into consideration. At this juncture it is worth mentioning the role of geoscientists', particularly environmental hydrogeologist, in local and regional land use planning that most of, if not all of, the organizations are not aware of.
- Detailed *specific* and/or *integrated* vulnerability mapping of the urbanized areas will be of prime importance for further assessment of the potential pollution from specific/group of pollutants and/or pollutant sources.
- Formulation of practicable *regulatory/ legal/* and *non-regulatory /voluntary/ options* that will be used for the implementation of the general *environmental/water/ policy* of Ethiopia from different pollutant generating activities/sectors; particularly threatening surface- and groundwater resources.
- Awareness creation on groundwater vulnerability to pollution among the decision/policy makers and planners to give an impulse to environmental thinking and public concern will be of an important risk averting strategy for future *groundwater pollution protection* in the catchment. In addition, it is important to inculcate environmental education in the curricula of the country with particularly emphasis on *waste disposal and management*.

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ANNEXES

Annex 1. Gives some general results of different studies on most frequent values of permeability of volcanic material (Custodio, 1989).

Material	Permeability, k (m/d)	Specific Yield	Total porosity
Basalts:			
Fissured lavas	1- 200	—	0.01- 0.2
Porous lavas	≤ 0.4	—	0.05- 0.3
Dense lavas	10^{-5}	≤ 0.01	0.1-0.05
As a whole, young, fresh			
As a whole, old, altered	0.2 – 1000	0.07	0.1-0.15
As a whole, very old			
Trap, fresh	< 0.05- 0.5	0.01- 0.05	0.02- 0.06
Trap, weathered	< 10^{-4}	—	—
Pyroclasts, welded	0.05- 0.5	0.01- 0.08	0.15
Pyroclasts, loose	0.1- 50	0.05- 0.15	0.1- 0.3
Intrusions	<0.01	—	—
Vesicular scoria, lapillis	0.1- 10	—	0.25- 0.5
- Ash and cinder cones	<0.001- 0.02	0.1- 0.4	0.1- 0.02
	—	—	0.4- 0.8
	—	—	0.25- 0.4
Tephritic agglomerates	0.1- 1.0	0.01- 0.03	0.1-0.25
Andesites	0.3- 0.5	-----	-----
Trachytes	0.03- 0.1	-----	-----
Phonolites:			
-Fissured flows	0.1- 0.5	-----	0.02
-Ignimbrites, loose	0.1	-----	0.1- 0.7
-Ignimbrites, welded	< 10^{-6}	-----	0.01- 0.4
-Pumites	-----	-----	0.4- 0.8
Rhyolites:			
-Lavas	-----	----	0.01- 0.4
-Tuff, loose	10^{-5} - 10^{-3}	----	0.3- 0.6
-Tuff, welded	< 10^{-6}	----	0.05- 0.4
-Ignimbrites	0.02-2	----	0.1- 0.5
-Interflows	---	----	0.3- 0.7
Lahars	5- 30	----	0.3

Annex 2. Grain size distribution and textural classification of soil data according to U.S. SCS (1951).

A) BCEOM/GKW(1993)

Test Hole No.	Location	Sample depth(m)	Total Sand	Silt	Clay	SCS Class Texture
1	UDPO Market	0-1.5	15	36	49	Clay
		1.5-2.44	17	52	32	Silty Clay Loam
2	Bole Air Port	0 - 2.30	8	32	60	Clay
		2.30 - 3.40	4	36	60	Clay
		3.40 - 4.20	2	40	58	Silty Clay
3	Kotebe	0 - 0.72	10	36	54	Clay
		0.72 - 2.8	27	46	27	Clay Loam
4	Filwoha	2.10 - 2.80	23	50	27	Clay Loam
		2.80 - 3.96	8	55	37	Silty Clay Loam
5	Jan Meda	1.30 - 1.80	28	33	39	Clay Loam
6	Near Ras Hailu	4.3	8	26	66	Clay
7	Kolfe Market	4	7	20	73	Clay
		Below 4.0	28	32	40	Clay Loam
8	Tekle Haymanot	0 - 1.65	21	37	42	Clay
		1.65 - 2.70	28	37	35	Clay Loam
	Gola Michael	2.70 - 3.22	18	28	54	Clay
9	Kera Area	0.8 - 2.0	15	26	59	Clay
10	Kality Treatment	0 - 1.98	7	25	68	Clay
		1.98 - 3.22	7	28	65	Clay
		3.22 - 3.54	6	32	62	Clay
		3.54 - 3.88	34	35	21	Loam
		Mean	15.72	35.33	48.95	Clay

B) Kebede Tsehayu and Tadesse H/ Mariam (1990)

Test Hole No.	Total Sand	Silt	Clay	SCS Class Texture
Sal - 1	25	47.1	27.9	Clay Loam
Sal - 3	15	49	36	Silty Clay loam
Sla - 1	3	22.3	74.7	Clay
Sla - 2	4	19	77	Clay
Sla - 3	0	14.8	85.2	Clay
Sre - 4	12	34.6	53.4	Clay
Sre - 5	3	31.3	65.7	Clay
Sre - 6	8	26.3	68.6	Clay
Sla - 7	3	25.3	71.7	Clay
Sla - 8	3.2	19.1	77.7	Clay

C) Oromia Water, Mineral and Energy Resource Development Bureau (2001)

Test Hole No.	Location	Sample depth (m)	Sand	Silt	Clay	SCS Class Texture
P1	East of Lega Tafo	2.5	3.3	6.8	89.9	Clay
P3		3.8	0.35	-	99.6	Clay
P5		-	32.5	29.7	37.8	
P7	North of Main Road West of Lega Wako	4	10.2	14.4	75.4	Clay

D) Building Corporation Share Company (Different date)

Test Hole No.	Location	Sample depth (m)	Total Sand	Silt	Clay	USCS Class Texture
BH1	West of Tewodros Square (AA City Administration Complex)	2.35	50	20	30	Sandy clay loam
-	New British Council Building	1.5	21	38	41	Clay
-		3	20	48	32	Clay loam

-		5	28	48	24	Loam
BH4	Pharmacure PLC	2	15	35	50	Clay
-		4	13	42	45	Silty clay
-		6	16	23	61	Clay
-	Megenagna Bole Road (Ato Tesfaye Solomon College)	-	7	45	48	Silty clay
-	Kebena Signal G+5 Apartment (Defence Ministry)	1.50 - 1.90	19	52	29	Silty clay loam
BH3	Gofa Campy New Family Quarter	1.50 - 1.90	4	48	48	Silty clay
BH2	AA Flood Control and Protection Office	2	2	28	70	Clay
-		4	1	19	80	clay
TP No 6	Ferencay G+1 Apartment Building	3	5	50	45	Silty clay
BH1	Italian Embassy	1.5	11	31	58	Clay
		3	12	41	47	Silty clay
BH2	Ethio-tele at Bole Michael	1.6	2	18	80	Clay
BH2	Ethio-tele at Shegole Meda	1.5	7	35	58	Clay
BH1	Holland Embassy	2.52	5	35	60	Clay
	Ethio-tele at Keranio	2.52	5	35	60	Clay
		2.45	17	46	37	
BH2	Ethio- tele at Gerji	1.5	6	32	62	Clay
		3.6	20	60	20	Silt loam

