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A multi-criteria analysis for solid waste disposal site selection  
using Remote sensing and GIS

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By

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degree of Masters in remote sensing and GIS**

## ABSTRACT

Solid waste management continues to be one of the major issues facing municipal planners, which involves managing activities associated with generation, collection, transport and disposal of solid waste in an environmentally compatible manner. Land filling is a common method of waste disposal in Ethiopia. Recently, due to an increase in the awareness of environmental risks from land fills, there has been a movement towards the selection of new solid waste disposal sites for the city, however due to the lack of appropriate criteria and a set of detailed criteria that consider all aspects of the water resource protection all the results of the previous researches were inadequate.

In order to alleviate this acute environmental problem, a multi criteria analysis approach using remote sensing and GIS is necessary and immediate.

GIS can be used to convert geo-referenced data into computerized maps and map analysis tools can be used to manipulate maps in an efficient way. This is especially useful when dealing with large amounts of data, which is typical in landfill siting.

The result of the study shows that the areas, the city planners proposed for the landfill site be revised in a way to consider the best sites, some areas of the central east and southern part of the city, are appropriate as land fill site shown in the final out put map of the study area.

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This work is dedicated to

My Late Mother

Belaynesh Tsehaye

&

My sisters and brother

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# Chapter one

## INTRODUCTION

### 1.1 Background

Solid Waste is defined as any material, which arises from human or animal activities, and thrown away as being useless or unwanted (J.Chilton 1992). Solid wastes indiscriminately thrown about are aesthetic problems and nuisance; they pollute land and water bodies of an area.

Urbanization has brought forth several maladies and suffering to human kind, besides bringing economic and cultural development in its fold. Due to pressure of urbanization most of the cities are growing fast and sometimes they develop beyond the planned limits. Generally the unplanned areas of the city contain a quarter of the total population, where the spatial information is missing because of non-availability of up to date maps.

Due to increasing industrialization and population large quantities of wastes are being generated in different forms such as- solid, liquid, sludge and gases. Each city produces tones of solid wastes daily from house holds, hospitals, industry offices, market centers etc. some of these are biodegradable some are non biodegradable and Hazardous waste. Wastes are directly thrown away on the street roads, city garbage collecting places etc. Out of which most of it still remain there, which later piles up and chocks cities drainage lines. Earlier waste disposal did not pose problem due to less population and lack of public awareness. But due to rapid urbanization, proportionate increase in domestic and industrial solid waste generation was observed in large cities. The collection, handling and disposal of this large waste with conventional methods have become increasingly difficult

Municipal solid waste management is one of the major problems facing city planners all over the world. The problem is especially severe in most developing-country cities where increased urbanization, poor planning, and lack of adequate resources contribute to the poor state of municipal solid waste management (Obirih-Opareh & Post, 2002; Mato, 1999; Doan, 1998; Mwanthi et al., 1997). In Africa, rapid urban growth since the 1960s has put pressure on the land

resources within the area surrounding the cities, and has led to increased generation of waste. The problem is aggravated by the open dump nature of disposing waste especially in the slum areas of most African cities. An example of this is found in the waste management practices in Ethiopian municipalities. Traditionally, their administrations permitted uncontrolled in an abandoned quarry sites with no provision for sanitary landfill, causing health problems (Mato, 1999; Hammer. 2003).

Solid waste management continues to be one of the major issues facing municipal planners which involves managing activities associated with generation, collection, transport and disposal of solid waste in an environmentally compatible manner, adopting principles of economy, aesthetics, energy and conservation. As urban populations rise, so does the build up of waste. Planners are thus forced to consider alternate and available means of disposal, especially by minimizing damage to the ecosystem and human population.

The International Environment Technology Center in Osaka (Japan) under the United Nation Environment Program (UNEP) has identified recycling, incineration, composting, and Land fill (Dumping) as a suitable method for solid waste management (UNEP 1996). The most common waste management practice is landfill, mainly because of its cheapness in comparison to other methods.

The high rate increase in commercial, residential and infrastructure development of Addis Ababa due to the population growth is causing serious problem on the environment. Since Addis Ababa is the capital city of Ethiopia, modern economic activities, social and infrastructural services are found relatively in a better situation than other cities of Ethiopia. However, their development is too slow to meet the demands of the increasing population due to both natural growth and rural-urban migration. In particular, the complete inadequacy of the solid waste management system is the major environmental problem in the city.

One of the many reasons for the cause of the environmental problem is Location of dumping site in unsuitable areas. Leakage from these sites usually contains significant amount contaminants such as ammonia, nitrate, chloride and metals, these contaminants may reach aquifers, degrade the water resource and become hazardous to human health. The amount of waste generated by the city in 1996/97 is estimated to be 1386 m<sup>3</sup>/day. Out of this, 750 m<sup>3</sup> is collected by the

municipal services. According to a study by Meson (1996), solid waste is ranked top of environmental Problems in Addis Ababa, scoring 26.47, and immediately followed by sewerage (20.59), then population congestion (14.71).

As stated above, one of the major problems in waste management is concerned with the selection of appropriate site for the waste disposal. The efficacy of solid waste disposal depends upon selection of proper site and there are several issues that have impact for site selection. Broadly they are divided into three categories i.e. Economic, Social and Environmental. The Geological, Geotechnical and Hydro geological parameters fall within the environmental category. The ultimate aim is to select a site where the greatest protection of the environment is provided. Site selection is a part of environmental planning, where the principal part is of problem to select Landscape that is functional safe.

Locating suitable dumping site is a very time consuming process. The use of remote sensing and Geographic Information Systems (GIS) will reduce the time and enhance the accuracy. Satellite Remote Sensing images can provide information about the wasteland and other associated features, which help in selection of sites. Coupled with GIS it can provide an opportunity to integrate field parameters with population and other relevant data

The role of GIS in solid waste management is very large as many aspects of its planning and operations are highly dependent on spatial data. In general, GIS plays a key role in maintaining account data to facilitate collection operations; customer service; analyzing optimal locations for transfer stations; planning routes for vehicles transporting waste from residential, commercial and industrial customers to transfer stations and from transfer stations to landfills; locating new landfills and monitoring the landfill. GIS is a tool that not only reduces time and cost of the site selection, but also provide a digital data bank for future monitoring program of the site.

This paper aims at demonstrating the utility of Remote Sensing Technology in identification of wasteland, and assesses the capability of GIS Technology for site selection for solid waste disposal.

## 1.2 Statement of the problem

Solid wastes are the potential sources of environmental pollution in the city. The water bodies are contaminated to an extent that they are completely unfit for an industrial, agriculture and domestic use purposes. These detrimental pollution situations in effect retard the influx of investors in particular and the economic growth of the city in general. The prevailing environmental pollution problem is partly due to the absence of well-established solid waste management systems in the city administration. In order to alleviate this major problem some studies were conducted by different governmental bodies and proposed a solid waste management for the city in general and selected few land fill sites in particular to the only land fill site known as Koshe which had been used for decades; however, most of the results of these investigations were not best suitable sites for several reasons. In order to alleviate this acute environmental problem, a multi criteria analysis approach using remote sensing and GIS is necessary.

GIS can be used to convert geo-referenced data into computerized maps and map analysis tools can be used to manipulate maps in an efficient way (Kao et al., 1997). This is especially useful when dealing with large amounts of data, which is typical in landfill siting.

## 1.3 Objectives

### 1.3.1 General Objectives

This study in general focuses on the role of remote sensing and GIS techniques in selecting suitable solid waste disposal site using a multi criteria analysis technique for the Addis Ababa city there by decreasing the negative environmental impact in general and water resource contamination in particular from the land fills.

### 1.3.2 Specific objectives

To select new waste disposal sites.

To generate the digital database of the area for decision support system.

To visualize the results.

## 1.4 Materials and data

The following data were used in this research work:

- **Digital Elevation Model (DEM)**

A Digital Elevation Model derived from SRTM (Shuttle Radar Topographic Mission) data has been used in analysis of the morphology of the studied area.

- **Topographic and thematic data**

The topographic map of the area Prepared by the Addis Ababa City administration Geographical Information Systems department has been used as base map. From this map TIN has been created and then the Slope map of the area was derived.

- **Geological map**

Geological map of the Addis Ababa area was used (Source: Tamiru et al., 2005)

- **Soil Map**

Soil map of the Addis Ababa area was used (Source: Tamiru et al., 2005)

- **Hydraulic conductivity map**

Hydraulic conductivity map of Addis Ababa was prepared from the borehole data collected by different organizations.

- **Drainage Network Map**

Drainage network Map of the Addis Ababa area, which was prepared by the Addis Ababa City administration Geographical Information Systems department, was used.

### **Road Network map**

Road network Map of the Addis Ababa area, which was prepared by the Addis Ababa City administration Geographical Information Systems department was used.

### **Landuse Landcover Map**

Landuse Landcover Map of the Addis Ababa area which was by Prepared by the Addis Ababa City administration Geographical Information Systems department were used

#### **▪ Tabular data**

Data on hydro geological and different hydraulic characteristics in dbf format (spatial data base) were collected and from which piezometric map was produced.

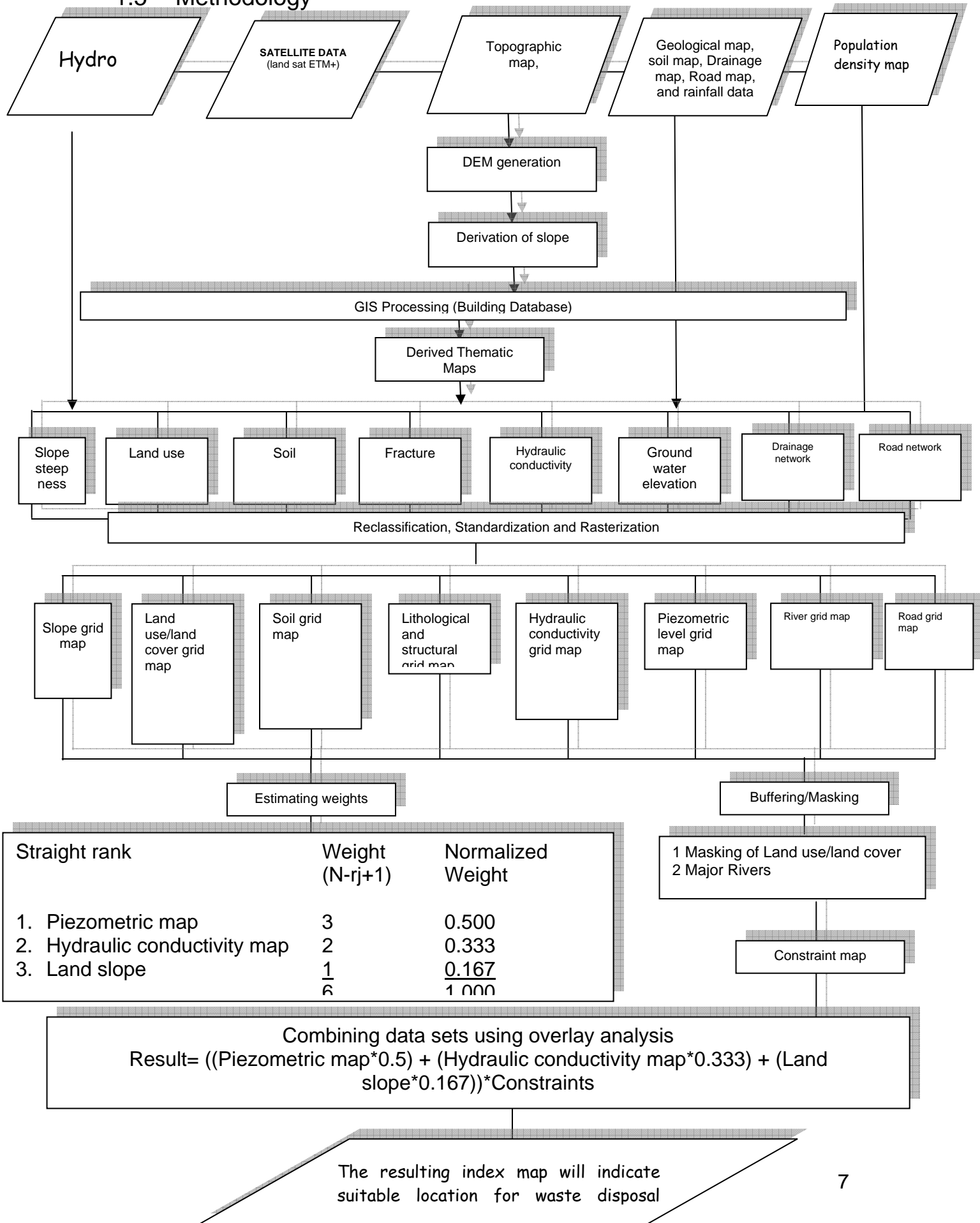
Data on population growth and generation of solid waste in dbf format was used.

### **Software**

The followings are software used in the study

- Ms Access 2000
- ERDAS Imagine 8.6 used for georeferencing, digitization.
- Arc view 3.2a and ArcGIS 9 used for GIS analysis, Mapping and presentation
- Global Mapper used for extraction of Elevation data
- AutoCAD 2004 for digitization

# 1.5 Methodology



## 1.6 Previous works on Solid Waste disposal Site Selection

Some researches have been conducted to propose a new solid waste management system and select new solid waste disposal sites as an alternative to be used together with the only used solid waste disposal site in the city known as Repi. However these researches have not considered the possible water resources contamination caused by Leachate as their criteria to select the sites considers only the following parameters.

- Access road network to waste generating points.
- Capacity of land to hold up wastes generated in its vicinity according to the types.
- Free from any objectionable odor and appearance.
- Less densely populated residential area.
- Minimum area of 6-8m<sup>2</sup>.

Moreover these researches were limited only to the existing landfills and quarries, which made it very incomplete and they have finally selected the following three sites, which are listed according to their rank to be used temporarily.

- Gurd sholla Quarry (1<sup>st</sup> Alternative)
- Kilinto Quarry (2<sup>nd</sup> Alternative)
- Roll Quarry (3<sup>rd</sup> Alternative)

Even considering only the above-proposed criteria by the researchers and applying them in a non-GIS environment, it would end up with an erroneous result. From their result we can observe that most of the sites are close to the ground water source of the city.

Therefore considering the potential causes to the water resource contamination of the city in addition to the criteria they used and applying them in GIS environment, we would select better sites so that the water resource contamination would be less.

## 1.7 Location

The study area has been conducted on Addis Ababa, the Capital city of Africa in general and that of Ethiopia in Particular; it is bounded between  $38^{\circ}30'$  and  $39^{\circ}00'$  E longitude  $8^{\circ}45'$  and  $9^{\circ}15'$  N latitude (Figure1). Addis Ababa was founded in 1887 by emperor Menelik II (and his wife). It is located in the central highlands of Ethiopia, covering an area of 530 km<sup>2</sup>. With an elevation ranging from 2000-2800 m a.s.l. It is the highest capital of Africa. Hills, valleys, rivers and streams constitute its topography. The air temperature is fairly constant throughout the year, with variations between 20 to 25 °C during the day, and between 7 and 11 °C at night. Average rainfall is 1200 mm per year, with the major rains occurring between July and September.

Unlike the other African cities of colonized countries, Addis Ababa is characterized by its spontaneous growth as an indigenous city with very little impact of external forces. The city began to develop as a political, economic and cultural centre in subsequent years. Services such as piped water, electric light and other facilities attracted migrant population from other parts of the country. In addition to this rate of rural-urban migration drained rural labour force from agricultural production created problems of unemployment, congestion and strains on existing inadequate social services in Addis Ababa (Solomon Gebre, 1996).

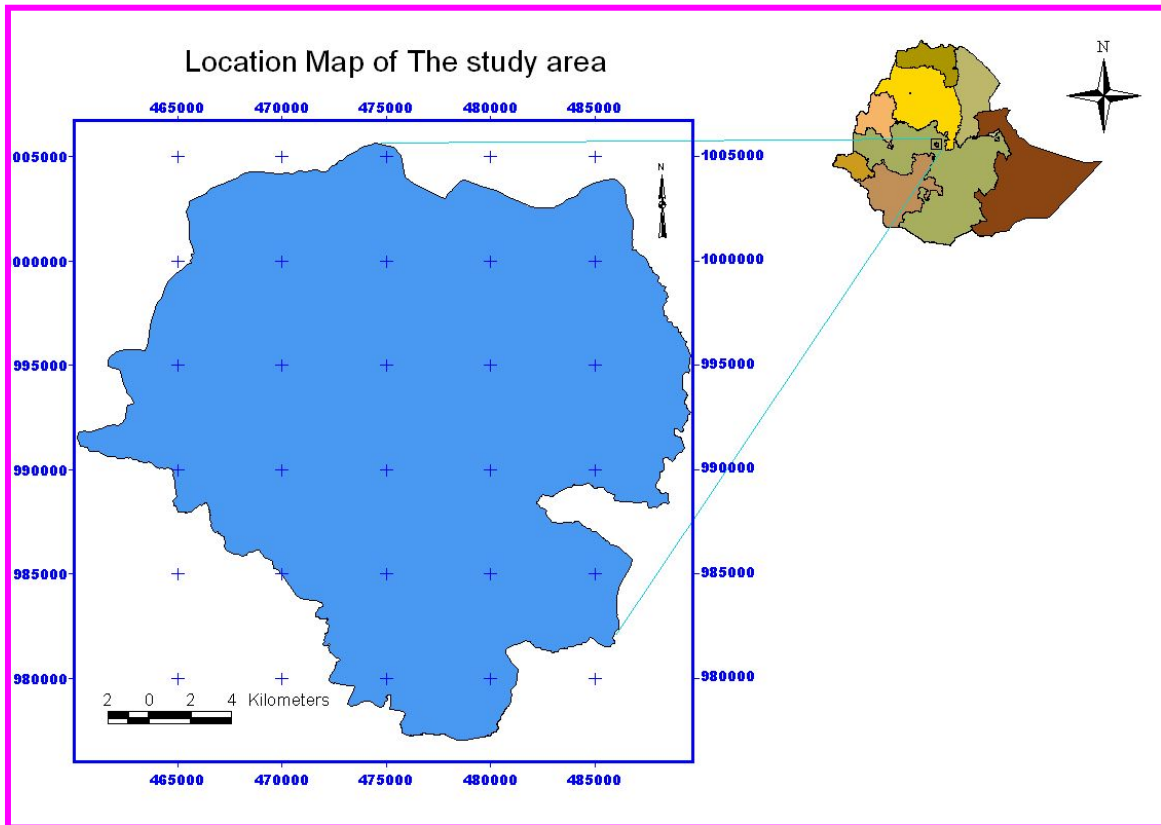


Figure 1 Location map of the study area

## 1.8 Climate

According to Daniel (1977) classification of Ethiopia's rainfall region, Addis Ababa is located in the region where the rainy months are contiguously distributed (Regime IE). In this region there are seven rainy months from March to September/and the small rains occur from March to May. The big rains are from June to September. High concentration of rainfall occurs in July and very high concentration in August. The highest mean monthly maximum temperature occurs in the months of March (24.56 °C) and the lowest is in the month of August (20.07 °C). While the mean monthly minimum temperature ranges, for the lowest from 7.47 °C in December to the highest 11.66 °C in the month of March. Thus, the average temperature of Addis Ababa (47 years data 1951-1998) is 16.02 °C.

For the past 47 years the lowest mean monthly temperature occurred in the months of November 1956 and January 1962, which was 4.7 °C; while the highest mean monthly temperature occurred in May 1958 and it was 28.2 °C. In Addis Ababa, generally the altitudes vary from 2000m to about 2400m a.s.l. And the mean annual temperature is 16.02 °C. This categorizes Addis Ababa under "Weina Dega" (Subtropical) climatic condition.

## **Chapter Two**

### **Literature Review and Previous works**

#### **2.1 Introduction**

Landfilling is a common solution for the final disposal of wastes in lower-income countries (Diaz and Savage, 2002 in Laura McNally, 2003), and a large majority of communities practice subsistence Landfilling or open dumping as their main method of waste disposal (Rushbrook, 1999 in Laura McNally, 2003). Recently, due to the growing urgency of urban environmental problems, solid waste management in lower income countries has attracted much attention (Schubeler, 1996 in Laura McNally, 2003) and there is now a movement toward landfills designed to increase environmental protection. However, many areas do not have a process and criteria or guidelines for landfill siting and design, and in some large areas, there has been a tendency to adopt guidelines or regulations of higher-income countries without modifying or adapting them to local conditions (Diaz and Savage, 2002 in Laura McNally, 2003).

This creates a problem because the development of engineered landfills involves complex engineering design and construction techniques. In addition,

sophisticated landfills typically have measures to control or use landfill gas, extensive environmental monitoring points, leachate collection and treatment systems, and require a highly trained work force. As such, the adoption of sophisticated engineered landfills can only occur where the local economy can afford the high level of expenditure required for construction and operation of the landfill and where the technical resources to achieve high standards of construction and operation are made available (Rushbrook, 1999 in Laura McNally, 2003). It is therefore important to ensure that when new landfills are sited, the construction and operational capabilities of the local communities are considered in developing sitting criteria so that environmental protection objectives can be met. For example, if the material and equipment needed for installing plastic landfill liners is not available within the country, and importing is beyond budget capabilities, an objective of landfill sitting should be to find sites with soil suitable for liner material, or sites with borrow material in the proximity. In addition to available financial and human resources, there are two other reasons why the design and operation of landfills in low-income countries can be different from those in high-income countries: the composition of the waste differs, and the climate of the area differs. The climates in low-income countries range from tropical to arid, and the potential for leachate production differs greatly in these two regions. In arid areas, there may be little or no leachate generated from waste, and thus site selection criteria and design requirements may be relaxed, and use of high-income country standards would result in unnecessary expenditure for sophisticated leachate collection and treatment systems (Rushbrook and Pugh, 1999 in Laura McNally, 2003). Johannessen and Boyer (1999) compiled a report of observations made during visits to over 50

landfills in Asia, Africa, and Latin America in 1997-1998. The report identifies emerging features, practices, and necessary improvements in solid waste disposal. One operational issue common to all areas was problematic or inadequate leachate management measures. They indicated that the economic and environmental impacts of poor leachate management practices on groundwater and surface water were not clearly understood. Also, the costs of leachate management for the lifetime of the landfill, and management of leachate until it no longer poses threat to the environment were rarely included in the overall budget for landfill operations. A second concern was the use of low permeability landfill cover, which in some cases attributed to fifty percent of the operating costs. The concern with low permeability cover material is that it limits infiltration of water into the landfill, thus inhibiting the biodegradation of waste. This will result in a longer time for landfill stabilization, and thus a longer period of leachate generation and longer potential pollution period from the landfill. A recent review of the design and construction of engineered landfills in Thailand by Ashford and Visvanathan (2000) found that sites selected for landfills were often not ideal areas for locating waste disposal facilities. The sites selected were often those unsuitable for and thus passed over for other development purposes. At most of the sites, groundwater levels were between 1 and 2 meters below the ground surface, and some landfills had experienced major flooding in past years. It is evident that there is much room for improvement in environmental protection in Landfilling of municipal solid waste in lower-income countries. Although the awareness of potential environmental impacts is increasing, the knowledge of the relationship between landfill sitting, design, construction, and operation of landfills and potential environmental impacts is not fully understood. Imposing

landfill standards such as those used in high-income countries may be desirable; however, the use of such standards requires a comprehensive knowledge of landfill characteristics, such as leachate and gas generation, and high construction and operating costs. The use of such standards without a complete understanding of the potential environmental impacts of landfills can lead to large expenditures that provide a false sense of environmental protection. The case in Thailand, where the use of sophisticated liner systems may be perceived as providing groundwater protection, but failure of the liner system would result in a potentially hazardous situation, is an example. In addition, high-income countries often have standards for leachate treatment that may not be attainable in low-income countries due to technological and economic constraints. As mentioned above, leachate treatment was one of the most problematic operational issues. As such, it is important that an appropriate landfill site provides environmentally acceptable properties for a long-term leachate management strategy that is feasible, technologically and economically, for the community.