E) Lulseged Ayalew (1990)

Test Hole No.	Gravel	Sand	Silt	Clay	SCS Class Texture
7s	-	97.5	2.5	-	Sand
10s	-	5.9	22.9	71.2	Clay
11s	16.3	19	4.1	-	Loamy Sand (Sand with gravels)
12s	-	1.3	17.5	75.2	Clay
15s	-	11.4	20.6	67.6	Clay
16s	-	10	2.	65.8	Clay
			4		
			2		
17s	-	8.6	18.4	73	Clay
19s	-	8.6	17.7	73.7	Clay
20s	-	1	17.8	81.2	Clay
21s	-	9.4	15.2	75.4	Clay
24s	-	35.2	12.8	50.1	Clay
25s	-	3.3	22.7	14	Clay
27s	-	47.5	17.5	35	Clay
28s	-	11.4	28.9	59.7	Clay
30s	-	55.6	19.9	24.5	Clay
34s	-	6.7	22.3	10	Clay
35s	-	5.4	9	84.7	Clay
36s	-	3.7	11.9	84.4	Clay
37s	-	11.4	39	49.6	Clay
38s	-	14.3	39.3	46.4	Clay
39s	-	46.1	5.7	38.2	Clay
40s	-	52.7	18.5	28.5	Clay

Note: The project location is around Bole, Megenagna, Kotebe, Urael, Air Port and CMC

F) Saba Engineering (2002) for Addis Ababa Ring Road

Test Hole No	Location	Depth(m)	Sand	Silt	Clay	SCS Class Texture
13 + 585	Holland Embassy Foot Bridge	3.7	20.5	28.5	51	Clay
		4.7m - 4.9m	8.6	27.4	64	
22 + 650	Mekanissa Foot Bridge	2.8	1.9	49.1	49	Silty Clay Loam
		4.80 - 5.0	3.7	30.2	66.1	Clay
32 + 850	Saris Abo	5	36	36	64	Clay

Annex 3. Main Industries in Addis Ababa Metropolitan Area

Name Of Industry	Location	Major Products	Capacity	Raw Material Used	Major Chemical Used	Present Water Consumption (m3/d)
Addis Ababa Tannery	Kolfe	Leather		Skin Hide	Ca (OH) ₂ , Cr NaCl, Na ₂ S	350
Tikur Abay Shoe Factory	Kolfe	Shoes	3000/Day	Plastic Rubber		275
Gulele Soap Factory	Kolfe	Soap	24 Tons/Hrs	Fat	NaOH, NaCl	64
Ethio Marble Industry	Kolfe	Polished Marble				16
Shegate State Garage		Oil	4500/Day	Different Seeds	NaOH	20
Idgate Food Oil Factory	Gulele					42
Research Institute Lab.	Gulele					135
Oil Factory	Kolfe	Oil	3600/Day	Different Seeds		35
Edible Oil Factory	Kolfe	Oil	10000/Day	Different Seeds	NaOH	100
Oil Factory	Gulele	Oil		Different Seeds		25

Abay Soft Drinks Factory	Kirkos	Soft Drinks	500000 Bottles/Day	Sugar Sirop	Sod.Benzo.Citr/ Acid	360
Anbessa Flour	Lideta	Flour Pasta	Fl. 600qt/Day Pa.80qt/D	Wheat		35
Addis Soft Drink Factory	Teklehaima not	Soft Drinks	7500000 Bottles/M	Sugar Concentr.	Naoh Phos. Acid	345
Ethiopian Tyre & Rubber Factory	Teklehaima not	Heal, Strap Neolit		Durant B Rubber	S,CaCo3ZnO,St e.Ac.	45
Awash Wine Factory	Lideta	Wine	49000 HI/Year	Grapes	Sod.Metabisulfate	178
Anbessa Shoe Factory	Teklehaima not	Shoes	2000/Day	Leather	Glue	25
A.A Foam & Plastic Factory	Lideta	Foam Plastic		Tde, Hdpe	Dyes,Tin Silicone	17
National Chemical Corporation	Kirkos	O2,C2h2 Shoe Pol.			NaOH,CaCl2 HCl, Paraf.	173
Beer Factory	Teklehaima not	Beer Malt	185000 HI/Year		Antifoam NaOH,Glyc.	900
National Dist. Liquor Factory	Teklehaima not	Liquors	24000 L/Day	Alcohol		175
ekatit Paper Factory	Nifas Silk	Covered Paper			Inks	30
Plactic Factory	Kirkos					51
A.A. Gas & Plastic Creats Factory	Kirkos	Creats, Co2 Seals	Cr.500/Day S.600/Day	Polypr.Polye th Naft.	NaCo3,NaCl,KM nO4	290
Bole Printing Press	Nifas Silk	Printed Products	7650000 Books/Year	Paper, Ink	Fix & Dev.Arabic Gum	16
Paint Factory	Lideta	Paint	4000 M3/Year		TiO2 Resin	40
Ethiopian Pharmaceutical Factory	Lideta	Drugs				200
Cotton Factory	Lideta	Cotton Yarn	1500t/Year	Cotton		440
Fait.Diaboaco Anbessa						20
Abattoris	Kirkos	Meat	9000sh 180c 1800qt/Day			750
Ethiopian Spice Extraction Factory	Akaki	Oleoresins		Pepper Ginger	Hex. Metha Acetone	50
Repi Soap Factory	Lideta	Detergent Powder &	P. 6t/Day B. 10t/Day	Sod. Tripoly Phosph.	Na Compon Urea	50

		Ba				
Automotive Factory Company	Bole					167
Dairy Products Org.	Bole	Milk	60000 T/Day	Milk	Sodash	177
Ethiopian Metal Tools Factory		Agricult. Hand Tools	1000000 Pieces/Y	Steel		27
United Abilities Factory	Lideta	Dry Cells Umbrellas		Zn, Brass Steel, Nyl.	ZnCl2, ZnO, Cr, H2SO4	210
National Dist. & Liquors Factory	Lideta	Ethanol	7000 L/D	Molasse	Aldehydes Glycerol	75
Abay Soft Drinks Factory	Kirkos	Soft Drinks		Sugar		360
Misrak Flour Bakery	Nefas Silk	Bread Bisc. Flour	Br. 280qt/D Fl. 450qt/D	Wheat	Ascorbic Acid	30
Cement Factory	Nefas Silk	Cement	70000 T/Y	Gyps. Clay Limestone	HCl, H2SO4 HNO3, NH4OH	116
Teday Paint Factory	Nefas Silk	Paint	2500 G/Day	Solvants Bind. Pigm.	TiO2, CaCO3 FeO2, Resins	10
Termay Oil Mills Factory	Nefas Silk	Oil, Ghee	2000000/Y 647000Kg/Y	Cott. Seeds Sunflower	NaOH	25
Addis Ababa YaM Factory	Nefas Silk	Cott. Yarn Blankets	Bl 2400 Kg/D	Wool Wast Cott. Yarn	NaOH, H2O2	700
AA Car Battery Factory	Nefas Silk	Batteries	10000 B/Y	Bitumen Pvc	Pb Antimon H2SO4, PbO2	4
Akaki Oil Mills Factory	Nefas Silk	Oil, Ghee		Cott. Seeds Sunflower	NaOH	47
Kokeb Pasta & Flour Factory	Nefas Silk	Pasta Macaron, Flour	Fl 1200 Qt/D	Wheat		100
National Dist. & Liquors Factory	Nefas Silk	Ethanol Alcohol	1600 L/Day	Molasses	H2SO4	40
Canvas & Rubber Factory	Nefas Silk	Shoes		Rubber	ZnO, S, FeO, Anti oxyd.	60
A.A. Tyre Factory	Nefas Silk	Tyres, Inner Tubes	10000 Ty/Y 60000 Ty/Y	C, Nylon Rubber		375
Ethiopian Food Corporation (Fafa)	Nefas Silk	Food For Children		Milk Pow. Wheat	Ca, Fe, Zn, Mg, I, Vitam	36
Awash Tannery	Nefas Silk	Leather		Hides & Skins	Ca(OH)2, CrNa2s	800
Ethiop. Freight	Debrezeit					12

Transport Corp.	Road					
Ethio Meat Factory	Akaki	Fish Pork Chick Prod	30000 Cans /8 Hous	Meat Oil Salt	NaOH, Bioacid, H ypoc	200
Crown Cork Factory	Akaki	Crown Crhcans		Tinplates Pvc	Ink Lacquers	12
Akaki Textile Factory	Akaki	Blank Sock Text Sheet	Text. Sh. 88000 M2/D	Cotton		1440
National Tobacco & Matches Fact.	Lideta	Tobacco	3 Billion Packs/Year	Tobacco Leaves		139
Artistic Print	Arada	Magazines, Books			Ink, Lubr, Clean. A g.	185
Poultry Dev.	Bole					665
Universal Leather Articles Factory	Nefas Silk	Leather Articles		Leather		14
Commercial Printing Press	Nefas Silk			Paper Ink Metal	HNO3	39
Nefassilk Thread Factory	Arada	Embroid & Sewing Thr	324000 Kg/Year	Cotton Yarn	Acids, Salts Alcohol	400
Ethiop. Picking & Tanning Factory	Akaki	Pickle & Wet Blue	8000 P/D	Sheep & Goat Skin	Na2S, H2SO4 Cr, Ca(OH)2	450
Bethan & Selam Printing Press	Akaki	News Paper		Paper Ink Metal		40
Kaliti Metal Factory	Akaki	Metal Door Wind Frame		Al & S. Steel		15
Kaliti Food Factory	Akaki	Bread, Bis. Flour		Wheat	NH4OH Na2 CO3	12
Akaki Farment Factory	Akaki	Shirts	5000 Sh/D			81
Ethiopian Fibre Prod. Factory	Akaki		25 T/Day	Jute	Miniral Oil	96
Akaki Metal Products Factory	Akaki	Sheets Pipes	22000 T/Y Steel Sh.	Steel	HCl, Pb, Zn NH4Cl	715
Fana Hollow Blocks Factory	Akaki	Hol. Blocks & Pipes	Hb 2000 P/D	Cement Sand		
Akaki Spinning & Knitting Plant	Akaki	Cott. Yarn Socks	Cy 4800 Kg/D S. 7980 P/D	Cott. Rubber Nylon	Naphtol Salt	144
Prefab. Housing Factory	Akaki	Prefab Elements	40000m3/D	Sand, Steel, Agr.		165
Kaliti Animal Feed	Akaki	Cattle	40 T/Hr	Wheat &		5

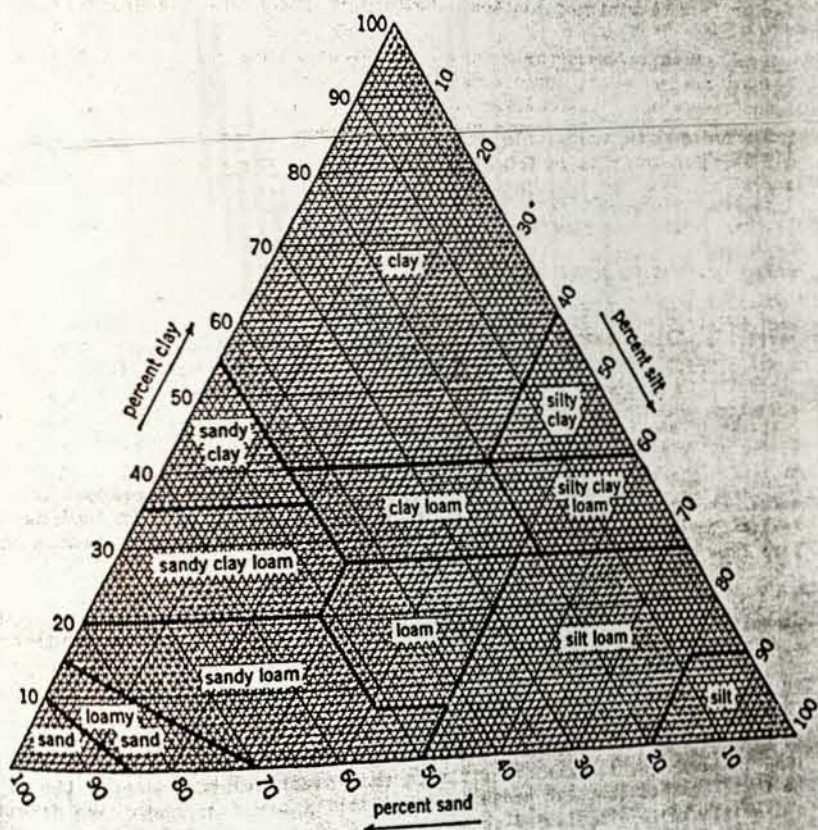
Process Pl.		Feed		Maize Seeds		
Kaiti Animal Feed Process Pl.	Akaki	Cattle Feed	60 T/Hr	Scrap Metal		5
Ethiopian Iron & Steel Foundry	Akaki	Bars,Nails Barb.Wires	20000 T/Y	Steel	Paint Products	925
OCFA Share Company	Akaki	Iron & Metal Works		Wheat		10
Adwa Flour Mills Factory	Akaki	Flour Pasta	400 Qt/Day			22
Akaki Spare Parts Factory	Akaki			Steel		121
Pumps Factory	Akaki	Pumps	250 Pumps Per Year	Cotton		34
Yerekesem Factory	Akaki	Refined Cotton	150000 Qt Year	Gouts Sisal		12
Meher Fiber Factory	Akaki	Bags	12000 Bags Per Year	Linseed Oil	Octanol Diophtalanh	110
Alkyd Resin Factory	Akaki Road	Alkaline Resin	1368 t/y			
Engineering Design & Tool Center-Worksh	Asmara Road			Sio2,NaOh FEL.QUAR TZ	NaOH,K2CO3 MgCO3	
Electric Bulb Factory		Glas Lamps	12 million bulb/year			
Addis Ababa Cigarettes Factory	Addis Ababa		3 million cig./year			
Electronic Product Complex (Assemb. Pt.)	Asmara Road	Radio and TV	R300000p/y TV25000p/y			