When seeking to improve solid waste management practices, one of the key issues to be addressed is environmental protection. For landfills in particular, this requires appropriate siting, design, construction and operation of engineered facilities. Perhaps the greatest environmental concern associated with Landfilling is the risk of water contamination, which can have adverse effects on both people and the environment. As such, engineered landfills focus on protection of water resources through measures such as control of surface water, installation of landfill liners and removal and treatment of Leachate from the landfill. To achieve this requires consideration of necessary site criteria when choosing a landfill

location and careful attention to detail in design and construction to avoid or significantly reduce future environmental problems.

In low-income countries, affordability of environmental controls may be one of the barriers to engineered Landfilling. Through proper site selection, however, the overall cost for environmental controls can be reduced. By choosing sites with natural protection against adverse impacts and sites where the release of contaminants into the environment will have the least impact, the required level of engineering can be decreased, leading to a decrease in construction and operation costs. Thus, in order to protect water resources, it is important to consider site characteristics and their interrelationship with the design and construction of landfills during the site selection process. This chapter provides a literature review of landfill siting processes, and outlines a step-by-step process, adapted from the literature, that considers design and operational aspects of landfill siting, specifically for water resource protection.

### 2.1.1 Landfill Site Selection Process

Landfill site selection is an important step in implementing a waste management program. Proper siting can contribute to a reduction in design, construction, and operating costs, as well as help to minimize environmental impacts. From an environmental engineering perspective, an important objective of the process is to select a site that will provide the greatest public health and environmental protection in the event of landfill containment failure by making the best use of the land resources available (Qian, et al., 2002 in Laura McNally, 2003). To ensure that an appropriate site is chosen, a systematic process should be developed and followed (Rushbrook and Pugh, 1999 in Laura McNally, 2003). Unsuccessful landfill siting is typically the result of strong public opposition, and much research has been conducted to explore reasons for siting failures and to recommend changes in siting procedures (Baxter, et al., 1999 in Laura McNally,

2003). As such, it is important that an appropriate method be used so that the process results in the selection of a site that meets social, environmental and economic criteria. Lawrence (1996) identified three major siting approaches: the environmentally suitability approach; the social equity approach; and the community control approach. The basic idea behind each of these three approaches is as follows:

- Environmental Suitability Approach

This approach follows a rational planning process through which alternatives are identified, screened and compared. The goal of the process is to minimize the negative and maximize the positive environmental effects of the project. There are typically three major stages in the process: area screening and identification; site screening and identification; and finally, site comparison. There are many different qualitative and/or quantitative evaluation methods that can be used for screening and comparing site alternatives. The process and level of detail used can be designed to reflect project types and regional needs and characteristics (Lawrence, 1996 in Laura McNally, 2003).

- Social Equity Approach

This approach focuses on fairness in the planning process, and a fair distribution of facilities, costs and benefits among stakeholders. Direct involvement of all interested and affected parties is considered essential. Equity concerns have only recently been incorporated into landfill siting processes (Lawrence, 1996 in Laura McNally, 2003).

- Community Control Approach

This method uses a high degree of process and outcome control by interested and potentially affected parties. Proponents of the landfill and community groups work together to make decisions. There are various ways in which the community can have control over the process: procedural control on the structure and

implementation of the siting process; location control, or the freedom to choose whether or not to accept a site; and facility control, the control over the need for, size and operation of a facility (Lawrence, 1996 in Laura McNally, 2003). Each of these approaches can be applied in a variety of ways, and they can be combined in numerous fashions to suit the needs of the project. The success of landfill siting can be strongly influenced by the choice and application of the siting method (Lawrence, 1996). When considering protection of water resources in the selection of a landfill site, the potential effects of the site on surrounding groundwater and surface water quality and quantity must be assessed (McBean, et al., 1995 in Laura McNally, 2003). This can be accomplished by applying a series of constraints and criteria in a systematic process, such as the environmental suitability approach mentioned above. A step-by-step approach offers the advantage of reducing the total amount of data to be handled and restricts the detailed analysis to few sites (Frantzis, 1993). This is extremely important due to the technical and financial requirements for obtaining site-specific data such as geological and hydrogeological conditions. The social equity and community control approaches are not as applicable for site selection based on technical requirements, as they tend to focus on social aspects and community participation. These approaches however, can be used for some aspects of the process, such as deciding on the importance or weighting of criteria or locally suitable constraints.

## **Terminology**

Before engaging in a discussion about landfill siting, it is important to clarify the difference between the terms used. "Objectives" of the landfill siting process describe the goals that are to be achieved. For example, an objective could be to

minimize construction costs, or maximize environmental protection. “Criteria” are sub objectives used to compare the suitability of potential sites (Shah, 2000 in Laura McNally, 2003) and measure how well the sites meet the objectives. Criteria should be chosen to minimize or eliminate the negative impacts associated with landfills (Noble, 1992 in Laura McNally, 2003). For example, to minimize construction costs, criteria may include maximizing use of native soil for liner material or maximizing use of existing topography to reduce earth-moving requirements. At the start of the process, regional criteria, such as the location of natural features, are used to identify potential sites. As the process continues, the level of detail increases and local, more site-specific criteria are used. “Constraints” are restrictive criteria that screen out areas considered unsuitable for use as landfill sites. They are often a minimum or maximum allowable level of a criterion; they can be a set of regulations enforced by the government, or constraints due to required site size or environmental conditions (Rushbrook and Pugh, 1999 in Laura McNally, 2003). For example, landfills must be located a minimum distance, stipulated by regulations, from residential areas. Data are used as a means of measuring the degree to which a site meets the criteria. For example, the permeability, thickness, and type of soil at the site will provide an indication of how suitable the native soil is for a landfill liner. Finally, the term “area” is used to mean the general location that may be suitable for a landfill during the early stages of landfill siting. The term “site” is used to describe a specific location that could potentially be used for a landfill.

## **A Landfill Siting in Lower-Income Countries**

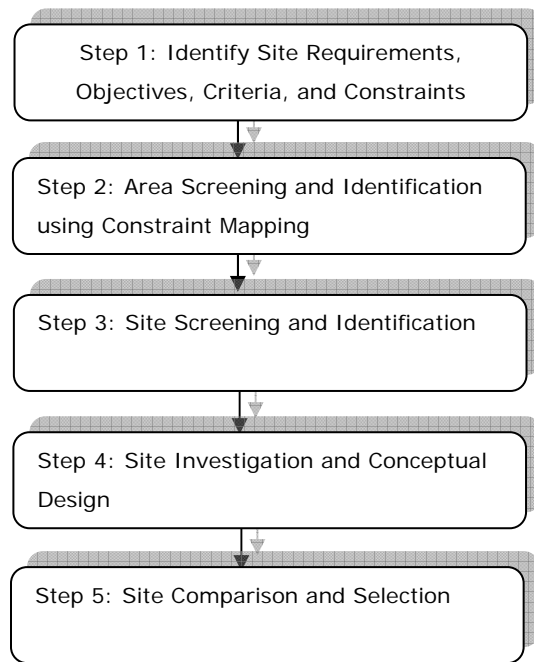
Siting and designing engineered landfills in low-income countries is a difficult task. Often, affordability of environmental control measures is a key issue.

Ideally, objectives for Landfilling in low-income countries should match corresponding objectives in high-income countries, and objectives for landfills serving large towns and cities should be the same as those for landfills serving small villages (Blight, 1996 in Laura McNally, 2003). However, the communities of small towns and villages in low-income countries usually cannot afford landfill design, construction and operation standards equal to those applied in large cities, and in some cases, large cities cannot afford to apply standards equal to those of high-income countries. Perhaps the first question to be addressed when siting a landfill is: What constitutes an appropriate level of environmental protection for the community? This will differ from community to community, and will depend on the climate in the area and the available resources for construction and operation of the landfill. Often, construction and operation resources are limited, and this must be reflected in the siting process. As was previously mentioned, Leachate management is one of the key issues in landfill management in development in low-income countries. Design, construction and operation of a Leachate control system often require the highest development cost, and its failure has the greatest potential to affect human health by contamination of water resources. As such, emphasis should be placed on siting landfills in areas that provide natural protection of water resources in order to reduce the costs and risks associated with landfills. There are little literature available covering technical aspects of landfill siting in developing countries. Two publications (Diaz and Savage, 2002; Rushbrook and Pugh, 1999 in Laura McNally, 2003) provide general guidance and criteria for a landfill siting process, and a third publication (Blight, 1996 in Laura McNally, 2003) describes an approach for classifying landfills that allows the use of graded standards. The

following landfill siting process has been adapted from a World Bank publication by Rushbrook and Pugh (1999), with additional information from other sources as noted. Water resource related criteria have been highlighted for each section. Following the discussion of the landfill siting process is a description of the application of graded standards for Landfilling in lower income countries.

## B Steps in the Landfill Siting Process

The following flow chart provides an overview of the steps in the landfill siting process:



### **Step 1: Identify Site Requirements, Objectives, Criteria, and Constraints**

The first step in the process is to identify the landfill requirements (site size, etc.) and determine the objectives, constraints and criteria to be used in the process. For example, one objective may be to minimize the risk of groundwater contamination. One of the criteria may be to maximize the depth to the water table, with a constraint that the water table must be, for example, 1.5 m below the base of the landfill. Once the criteria and constraints are established, the data requirements can be determined. The search area must also be defined. This will be influenced by for example, an acceptable travel distance from the city, or

administrative boundaries. In some cases, neighboring communities may wish to work together or be host communities for landfills.

### **Step 2: Area Screening and Identification using Constraint Mapping**

An important element of a successful landfill siting process is evaluating the basic suitability of all available land for Landfilling to aid in the selection of a limited number of potential sites for more detailed evaluations. This should be practical, taking into consideration the resources and constraints of the government agencies and consultants involved in the process (McAllister, 1986 in Laura McNally, 2003). As such, it should be based on published data, such as topographic maps, aerial photographs and official development and zoning plans, and not requires fieldwork. **Constraint mapping** is a commonly used technique that involves creating a series of maps to show the areas identified as unsuitable for Landfilling based on each of the constraints. When the maps are overlaid, the potential candidate sites can be easily identified (McAllister, 1986 in Laura McNally, 2003). Recently, geographical information systems (GIS) have been used to facilitation landfill siting. GIS can be used to convert geo-referenced data into computerized maps and map analysis tools can be used to manipulate maps in an efficient way (Kao et al., 1997 in Laura McNally, 2003). This is especially useful when dealing with large amounts of data, which is typical in landfill siting. The outcome of this step is a long list of potential candidate sites. Typical constraints relating to water resource protection are:

- Landfills should not be constructed in areas with fractured bedrock, karst topography, etc. to ensure groundwater protection.
- Water bodies (lakes, streams, wetlands, etc.) are not suitable for landfill development.

- Areas with complex geology are not suitable as it will be difficult to monitor and remediate in the event of groundwater contamination.
- Landfills should not be sited in protected areas such as forests, wetlands, and endangered species habitats.
- Landfill should not be constructed in the floodplain of a river or other areas susceptible to frequent flooding.

This step may require iteration, as the constraints may need to be relaxed if too few areas are identified, or further constraints applied if too many or too large of areas are identified. The level of constraints used depends on the minimum level of criteria and will vary depending on local regulations and attitudes. For example, a constraint can be applied that screens out surface water bodies, or, the constraint can screen out areas within a minimum “acceptable” distance from water bodies, for example, 500 m. In addition, this step can be divided into two steps, applying a general set of constraints to the entire search area, and then applying a second, different set of constraints for the remaining area. The purpose of this is to reduce the data required to apply the second set of constraints by reducing the area.

### **Step 3: Site Screening and Identification**

In this step, the areas identified from the constraint analysis are evaluated and compared in order to identify potential sites suitable for Landfilling. The objective is to reduce the number of sites to an appropriate number for detailed comparison in the next step. Rushbrook and Pugh (1999) recommend reducing the number of candidate sites to three; however, it may be practical to consider more than three sites. The key issue to keep in mind is that in the next step, each site will require detailed data collection, which is time consuming and costly; thus,

given time or budget constraints, comparing many sites may not be feasible. The data used to compare and evaluate the sites in this step is usually based on published data, and walk over or field surveys if required (IWA, 1992). Walkover surveys may not be required if published sources provide enough data for site comparison. Site investigations can also be used to confirm published information. A consistent approach can be achieved by using a checklist of points, and a suitability matrix to compare various aspects of the site. Ideally, potential sites should be identified based on the full set of criteria established in step 1. This will include the water resource criteria, as well as social, land use, infrastructure, etc. criteria. In reality however, the data required to identify potential sites using all criteria may be general or not available at all. Thus, this step will require judgment by those trained in the areas of geology, hydrogeology, and hydrology, to identify potential sites that meet water resource related criteria based on the data available and site walk over surveys. If this step results in the identification of many potential sites, they must be compared based how well they meet criteria using the available data in order to reduce sites for further consideration to a reasonable number. Using a matrix to compare the sites for each criteria and then selecting a few of the most suitable sites for further consideration can accomplish this. Alternatively, there may be further criteria used to identify sites, such as the travel distance from the city. For example, sites within a 20 km travel distance may be preferred, and thus, sites further will be excluded from further consideration, unless a suitable site cannot be identified within the 20 km distance. Finally, if this step fails to identify potential sites, either the constraints used in the first step must be relaxed or the search area must be increased, or both.

#### **Step 4: Site Investigation and Conceptual Design**

In this step, detailed data are collected for each candidate site and basic designs are completed. Site investigations should be designed to confirm published data, and collect data required measuring how well each site meets the criteria. To fully understand how each site may affect water resources, subsurface exploration and topographic surveys are carried out at the candidate sites. Designs are then completed to the point where approximate cost estimates can be made for comparative purposes. For example, the resources needed to install and operate a Leachate control system would be estimated. This requires formulating a Leachate control strategy for the site, including Leachate treatment and discharge options, monitoring programs requirements, etc. Other aspects to be included are liner design, daily and final cover, requirements for an environmental monitoring program, and site preparation (earth moving, road construction, etc.). The estimate can be used to develop “cost per cubic meter of waste” for each design component considered. Several design alternatives for a site that result in a range of site suitability based on the criteria may exist. This may also result in a range of construction and operation costs. For example, a site with permeable native material can be designed with or without a liner. A site without a liner will provide less protection against contamination of water resources, but will be less costly to build, as the liner material is not required and construction costs are decreased. However, if groundwater becomes contaminated and has an impact on groundwater use, thus requiring remediation, the operation costs will increase. Conversely, constructing the site with a liner will be more costly, but will decrease the risk of groundwater contamination, and the risk of future remediation requirements. Considering design alternatives for a site

will allow the tradeoffs between the level of design and the level of environmental protection to be analyzed.

### **Step 5: Site Comparisons and Selection**

This step involves a detailed evaluation and comparison of the candidate sites. This requires comparing the data collected from site investigations and published sources, and conceptual designs to determine which site best meets the criteria. Often, this is achieved by weighting and rating criteria (McAllister, 1986 in Laura McNally, 2003). With this method, the weight of each criterion is determined according to its relative importance and each site is rated for each criterion. The method used for rating does not necessarily need to be the same for all criteria. Numerical ranking such as a scale of 1 to 10, or a qualitative ranking such as high, medium or low can be used. For example, a site with no groundwater resources underlying the landfill may receive a rating of 8, or high acceptability, and a site with groundwater resources less than 5 m below the landfill may receive a rating of 3 or low acceptability. Sites are also being compared based on the conceptual design, and more than one design alternative may be considered for a site. A matrix can be used to compare all the sites based on the criteria by filling in the ratings, such as shown below.

Table 2-1: Site Comparison Matrix Site

Criteria	Site suitability		
	Site A	Site B	Site C
Maximize depth to water table	High	High	Low
Minimize risk of flooding	Medium	Medium	Low
Minimize permeability of underlying geology	High	Medium	Low
Cost of linear construction	Low	Medium	High

In the above example, Site A has soil with low permeability that is suitable for a landfill liner, and therefore the cost for liner construction is low. However, there is a risk of flooding which will need to be addressed in the landfill design, and could lead to increased construction costs. Site C does not have a suitable soil for a liner, increasing the construction costs, and the water table is closer to the ground surface, thus increasing the risk of groundwater contamination. However, the risk of flooding at Site C is low. With respect to water resource protection, Site A would be more suited to minimizing the risk of water contamination, if the risk of flooding can be addressed in the landfill design. The above process provides an effective, systematic way to assess the suitability of sites for environmental control and cost of implementing the control systems. A more formal approach to dealing with tradeoffs between environmental controls and cost is to apply graded standards or minimum acceptable standards that provide guidance for situations where the level of environmental control can be relaxed. These are discussed in detail in the following section.

### **C Graded Standards for Landfill Siting**

In some cases, smaller communities lack the resources available in larger communities for waste management. Smaller communities also generate less waste, and therefore have smaller landfills. Thus, the smaller communities may not be able to meet strict standards. However, environmental risks associated with small landfills are less, and if sited properly, small landfills may not need to meet strict standards in order to provide an acceptable level of environmental protection. Blight (1996) has developed a set of graded standards that are used in South Africa for landfill requirements. Rushbrook and Pugh (1999) have

provided guidelines for minimum acceptable standards of design and construction of landfills depending on the level of groundwater protection required. The following is a review of these two methods.

Blight (1996) has identified the following three factors that can be used to determine what level of standards apply in a specific area:

1. Waste Type: Waste composition may be very different – e.g. proportion of biodegradable components may be vastly different, resulting in different Leachate characteristics. Waste with a high biodegradable content is likely to produce Leachate with higher BOD and COD. The waste type is classified based on amount of biodegradable content, allowing relaxed standards for low-biodegradable waste.

2. Landfill Size: Waste generation rates may be smaller by a factor of 3 or 4, due to differences in climate, diet, culture, and type of fuel. If less waste is produced, landfills of the same age will be smaller, or landfill life will be longer, and therefore have a smaller source of pollution potential. The size of the landfill is classified by considering the maximum rate of deposition (tones of waste/year) or by considering the total volume that can be accommodated at the site. The landfill is then classified as communal, small, medium, or large, with higher standards applied to larger landfills.

3. Climate Characteristics: Climates in developing countries may be humid, where the potential for Leachate generation is high, or they may be arid, where the potential for Leachate generation is low. Climate characteristics are classified based on a climatic water balance to determine whether the site will generate significant amounts of Leachate, and therefore, whether or not Leachate collection system and landfill liners are required.

For details of the classification system. The process tends to be more useful for countries that have a range of climate conditions and waste characteristics. For example, a country may have the same climate throughout, and thus climatic considerations would be omitted. The same country could have the same waste composition throughout, and thus landfills could be classified based on size only. Graded standards could still be based on landfill size, especially in countries where funding for waste management in smaller communities is low. Minimum requirements can be outlined for each phase of a landfill project (siting, site investigation, environmental impact assessment, design, operation, closure, monitoring, etc.) for each combination of landfill type. The landfill classification method suggested by Blight could easily be adapted and made suitable for different countries. However, there may be resistance from regulatory agencies to allow graded standards, as they may wish to apply the same standards everywhere. In reality, if the standards cannot be met because of financial constraints, they may be ignored, so in fact, graded standards would ensure that some appropriate level of environmental protection is provided. In another approach, Rushbrook and Pugh (1999) have identified the following three levels of required groundwater protection:

- **Minimum** – where groundwater is already unsuitable for human or agricultural use, where its degradation will not impact on the local ecology, or where the local climate will prevent the generation of Leachate from any landfill. Although Leachate may not pose a threat to the environment, good management practices should still be implemented. Efforts should still be made to reduce surface water runoff entering the landfill; areas prone to flooding should not be selected, etc.

- **Intermediate** – where attenuate and disperse designs may be sufficient. Ideal conditions for attenuate and disperse sites are:
  - Low local groundwater recharge
  - At least 3 m of unfractured, unsaturated low permeability (i.e. clay, silt) material between the base of the landfill and the seasonably high groundwater table
  - High rate of groundwater flow with a high permeability (sandy) aquifer immediately below. This implies either a confined aquifer or relatively steep topography
  - Low importance of groundwater as a resource Once again, best management practices should be observed, and groundwater-monitoring programs should be in place to monitor Leachate migration from the site.
- **Maximum** – where full containment designs are needed to ensure minimal risk of groundwater contamination in areas where groundwater resources are in use or considered valuable. These sites have natural or constructed liners and Leachate collection and treatment systems to minimize the risk of groundwater contamination.

This approach, which applies on a site-to-site basis, can be very useful in step 4 to do the conceptual designs. Caution should be taken, however, in ensuring that enough data are available to adequately assess a site and determine whether, for example, an intermediate level of protection is sufficient.

Overall, it must be recognized that some areas will not be able to meet high standards and provide adequate protection against groundwater contamination. In these circumstances, every effort should be made to site landfills where the impact of groundwater contamination will be the least.