Annex 4. Groundwater quality indicators for selected wells (BCEOM-Seureca, 2000)

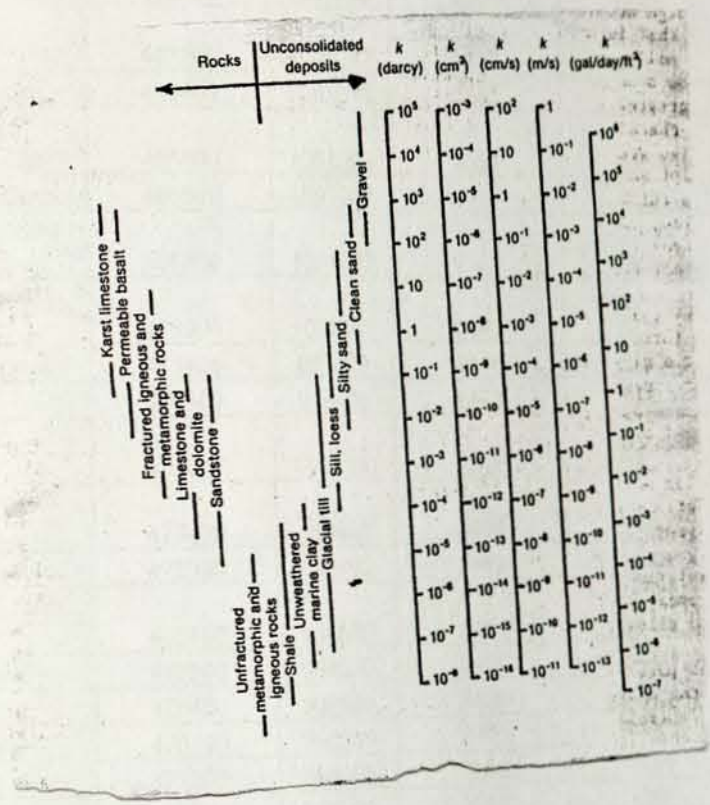
BH	LOCATION		TDS/mg/l	Cl/mg/l	NO3/mg/l	Sampling date
	X	Y				
BH-13	468800	1001007	110	14	0.7	15/4/00
BH-15	469900	1001000	101	6	1.1	4/4/00
BH-37	470000	996400	616	111.5	82.5	4/7/00
BH-42	472600	997400	535	30	34.8	
BH-53	473300	996100	1470	1.5	0.7	
BH-58	472900	995900	295	15	4.4	
BH-83	470900	994800	145	5.5	1.1	4/10/00
BH-99	471705	973386	333	0.7	1.5	16/4/00
BH-105	471000	993800	201	5.5	1.5	4/10/00
BH-123	469900	991200	172	3	1.7	4/7/00
BH-131	473900	990100	354	15	4.3	13/12/99
BH-137	474100	989300	249	17.5	<0.3	13/4/00
BH-139	473900	989000	103	5.5	<0.3	13/4/00
BH-144	473500	987600	320	35	2.8	
BH-149	475000	985800	271	2.5	5.5	
BH-156	476369	981717	452	2.5	1.1	
BH-164	477500	979300	254	5	2.8	13/12/99
BH-164	477500	979300	308	5	2.9	13/4/00
BH-166	477446	978851	286	10	2.4	13/12/99
BH-171	476000	980900	536	75	24.1	13/12/99
BH-171	476000	980900	516	62.5	27.4	
BH-173	475300	983800	256	7.5	3.9	
BH-203	471800	994800	320	52.5	22.2	4/7/00
BH-213	471400	995900	420	70	23.2	4/7/00
BH-232	476521	980711	376	5	0.3	
BH-265	479340	981400	287	5	5.7	
BH-266	481600	98850	282	2.5	2.3	
BH-270	477972	974859	257	8	7.3	
BH-272	480517	977974	220	2.5	2.5	
BH-275	476574	975607	271	3	3.7	
BH-283	478694	976490	274	2	2.4	
BH-288	478019	977985	560	3	1	
BH301	478450	979950	317	8.5	3.1	
BH-305	472870	980925	303	5	4.8	
BH-306	477900	982875	289	5	1.2	
BH-307	478775	983133	312	2	2.7	
BH-333	499700	1008450	176	2	1.2	
BH-356	485925	1000975	267	10	<0.3	12/9/00
BH-356	485925	1000975	269	3	0.5	23/4/00

BH-359	491300	1004800	182	6	5.9	4/7/00
BH-360	481700	999150	197	10	0.4	12/9/99
BH-362	478425	981350	317	3	2.6	
BH-365	465550	1003250	69	1.7	0.6	22/4/00
BH-366	463200	100650	83	1	<0.3	22/4/00
BH-367	461300	1002250	74	1.2	1.3	22/4/00
BH-379	474075	989600	68	1	0.8	22/4/00
BH-390	455300	985250	117	3	2.5	22/4/00
BH-392	455550	983750	155	2.5	4.3	
BH-394	463675	987975	227	4.5	3.4	22/4/00
BH-397	460500	986500	183	1	1.9	
BH-401	467100	1000550	102	1	0.3	20/4/00
BH-411	46980	993350	311	37	<0.3	4/10/00
BH-413	473350	987450	24.6	9	<0.3	4/6/00
BH-414	473900	993100	367	32.5	3.2	4/6/00
BH-416	471950	995050	319	53.9	1.2	4/6/00
BH-438	471400	98850	254	3	2.5	15/4/00

Annex 5. Soil textural classification chart (After US Soil conservation Service, 1951)



Annex 6. Hydraulic conductivity and permeability ranges of common geological materials (Freeze & Cherry, 1979)



Annex 7. Water level data base used for the interpolation depth to water map

WELL_LOCAT	X	Y	GROUND_ALT	DEPTH_TO_S	Z_WATER_L
American Embassy-1	473600	1001013	2550	28.00	2522
American Embassy-2	473700	1001012	2555	27.00	2528
French Embassy	474300	1001005	2523	22.00	2501
Tikur Abay Shoe Factory	466200	1001008	2562	22.60	2539
Glass and bottle factory	467200	1001017	2517	35.30	2482
Anbessa Transport	468400	1001016	2580	3.00	2577
Women's Rehabilitation Center	466600	1001003	2500	22.60	2477
General Winget School	468300	1001003	2525	41.00	2484
Ethio-Marble Industry- 1	468800	1001007	2529	18.00	2511
Ethio-Marble Industry- 2	468900	1001007	2540	72.00	2468
Meskerem Soft Drinks	471400	997400	2416	5.00	2411
Total Sidist Kilo	474000	999400	2473	6.80	2466
AAWSA Ras Kassa Sefer/Ferensay	475000	1001300	2542	73.54	2468
Addis Ababa University, 6 killo	473400	999600	2490	21.00	2469
Yekatit 12 Hospital-1	473300	999300	2482	18.00	2464
Ethiopian Metal Tools Factory	480400	998500	2455	30.10	2425
British Embassy-1	476500	998250	2425	22.00	2403
British Embassy-2	476450	998100	2420	11.00	2409
Belgian Embassy	476100	998300	2440	17.40	2423
Anwar Mosque	471300	998200	2445	16.50	2429
Armay Hospital	469800	996300	2350	1.50	2349
Coca Cola Factory-1	470000	996400	2335	14.00	2321
Coca Cola Factory-2	470000	996400	2338	13.30	2325
Civil Aviation	469800	996200	2342	7.00	2335
Ethio- Plastic Factory	478450	995600	2353	86.97	2266
Ghion Hotel-3	473300	996300	2342	59.00	2283
St. Joseph's School	473400	995800	2338	6.00	2332
Addis Abeba Brewery- 1	471600	995800	2345	19.00	2326
Addis Abeba Brewery- 2	471500	995900	2345	17.00	2328
Addis Abeba Brewery- 3	471400	995800	2345	12.00	2333
Addis Abeba Brewery- 4	471400	996000	2345	23.00	2322
Addis Abeba Brewery- 5	471500	996000	2345	19.40	2326
Addis Abeba Brewery- 6	471550	995950	2346	23.00	2323
Genet Hotel	472000	995100	2320	44.00	2276

Campo Asmara Garage	471800	995200	2303	5.00	2298
AAWSA Near Cigarette Factory	470900	994800	2302	0.50	2302
SEDE(plant-A) - 2	471700	995000	2320	10.80	2309
SEDE(plant-A) - 3	471700	994900	2320	10.40	2310
Former Golf Club	469700	994500	2332	6.70	2325
Africa Hotel	471700	996300	2342	40.95	2301
Hope Enterprise-2	466300	993100	2317	60.00	2257
Dewara Gud NWR	471705	973386	2062	42.60	2019
Repi Soap Factory	466250	993050	2335	50.00	2285
Voice of Revolutionary Ethiopia	467200	993600	2330	48.00	2282
ALERT-1 Gate Well	468000	993200	2315	16.80	2298
ALERT-2 West Well	468100	993100	2320	50.00	2270
ALERT-3 East Well	468100	993200	2325	45.00	2280
Progress/Edget Cotton Factory	471000	993800	2305	68.00	2237
Anbessa/Walya Transport (Diabaco)	471200	993700	2300	23.30	2277
Slaughter House	472000	993500	2260	50.50	2210
Abay Mesk Soft Drinks-2 (pepsi Cola)	473100	992600	2290	36.00	2254
Misrak Flour and oil Mills-1	473500	992900	2280	123.30	2157
Misrak Flour and oil Mills-2	472900	992500	2280	89.60	2190
Telecommunications Ware House	474300	993300	2325	126.00	2199
Army Camp Construction, Wollo Sefer	474300	992700	2381	89.20	2292
United Oil Mills-1	473200	992400	2287	29.00	2258
United Oil Mills-2	473200	992400	2287	39.90	2247
Cement Factory-1	473100	991800	2280	56.40	2224
Cement Factory-2	473100	991900	2270	112.70	2157
Cement Factory-3	473050	991800	2270	94.00	2176
Mekane Iyesus	470465	991100	2220	16.00	2204
ETHARSO-1	470250	991500	2225	19.00	2206
ETHARSO-3	469800	991200	2225	7.10	2218
Mekanisa Distillery-1	470400	992100	2230	11.30	2219
Gofa Sefer Army Camp	471400	991000	2240	25.90	2214
Adey Abebe Cotton Mill-1	473800	990250	2247	37.80	2209
Adey Abebe Cotton Mill-2	473848	990072	2260	40.70	2219
ECAFCO	473750	990050	2250	51.60	2198
Awash Tannery-1	473500	987900	2195	9.10	2186
Awash Tannery-2	473600	988300	2195	11.30	2184

Kokeb Flour and Pasta Factory	473230	988878	2200	13.70	2186
Adcis Tyre Factory-1	473900	989000	2224	45.40	2179
Adcis Tyre Factory-2	473900	989000	2215	34.50	2181
SEDE(Plant B)-1	474000	989100	2225	18.00	2207
SEDE(Plant B)-2	474100	989000	2220	35.00	2185
National Road Transport Corp	475000	987800	2180	27.80	2152
Ethio- Pickling and Tanning Factory, near Behere	473225	989850	2205	12.00	2193
Ethio-Meat Concentrete Factory	473500	987600	2180	25.20	2155
WWDA Ware house	473300	987300	2163	25.20	2138
AAWSA Kality Well	475000	985800	2112	0.00	2112
Military Food Service Kitchen	473900	985100	2165	8.00	2157
Meher Fiber Factory-1	475662	980784	2055	27.40	2028
Meher Fiber Factory-2	475336	980717	2075	17.10	2058
Akaki Indo-European Textiles-1	476500	981300	2055	3.70	2051
Akaki Indo-European Textiles-2	476600	981500	2070	3.50	2067
Akaki Indo-European Textiles-3	476369	981717	2062	7.00	2055
Akaki Dairy Farm	481507	976221	2100	120.00	1980
Ethio-Metal Meal-1	476400	980600	2056	16.90	2039
Ethio-Metal Meal-2	476400	980700	2058	53.40	2005
Akaki Koye Air defence -1	482400	983000	2230	56.15	2174
Kality Airforce-1	476400	984800	2125	12.00	2113
Gaetti Project	474800	984700	2140	0.50	2140
Akaki Ethio-fiber-1	477400	979500	2080	27.40	2053
Akaki Metal Products/Sabean Utility Factory -4	477446	978851	2070	52.40	2018
Akaki Metal Products/Sabean Utility Factory-1	477233	979000	2070	51.00	2019
Akaki Metal Products/Sabean Utiity Factory-3	476500	981500	2070	73.00	1997
Akaki Telecommunications	476600	978200	2065	46.40	2019
Adwa Elour Mill	476000	980900	2060	13.00	2047
Minilik Hospital	475200	999200	2440	39.00	2401
Building College	470500	996000	2200	23.00	2177
Ministry of Defence	472700	996500	2540	2.60	2537
Old Airpor-2	470500	994500	2320	41.70	2278
Gulele Glass-Factory-3	466900	1001005	2517	20.40	2497
Addis Beer-9	471400	995900	2345	18.75	2326