## **4 Objectives, Criteria, Constraints, and Data for Water Resource Protection**

This chapter discusses the development of criteria and constraints for landfill siting relating to water resources protection. When siting landfills in lower-income countries, data availability and data collection capabilities must be considered in parallel with setting criteria and constraints. In some cases, it may not be possible to obtain information required to measure how well the candidate sites meet a criterion, and thus, either a surrogate measure must be used, the criterion must be adapted so that it may be measured, or the criterion may not be used at all and the decision must be made without the information. The objectives of developing water resource related criteria in this paper were: firstly to ensure that the criteria cover all aspects that should be considered for water resource protection; secondly, that the criteria and data requirements reflect the needs and address important issues in Ethiopia. Finally, as much as possible, potential data sources in Ethiopia and constraints or regulations relating to the criteria are discussed.

### **4.1 Objectives for Water Resource Protection**

In the first step of the landfill siting process, the objectives must be determined, and from the objectives, criteria (sub-objectives) will be established. In relation to the protection of water resource, three major objectives have been identified. They are:

**1. Minimize risk of groundwater contamination** - This is critical for protecting groundwater supplies, and thus public health, in areas where there are water supply well. There may also be underlying aquifers that may be a future water supply source. In addition, groundwater may flow into surface water bodies, thus,

creating another potential pathway for contamination, and potential hazard for public health.

2. *Minimize effects on surface water and sensitive areas* – In many areas surface water is used as a source of domestic water (drinking, bathing, etc.), and for agricultural purposes (irrigation and livestock). Surface water contamination by landfill leachate can be harmful to human health and agriculture, and can be transported to areas downstream of the immediate landfill area. As such, the potential for surface water contamination should be minimized.

3. *Minimize construction and operation costs related to water resource protection* – Protecting groundwater and surface water from contamination requires use of landfill liners, and leachate collection and treatment systems. These systems can be costly to construct, operate and maintain.

## **D Criteria**

Criteria are sub objectives that are used to measure how well each site meets the above objectives. In addition to criteria, constraints can be used to place restrictions so that sites meet specified minimum levels. The criteria discussed in this section include, directly or indirectly, all criteria suggested in the literature discussed above relating to water resource protection, and additional criteria that emphasizes the construction and operational aspects of landfills relating to water resources that are important for landfill siting. Selecting criteria should be an iterative process, and should allow for changes as necessary. Also included in this section is a discussion of suggested constraints related to the criteria. The criteria and constraints discussed herein should by no means be taken as a requirement for all landfill siting projects, but rather, should be used as a starting

point and a reference for projects, and should be adapted to suit local conditions and requirements.

#### **4.2.1 Objective 1 – Minimize Risk of Groundwater Contamination**

When considering the protection of groundwater, several criteria apply and the following must be addressed: geology of the area, groundwater conditions, and groundwater use in the area. Five criteria are suggested to address these, as discussed below.

**1.1 Maximize the depth to the water table** – In general, as the distance between the water table and the base of the landfill increases, the potential for water contamination decreases. This of course depends of the geological conditions. The elevation of the water table may fluctuate depending on the season, and thus, the seasonal high level of the water table should be the key level considered. Rushbrook and Pugh (1999) recommend that the seasonably high water table (e.g. 10-year high) be below the base of the landfill, and Diaz and Savage (2002) recommend that the 10-year high water table be at least 1.5 m below the base of the landfill. If leachate ponds or lagoons are to be constructed, their impacts on groundwater must also be considered.

**1.2 Minimize permeability of underlying geology** – Ideally, sites with low permeability soils should be used for landfills in order to slow the movement of leachate from the site. To provide an adequate liner, soil should have permeability less than  $1 \times 10^{-7}$  cm/s when compacted under field conditions, and should not be susceptible to loss in permeability when exposed to waste or leachate (Rushbrook and Pugh, 1999). Well-compacted clay is one of the most commonly used soils for landfill liners. It should be noted that clay can be fractured, and would thus not provide a suitable liner as fractures provide a pathway for leachate migration. Fractures in clay can be caused by a variety of

mechanisms, including historical desiccation and stress relief. The vertical profile of the underlying geology is also of concern, as the presence of fractured or porous rock will provide a pathway for leachate and landfill gas migration. Rushbrook and Pugh (1999) recommend that there should be no underlying limestone, carbonate, or other porous rock formations that would be ineffective barriers to leachate and landfill gas migration, where the formations are more than 1.5 m thick and present in the uppermost geological unit.

**1.3 Maximize distance to faults and fractures** – The presence of faults and fractures in the area of the landfill can provide a pathway for leachate and gas migration, and present difficulties in predicting and monitoring contaminant movement. This criterion differs from 1.2 in that it considers faults and fractures in the area, rather than at the specific site. Rushbrook and Pugh (1999) suggest that there should be no faults or significantly fractured geological structures within 500 m of the perimeter of the landfill.

**1.4 Minimize effect on aquifers** – This criterion differs from 1.1 in that it considers aquifers (current or potential water supply sources) in the surrounding area and the effects a landfill may have on water quality and quantity. In areas where landfills are constructed, reduced infiltration and diversion of precipitation may have an impact on aquifer recharge, especially for shallow aquifers. Shallow aquifers may be more susceptible to contamination because they are closer to the surface. The existing quality of groundwater in the area will determine the value of the groundwater as a resource. If the quality is exceptional, it is an extremely valuable resource, where as, if the quality is poor, it may be less valuable. For example, in coastal regions, groundwater may be saline and not acceptable for domestic or industrial use, thus the requirements for groundwater

protection may be reduced. In areas where aquifers are or will be used for water supply, the impacts of landfill construction on the aquifer should be thoroughly considered. Rushbrook and Pugh (1999) recommend that landfills should not be located in areas within the 10-year groundwater recharge area for existing or pending water supply development. They also suggest that designated groundwater recharge or sole source aquifer should be excluded from the area of potential landfill sites.

**1.5 Maximize distance to groundwater supply sources, and minimize the number of sources in the area** – Water supply wells down gradient of the landfill should not be affected. This is particularly important if there is no alternative water supply available in the event of contamination. The number or density of wells down gradient of the landfill should also be considered, as the impacts of groundwater contamination will increase as the number of wells increases.

#### **4.2.2 Objective 2 – Minimize Effects on Surface Water and Sensitive Areas**

Three criteria are suggested to assess the suitability of a site for minimizing the risk of surface water contamination and the effects on sensitive areas.

**They are: 2.1 maximize the distance to surface water bodies and protected areas** – In general, the greater the distance between the landfill and lakes, rivers, wetlands, etc., the lower the risk of contamination. Protected areas may include wetlands, forests, areas with protected species, etc., and may vary locally. Landfills should not be located at water bodies (this can be applied as a constraint) and a safe distance between the water body and the perimeter of the landfill should be established. For example, Diaz and Savage (2002) recommend that waste should not be placed into environmentally important wetlands with

significant biodiversity, and the perimeter of a site should not be located within 250 meters of protected forests. The site should be selected so that no known living or breeding areas of environmentally endangered or rare species are present within the site. Diaz and Savage (2002) also recommend the following minimum distances: 200 meters around ponds, marshes and swamps; 250 meters from flowing bodies of water less than 3 meters wide; 300 meters from flowing bodies of water greater than or equal to 3 meters wide. A safe distance may change from site to site depending on topography, use of the water body, etc. and should be adapted to meet local requirements.

***2.2 Minimize risk of flooding by maximizing the distance from the flood plain and avoiding areas susceptible to flooding***

– The potential for flooding at a site is an important consideration as floods can cause water contamination and increase the risk of landfill failure. Rushbrook and Pugh (1999) recommend that sites should not be located in the 10-year floodplain, and sites located within the 100-year floodplain must be amenable to an economic design that eliminates the potential for washout. Diaz and Savage (2002) recommend that landfills should not be located in the 25-year floodplain, with the same suggestion for sites located in the 100-year floodplain. The 10-year, 25-year, or other appropriate floodplain level can be applied as a constraint. In addition, low-lying areas that are subject to frequent flooding should be avoided.

***2.3 Maximize distance to downstream water supply sources and minimize the number of water supply sources***

– This criterion is similar to the criteria applied for groundwater supply sources. Again, landfills should not be sited upstream of water supply sources especially if there is no other source available in the event of contamination. This is most applicable in cases where leachate

will be discharged into rivers or streams, and could have potential impacts downstream.

#### **4.2.3 Objective 3 – Minimize Construction and Operation Costs Related to Water Resource Protection**

Six criteria that can be used to indicate site suitability for minimizing construction and operation costs relating to water resources are:

**3.1 Maximize suitability of native soil for landfill liner material. If native soil is not suitable, minimize distance to sites with borrow material** – Selecting a site with native material that is suitable for use as a liner is both convenient and less costly than construction of a liner. If the native material is not suitable, offsite material can be used to construct a liner at the site. Obviously, the cost of transportation of the material to the site is important, and as the distance increases, the cost will increase. A suitable liner material is clay or silty clay of low permeability (e.g.  $10^{-7}$  cm/s or less) and must be able to support the weight of overlying material.

**3.2 Minimize surface water diversion requirements** – Diversion of small surface water bodies increases construction costs, as does the amount of runoff that must be controlled at the site through the construction of ditches. Drainage ditches also require maintenance to control the accumulation of debris and maintain water flow. The position of the site in the watershed, and the size of the area upstream will affect the amount of runoff at the site. Areas with high slopes may have higher runoff potential, and thus require higher runoff management requirements.

**3.3 Maximize the use of existing topography to reduce earth-moving requirements** – Since leachate collection systems require a minimum gradient of 2%, gently sloped sites (e.g. 3 to 5%) are preferred. This will reduce the amount of earth moving required during landfill construction, thereby reducing the overall costs.

**3.4 Minimize cost and maximize ease of leachate collection, treatment, and discharge** - Since installing and operating a leachate collection and treatment system can be very costly, a preliminary leachate management strategy should be used to compare the costs for candidate sites. Leachate quantities can be estimated using climatic water balance. Regulatory requirements, such as leachate discharge standards and surface water body monitoring requirements must be considered. The type of leachate treatment system to be used and the operation costs, during the operation of the landfill as well as post closure, and technical requirements must be thoroughly considered.

**3.5 Maximize ease of implementing a monitoring system** - Landfill sites need to incorporate a monitoring system to enable failure of environmental controls, and thus contamination, to be detected. The location of the landfill should allow for the construction of a monitoring system to detect pollutants, and for their containment and management in the event of releases. Areas with complex geology and groundwater conditions, such as karst topography (soluble limestone, presence of underground streams, caverns, etc.) may be difficult to monitor, and in the event of contamination, difficult to remediate.

**3.6 Minimize risk of landfill failure** – Since landfill failure can be costly to remediate and can cause significant environmental damage, effects of natural hazards (floods, landslides, earthquakes, storm events, etc.) and the costs

associated with constructing landfills to withstand such events should be considered. Areas prone to subsidence (e.g. due to dissolution of limestone and the formation of sinkholes), areas with collapsing soils (loess) and areas with high slopes (high risk of erosion and potential failure) may not be suitable for landfill construction.

### **4.3 Interrelationship between Criteria**

Many of the criteria outlined above are interrelated and satisfying one criterion may result in another criterion being satisfied, or may make another criterion less important. For example, if the soil at the site is a low permeability clay, the depth to the water table may become less important in deciding site suitability, provided that the constraints, or minimum criteria (e.g. seasonably high water table is 1.5 m below the base of the landfill) are met. A site with a low permeability clay soil satisfies two criteria – 1.2 and 3.1 - which both relate to permeability of underlying soil; in 1.2 for the protection of groundwater resources, and 3.1 liner construction costs. Another example is the relationship between 2.2 and 3.6, which both consider floods, the former relating to water quality, and the later to landfill stability and construction requirements. Due to overlaps in the criteria, there are also overlaps in data requirements. For example, for criteria 2.2 and 3.6, the location of flood plains is required. Although there is overlap between criteria, the purpose for using all of them is to ensure that all aspects related to water resource protection are considered.

### **4.4 Constraints**

Constraints are conditions that make an area unsuitable for landfill construction, due to regulatory requirements (e.g. standards), physical requirements, or to

ensure minimum levels of the landfill siting criteria as discussed above.

Constraints relating to water resource protection are summarized below.

- The seasonably high water table must be below the base of the landfill.
- Landfills should not be constructed in areas with fractured bedrock, karst topography, etc. to ensure groundwater protection
- Areas with complex geology are not suitable as it will be difficult to monitor and implement contingency plans
- Water bodies and protected areas (lakes, streams, wetlands, etc.) are not suitable for landfill development
- Landfill should not be constructed in the floodplain of a river or other areas susceptible to frequent flooding, or in unstable areas.

It should be noted that ensuring the minimum distance from wells does not ensure that the wells will not be impacted by the landfill, as this is highly dependent on local hydrogeological conditions. As such, minimum distances should be used for constraint mapping purposes, and the further analysis of the potential impacts of a landfill on surrounding wells should be conducted as part of the site investigation.

#### **4.5 Data Requirements**

Data availability is one of the key requirements for site comparison. The difficulty in comparing sites based on suitability for water resource protection is that there is a large variety of geologic and hydrogeological conditions and it may be difficult, time consuming, and expensive to investigate all areas. In order to ensure that the appropriate data are collected and to avoid collecting unnecessary data that can waste both time and money, a method that enables the strong and weak points of a site to be highlighted is required. This is in part

established by setting criteria that can be measured based on readily available data, obtained from published sources and walkover surveys. This type of data includes the location of surface water bodies, wells; protect areas, site topography, etc. There are however, important criteria, specifically relating to geological and hydrogeological conditions that require site-specific data. As this type of information is typically not readily available in most areas, an effective strategy for site investigation and data collection is required. This subsection outlines data requirements and provides guidance for key data to be collected.

Some of the data listed, such as location of water bodies and water supply sources do not require further discussion, as this information should be easily obtained. Data such as past storm events will either be recorded and available, or not. In the later case, sites will have to be compared without this information. Other data requirements, however, are critical for indicating site suitability. These may not be available or may be costly or infeasible to obtain, and thus require further discussion. They are:

***Location of the water table*** - Seasonal fluctuations in groundwater levels are common in many regions. It is the high position of the water table that is of concern when assessing the groundwater contamination potential of a landfill site. The greater the distance from the base of the landfill to the groundwater table, the more favorable the site (LeGrand, 1980). Site-specific water table data can be determined from a site investigation; however, as it is not likely that past water table elevations will be available; this information will have to be inferred from other sources. Rainfall records may provide an indication of whether the current and past seasons have been average or above or below average. For example, if the past several years have been drier than average, the current

location of the water table may be lower than usual. Local residents who have wells may also be able to provide an indication of seasonal fluctuations in the water table.

***Characteristics of underlying geology*** – Knowledge of the underlying geology at the site is very important; however, site-specific geological data is not typically available, and thus must be found from site surveys. Permeability and sorption of the underlying material provide an indication of the amount of natural protection there is against contamination of underlying groundwater. Permeability provides an indication of the rate at which contaminants can move through the subsurface, and sorption capacity provides an indication of the natural attenuation capacity of the soil (LeGrand, 1980 in Laura McNally, 2003). Other important characteristics include: soil types, thickness of geological layers, and depth/thickness of aquifers. In many areas, general information regarding the type of soil or bedrock present at a site may be available. This information may be sufficient for area screening; however, when potential candidate sites are being compared it is recommended that a site investigation be conducted to confirm the geological characteristics of the site.

***Approximate slope of the water table***: The slope of the water table will indicate the direction of groundwater flow, and thus the area of potential groundwater contamination. It is important to note that if the slope of the water table is very low, or if mounding of the water table occurs, there may be radial flow of contaminated groundwater (LeGrand, 1980). Again, it is not likely that this information will be available for specific sites. Installation of wells can aid in determining the direction of groundwater flow. The wells can be used for several purposes – to determine the depth to the water table, direction of groundwater

flow, obtain samples of underlying material, and obtain water samples to test water quality.

***Locations of floodplains– Typically, floodplain maps are*** used to determine the potential for flooding; however, in some areas, floodplain maps may not be available. In this situation, the potential for flooding can be inferred from past records of flood events, or from discussions with residents in the area of the landfill.

Further to this list of key hydrogeological factors are data that are required in order to formulate preliminary Leachate management strategies for candidate sites. A Leachate management strategy should include options for Leachate collection, treatment and discharge. Leachate treatment options will depend on what methods are most feasible for the area. This requires knowledge of methods that have been successfully employed in other areas for leachate treatments, the approximate cost of these methods, etc. Factors that affect leachate treatment requirements, such as the standards that must be met for discharge to a specific water body, must also be considered. The relation of the leachate management strategy to the other criteria will become important when the criteria are weighed in the decision making process. For example, if it is decided that the best leachate management strategy is to “attenuate and disperse” leachate (this may be the best option for a small landfill with limited financial and technical resources) then criteria such as low permeability soil with a high sorption capacity, and maximizing the distance from wells, aquifers, and surface water bodies may be most important. When the candidate site comparison step of the process is reached, the sites must be compared based on the criteria and data collected. The decision made will be depend on the

importance placed on the criteria, and the conceptual designs for the sites. In some cases, there may be data that are not available to measure all criteria, and thus decisions must be made based on the information that is available. Also at this stage, tradeoffs must be made between sites for various criteria. For example, a tradeoffs may occur when one site is located a further distance from the city, and thus has an increased transportation cost, but has native soil suitable for a landfill liner, thus decreasing the construction costs and increasing groundwater protection compared with other sites. Applying criteria and data and discussing tradeoffs is best shown by examining an illustrative example. The following section presents a landfill-siting situation, and discusses the steps involved in the landfill siting process.

# Chapter three

## GEOLOGY

### 3.1 General

Many researchers systematically proposed the geology and volcanic stratigraphic sequences of Addis Ababa area. Haileselassie Girmay and Getaneh Assefa (1989) proposed the stratigraphy of the area starting from Sululta to Nazareth, based on Morton's geological map, unpublished student reports, K/Ar absolute age determination taken from different literature and fieldwork to clarify some geological uncertainties. They redefine the lithostratigraphic units and modified the existing stratigraphic sequence. The suggested Miocene-Pleistocene volcanic succession in the Addis Ababa area from bottom to top are: Alaji basalts, Entoto silicics, Addis Ababa basalts, Nazareth group, and Bofa basalts (Tamiru et al., 2005)

### 3.2 Regional geology

#### 3.2.1 LITHOLOGY/ STRATIGRAPHY

##### ◆ ALAJI BASALTS

The Alaji group volcanic rocks (Alaji rhyolite and Basalt) in this part of the escarpment were outpoured from the end of Oligocene until middle Miocene (Zanettin et al., 1974 in Tamiru et al., 2005). This unit is composed of basalts, which show variation in texture from highly pophyric to aphyric. Within this unit there is an intercalation of gray and glassy welded tuff. The outcrop of Alaji basalt extends from the crest of Entoto (ridge bordering the northern parts of Addis Ababa) towards the north (Haileselassie Girmay and Getaneh Assefa, 1989).

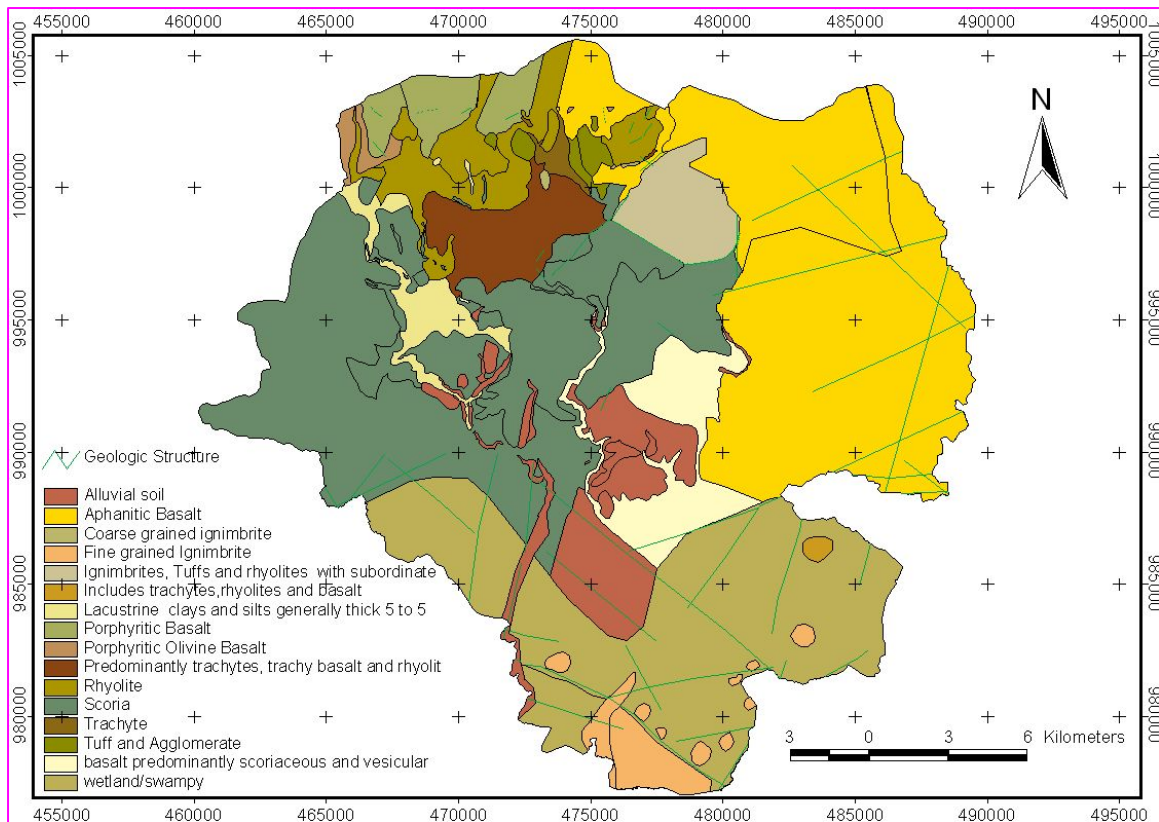
This unit is underlain by tuffs and ignimbrites; on the other hand its stratigraphic relationship with the Entoto silicics is difficult to determine as they occur in a fault contact. Mohr (1967) proved that the Entoto trachyte overlies the Alaji basalt. The age of the rock is 22.8 M.Y (Morton et. al., 1979 in Tamiru et al., 2005).

◆ **ENTOTO SILICICS**

These early Miocene age silicic volcanics could represent localized terminal episodes to massive Oligocene fissure-basalt activity in the Addis Ababa region (Morton et.al. 1979 in Tamiru et al., 2005). The thickness of the flow become maximum on the top of Entoto ridge and thin both towards the plateau and the plain east of Addis Ababa. According to Zanettin and Justin-Visentin (1974) these lavas make up a thick pile of flows accumulated along east west fissures (east-west fault running from Kassam river to Ambo) and uplifted northwards. The unit is unconformably overlain by Addis Ababa basalt on the foothill of Entoto and underlain by Alaji basalt. The Entoto silicics composed of rhyolite and trachyte with minor amount of welded tuff and obsidian (Haileselassie Girmay and Getaneh Assefa 1989). The rhyolitic lava flows outcrop on the top and the foothills of the Entoto ridge, predominantly in the western side. It also outcrops in the eastern part of the town from the Kokebe Tsebah School to the Benin Embassy. The thickness is quite variable as it frequently forms dome structure. In this rock unit flow banding, folding and jointing are common. The rhyolites are overlain by feldspar porphyritic trachyte and underlain by a sequence of tuffs and ignimbrites. Tuffs and ignimbrites are welded and characterized by columnar jointing. The rhyolite made up of phenocrysts of plagioclase and altered rebeekite in a groundmass of glass with iron oxide.

The trachytic lava flows outcrop on the top of Entoto ridge and its foothills. The thickness varies and reaches the maximum of 30m nearby Kotebe covering the rhyolitic lava flows. It shows a quite uniform texture, and is constituted by phenocrysts of oligoclase, sandine and rebeckite within a groundmass of plagioclase, iron oxide and minor quartz and mafic minerals. Two varieties of trachytic lava flows have been identified in the eastern side of the town, near Kotebe: a pale gray and a pink trachyte. The latter one is characterized by veins of hematized opal and by feldspar phenocrysts, which are often completely or partially altered with fine fractures filling of hematite (Varnier et al., 1985 in Tamiru et al., 2005).

The Entoto silicics are dated 21.5my by Morton (1974) and 22 my by Morton et al. (1979). Thus from the general stratigraphy established by Zaneitin et al. (1974) both rhyolite and trachyte of the Entoto silicics belong to the “Miocene Alaji Rhyolite and Basalt” sequences.



**Figure 2 Geological map of the study area (Source: Tamiru et al., 2005)**

- ◆ ADDIS ABEBA BASALT In the study area the oldest visible rock post-dating the Entoto silicic is the Addis Ababa basalt. These units, which are mainly present in the central part of the town, are underlain by the Entoto silicics and overlain by Lower welded Tuff of the Nazareth group. The maximum thickness exceeding 130 meters was found at ketchene stream. It is porphyritic in texture, composed of labradorite, - bytownite, olivine and augite as phenocrysts. The ground mass is made of andesine, labradorite, olivine, magnetite and pyroxene (Haileselassie Girmay and Getaneh Assefa 1989).

Olivine porphyritic basalts outcrop in the central part of the town that includes Mercato, Teklehaymanote and Sidist Kilo. The distribution of plagioclase porphyritic basalt is almost the same as that of the olivine porphyritic basalt, but only little more northwards. It outcrops in an area, which includes Sidist Kilo, General Winget School and French Embassy. The thickness of the former varies from 1m or less in the foothills of Entoto, Lideta Airfield and Filwoha to greater than 130 meters at Ketchane stream (Morton, 1974; Varnier et al., 1985 in Tamiru et al., 2005). The Lower Welded Tuff overlies both types of basalt nearby the Building College, the Kolfe Police School, the Kokobe Tseba School and YecaMariam Church. On the other hand, only in the gorge of the Ketchane stream the olivine porphyritic basalt is overlain by the plagioclase porphyritic basalt, while elsewhere the relationship between them is very difficult to determine (Varnier et al., 1985 in Tamiru et al., 2005). Addis Ababa basalt yield ages clustering around 7my and seems to have no time /composition equivalent (Morton et al., 1974 in Tamiru et al., 2005).

◆ **NAZARET GROUP**

The units identified in this group denoted as Lower Welded Tuff, Aphanitic basalt and Upper Welded Tuff. The group is underlain by Addis Ababa basal and overlain by Bofa basalts. The rocks outcrop mainly south of Filwoha fault and extend towards Nazareth.

◆ **Lower Welded Tuff**

This rock outcrops as small discontinuous body in Filwoha, western parts of Addis Ababa and Sululta. It is glassy with abundant fiamme and has columnar

joints. Generally it is overlain by the aphanitic basalt and underlain by the olivine and plagioclase porphyritic basalt. The age of this rock as dated by Morton et al.

(1979) at Addis Ababa and Sululta is 5.1 and 5.4 million years respectively. This age overlap with the period of the activity of Wachecha trachyte volcanoes, dated 4.6 million years. Wachecha is located 15 km west of Addis Ababa and probably the sources of the Lower welded tuff at both localities (Morton et al., 1979 in Tamiru et al., 2005).

◆ **Aphanitic Basalt**

This basalt covers the southern part of the town, especially the areas of Bole International Airport and Lideta Airfield. The rock body shows vertical curved columnar jointing together with sub-horizontal sheet jointing. Kaolin, lenses are present at the contact of this basalt with the younger ignimbrite. This is sure evidence for the hydrothermal alterations along a NE-SW fracture system, which may affect both the basalt and the Entoto trachyte. Moreover the basalt is overlain by pumaceous pyroclastic falls and the pyroclastic falls. It is underlain by a soil horizon that covers the plagioclase porphyritic basalt and overlain by soil horizon and tuff layers that lie below the young ignimbrite. It consists of: Labradorite, augite, rarely olivine and magnetite. The crystals of plagioclase show marked flow alignments. The age of the basalt in Addis Ababa ranges from 3.4 to 3.6 million years (Morton, 1974).

Trachy-basalt outcrops around Repi and nearby General Wingate School. 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. Its

relation with the rocks of the group is not clear, but probably younger than the aphanitic basalt (Getaneh et al., 1985 in Tamiru et al., 2005). Moreover, phenocrysts that occur mainly in the rock are: sandine, labradorite, magnetite and augite.

◆ **Upper Welded Tuff**

This rock outcrops all over the southern part of the town including Bole, Nefas Silk and Railway station; nevertheless it is also present in the central and northern parts of the town. It is gray colored, vertically and horizontally jointed and composed of sandine, anorthoclase, rebecite, quartz, pumice and unidentified volcanic fragments (Getaneh Assefa et al., 1989 in Tamiru et al., 2005). The welded tuff is underlain by aphanitic basalts and overlain by young olivine basalts. An age determination made on a sample collected near by Haile Gebreselassie road resulted 3.2 million years, that overlap with the activity of Yerer trachytic volcanos (Morton et. al., 1979 in Tamiru et al., 2005).

◆ **Young Trachytic Flow**

This rock is predominating in the southwest part of the town, from Dama hotel towards Furi and Repi along the hills and foothills of Hana Mariama and Tulu lyou. It is porphyritic with phenocrysts of plagioclase (albite-oligoclase) sandine, biotite within a groundmass of microlites of feldspar.

Moreover, it is underlain by the tuff that covers the young ignimbrite and overlaying by alternating flows of plagioclase porphyritic basalt and rhyolite especially in the Repi hill. Its relation with the young olivine porphyritic basalt is not clear as they outcrop in different parts of the areas; however, in a small outcrop nearby Aba Samuel Lake south of the Study area, the trachyte underlies the olivine porphyritic basalt.

◆ **Young Olivine porphyritic basalt**

They outcrop southward from Akaki River where they appear in the form of boulders reaching a thickness of 10 meter. They are restricted and dominant in the southeast part of the town i.e. Debre Zeit Road. They contain phenocrysts of plagioclase, olivine that is partially and completely altered to iddingsite and augite within a groundmass composed of plagioclase magnetite pyroxene and olivine. This basalt is underlain by the tuffs, which cover the welded tuff. The age of this basalt is 2.8 MY.

### **3.2.2. GEOLOGIC STRUCTURES**

In the study area the occurrence of faults, joints and other structures within the different volcanic rocks were reported by different authors. Long fault line running east west via Kassam river, Addis Ababa and Ambo, cut across the western rift escarpment and uplifted its northern block (Zanettin et al., 1978 in Tamiru et al., 2005) at about 8 My ago. This fault marks the upper (outer) boundary of the western Ethiopia Rift margin immediately north of Addis Ababa-Ambo road (Zanettin et al., 1974 in Tamiru et al., 2005). The Entoto silicics confined along this fault and form a ridge. This ridge bounded the city in the northern direction. The fault has a down thrown to the south in the Addis Ababa area (Haileselassie Girmay, 1989). Another prominent normal fault in the city is the Filowha Fault. This fault has a trend of NE-SW (Kundo, 1958; Morton, 1974; Haileselassie Girmay, 1989). The fault has a northwest down thrown side according to Morton (1974). However, Haileselassie (1985) carried out detail mapping of the Filowha Fault using resistivity method and found that the fault has down thrown to the south, shallow depth and covered by very thin soil layer (1-4m).

Haileselassie Girmay (1989) found that the fault is not vertical and its throw can be estimated to be about 40m, which is approximately the thickness of the welded glassy ignimbrite. This fault has acted as a dam to the welded glassy ignimbrite, but not to the basalt as it was assumed previously. For this reason there is quite different geology in the south and north parts of the area. Thus, the age of the fault may be bounded by 5.0My (the age of the welded glassy ignimbrite) and 6.4My (the age of plagioclase-phyric basalt).

Kundo (1958) proposed that the hot springs in Filowha are controlled by this fault. The presence of hot springs, south of the fault gives resistivity contrast on the either side of the fault.

The Filowha fault, having a trend of N55OE (Haileselassie Girmay, 1989) is thought to be a major NE fault that continues up to Debre Berehane (Mohr, 1964). Moreover, AI consult (1996) interpretation map indicates the continuation of the Filowha fault towards the southwest periphery of the city in the same direction.

Morton (1974) map shows four other northeast trending faults, which have southwest and northeast down thrown side.

The other major structural feature in the study area is joints, which have different spacing, opening and orientation. The dominant preferred orientation of joints occurring in different rock unit is NNE-SSW (Kebede et al., 1990 in Tamiru et al., 2005), which is sub parallel with the general trend of rifting. They found joint spacing of 15-200 cm (in most basalt), 5-100 cm (in trachy basalt, trachyte and rhyolite) and 2-100 cm (in ignimbrite)

# Chapter Four

## Geomorphology and Hydrogeology

### 4.1 Geomorphology and land use

Addis Ababa is located on the shoulder of the Western Main Ethiopian Rift Escarpment. The morphology is a direct reflection of the different volcanic stratigraphic successions, tectonic activities and the action of erosion between successive lava flows (tamiru et al., 2005)

The city was founded at the southern flank of Entoto ridge (3199m a.s.l.) and expanded in all directions. This ridge marks the northern boundary of the city following the east-west trending major fault (Ambo-Kassam). Other prominent volcanic features surrounding the city are Mt. Wochacha in the west (3385m a.s.l.), Mt. Furi (2839m a.s.l.) in the southwest and Mt. Yerer (3100 a.s.l.) in the southeast.

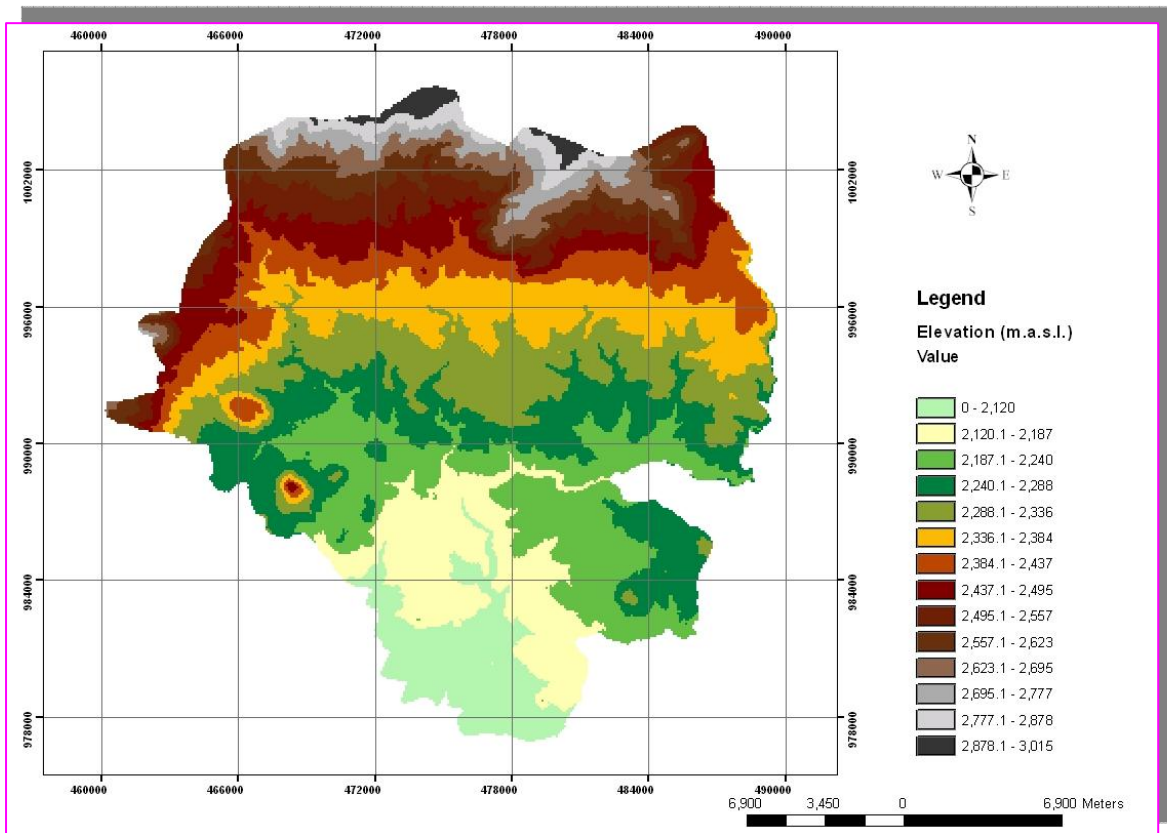
These typical volcanic features are mainly built up of acidic and intermediate lava flows. Thus, they are characterized by rugged landscapes and steeper slopes. The general inclination of the slope becomes lower towards the southern part of the Study area.

The center of the city lies on an undulating topography with some flat land areas. The topography is undulating and form plateau in the northern, western and southwestern parts of the city, while gentle morphology and flat land areas characterize the southern and southeastern parts of the city. Moreover, it is not uncommon to see sharp changes in the inclination of the slope and some flat land areas in different parts of the city. On the top of the hills and ridges streams are dense and form radial drainage pattern, whereas on the slope and most parts of the study area they form dendritic features.

The climatic condition and topography of the study area favors the development of thick soil profile by the decomposition of rocks on which it lies. Thus, residual soils are commonly seen in most parts of the city with varying thickness. On the other hand, due to intensive erosional activities there is poor soil development (shallow soil profile) or patchy occurrences on most parts of the slope. The dominant type of soil in the southern parts of the city, where erosion superseded by deposition, is black cotton soil. Moreover, waterlogged areas are found in the central parts of the city around Filwoha, in the eastern parts of the city around Lamberet and in other different parts with small aerial extent.

In the surrounding of the urban parts of Addis Ababa, cereal crops like wheat, teff, barely and maize are cultivated seasonally. Vegetable farms on small plots of land on the terraces of the valleys are a common practice in different parts of the city. Besides, household plantations of different species (garden parks, road side vegetations etc.) and eucalyptus trees cover large parts of the city.

The foundation and expansion of Addis Ababa was associated with the rapid conversion of land from rural to urban uses more than anywhere else in the country. For the last one hundred seventeen years it has been noticed that there is an intensive conversion of rural land to urban development like buildings, transportation networks and facilities (airports and highways), recreation areas, reservoirs and other man made structures. The introduction of eucalyptus tree in the beginning of the century was partly due to the shortage of timber for residential houses at the time. At present eucalyptus tree covers most parts of the city and it is the main sources of firewood.



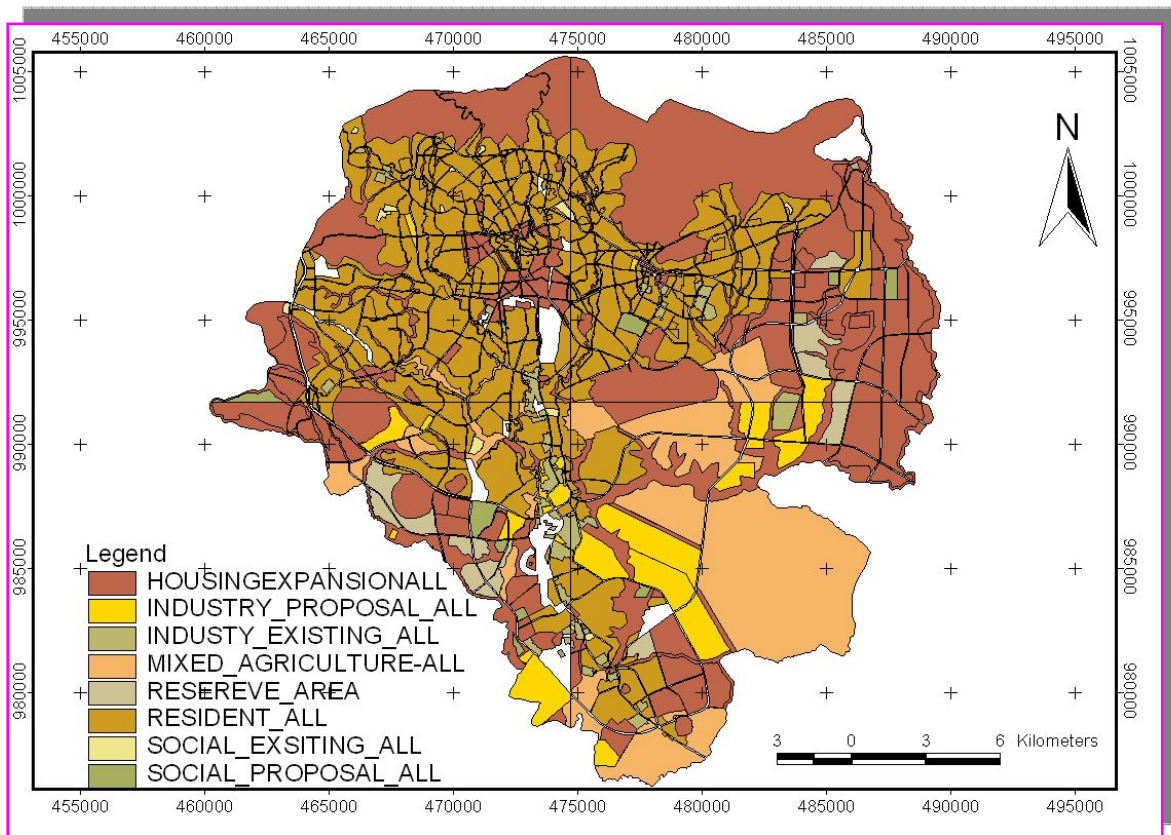
**Figure 3 Elevation map of the study area (Based on SRTM data of 2000 G.C.)**

The less controlled urbanization that includes construction of residential houses, commercial centers, transport infrastructure, various types of industry (which contains 65.32 % of the country industry), parks, and recreational areas covered most proportion in the urban parts of Addis Ababa.

Agricultural activities that include crop production, cattle breeding and planting trees covers the major proportion in the rural parts of Addis Ababa. Moreover, to satisfy the demands of construction materials, like dimension stone and

aggregates, hundreds of quarries are actively operating around the city. In some places of the city center old abandoned quarry site, having very steep and unsafe slopes, are commonly seen.

Since Addis Ababa is the capital city of Ethiopia, modern economic activities, social and infrastructural services are found relatively in a better situation than other cities of Ethiopia. However, its development is too slow to meet the demands of the increasing population due to both natural growth and rural-urban migration. In particular, the complete inadequacy of the solid waste management system is the major environmental problem in the city.