NMWC Spare Parts & Hand Tools Factory-1	478463	977722	2090	50.00	2040
NMWC Pump Factory	477609	978690	2090	57.70	2032
Kality Metal Products Factory	474225	982650	2150	30.78	2119
Meta Abo Brewery	455500	985200	2200	75.90	2124
Sidamo Awash Village	479820	977156	2085	62.50	2023
NMWC Spare Parts & Hand Tools Factory-2	478463	977506	2090	50.00	2040
Ethiopian Iron And Steel Faundry BH-1	476427	980749	2060	4.00	2056
Ethiopian Iron And Steel Faundry BH-2	476430	980669	2060	6.50	2054
Police College Sendafa	502600	1011700	2550	82.00	2468
Legetafo-Nigata, Sendafa	489200	1001025	2455	31.00	2424
Gen. Gebre Kebede, Alemgena	463600	988200	2280	27.50	2253
Highway N. 1, Alemgena	462500	987000	2300	83.50	2217
Bisrate Wengel, Boneya	461900	974300	2120	38.10	2082
Ato Abebe Dima, Sebeta	451900	983000	2140	40.00	2100
Tatek Tor Sefer-5	459700	998075	2580	10.20	2570
Tatek Tor Sefer-6	459375	998350	2600	24.50	2576
Kokebe Thebah school	476200	998600	2410	10.00	2400
Water III Testwell-B2	464000	997000	2480	51.00	2429
Water III Testwell-B4	486200	1001042	2450	10.00	2440
Water III Testwell-B8	487300	995300	2350	88.00	2262
Water III Testwell-B9	481600	982900	2205	35.10	2170
Water III Testwell-B10	461500	1001023	2630	82.00	2548
Water III Testwell-T5	481600	982900	2205	37.33	2168
Water III Testwell-T14	480900	978800	2126	86.00	2040
Akaki Water Supply Test Well EP-1	479340	981400	2131	0.73	2131
Akaki Water Supply Test Well EP-2	481600	982850	2204	33.48	2171
Akaki Water Supply Test Well EP-3	479740	981400	2134	3.38	2131
Water III Borehole BH01	477972	974859	2079	59.00	2020
Water III Borehole BH02	478399	975589	2073	53.00	2020
Water III Borehole BH03a	480517	977974	2100	65.00	2035
Water III Borehole BH3b	478713	974977	2083	64.00	2019
Water III Borehole BH04	477992	975552	2068	48.00	2020

Water III Borehole BH05b	476574	975607	2070	51.40	2019
Water III Borehole BH06	479696	976936	2087	67.80	2019
Water III Borehole BH07	479405	976735	2086	67.20	2019
Water III Borehole BH08	479061	976370	2087	67.20	2019
Water III Borehole BH09	479246	977104	2078	58.70	2019
Water III Borehole BH10	479058	976020	2091	72.20	2019
Water III Borehole BH11	478780	977307	2080	61.10	2019
Water III Borehole BH12	478808	976867	2071	47.50	2023
Water III Borehole BH13	478694	976490	2074	50.20	2024
Water III Borehole BH14	478580	976051	2079	59.20	2019
Water III Borehole BH16	478347	976752	2068	47.50	2020
Water III Borehole BH17	478199	976361	2065	45.90	2019
Water III Borehole BH18	478154	975966	2074	54.10	2019
Water III Borehole BH19	478019	977985	2070	51.50	2019
Water III Borehole BH20	477945	976985	2068	49.90	2018
Water III Borehole BH21	477856	976402	2064	44.70	2019
Water III Borehole BH22	477651	975923	2067	47.90	2019
Water III Borehole BH23	477477	977216	2064	44.00	2020
Water III Borehole BH24	477330	976793	2062	42.90	2019
Water III Borehole BH25-2	477162	976038	2061	42.00	2019
Water III Borehole BH26	477181	975680	2070	51.00	2019
Water III monitoring well 02	476523	976374	2055	35.55	2019
Water III monitoring well 03	476972	976152	2059	40.30	2019
Water III monitoring well 04	477185	975729	2069	46.50	2022
Akaki Water Supply Well EP-6	479526	977468	2090	70.20	2020
Akaki Water Supply Well EP-7	479021	977596	2090	64.82	2025

Akaki Water Supply Well EP-8	478998	977937	2090	71.98	2018
Akaki Kebele 06 Kilento	477900	982875	2130	20.00	2110
Akaki Kebele 06 Kilento	478775	983133	2165	24.00	2141
Atlas Resort Hotel, Dalota	482480	976133	2150	5.80	2144
Teshome Augna PLC, Dalota	486006	974882	2053	96.20	1957
Arena Dukem	487900	972421	1948	75.75	1873
Dimtu Peasant's Village	481694	965913	1920	95.40	1825
Oda Nabe Peasants village	484325	969692	1950	118.40	1832
Chelaba Silasie Borehole	481162	958481	1841	58.32	1783
Shoki-1 village borehole	483216	961334	1874	99.00	1775
Merdia	499700	1008450	2520	3.60	2516
Dire dam	493250	1012115	2585	24.00	2561
Kuskuam St. Peter Hospital BH2	473350	1003000	2625	10.05	2615
Dukem East Africa Ethipia Plc. Factory	490193	968059	1900	93.00	1807
Day light Legedad	485925	1000975	2482	7.59	2474
Gedera 2 Legedad	486000	1001115	2482	9.80	2472
Legedadi, Community borehole	491300	1004800	2440	5.42	2435
Kotebe, Selam Vocational School	481650	998650	2460	79.56	2380
Kotebe, Selam Children's Village	481650	997725	2406	42.79	2363
Asco, Black Lion Shoe Factory	466175	1001800	2560	25.60	2534
Burayu, Ethio-Libya Joint Venture PLC.	464600	1003075	2620	14.45	2606
Kotebe, Summit Soft Driks Factory	483750	994550	2340	50.87	2289
St. Gabriel Hospital	476750	995800	2342	53.20	2289
International Livestock Research Center (ILRI)	479450	996115	2358	32.10	2326
San Francisco, Asco	466440	1001760	2560	17.70	2542
Hollow Block and Brick Factory, Nifas Silk	474075	989600	2235	24.00	2211
Meat Concentrate Factory BH-2	473760	987300	2180	23.00	2157
Waliya Tannery BH1, Kality	473925	987175	2175	15.60	2159
Peacock Park, Bole	475300	994800	2318	60.90	2257
Nejat Coffee Exporter	475650	984750	2120	57.00	2063

(Kality)					
Abune Yosef School, Alert	467150	992150	2275	29.00	2246
Meta Abo Brewery BH7	455350	985100	2220	70.00	2150
Meta Abo Brewery BH5	455300	985250	2218	68.00	2150
Meta Abo Brewery BH8	455525	984000	2140	63.30	2077
Meta Abo Brewery BH9	455550	983750	2138	46.80	2091
Glass Factory BH2, Asco	467100	1000550	2515	12.00	2503
Mohamed Abdo Borehole, Burayu	464500	1003150	2590	5.75	2584
Micky Layland Children's Home	466550	1000150	2510	22.60	2487
Greece Community, Olympia Bole area	474500	995450	2338	66.10	2272
Netherlands Embassy, Keranio area	468800	996600	2360	50.35	2310
Ato Temesgen Chaka, Ketana Hulet area	469050	994450	2260	26.50	2234
Korea Embassy, Ketana Hulet area	468425	996350	2320	19.60	2300
Hagbes PLC., Bisrate Gabriel area	468875	993750	2298	11.16	2287
Donbosco Fathers, Yared Church	473900	993100	2310	118.00	2192
Indonesian Embassy, Vatican	470950	993300	2290	18.93	2271
Apostlic, Tero, Kolfe	467250	999800	2510	58.79	2451
Nigeria Embassy, Afinchober	472700	999800	2485	8.55	2476
Bole Medihanialem Church BH2	476800	994200	2337	52.00	2285
Italian Embassy, Bela	476105	1000050	2455	50.20	2405
DL.M.PLC, Kality	475050	985050	2110	5.31	2105
AAWSA, Shegole	468100	1001625	2585	31.69	2553
AAWSA, Repi behind Roll Soap Factory	463850	993100	2400	83.71	2316
AAWSA, Ayer Tena, near Kidanemeheret	466050	993650	2360	71.28	2289
AAWSA, near Kotebe EELPA	480395	998100	2440	8.51	2431
AAWSA, Lafto Hana Mariam	471400	988250	2205	12.50	2193
Japan Embassy	475750	993650	2310	97.15	2213
Tafo, Ropack International real estate	487800	1002200	2480	26.00	2454
Dire, AAWSA1	495300	1012000	2560	27.00	2533

Dire, AAWSA2	491000	1012600	2620	16.00	2604
Dire, AAWSA3	494600	1008000	2515	30.00	2486
Burayu Spring water Bh2/ Aqua Addis	462558	1002487	2620	35.00	2585
Gulele Misionery of Charity No.1	465651	1001575	2540	7.30	2533
Gulele Misionery of Charity No.2	465600	1001855	2545	13.20	2532
Genesis Farm, Debrezeit	495447	968068	1902	49.68	1852
Dragados, Debrezeit	494040	968454	1922	66.11	1856
Sino-Ethiopia Sunshine Pharmaceutical PLC	493497	968497	1918	66.60	1851
AAWSA/IAEA Piezometer No.3 (P3)	475402	976807	2060	31.40	2029
AAWSA/IAEA Piezometer No.4 (P4) Dimtu	482950	963800	1860	67.11	1793
AAWSA/IAEA Piezometer No.5 (P5) Abu Sera	475780	956477	1885	89.34	1796
Dukem, Gedera Resort Hotel	487700	973600	1985	59.63	1925
Addis Ababa Kera	472150	993300	2270	50.50	2220
TW2 Test well No.2	473576	972821	2081	70.00	2011
TW3 Test well No.3	484475	975622	2104	100.00	2004
TW4 Test well No.4	489950	976019	2067	91.00	1976
TW5 Test well No.5	485798	968308	1900	70.00	1830
Burayu Cartoon Factory	463266	1001971	2600	26.17	2574
Ato Asrat Abebe/Lega Tafo	486250	1000425	2460	8.00	2452
Ato Abebe Werkie/Lega Tafo	486050	1001100	2480	8.00	2472
Community/Lega Beri	496550	1005675	2500	11.00	2489
Ato Feyisa/Lega Beri	496550	1005700	2500	10.00	2490
Ato Terefe /Lega Beri	496700	1006000	2500	10.00	2490
Ato Hailu/Lega Beri	496700	1005950	2500	9.00	2491
Ato Asefa/Lega Beri	496850	1005550	2500	9.00	2491
Alemayehu/Lega Beri	496600	1006150	2500	9.00	2491
Community/Lega Bole	498350	998050	2520	10.00	2510
Etege Taytu Hotel/Piazza	472850	1001250	2442	10.00	2432
Ato Abdula/Alem Gena	463600	1003300	2280	10.00	2270
Burayu Brick Factory/Burayu	464250	1002650	2610	12.00	2598
Ato Alebachew/Burayu	463700	996200	2580	0.00	2569
Italian Hotel/Lideta	470850	1002200	2342	0.00	2342
Ras Kasa Sefer/Near Eyesus Church	474750	1002350	2618	0.00	2617