**Figure 4 Landuse/land cover map of the study area. (Addis Ababa City Administration)**

The following tables show the solid waste generation of the city

#### 4.1.1 Solid Waste Generation from Each Kifle Ketema for Years 2003 – 2012

Year	Population	Dally SW Generation			Yearly SW Generation			
		kg	ton	m <sup>3</sup>	kg	ton	m <sup>3</sup>	M <sup>3</sup> cumu.
2003	315,355	69,693	70	209	25,438,111	25,438	76314	76314
2004	327338	72,342	72	217	26,404,759	26,405	79214	155528
2005	339777	75,091	75	225	27,408,140	27,408	82224	237753
2006	352689	77,944	78	234	28,449,649	28,450	85349	323102
2007	366091	80,906	81	243	29,530,736	29,531	88592	411694
2008	38003	83,981	84	252	30,652,904	30,653	91959	503653
2009	39443	87,172	87	262	31,817,714	31,818	95453	599106
2010	409431	90,484	90	271	33,026,788	33,027	99080	698186
2011	424990	93,923	94	282	34,281,806	34,282	102845	801031
2012	441139	97,492	97	292	35,584,514	35,585	106754	907785

**Table 1 Arada Sub City (source: Addis Ababa city road Authority)**

Year	Population	Dally SW Generation			Yearly SW Generation			
		kg	ton	m <sup>3</sup>	kg	ton	m <sup>3</sup>	m <sup>3</sup> cumu.
2003	332,564	73,497	73	220	26,826,275	26,826	80479	80479
2004	345201	76,290	76	229	27,845,674	27,846	83537	164016
2005	358319	79,189	79	238	28,903,809	28,904	86711	250727
2006	371935	82,198	82	247	30,002,154	30,002	90006	340734
2007	386069	85,321	85	256	31,142,236	31,142	93427	434161
2008	400739	88,563	89	266	32,325,641	32,326	96977	531138
2009	415967	91,929	92	276	33,554,015	33,554	100662	631800
2010	431774	95,422	95	286	34,152,572	34,829	104487	736287
2011	448182	99,048	99	297	36,152,572	36,153	108458	844745
2012	465213	102,812	103	308	37,526,370	37,526	112579	957324

**Table 2 Addis Ketema Sub City (Source: Addis Ababa city road Authority)**

Year	Population	Dally SW Generation			Yearly SW Generation			
		kg	ton	m <sup>3</sup>	kg	ton	m <sup>3</sup>	m <sup>3</sup> cumu.
2003	307,324	67,919	68	204	24,790,290	24,790	74371	74371
2004	319002	70,500	70	211	25,732,321	25,732	77197	151568
2005	331124	73,178	73	220	26,710,150	26,710	80130	231698
2006	343707	75,959	76	228	27,725,135	27,725	83175	314874
2007	356768	78,846	79	237	28,778,691	28,779	86336	401210
2008	370325	81,842	82	246	29,872,281	29,872	89617	490827
2009	384398	84,952	85	255	31,007,427	31,007	93022	583849
2010	399005	88,180	88	265	32,185,710	32,186	96557	680406
2011	414167	91,531	92	275	33,408,767	33,409	100226	780632
2012	429905	95,009	95	285	34,678,300	34,678	104035	884667

**Table 3 Lideta Sub City (source: Addis Ababa city road Authority)**

Year	Population	Dally SW Generation			Yearly SW Generation			
		kg	ton	m <sup>3</sup>	kg	ton	m <sup>3</sup>	m <sup>3</sup> cumu.
2003	348,073	76,924	77	231	28,077,309	28,077	84232	84232
2004	361300	79,847	80	240	29,144,246	29,144	87433	171665
2005	375029	82,881	83	249	30,251,728	30,252	90755	262420
2006	389280	86,031	86	258	31,401,293	31,401	94204	356624
2007	404073	89,300	89	268	32,594,542	32,595	97784	454407
2008	419428	92,694	93	278	33,833,135	33,833	101499	555907
2009	435366	96,216	96	289	35,118,794	35,119	105356	661263
2010	451910	99,872	100	300	36,453,308	36,453	109360	770623
2011	469082	103,667	104	311	37,838,534	37,839	113516	884139
2012	486908	107,607	108	323	39,276,398	39,276	117829	1001968

**Table 4 Cherkos Sub City (source: Addis Ababa city road Authority)**

Year	Population	Dally SW Generation			Yearly Generation			
		kg	ton	m <sup>3</sup>	kg	ton	m <sup>3</sup>	m <sup>3</sup> cumu.
2003	308338	68143	68	204	24872085	24872	74616	74616
2004	32005	70732	71	212	25817224	25817	77452	152068
2005	332217	73420	73	220	26798279	26798	80395	232463
2006	344841	76210	76	229	27816613	27817	83450	315912
2007	357945	79106	79	237	28873644	28874	86621	402533
2008	371547	82112	82	246	29970843	29971	89913	492446
2009	385666	85232	85	256	31109735	31110	93329	585775
2010	400321	88471	88	265	32291905	32292	96876	682651
2011	415533	91833	92	275	33518997	35519	100557	783208
2012	431324	95323	95	286	34792719	34793	104378	867586

**Table 5 Yeka Sub City (source: Addis Ababa city road Authority)**

Year	Population	Dally SW Generation			Yearly SW Generation			
		kg	ton	m <sup>3</sup>	kg	ton	m <sup>3</sup>	m <sup>3</sup> cumu.
2003	285,198	63,029	63	189	23,005,497	23,005	69016	69016
2004	296036	65,424	65	196	23,879,706	23,880	71639	140655
2005	307285	67,910	68	204	24,787,134	24,787	74361	215017
2006	318962	70,491	70	211	25,729,045	25,729	77187	292204
2007	331082	73,169	73	220	26,706,749	26,707	80120	372324
2008	343663	75,950	76	228	27,721,606	27,722	83165	455489
2009	356723	78,836	79	237	28,775,027	28,775	86325	541814
2010	370278	81,831	82	245	29,864,478	29,868	89605	631419
2011	384349	84,941	85	255	31,003,480	31,003	93010	724430
2012	398954	88,169	88	265	32,181,612	32,182	96545	820975

**Table 6 Bole sub City (source: Addis Ababa city road Authority)**

Year	Population	Sally SW Generatio			Yearly SW Generation			
		kg	ton	m3	kg	ton	m3	m3 cumu.
2003	173890	38430	38	115	14026837	14027	42081	42081
2004	180498	39890	40	120	14559857	14560	43680	85761
2005	187357	41406	41	124	15113131	15113	45339	131100
2006	194476	42979	43	129	15687430	15687	47062	178162
2007	201866	44612	45	134	16283553	16284	48851	227013
2008	209537	46308	46	139	16902328	16902	50707	277720
2009	217500	48067	48	144	17544616	17545	52634	330354
2010	225765	49894	50	150	18211311	18211	54634	384988
2011	234344	51790	52	155	18903341	18903	56710	441698
2012	243249	53758	54	161	19621668	19622	58865	500563

**Table 7 Akaki Kaliti Sub City (source: Addis Ababa city road Authority)**

Year	Population	Dally SW Generation			Year SW Generation			
		kg	ton	m <sup>3</sup>	kg	ton	m <sup>3</sup>	m <sup>3</sup> cumu.
2003	342983	75,799	76	227	27,666,724	27,667	83000	83000
2004	356016	78,680	79	236	28,718,059	28,718	86154	169154
2005	369545	81,669	82	245	29,809,345	29,809	89428	258582
2006	383588	84,773	85	254	30,942,101	30942	92826	351409
2007	398164	87,994	88	264	32,117,900	32118	96354	447762
2008	413294	91,338	91	274	33,338,381	33338	100015	547777
2009	428999	94,809	95	284	34,605,239	34605	103816	651593
2010	445301	98,412	98	295	35,920,238	35920	107761	759354
2011	462223	102,151	102	306	37,285,207	37285	111856	871209
2012	479787	106,033	106	318	38,702,045	38702	116106	987316

**Table 8 Nefas Silk Lafto Sub City (source: Addis Ababa city road Authority)**

Year	Population	Daily Sw Generation			Yearly Generatio			
		kg	ton	m3	kg	ton	m <sup>3</sup>	m <sup>3</sup> cumu
2003	271162	59,927	60	180	21,873,283	21,873	65620	65620
2004	281466	62,204	62	187	22,704,467	22,704	68113	133733
2005	292162	64,568	65	194	23,567,237	23,567	70702	204435
2006	303264	67,021	67	201	24,462,792	24,463	73388	277823
2007	314788	69,568	70	209	25,392,378	25,392	76177	354001
2008	326750	72,212	72	217	26,357,289	26,357	79072	433072
2009	339166	74,956	75	225	27,358,866	27,359	82077	515149
2010	352055	77,804	78	233	28,398,503	28,399	85196	600345
2011	365433	80,761	81	242	29,477,646	29,478	88433	688778
2012	379319	83,830	84	251	30,597,796	30,598	91793	780571

**Table 9 Kolfe Keranio Sub City (source: Addis Ababa city road Authority)**

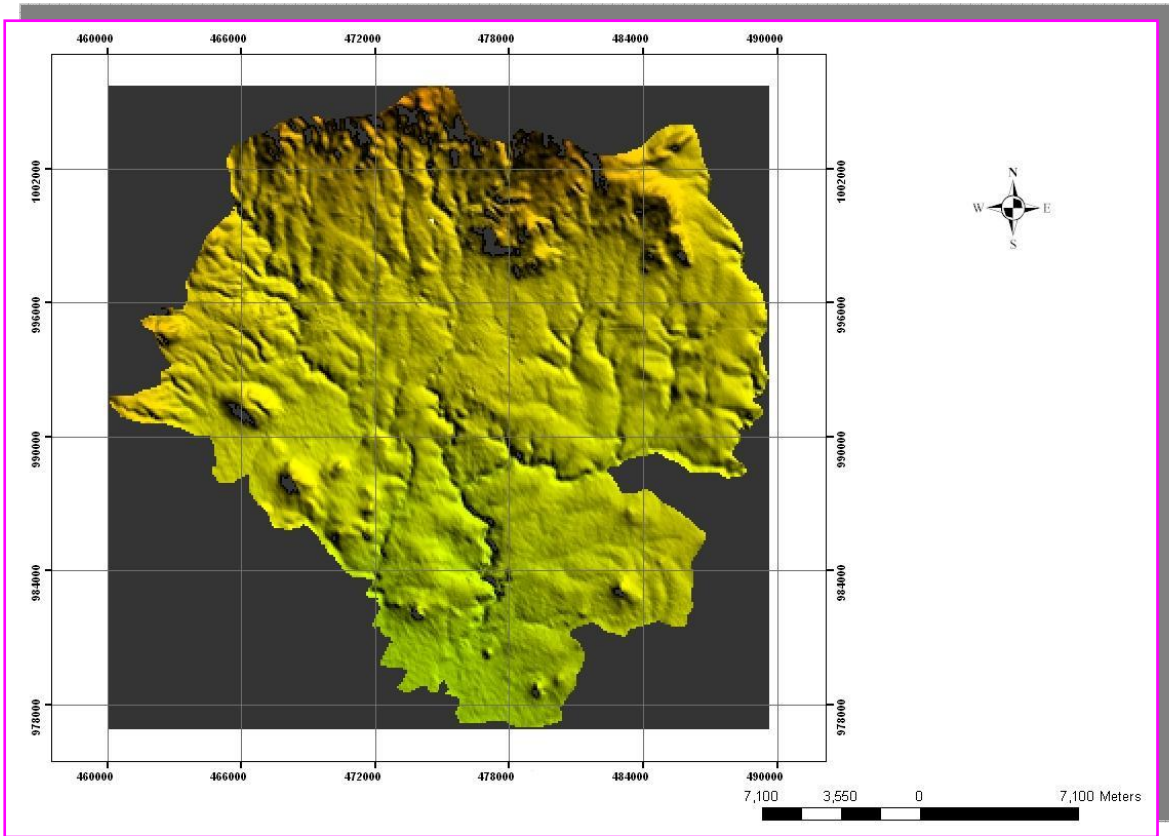
Year	Population	Dally SW Generation			Yearly SW Generation			
		kg	ton	m <sup>3</sup>	kg	ton	m <sup>3</sup>	m <sup>3</sup> cumu.
2003	330,611	73,065	73	219	26,668,736	26,669	80006	80006
2004	343174	75,842	76	228	27,682,148	27,682	83046	163052
2005	356215	78,723	79	236	28,734,070	28,734	86202	249255
2006	369751	81,715	82	245	29,825,965	29,826	89478	338733
2007	383802	84,820	85	254	30,959,351	30,959	92878	431611
2008	398386	88,043	88	264	32,135,807	32,136	96407	528018
2009	413525	91,389	91	274	33,356,967	33,357	100071	628089
2010	429239	94,862	95	285	34,624,532	34,625	103874	731963
2011	445550	98,466	98	295	35,940,264	35,940	107821	839783
2012	462481	102,208	102	307	37,305,994	37,306	111918	951701

**Table 10 Gulele Sub City (source: Addis Ababa city road Authority)**

### 4.1.2 Topography

Slope is an important factor in suitability assessment because it governs the amount of surface runoff produced, the precipitation rate and displacement velocity of water over the equipotential surface. Practically high rating is assigned to low slopes i.e. to surface zones where a pollutant may be less displaced under gravity action. Moreover, slope may be a genetic factor for the soil type and thickness, indirectly governing the attenuation potential of the hydrogeological system.

The topographic map of the area Prepared by the Addis Ababa City administration Geographical Information Systems department has been used as base map. From this map TIN has been created and then the Slope map of the area was derived.



**Figure 5 Digital Elevation map of the study area( from SRTM data of 2000 G.C.)**

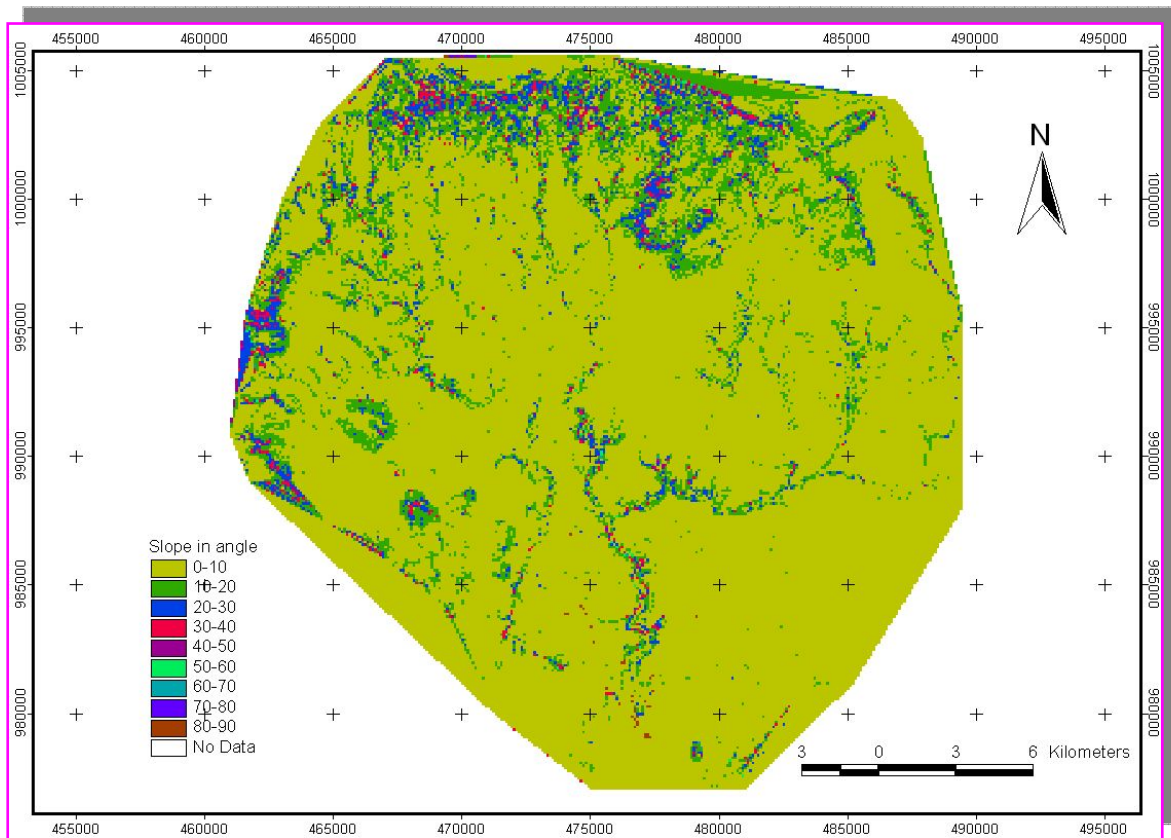


Figure 6. Slope map of the study area.

## 4.2 Hydrogeology

The groundwater circulation and the down ward flow of pollutants through rocks and soils are depending on the hydrogeological characteristics of the material more specifically hydraulic properties such as porosity, permeability, transmissivity etc. The origin, flow and chemical constituent of groundwater are controlled by the type of litho logy, distribution, thickness and structure of hydrogeological units through which it moves (UNESCO, 1972). Moreover, the stresses due to tectonism and weathering govern the hydrogeochemical characteristics of earth materials (tamiru et al., 2005) Therefore, to identify and select the best suitable site for the solid waste disposal it is necessary to describe the earth materials occurring in the study area with a particular reference to their infiltration capacity. Volcanic rocks mainly basalts, rhyolites,

trachytes, scoria, trachy-basalts, welded and unwelded tuffs are the dominant rock outcrops in the area. Besides, unconsolidated materials of different origin also occurred in the study area. These rocks are the major groundwater supply for large parts of Addis Ababa (Tamiru et al., 2005).

The study area is characterized by alternate eruption of basic and acidic lava flows from different centers. In between successive lava flows physical disintegration and chemical decomposition of rocks exposed at the surface; subsequent erosion and deposition; and tectonic activity taken place that has modified significantly the geomorphologic set up of the area. The main porosity groups identified are fracture porosity and interstitial porosity.

#### **4.2.1 Drainage**

The study area lies within the Awash River basin, which has a total drainage area of 110,000 square kilometers (Tefaye Chernet, 1993 in Tamiru et al., 2005). The surface water divides between Awash basin and the Abay (Blue Nile) basin, lies on the top of Entoto ridge, immediate north of the study boundary.

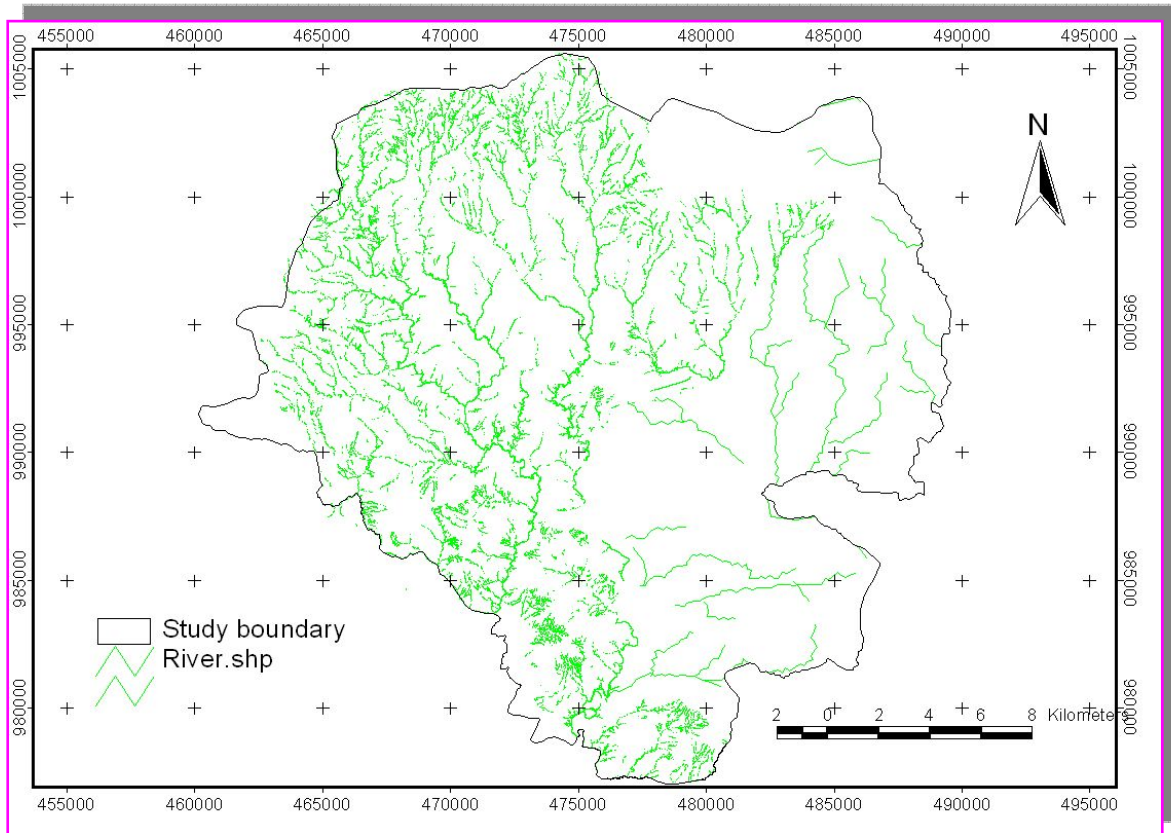
The total catchment area of the Akaki river basin, includes Addis Ababa, is divided into two sub-catchment areas by approximately north-south running surface water divide. These are the Big Akaki River (Eastern) sub-catchment and the Little Akaki river (Western) sub-catchment. In the study area the stream drains towards south from the Entoto ridge; southeast direction from Mt. Wechecha and Mt. Furi; and towards southwest direction from Mt. Yerer and other elevated areas of the eastern outskirts of the city. The perennial streams in the city are Little Akaki, Bantiyktu, Kurtume, Kebena, Ginfile, and Big Akaki. Other streams are intermittent in nature.

On the top of the mountain streams are dense forming radial drainage pattern, whereas on the slope and most parts of the city core they form dendritic drainage pattern. Moreover, on the slopes the processes of erosion is very conspicuous in excavating (down cutting) the valley floor. Thus, deep gully developed in highly weathered volcanic rocks constituting the slopes. A transverse profile of most streams is more or less "V" shaped. In places where the gradient of the slope is unusually steep waterfalls are found. These can be seen on the southern flanks of Entoto ridge, during the rainy season immediate north of Kidane Mehret church. It has a height of about 60-70 meters from the ground surface.

On the other hand, in the center and southern parts of the city the density of the streams is reduced and the main rivers or big tributaries show a wide meandering type of flow. This is due to much less gradient of the valley floor than what it is in the hills and /or ridges. Moreover, the floor of the valley becomes wider and the slope of the wall is relatively quite gentle. However, in most parts of the city, the width of the channel is reduced perhaps due to the construction of man made structures like retaining walls on the bank of the streams, and the natural path of the flow changes accordingly.

Moreover, significant decreases in the gradient of the topography, reduction in the eroding activity of the rivers and minimum flow velocity and transporting capacity towards the south lead to the formation of alluvial deposits. On the contrary, alluvial fan deposits occur where there is a change in topography from a hill or ridge to a plain like the area around the foot of Entoto ridge. Towards the

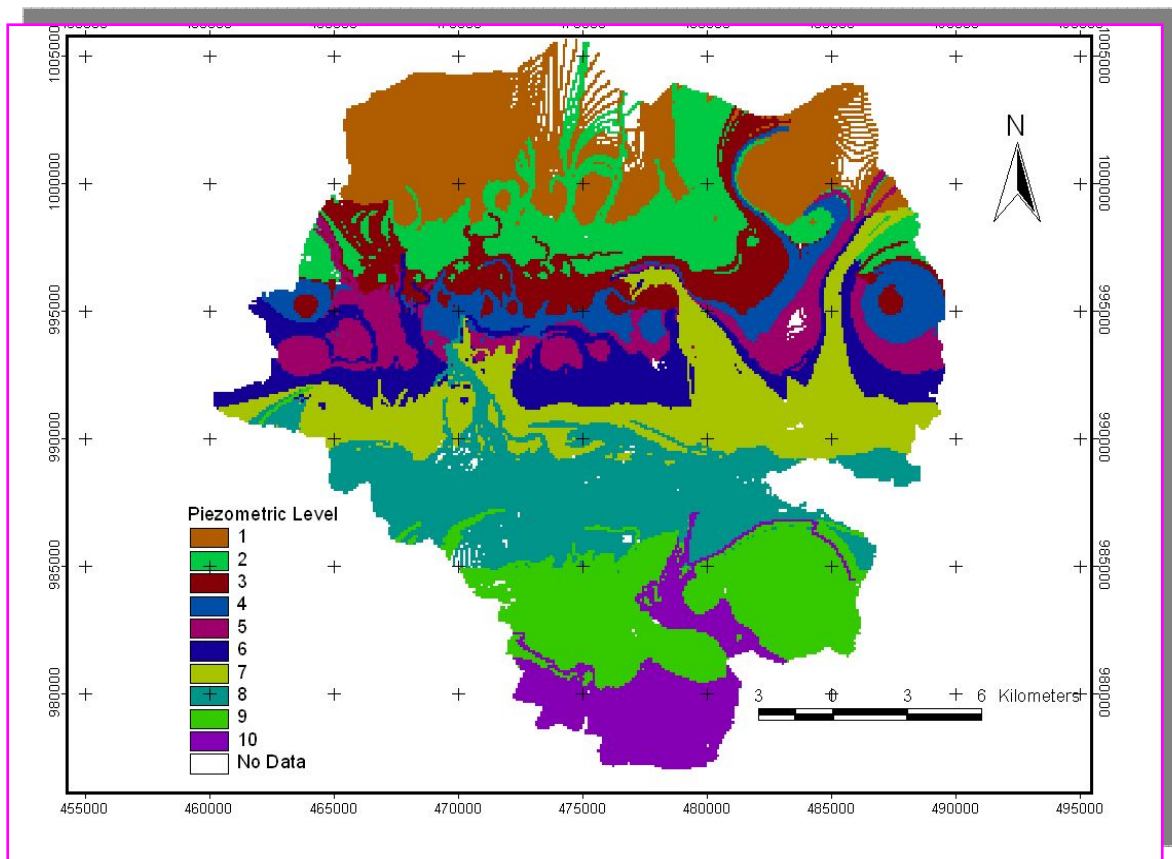
south almost all streams /or big tributaries crossing the city in different direction join either Little Akaki or Big Akaki river. The two rivers flow on either side of Addis Ababa – Debrezeit road (which is the surface water divide at this part of the city) and complete their courses entering Lake Aba Samuel.



**Figure 7 Drainage map of the study area. (Source: Addis Ababa City Administration)**

#### 4.2.2 *Depth to water table*

This is defined as the depth of piezometric level referred to ground surface and has a large significance on Vulnerability assessment there by giving a clue in selecting a solid waste disposal site because its absolute value together with the unsaturated zone characteristic determine the travel time of hydro-vectored contaminant. The closer the water table to the surface, the more vulnerable it is to contamination, and unsuitable to landfill.



**Figure 8 Piezometric map of the study area.**

### **4.2.3 FRACTURE POROSITY**

#### **◆ BASALTIC LAVA FLOWS**

The texture of basaltic lava flows in the study area varies from porphyritic (olivine and plagioclase) to aphanitic. Basically, high water storage and transmitting capacity of basaltic lava flows is due to joints caused by cooling, lava tubes, vesicles that are interconnected, tree moulds, fractures caused by buckling of partly congealed lava (*aa* lava surface) and voids left between successive flows. Old porphyritic basaltic lava flows dominantly cover the slopes of Entoto, central and western parts of Addis Ababa. It's water circulation and storage capacity is dependent on the degree of weathering and secondary fractures (weathering types). The presence of faults and fractures modify the hydraulic properties of the rock. Moreover, the development of soil is mostly related to the topography on which this rock outcrops. In steep slopes the weathering products are immediately removed by the concomitant erosion, while in the southern part of city, where slopes of the topography is low to moderate weathering processes produce in situ soil horizon in addition to transported materials.

Depending on the degree of weathering and the resulting weathering zones the porphyritic basalts show difference in water infiltration properties. In some localities, like the area around Kidane Mehrat Church (east of Shiro Meda), the secondary permeability of porphyritic basalts is due to deep weathering zone. Besides large concentration of weathering fractures that have different orientation and opening increases the overall water transmitting properties of the rock body. Usually the greatest permeability is found within the partly decomposed weathering zone, which varies in thickness from about 2 to 4

meters. The thick vegetation cover in the area also facilitates infiltration of rainwater. On the other hand, the degree of weathering and associated fractures is less developed in the lava flows that outcrop in the central and western part of the study area. In these localities scattered massive boulders are not uncommon and fractures are minor. Although there is thick soil cover in some places (e.g. Shegole Meda) the zone of partly decomposed parent materials below the soil horizon is small in thickness. Thus, the permeability of porphyritic basalts in these localities is less when we compare it to the same rock outcrop in the former areas.

The young porphyritic basalt that outcrops in the southern parts of Addis Ababa varies from massive to fractured type. It is fresh to slightly weathered. The fractured variety is the most permeable and productive aquifer in Akaki area (Anteneh Girma, 1994). Aphanitic basalts dominantly cover the southern and southwestern parts of Addis Ababa. Outcrop of this rock vary from massive to vesicular type. Vesicles, which are abundant on the aphanitic basalts, are not interconnected and in some cases partially filled by secondary minerals. Thus, vesicles have little or no effect on the overall rock permeability. However, in some localities (e.g. near Bole Air Port) due to weathering fractures and/or tectonic discontinuity, vesicles are interconnected. Consequently, the water transmitting capacity of vesicular basalts increases to some extent. The shape of vesicles varies from circular to cylindrical cavities.

The presence of vertical and horizontal fractures significantly increases the water circulation and storage capacity of massive aphanitic basalts. However, the same rock shows difference in hydraulic property depending upon the fracture spacing, extent and openings. Measurements taken from different places show that there

is variation in the spacing of vertical fractures from about 0.3 to 1 meter and horizontal fractures from about 1.5 to 2 meters. Likewise, the aperture in the vertical and horizontal fractures varies from about 10 to 30 mm and 10 to 20 mm respectively. Moreover, there are also inclined fractures that run in different directions and intersect at some point.

The other difference in water transmitting capacity is related to the extent to which the aphanitic basalts affected by weathering. The permeability becomes high in area where this basalt is intensively intersected by weathering fractures. In the southwestern Addis Ababa, near ALERT, for example the aphanitic basalt is highly weathered and affected by horizontal and inclined local weathering fractures. The spacing in the horizontal fractures varies from about 3 to 5 cm and the aperture reached up to about 2 cm. In some localities, the basaltic lava flow is slightly weathered and consequently, possesses low infiltration capacity.

Moreover, the degree of weathering, fracturing and morphology of the area plays a great role in controlling the development and thickness of soil horizon above the aphanitic basalts. The physical disintegration and chemical decomposition become more pronounced along the surface of joint sets.

#### ◆ **WELDED TUFF**

This rock unit is widely distributed in the northern, central and eastern part of the study area. The strongly welded tuff exposed in the central and western parts of the study area. While, young welded tuff varieties cover extensive area in the central and southern parts of Addis Ababa. According to Davis (1966) welded tuffs have medium to low primary porosity and very low permeability. Thus the water circulation and storage capacity of welded tuff depends on the secondary porosity and permeability developed through fracturing and weathering

processes. However, the degree of weathering and fracturing is not uniform through out the study area on this rock unit. In most places the welded tuffs are fresh to slightly weathered and there is thin soil cover or bare rock exposed. On the other hand, in the flat-laying areas of southern and southeastern parts of Addis Ababa as well as along most river valleys the welded tuff are deeply weathered and covered by soils having different thickness.

The secondary fractures are mainly the results of weathering and tectonic activity, affected the ignimbrite in different manner. In some localities the welded tuff is massive, slightly weathered and fractures are scarce or absent. Thus, the secondary processes produce only small increases in the overall water circulation and storage capacity of welded tuff. On the contrary, block fractures divided the massive welded tuff into rectangular blocks in large parts of the study area. Mostly these fractures are open to a considerable depth and transmit large amounts of water. On average the spacing and aperture of vertical fractures in ignimbrite varies from about 0.5 to 2 meter and 2 to 4 cm respectively. Likewise, the horizontal fractures vary from about 1 to 4 meters in spacing and 1 to 3 cm in fracture opening.

Therefore, in most localities welded tuff developed good secondary permeability largely from open fractures and to some extent from weathering zone. When there is high degree of fracturing and weathering, welded tuffs have the capacity to hold water and become a productive aquifer.

#### ◆ **SILICIC LAVA FLOWS AND DOMES**

The rhyolitic and trachytic lava flows are mostly considered as impervious rocks. The water storage and transmitting capacity is thus largely dependent upon secondary porosity and permeability.

Rhyolitic lava flows are found dominantly along the slopes and foothills of Entoto ridge. The secondary porosity in rhyolite is due to weathering and associated fractures. In the western parts of Addis Ababa weathering deeply obliterated the rhyolite that occurred in gentle slopes of Entoto. Weathering in this locality produce soils having a thickness of greater than 10 meter. Moreover, weathering fractures locally increases the porosity of the rhyolitic lava flows. In some localities vertical fractures having about 0.5 to 1 meter spacing and about 10 to 20 mm opening intersect the rocks. Thus, the weathering fractures and weathering zone significantly modify the limited primary porosity and permeability of rhyolitic lava flows. On the other hand, the rhyolitic lava flows outcrop in eastern parts of Entoto ridges is slightly weathered and less fractured. Consequently, there is poor soil development particularly on the slope and top parts of the ridge. Rock fragments are dominantly covering this part. Relatively shallow soil profile constitutes the gentle slope and foothills of the ridge. Therefore, in some place where the rhyolitic lava flows are intensively weathered and highly fractured, infiltrated water through fractures feeds the aquifers that lie on flat-laying areas. In slightly weathered massive part most of the precipitated water is readily lost as runoff.

Trachytic lava flows having different ages are found in the study area. Since trachytic rocks vary in age, structure and weathering conditions, their water circulation and storage capacity also vary accordingly. Trachytic domes have steeper slopes, massive and weathered slightly in the outer parts. There is thin or no soil formation. Therefore, the water that precipitated on the trachytic domes of Mt. Wechecha, Mt. Furi and Mt. Yerer are mostly lost as runoff rather than vertical infiltration. The trachytic lava flows cover the foothills and moderately

dipping topography of the southern and southwestern parts of Addis Ababa. Due to thick black cotton soil cover outcrops are scarce. It is slightly to moderately weathered and intersected by fractures. The fractures separate the flows into different columns, which may extend to the bottom of the flow. The major vertical fractures on the trachytic lava flow, that outcrop along the road side have spacing of about 0.5 to 1 meter and the opening in this fracture vary from about 2 to 3 cm. Likewise, local vertical fractures that have about 5 to 20 cm fracture spacing and up to 5 mm fracture opening are also observed in the same outcrop. The occurrence of major tectonic displacement and deep weathering zone in trachytic lava flows strongly changes the hydraulic characteristics of the rock. On the other hand, minor fractures have local permeability effect. However, an intensively weathered and fractured trachytic lava flow under favorable conditions develops not only water transmitting but also water holding properties.

The trachy-basalts are the major outcrops in the western parts of Addis Ababa, around Repi and General Wingate School. They are slightly weathered and intersected by fractures. The fractures are dominantly inclined and fracture spacing varies from about 20 to 40 cm. Although the spacing of fractures in trachy-basalts is small compared to other rock type, due to the tight fracture openings the resulting water infiltration capacity is minimum. Due to slight weathering there is thin soil cover on trachy-basalts.

#### **4.2.4 INTERGRANULAR POROSITY**

Intergranular porosity in the study area is mainly associated to the volcanic activity and /or weathering and erosion processes. Alluvial sediments are deposited in the southern and southwestern parts of Addis Ababa along the channel and terrace of the major valley. It is a loose material consisting of clay,

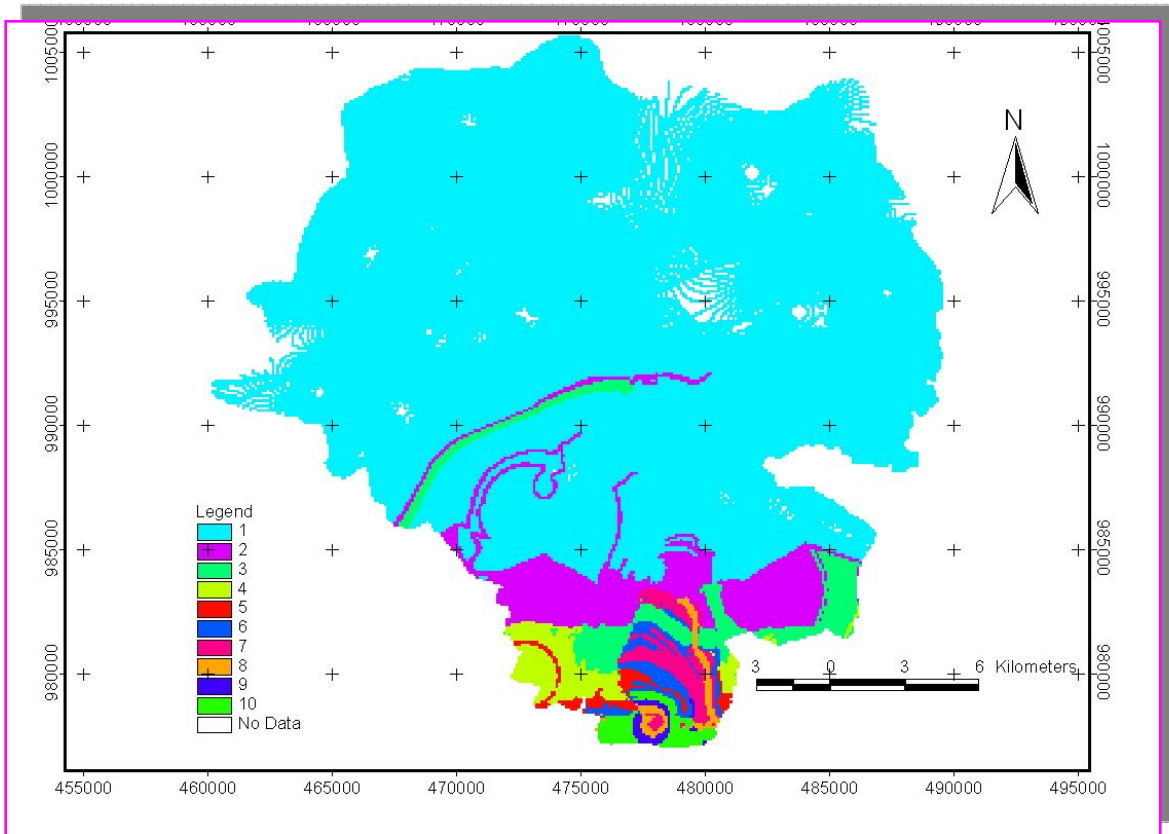
silt, sand and gravel in different proportions. In a vertical succession the deposits have coarse material (gravel) at the bottom of the channel and fine materials (silt & clay) at the top. The deposits are poorly sorted and highly porous. Mostly the alluvial deposits are localized in the narrow channel and terraces of the valley. Mostly the alluvial deposit is localized in the narrow channel and terraces of the valley. The thickness of alluvium deposits varies from place to place depending on the topographic variation in the area.

As it was confirmed from the lithologic log of boreholes, alluvium deposits occurred interbedded with different lava flows, pyroclastic materials and paleosols at different depths. Borehole drilled in Central Park (adjoining the Bantyeketu stream), for example, cut across about 24m thick sand layer before it encountered the underneath materials. Alluvial deposits also occur in flat-laying topography where there are swampy or waterlogged areas. The thickness of alluvium that covers swampy area of Filowha, for example, varies from 2 to 4 meters. The primary porosity and permeability in alluvial sediments result from voids between the grains. The magnitude in turn depends on the size, shape, sorting and packing of grains. The alluvial sediments in Addis Ababa are poorly sorted, highly porous and permeable. Thus under favorable conditions they may store appreciable amount of water and characterized by high water infiltration capacity. Although very localized colluvial deposits having high porosity and permeability occur in the foothills of Entoto ridge, Mt. Wochacha, Mt. Furi, Mt. Yerer and other elevated areas. Loose pyroclastic materials derived from different volcanic centers make up intergranular porosity. The most important characteristic features governing the groundwater movement and accumulation

in unconsolidated pyroclastic materials are related to fragment size, sorting and degree of cementation. In the study area loose pyroclastic material includes ash and agglomerates. Mapable units of young tuff and agglomerate occurred in the western and southeastern parts of Addis Ababa. At depth these materials are found to be interbedded with alluvial sediments, paleosols and lava flows. Volcanic ashes and agglomerates have high water transmitting and holding capacity. On the contrary, tuff has low permeability, but the secondary processes specifically weathering increases significantly the water infiltration capacity of tuff. Weathering products of volcanic rocks cover most parts of the study area. The type and development of residual soil is mostly dependent on the parent rock and topography on which the rocks outcrop. In moderate to steep slopes commonly shallow soil horizons develop, whereas in the area where there is gentle to flat topography thick residual soils form thick profile. The thickness further increases towards south where the topography is relatively flat. On the other hand thick soil horizon is also observed in some central and western parts of Addis Ababa. In boreholes drilled at Building College (Lideta) and Sunsuzi (Burayu) there is 16m and 18m thick clay soil found respectively. The black cotton soils in the south have a swelling and shrinkage properties. In the dry season cracks that have different aperture and lateral extent commonly observed. The infiltration capacity of black cotton soil thus become high in the beginning of the rainy season and reduces when the amount of precipitation increase. As a consequence the black cotton soil become saturated and acts as impervious materials. On the other hand when clay is not a dominant constituent of the soil, relatively there is a constant infiltration of water in the rainy season depending on other different factors.

The two major faults i.e. east west running fault at Entoto and NE-SW oriented Filowha fault changes the topography of Addis Ababa and it's surrounding significantly. The occurrence of many springs at the foot of the former and thermal water along the latter is indicating conducive, nature of these faults. Moreover, during faulting associated fractures and fissures developed on different lithologies modify the hydrogeological characteristics of the rock units affected by the fault. Paleosols are interbedded with successive lava flows and/or unconsolidated materials. They are made of clayey fragments and are less permeable and act as a confining bed. Moreover, these impervious materials form local perched groundwater. The paleosols that exposed along the valleys (e.g. Kebena, Ayere Tena) and quarry face (e.g. near Bole Air Port) varies in thickness from about 1 to 2 meters.

Ideally, sites with low permeability soils should be used for landfills in order to slow the movement of leachate from the site.



**Figure 9. Hydraulic Conductivity map.**

#### **4.2.5 Soil classification**

The variation in the characteristics of soils makes them different in water infiltration and holding capacity. Climate, topography, parent materials, maturity and biological activities are the major controlling factor that control soil formation. The resulting porosity and permeability of soil, on the other hand, control the vertical as well as horizontal movements of contaminants.

The soil development in the study area is mostly due to the physical disintegration and chemical decomposition of volcanic rocks. The weathering products are either remain in places and form residual soils or transported and deposited in the areas of Addis Ababa. Meanwhile, the difference observed in the

type and development of soils in the city is mostly depends on the topography, parent materials and the degree of weathering.

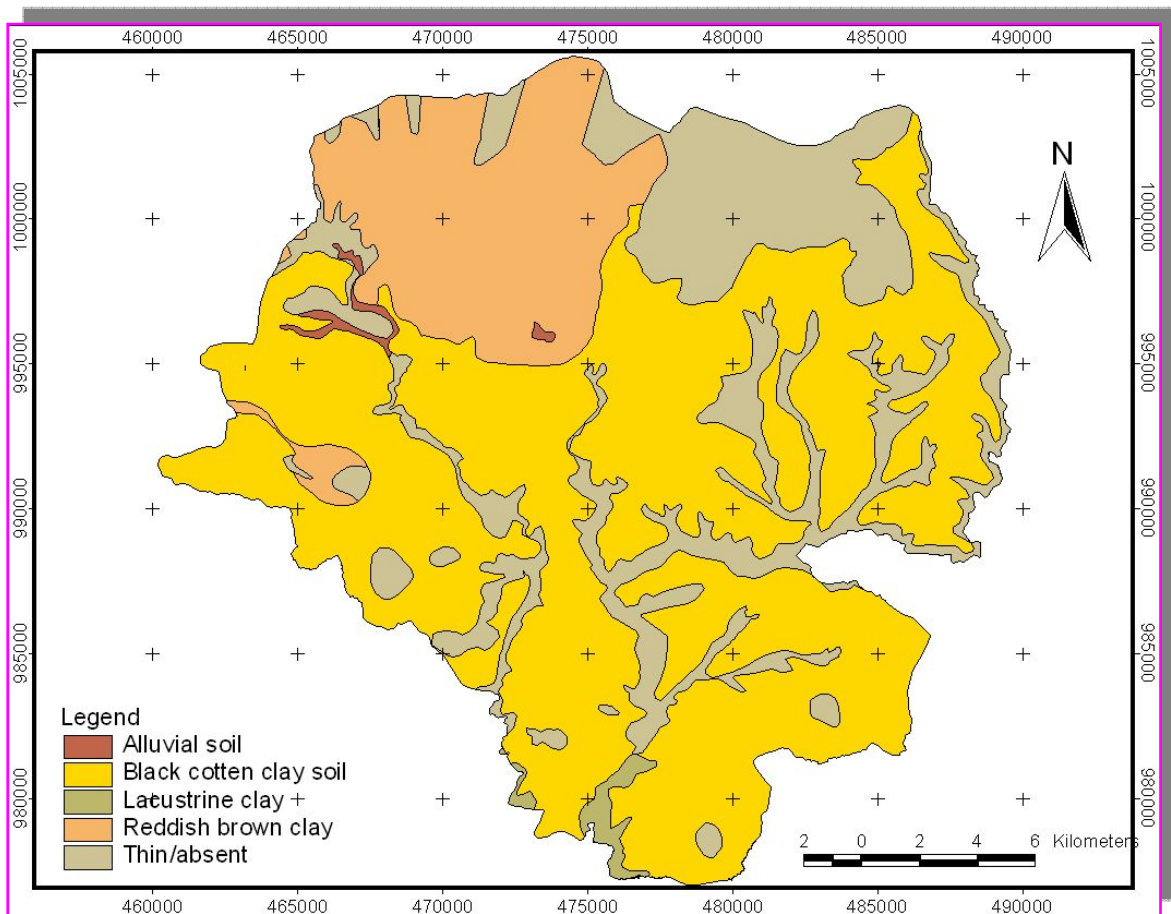
Although there is significant difference in the degree of weathering on the slopes, mostly soils are highly eroded and result in thin soil cover. In the localities where the topography is plain to gentle (central and southern part) of the area is covered by thick soil profile. The type of parent material and the length of time to which the parent material is subjected to weathering, control the variation in the thickness of soil. Thus, old basic and acidic rocks that outcrop in the central, western and southwestern parts of Addis Ababa are weathered and form thick soil profile. In places where young basalt and welded tuffs occur, the thickness of the soil cover is reduced. The grain size distribution made by Kebede Tsehayu (1990) showed that the residual soil in central part, Gulele and Kolfe regions have 62 % clay, 33% silt and 5% sand. In some localities reddish brown soil with a thickness of more than 10 meter is commonly seen.