W/o Fikrte/Near Eyesus Church	474700	996000	1630	0.00	1627
Mr.Richard Family/Lega Hare	472850	996850	2345	0.00	2343
Dejazmach Zewde G/s/Ferensay	475700	999550	2538	0.00	2534
Kotebe Nib Erbata,AAWSA/Kotebe	481750	1000300	2520	4.00	2516
Ato Geremew Denboba/Gulelle	469050	998550	2520	11.00	2509
Minilk School/ 4 Killo	474000	999250	2440	1.00	2439
Germany Embassy/ Kebena	475800	999100	2445	3.00	2442
Small Spring/Aba Samuel	476625	969450	2025	0.00	2025
Abo Tsebel Spring/Aba Samuel	468350	968425	2020	0.00	2020
Lotti Kidanemihret Spring/Aba Samuel	468350	967950	1960	0.00	1960
Burka Spring/Aba Samuel	468500	967750	1958	0.00	1960
Kabo Shenteralie Spring/Aba Samuel	468750	967100	1935	0.00	1935
St.Gebreal & Micheal Tsebel/Aba Samuel	469150	966900	1920	0.00	1920
Lege Meka Spring/Aba Samuel	469300	966775	1918	0.00	1918
Lege Memire Spring/Aba Samuel	469500	966750	1895	0.00	1985
Lege Meka Stream / Spring/Aba Samuel	469600	966650	1920	0.00	1920
Fanta Minch/ Spring/ Akaki	479600	981100	2140	0.00	2140
Eyassu Spring/Asco	466600	1009900	2560	0.00	2560
Gojam Ber Spring/ Gojamber	470750	1003800	2840	0.00	2840
Akako Spring 1/Akako Area(Intoto)	477450	1006250	3140	0.00	3140
Akako Spring 2/Akako area(Intoto)	478600	1006350	3150	0.00	3150
Asko Gebreal Spring/Asco	467150	1004250	2760	0.00	2760
Megenagna Spring/ MegenagnaMSR.S	478350	996700	2370	0.00	2370
Ankorcha Spring/ Kotebe Ankorcha	478850	1009500	2770	0.00	2770

Annex 8. Environmental Impact Assessment: An Overview of Environmental Policy, Legislation and Guidelines of Ethiopia

The national policy and sectoral strategy background regarding environmental protection in Ethiopia under various programs such as Environmental Policy of Ethiopia (EPE) and Conservation Strategy of Ethiopia (CSE), and the constitution are briefly described as follows.

A) The Constitution

The constitution provides important provisions relevant to the country's environmental policy. Articles 44 of the constitution of the Federal Democratic Republic of Ethiopia (FDRE) states that all persons have the right to a clean and healthy environment. It also states under Article 92 that:

- 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.

B) Environmental Policy of Ethiopia (EPE): General

The overall goal of Environmental Policy of Ethiopia (EPE) (EPA, 1997) is to improve and enhance the health and quality of life of all Ethiopians, and to promote sustainable social and economic development through the sound management and use of natural resources and the environment as a whole so as to meet the needs of the present generation without compromising

the ability of future generations to meet their own needs.

One of the specific policy objectives include prevention of land, air and water in the most cost effective way so that the cost of effective preventive intervention would not exceed the benefits; some of the key guiding principles (EPA,1997) are:

- The development, use and management of renewable resources shall be based on sustainability;
- When a compromise between short-term economic growth and long-term environmental protection is necessary, then development activities shall minimize degrading and polluting impacts on ecological and life support system;
- Full environmental and social costs (or benefits foregone or lost) that may result through damage to resources or the environment as a result of degradation or pollution shall be incorporated into public and private sector planning and accounting, and decisions shall be based on minimizing and covering these costs;
- Increased awareness and understanding of environmental and resource issues shall be promoted by policy makers, by government officials and by the population, and the adoption of a “conservation culture” in environmental matters among all levels of society shall be encouraged;
- Natural resource and environmental management activities shall be integrated laterally across all sectors and vertically among all levels of organization.

The Environmental Policy of Ethiopia has sectoral environmental policies too. From these sectoral environmental policies let us see the water resources policies.

C) Water Resources Policies

The Ministry of Water Resources has formulated the Federal Water Resource Policy for a comprehensive and integrated *water resources management*. The overall goal of the water

resources policy is to enhance and promote all national efforts towards the efficient and optimum utilization of the available water resources for socio-economic development on sustainable bases. The water resources policies are to establish and institutionalize *environment conservation and protection* requirements as an integral parts of water resources schemes and projects that shall have "Environmental Impact Assessment and Evaluation". The policy components where measures to mitigate negative impacts and enhance positive impacts are recommended for action as part of the development process.

The policies are also to ensure that the exploitation of groundwater shall be based on abstraction of the maximum amount equal to the sustainable yield as determined by competent authority. It is also to develop and put in place system and procedures for *groundwater monitoring and control*. The existing water resources policy of Ethiopia is very general without accompanying detailed description of regulatory processes for major, if not all of, polluting human activities.

D) Conservation Strategy of Ethiopia (CSE)

The conservation strategy of Ethiopia (CSE, 1996), which was approved by the Council of Ministries, provided a strategic framework for integrating environmental planning into new and existing policies, programs and projects.

The CSE provides a comprehensive and rational approach to environmental management in a very broad sense covering national and regional strategies, sectoral and cross-sectoral policies, action plans and programs. It also provides the basis for the development of appropriate institutional and legal frameworks for implementation (EPA, 1996).

The CSE recognizes the importance of incorporating environmental factors in to development activities from the outset, so that planners may take into account *environmental protection* as an essential component of economic, social and cultural development.

E) Environmental Legislation

Ethiopia lacks legislation used to mandate the EIA on the issues of policies, programs or projects. Currently, there is no regulation to implement the aforementioned police objectives and guiding principles of the proclamation.

The sectoral guidelines for EIA are envisaged to constitute an integral part of the laws and regulations to be applied by all government agencies mandated to grant permits for implementing projects.

The Environmental Protection Authority (EPA) is assigned the responsibility for appraisal of projects with regard to their environmental implications. In line with this power and duties, EPA has already prepared a draft EIA proclamation and a proclamation on the Establishment of Environmental Protection. In addition to the two draft proclamations, EPA has also prepared an Environmental Pollution Control Proclamation.

The proclamation of EIA states that projects shall be subject to EIA and no proponent shall commence its implementation without authorization from the Authority or from the relevant regional agency, as appropriate.

According to the draft proclamation, projects that require EIA include rural and urban water

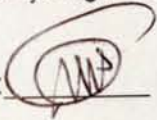
supply and sanitation services, and waste disposal projects. Projects likely to have inter-regional impacts shall also be subject to EIA, in consultation with regional state likely to be affected.

Whatever the policy/ proclamation may be there are no clear legal procedures to charge the polluter. Recently, one of the government news paper "Addis Zemen" reported that the ex-Ethiopian Electric Light and Power Authority (EELPA) now called Ethiopian Electric Light and Power Corporation (EELPC) buried around Gofa near Little Akaki River (some 500 metres away from it) one of the dangerous chemicals, *copper-chrome arsenic*. It was used for the strengthening of electric poles. According to this newspaper these chemicals could pollute the near by river and groundwater. It has the capacity to cause cancer to human beings (Addis Zemen Vol. 62-No.345- (21/8/2003)).

DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree on any other university or by any other person before. All sources of material used for the thesis have dully acknowledged.

Name: Dereje Nigussa Hunde

Signature: 

Place and date of submission: School of graduate studies, November 2003.