Moreover, according to Lulseged Ayalew (1990) studies the residual has a thickness of about 2-6 meters and characterized by very high clay fraction with respect to silt and sand. The color varies from reddish brown to black depending on the type of parent materials.

The detrital materials that are derived from elevated area of Entoto, Wechecha, Furi and Yerer are transported and deposited in the piedmont and along the stream courses of Addis Ababa. It covers most parts of Mekanisa, Ayere Tena, Kaliti, Akaki, Lideta, and Bole. The soil is black in color and the thickness varies from place to place primarily depending on the slope of the area. Samples taken from Mekanisa are has 76% clay, 22% silt, and 2 % sand. It shows extremely high plasticity and very high degree of swelling (Kebede Tsehayu, 1990). The

same work identified 46% silt, 34% clay and 20% sand in alluvial soil collected near Addis Ababa Bole Airport.

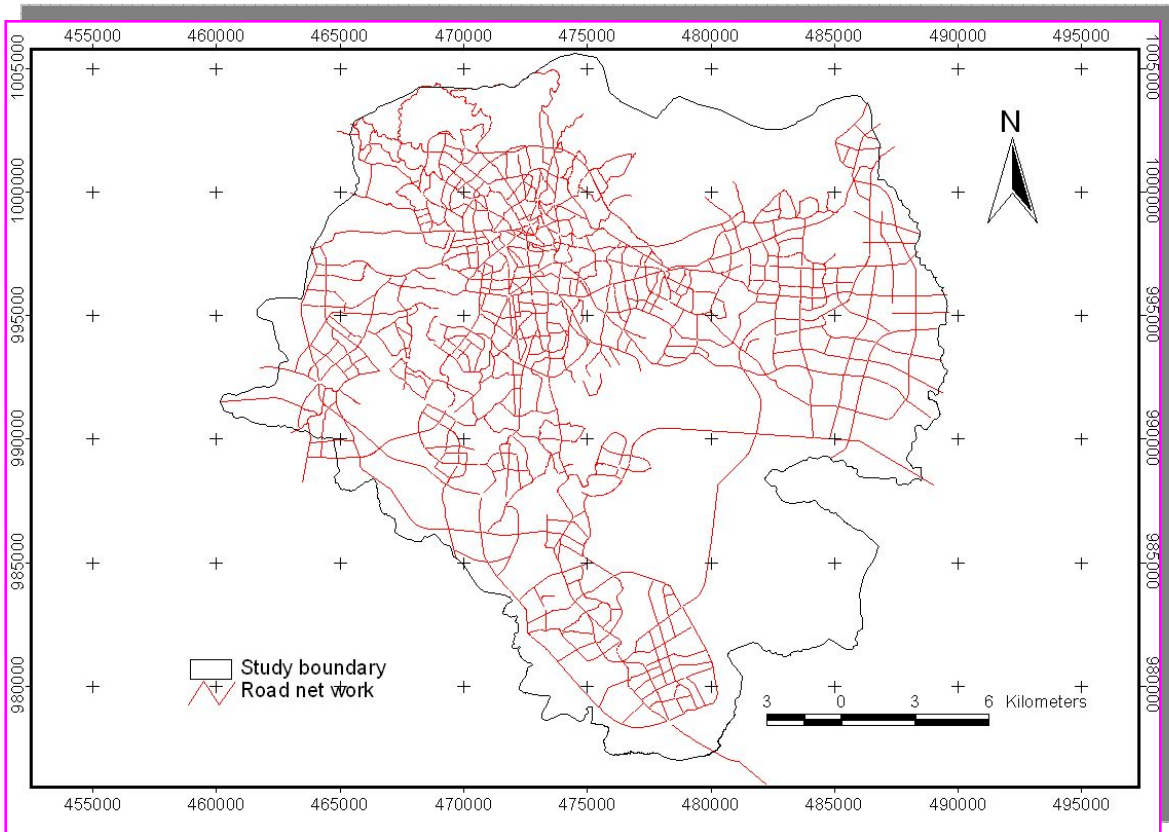
In areas where there is great contrast in the topography colluvial soils are found. These are loose and incoherent deposits, consisting of fine to coarse grain. The shape of the particles varies from angular to sub-round. Therefore the thickness, permeability, porosity and shrink/swell characteristics of soils are crucial and control largely the infiltration of pollutants into subsurface.



**Figure 10 Soil map of the study area (Source: Tamiru et al., 2005)**

#### 4.2.6 Road Network map

Road network Map of the Addis Ababa area, which was prepared by the Addis Ababa City administration Geographical Information Systems department was used. And will possibly be used for comparison of the alternatives



**Figure 11 Road network map of the study area. (Source: Addis Ababa City Road Authority.)**

# Chapter Five

## Discussion and Analysis

### 5.1 Introduction

One of the major objectives of this study is generating solid waste disposal site suitability analysis map of the study area based on various interrelated components of the environment using multi criteria analysis of the GIS techniques those components which are used in the study are Constraints and factors. These input data sets were selected based on globally accepted guidelines and a concern about the potential groundwater contamination. The data sets considered as inputs are verified to be operational (have some relation with the landfill activity), complete (full information about the input data is available), measurable in one or more of the scales, variable (non uniform) in the area, and it is not repeated (non redundant).

In order to achieve the above listed objectives of the study, A GIS technique has been employed. All hydro geological, geological, soil, Land use land cover, Drainage network, Road network, and related data have been collected, checked and analyzed. These data include information about surface and subsurface geology, water table, land use-land cover etc.

To form compatible and most up-to-date sets of thematic information, different data from various public institutions and government organizations have been crosschecked and harmonized.

The GIS methods, which plays a vital role in handling, visualizing, analyzing and presenting spatial attribute, vector and raster data has been used to integrate all geological, soil, land use land cover, topography, road, drainage and related data to conduct more realistic suitable solid waste disposal site for the area.

By the application of GIS, slope map of the study area was derived from the TIN which was created from the topographic map, and piezometric map was Prepared from the tabular data collected from different bore holes of the Akaki River catchments which was useful in identifying the shallow ground water of the study area which has to be given enough attention to be protected as the city highly dependent on these water sources. The identification of land use land cover map in conjunction with sufficient ground truth has made it possible to outline various ground features and the newly proposed solid waste disposal site by the municipality.

The following steps have been followed in producing the suitability map of the study area.

### **5.1.1 Step 1: Identify Objectives and Criteria**

The city gets their drinking water from a large underlying aquifer, and much concern should be given about the potential for groundwater contamination. As such, protection of water resources is a key concern.

Based on the government regulations, Selection of a landfill site must consider the environmental, socio-economic and infrastructure factors, as well as minimum distance from the waste generating centers. These objectives and the criteria identified above, with the focus on water resources, are used to guide the landfill siting process.

Although other socio-economic and infrastructure criteria should be considered in detail in a real case, they are not discussed in this study due to lack of data and time constraint.

### 5.1.2 Step 2: Site screening and identification using constraint mapping

A constraint serves to limit the alternatives under consideration. In this study, areas within 300 meters of major Rivers and areas occupied by built up areas are the constraint for the analysis. Areas excluded from the consideration are within the buffer zone of major rivers and built up areas and other parts of the study area opened for consideration.

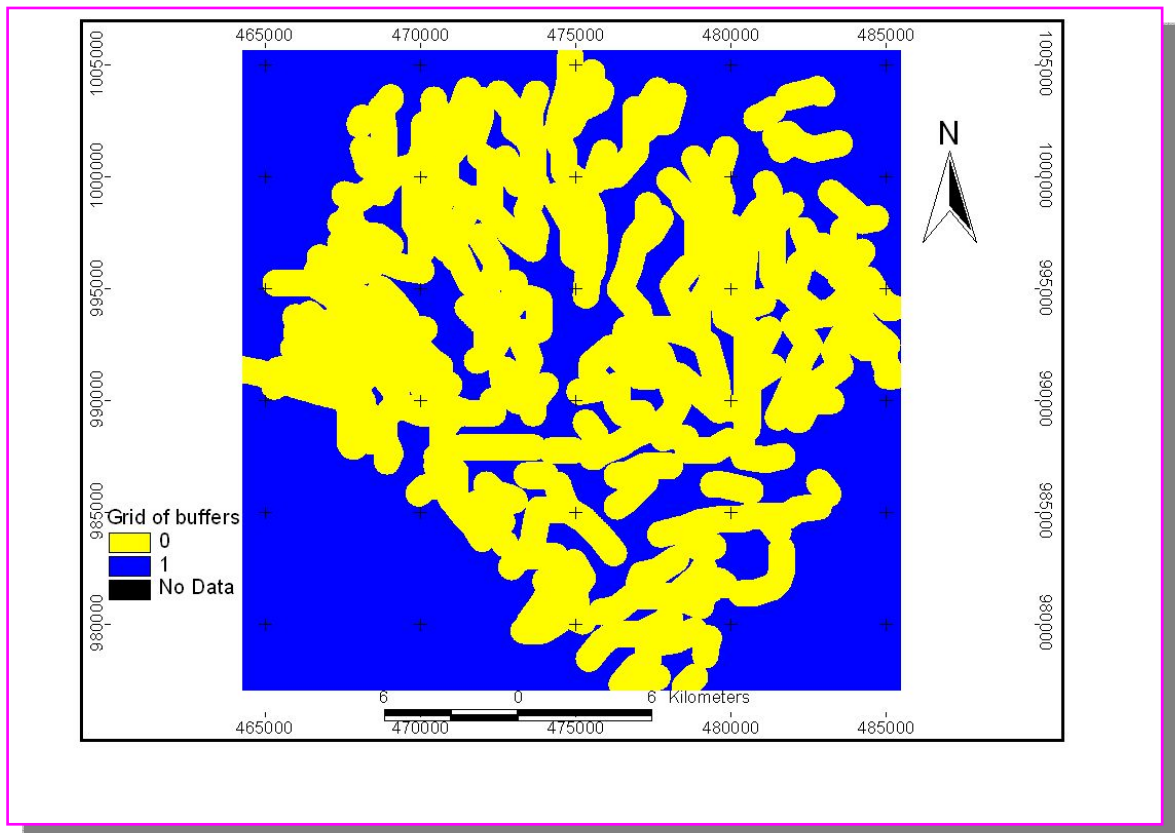


Figure 12. Raster map layer showing buffer zone of major rivers

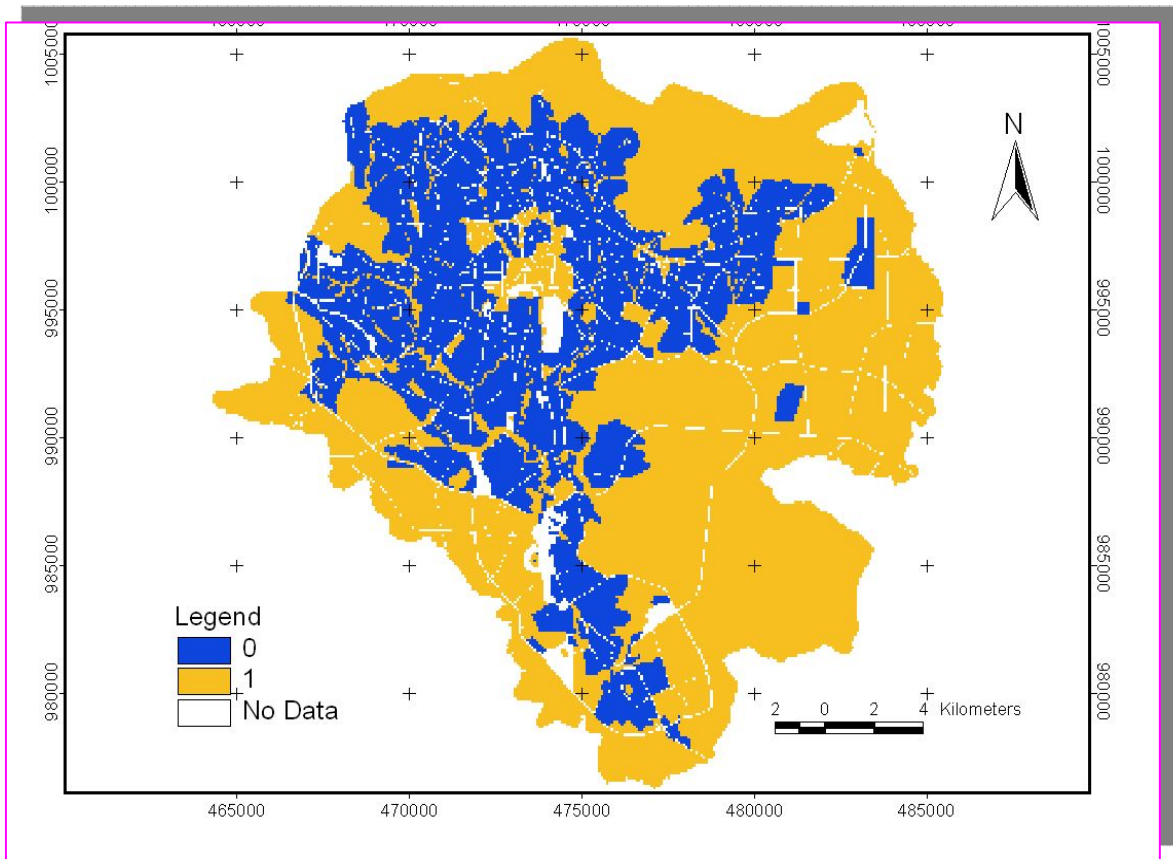
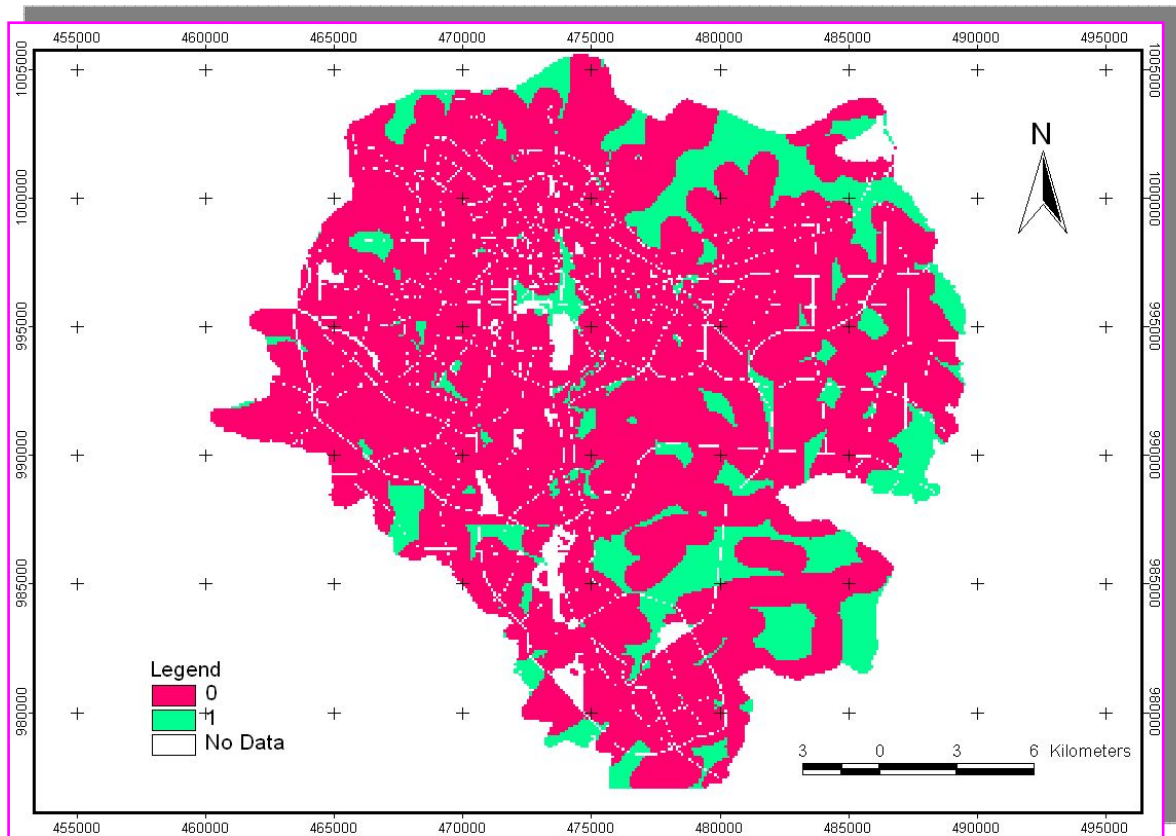


Figure 13. Grid showing reclassified map of land use/land cover

- ❖ Finally these two maps were rasterized and brought together to the same view and combined following a procedure called multi-criteria evaluation (MCE), to mask the unsuitable areas. This is accomplished by multiplication of the above two layers resulting in a Constraint map.

Constraint map= Constraint 1\* constraint 2



**Figure 14. Constraint Map**

### **5.1.3 Step 3: Criteria mapping, Standardization and Criteria weighting**

In order To select the best solid waste disposal site a number of parameters can be considered. Various thematic maps such as hydraulic conductivity, piezometric map and slope map data sets in spatial format brought to GIS environment and converted to a raster format. One of the problems in decision theory of multi-parameter analysis is the determination of the relative importance of each parameter. The site selection for solid waste disposal facility involves comparison of different options based on social evaluation of each of them for detailed environmental, social and community impact. Thus the problem requires human judgment at all levels. Hence based on experience and likely impact on surrounding environment different weights were assigned to all the parameters.

A weight can be defined as a value assigned to an evaluation criterion that indicates its importance relative to other criteria under consideration. The larger the weight, the more important is the criterion in the overall utility. Assigning weights of importance to evaluation criteria accounts for (1) changes in the range of variation for each evaluation criterion, and (2) the different degrees of importance being attached to these ranges of variation (Kirkwood 1997). To this end, it is misleading to interpret the weights as general measures of the importance of the evaluation criteria. The weight value is dependent on the range of the criterion values, that is, the difference between the minimum and maximum value for a given criterion. A Criterion weight can be made arbitrarily large or small by increasing or decreasing the range. For example, if all alternatives to be evaluated are characterized by the attribute SO<sub>2</sub> emission between, say, 1010 and 1011 units, the attribute would be less important than in the case where the attribute values range from 1 to 1000 units. The general rule is that we are concerned with the perceived advantage of changing from the maximum level to the minimum level of each criterion outcome, relative to the advantages of changing from the worst to the best levels for the other criterion under consideration (Pitz and McKillip 1984; Belton and Gear 1997). The weights are usually normalized to sum to 1. In the case of  $n$  criteria, a set of weights is usually defined as follows:  $W = (w_1, w_2, \dots, w_i, \dots, w_n)$  and  $\sum w_i = 1$ .

As the ease-of-use feature and time and cost involved in generating a set of weights are here the major concerns, the Ranking method is chosen to be applied for this purpose.

## Ranking Methods

The simplest method for assessing the importance of weight is to arrange them in rank order; that is, every criterion under consideration is ranked in the order of the decisions makers' preference. Either straight ranking (the most important =1, second important =2 etc) or inverse ranking (the least important = 1, next least important =2, etc) can be used. Once the ranking is established for a set of criteria, several procedures for generating numerical weights from rank-order information are available. We focus on the most popular approach: rank sum, rank reciprocal, and the rank exponent method (Stillwell et al.1981). Rank sum weights are calculated according to the following formula:

$$W_j = \frac{n - r_j + 1}{\sum (n - r_k + 1)}$$

Where  $w_j$  is the normalized weight for the  $j$ th criterion,  $n$  is the number of criteria under consideration ( $k= 1, 2\dots n$ ), and  $r_i$  is the rank position of the criterion. Each criterion is weighted  $(n - r_1 + 1)$  and then normalized by the sum of all weights that is  $\sum (n-r_k + 1)$ .

Given the variety of scales on which attributes can be measured, multicriteria decision analysis requires that the values contained in the various criterion map layers be transformed to comparable units (Jack Malczewski). To be more specific, if we want to combine the various criterion maps layers, the scales must be commensurate. A number of approaches can be used to make criterion map layers comparable.

Linear Scale transformation is the most frequently used deterministic method for transforming input data into commensurate criterion maps. Deterministic maps assign a single value to each object (point, line, polygon, or pixel) in a map layer.

The linear scale transformation methods convert the raw data into standardized criterion scores. A number of linear scale transformations exist (Voogd 1983; Massam 1988). The simplest formulae and the one used in this study for standardizing the raw data is the score range procedure.

The procedure uses the following:

$$X'_{ij} = \frac{X_{ij} - X_j^{\min}}{X_j^{\max} - X_j^{\min}}$$

Where  $X_j^{\min}$  is the minimum score for the jth attribute,  $X_j^{\max} - X_j^{\min}$  is the range of a given criterion,  $X_{ij}$  is the standardized score for the jth object (alternative) and the jth attribute,  $X_{ij}$  is the raw score, and  $X_j^{\max}$  is the maximum score for the jth attribute.

Therefore in order to combine all the layers. Standardization of each data set to a common scale 0-1 (giving lower values to more suitable attributes) is performed.

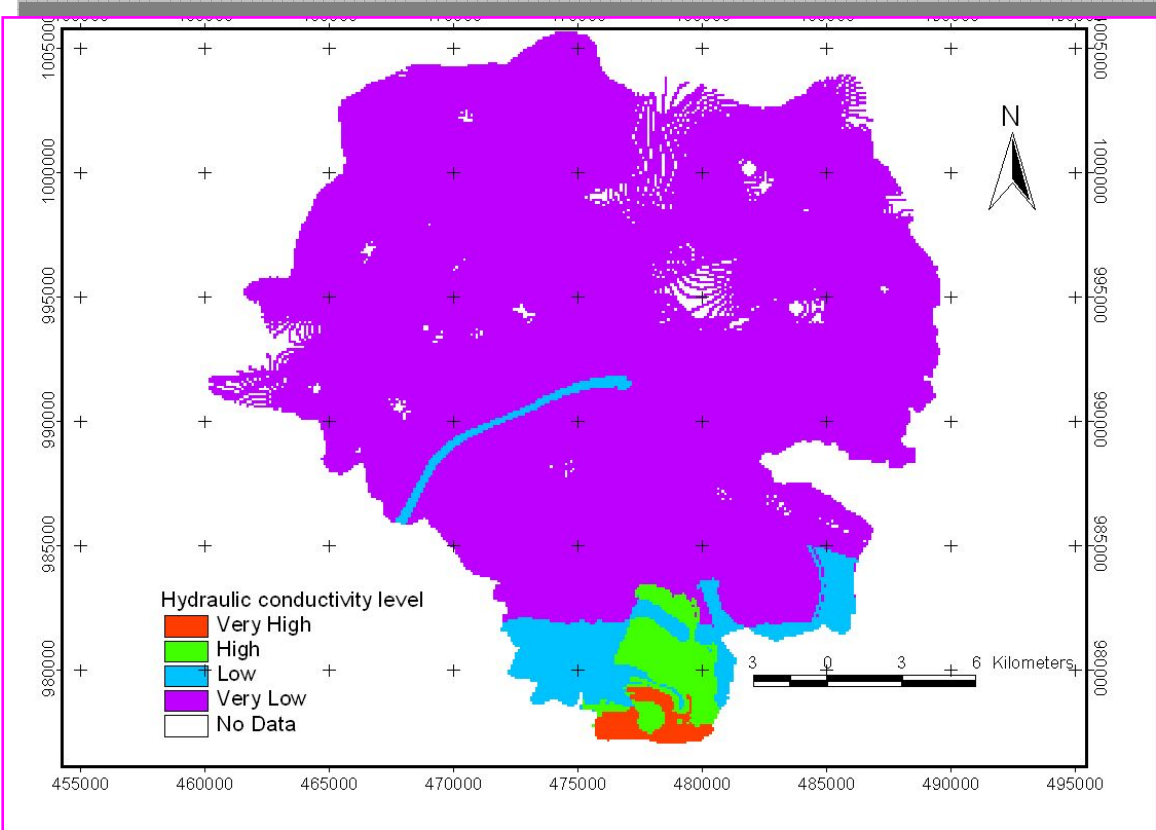


Figure 15 Reclassified Hydraulic conductivity map layer.

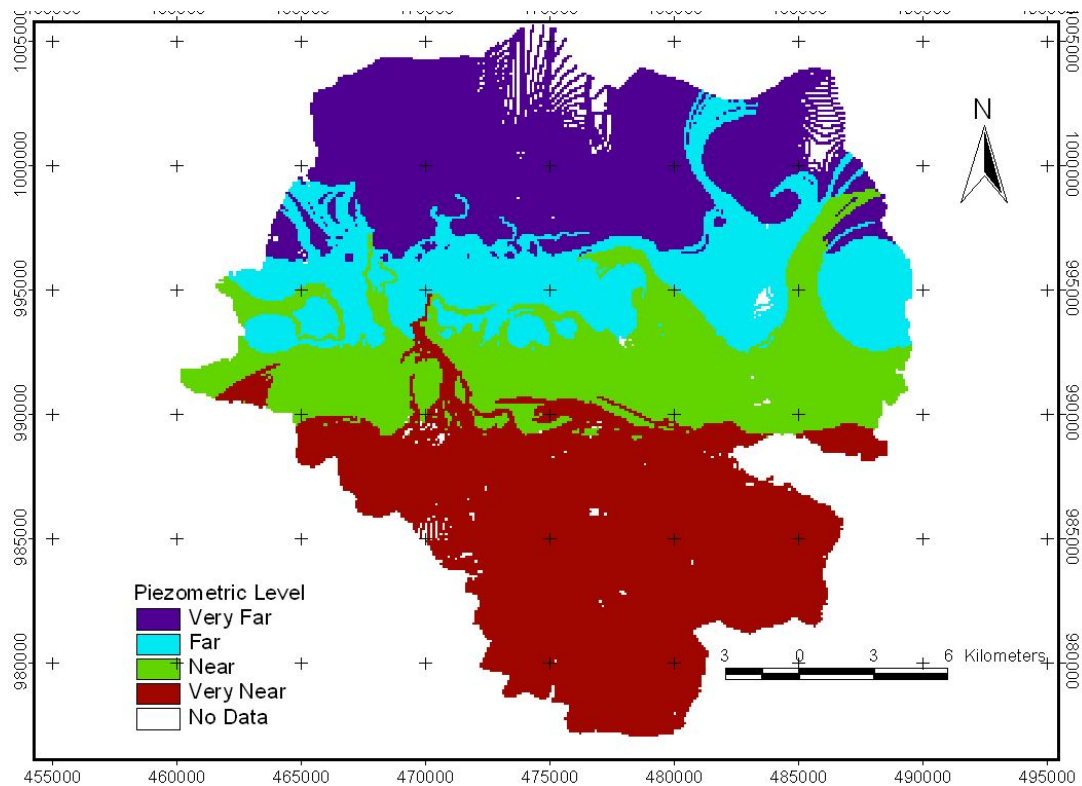
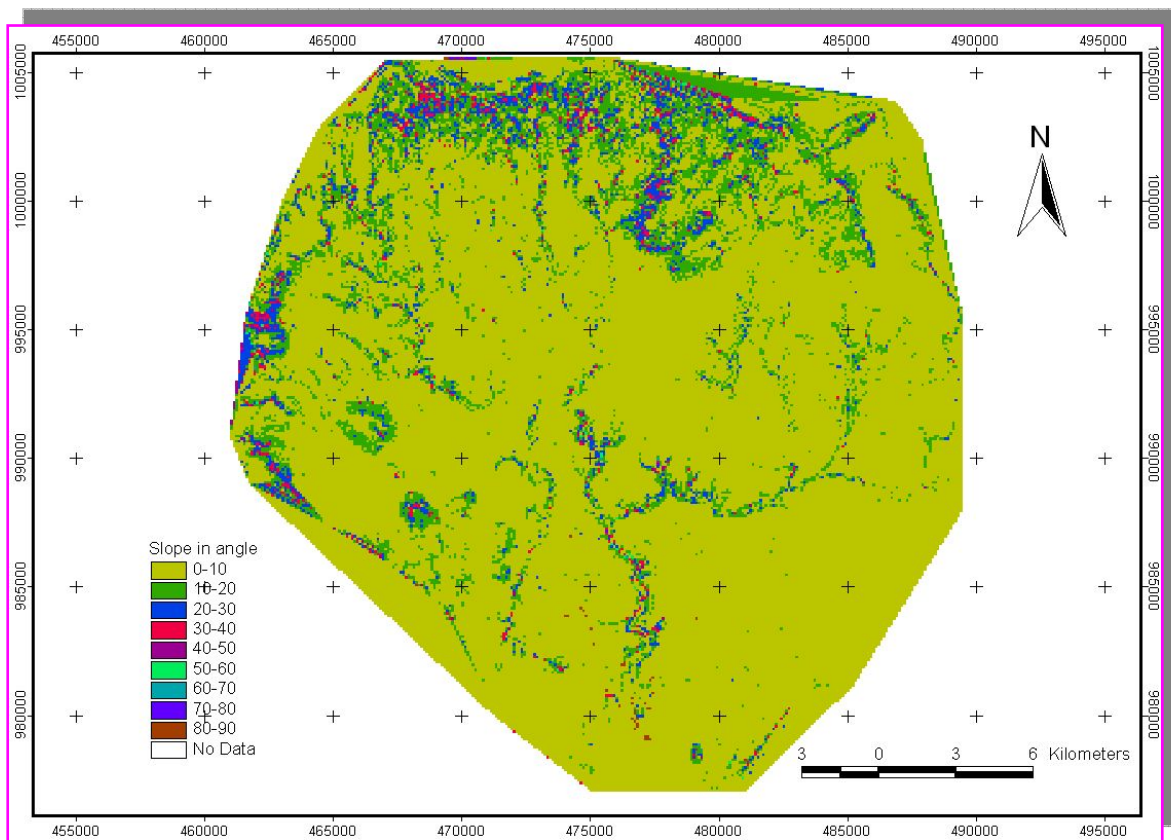


Figure 16 Piezometric maplayer



**Figure 17 slope map layer.**

#### **5.1.4 Step 3: MCE (Multi criteria Evaluation)**

In order to select the suitable land fill site in the study area, the above three standardized factors were evaluated following a procedure called multi-criteria evaluation (MCE), which in this case is achieved by weighted linear combination (WLC), which takes into consideration the value of each layer depending on their weight.

Weighted linear combination (WLC) result= ((factor1\*weight1) + (factor2\*weight2) + (factor3\*weight3))\*constraint

Areas greater than 100 m from an access road mostly will not be recommended. Therefore all alternative sites will be compared based on their proximity to these roads.

Which is done as follows

Weighted linear combination (WLC) result= ((Piezometric level map\*0.5) + (Hydraulic conductivity map\*0.333) + (land slope map\*0.167))\*constraint

There fore the following maps are obtained from the analysis. Figure 18 shows the final out put map of the study before the constraint is included. And figure 19 shows the final out put which after the constraint is included.

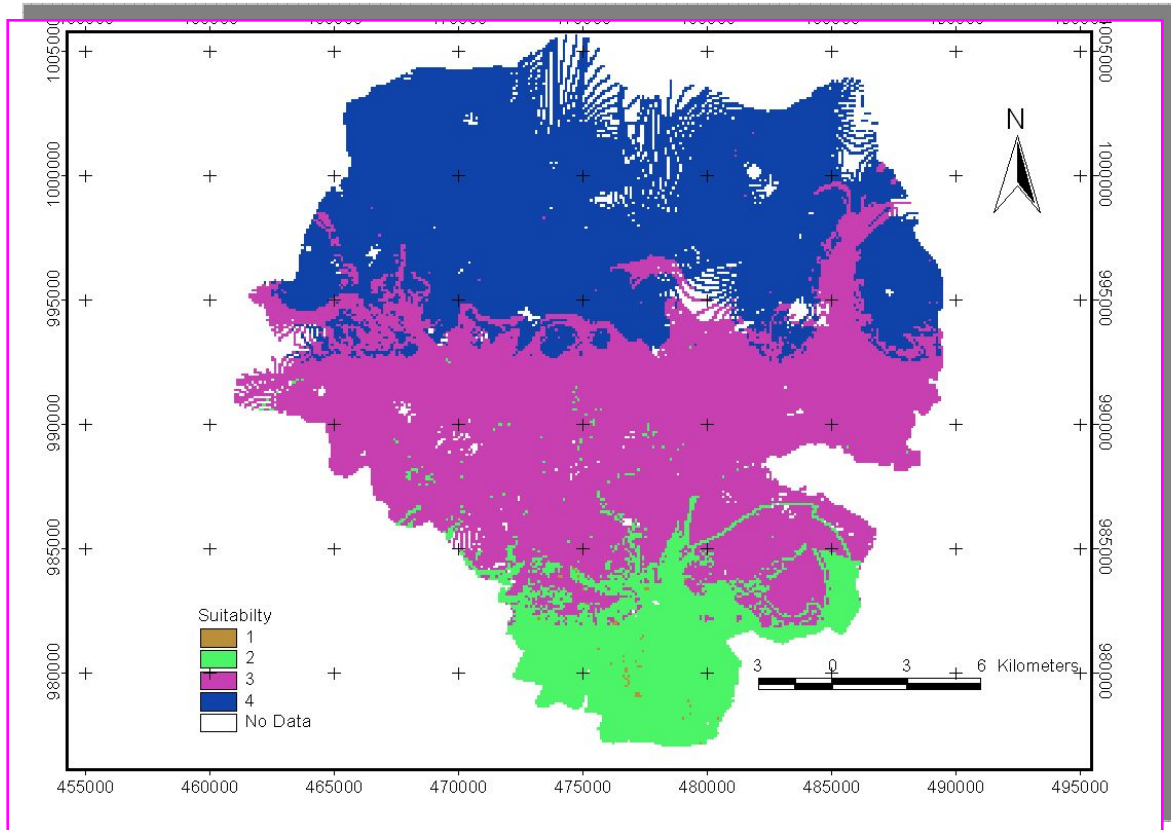
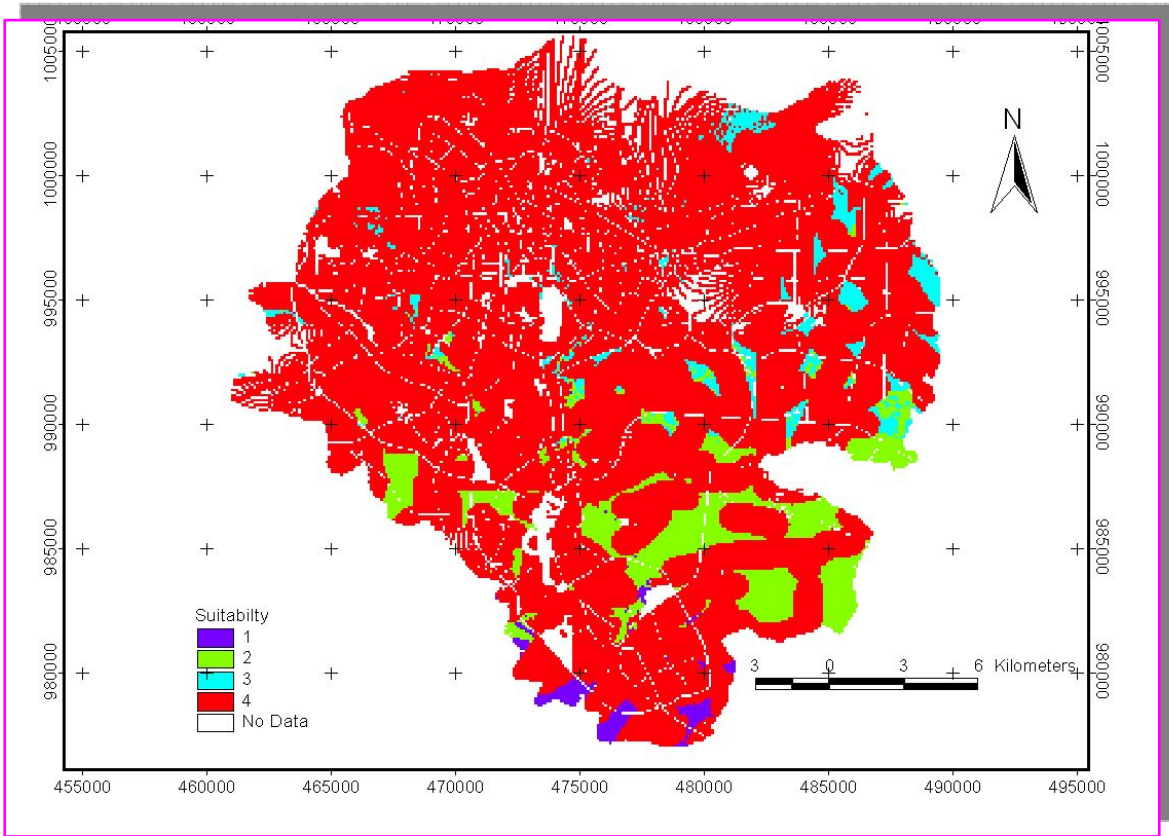


Figure 18 The resulted combined factor map.



**Figure 19 Suitability Map**

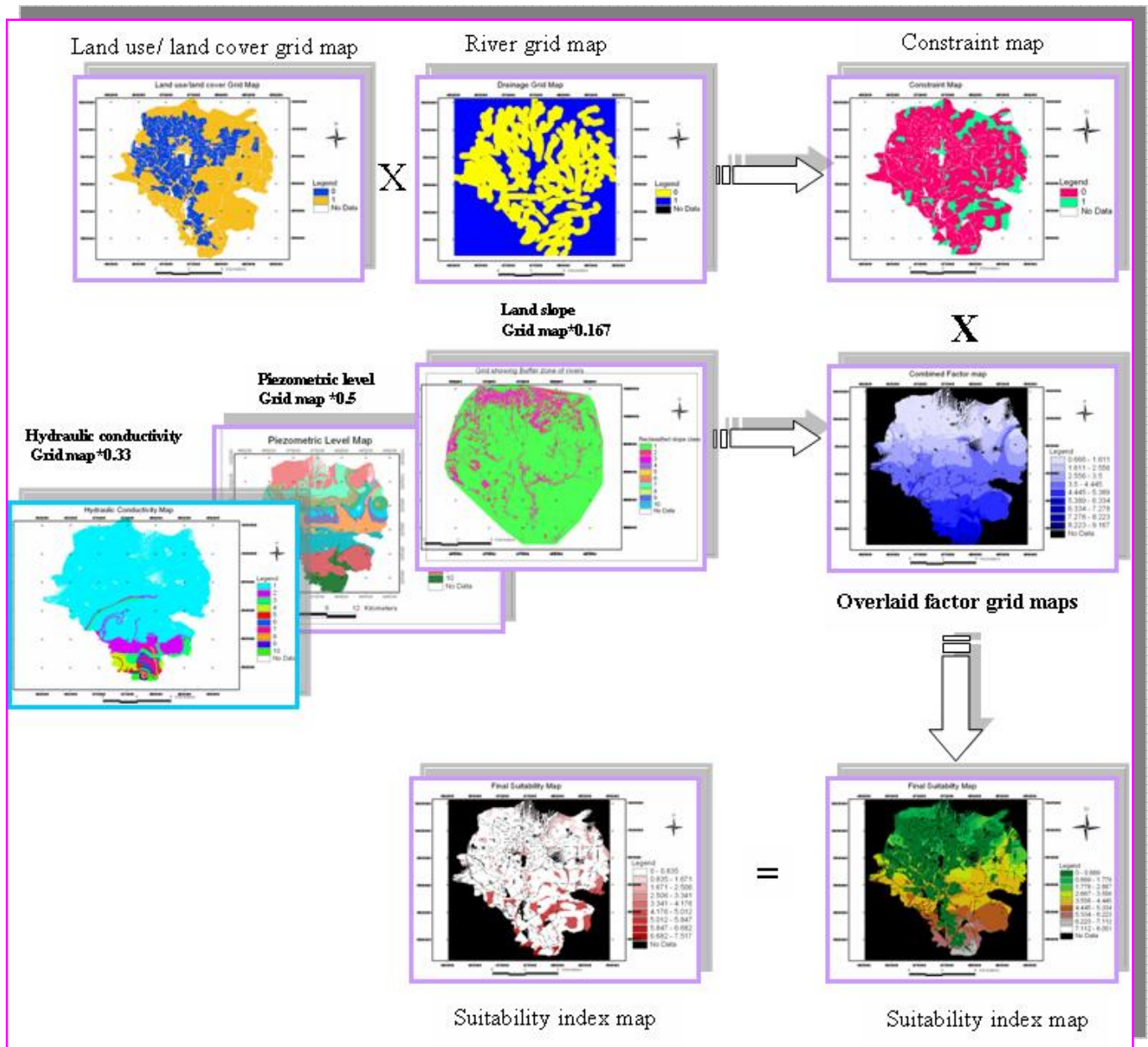


Figure 20. Schematic approach of the study

# CHAPTER SIX

## Conclusion and Recommendations

Ground water contamination is one of the problems encountered from landfills and much has been said about the need of decreasing this negative impact. The construction and operation of leachate systems is costly and difficult to establish in low-income countries like Ethiopia. There fore a method using remote sensing and GIS has been used in this research for the selection of suitable landfill. This research has outlined a method on the selection of suitable landfill and water resource related criteria adopted from different researches.

The following is a set of recommendations for changes or Additions to the existing landfill.

According to the final out put of the analysis, landfills should suitably be located at some areas of the central east and southern part of the city,

However most of the landfill sites proposed by the city administration are concentrated around the northeastern part of the city, which is close to the ground water recharge area of the city. Therefore the Master plan proposed by the city administrators should be reviewed and updated to ensure that the city water resource be safe.

Organizations involved in management of water resources and geological surveys should be involved in or consulted through out the landfill selection process.

## References

1. Kᶑᶑ=e ᶑuv ᶑT ¾'u[ᶑ< wt— ¾Å[p qhh SÉðÁ x ᶑSS<L~ Uj" Áf ᶑT^B x KT²ÖĔf ¾}Å[Ñ Ø" f, Seᶑ[U 1994 ᶑ.U ,ᶑᶑ=e ᶑuv
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3. A framework for Action for the improvement of Addis Ababa City Solid Waste management system  
A-Al-Hanbali,N.Al-Ansari and A.Kondoh (2005), Use of Remote sensing and GIS techniques in Selection of best Possible solid waste disposal sites in Marfaq city-Jordan, Graduate school of science and technology, Chiba university. Japan Institute of earth and Environmental sciences, Al AL-Bayt University,Jordan
4. Drought related health problems in Ethiopia (august 2002) Ministry of health Ethiopia.
5. David Brough (2001) Ethiopia says pesticide dumps are "time bomb", Reuters news service.
6. Environmental sanitation in Addis Ababa (2006), UNDP, World bank water and sanitation program.
7. Geological parameters for environmental protection (2000), Roving course in Africa.
8. H.Rugner & G. Teutsch (April-30, 2001), natural attention of organic pollutants in ground water, Center of Applied Geosciences university of Tübingen
9. J. Chilton , Water quality Assessments- A guide to use of biota, Sediments and water in Environmental Monitoring-second edition

10. Jack Malczewski ( 2000) In GIS and Multi criteria Decision Analysis, department of Geography University of Ontario”
11. Kang-Tsung Chang” in Introduction to Geographic Information systems,
12. Laura McNally (2003) protection of water resources in landfill siting management in Vietnam. Department of civil Engineering University of Toronto”
13. Lourdes V. Abellera (2006) Solid waste disposal site selection using image processing and Geographic information systems (GIS) techniques,. URL: [www.GISdevelopment.net](http://www.GISdevelopment.net)
14. Medical waste disposal, online chemical engineering information,
15. Solid and liquid waste management extension package (February 2004), Federal Democratic Republic of Ethiopia, Ministry of Health.
16. Stepwise review of suitability analysis procedure URL: [www.GISdevelopment.net](http://www.GISdevelopment.net)  
Center of Environmental Remote sensing, Jordan
17. Solid waste management (2006) Blue Earth County, Minnesota
18. Solid waste in Addis Ababa (2006) Environmental Development Action in the Third world (ENDA)
19. Sanitation crisis in Ethiopia (2006) The reporter
20. Tamiru et al (2005), Vulnerability mapping of water supply aquifers of Addis Ababa.
21. Solid waste disposal facility criteria, technical manual (1993), United states Environmental protection agency
22. Upasana shrivastava and Dr.M.S.Nathawat (2005), selection of potential waste disposal sites around Ranchi Urban complex using Remote sensing and GIS techniques. URL: [www.GISdevelopment.net](http://www.GISdevelopment.net)
23. Yaw A. Twumasi, Andrew Manu, Tommy L.Coleman, Brian schmid, and A.Moustapha (2002) Use of Geo-spatial data for Sustainable Management of Solid waste in Niamey, Niger