INTEGRATED REMOTE SENSING AND GIS TECHNIQUES FOR GROUNDWATER EXPLORATION AND MANAGEMENT IN AFRICA

A Case of Karamoja Region - Uganda

Lubang Benedict

Master (IWRM) Dissertation

University of Dar es Salaam

October, 2008

INTEGRATED REMOTE SENSING AND GIS TECHNIQUES FOR GROUNDWATER EXPLORATION AND MANAGEMENT IN AFRICA

A Case of Karamoja Region - Uganda

By

Lubang Benedict

A Dissertation Submitted in Partial Fulfilment of the Requirements for the Award of Masters of Integrated Water Resources Management of the University of Dar es Salam

October, 2008

Certification

The undersigned certify that they have read and hereby recommend for acceptance by the University of Dar es Salaam a dissertation entitled: ***Integrated Remote Sensing and GIS Techniques for Groundwater Exploration and Management in Africa. A Case of Karamoja Region – Uganda;*** in partial fulfilment of the requirements for the degree of Masters in Integrated Water Resources Management of the University of Dar es salaam.

Supervisors

Signed: ___________________________ Date: _________________________

Dr Nobert, Joel.

Signed: ___________________________ Date: ____________________

Dr Mtalo, E. Gerard.

Declaration and Copyright

I, **Lubang Benedict**, declare that this dissertation is my own original work and that it has not been presented and will not be presented at any other University for a similar or any other degree award.

Signature………………………

Acknowledgement

This dissertation was prepared under the guidance of Dr Nobert, Joel of University of Dar es Salaam and Dr. Gerard, E Mtalo of Ardhi University, to whom I give my utmost gratitude. Thanks also go to many individuals in both universities, who made key contributions in this dissertation.

I also thank my family for their support and prayers: my Father and Mother, my brothers and Sisters, above all my beloved wife Irene Lubang and daughter Vanessa Lubang, for all the moral support.

Thanks also go to all friends and colleagues whose encouragement made this work possible for all the supports, they rendered.

My utmost thanks to Lord and Saviour Jesus Christ who has proved to me that it is not by might nor by power but by His Spirit and guidance, especially the gift of health and wisdom during this period and always.

Dedication

I dedicate this work to my beloved wife Irene Lubang and daughter Vanessa Lubang

Abstract

The current groundwater assessment in Karamoja region, as in may part of the world, uses Apparent Resistivity and Vertical Electrical Sounding, which has limited coverage to some localized usually predetermined areas.

In the present study, an integrated remote sensing and GIS based methodology is developed and tested for the evaluation of groundwater resources of Karamoja Sub Region, Northeastern Uganda. The components of the study are (a) Delineation of the groundwater potential zones in the area, (b) Evaluation of the relationship between delineated groundwater potential zones and aquifer characteristics, (c) Identification of suitable sites and methods for artificial recharge to augment groundwater recharge in the area.

The ground water potential and recharge map of the area was determined by the relevant layers, that include hydro-geomorphology, lineament density, slope, drainage density, overburden thickness and aquifer depth, rainfall, geology, land use, and soil were integrated in Arc/Info grid environment.

Weighted index overlay method developed by Multi Criteria Analysis (Analytical Hierarchy Process) has been used to assign weights to the different map layers. All the information layers have been integrated through GIS analysis, employing the use of Natural Break (Jenks) method for classification. Groundwater prospective and artificial recharge site selections have been defined. Alexandru groundwater potential zoning using the Transmissivity values was used for the final classification of the potential zones and correlation with ground-truth data. Over 70% correlation was achieved showing the significance of GIS in groundwater mapping.

Table o f Contents

List of Tables

List of Figures

Appendices

List of Abbreviations

ADLG	-	Abim District Local Government
AHP	-	Analytical Hierarchy Process
DEM	-	Digital Elevation Model
GIS	-	Global Information System
GWP	-	Groundwater Potential
KBDLG	-	Kaabong District Local Government
KTDLG	-	Kotido District Local Government
MDLG	-	Moroto District Local Government
MoWE	-	Ministry of Water and Environment
NDLG	-	Nakapiripirit District Local Government
RS	-	Remote Sensing
SOI	-	Survey of India

CHAPTER ONE

INTRODUCTION

1.1 Background

Groundwater provides the largest available source of fresh water throughout the world. United State Geological Survey Figures indicate that groundwater provides about 22% of all freshwater withdrawals, 37% of agricultural use (commonly for irrigation), 37% of public water supply withdrawals, and 51% for all drinking water for total population and 90% of drinking water for the rural population. In Uganda, majority of rural population rely almost exclusively on groundwater for potable water source.

Dependency of groundwater in Uganda is more in the semi-arid region of Karamoja where prolonged draughts leave most of surface waters dry. Karamoja Data Centre (KDC) estimated that about 80% of the urban population and 60% of the rural population in the region depends on groundwater. With the population explosion, the need to meet the increased demands of water has resulted in complexities to the problems related with water resources sector, and solution to these problems needs immediate attention.

Water being an indispensable constituent for all life supporting processes, its assessment, conservation development and management is gaining prime concern to planners, resources scientists and technocrats. The most common question faced by planners and managers of water resources is how much do I have, how can I access it and is the source sustainable or worth investing in?

Optimal development of water resources requires that, analytical study of hydrological and hydrogeological investigations of existing natural resources be done. Effective water resources assessment is that which can provide the needed information in least possible time and cost. The search for promising groundwater areas involving satellite remote sensing, GIS, traditional hydrological data and field investigations integrations is becoming a common method for groundwater assessment. Due to large areas of coverage and multidisciplinary nature of water resources, Integrated remote sensing and GIS provide the appropriate platform for convergent analysis of diverse data sets for decision making in groundwater management and planning *(Arum, 2002)*.

The potential areas and recharge zones for groundwater resources in Karamoja region have not been assessed, making planning, development and management of the resource erratic. In the present study, an integrated remote sensing and GIS based methodology was used to evaluate the groundwater potential and recharge zones in the Karamoja Region. Inclusion of subsurface information inferred from borehole drilling logs can give more realistic picture of groundwater potentiality of an area. Keeping this in view, the present study attempts to delineate locations for groundwater exploration using integrated remote sensing, and GIS techniques.

1.2 The Study Area

Location

The region of Karamoja extends over an area of 27,900 square kilometres. Karamoja sub region lies in North-eastern part of Uganda in the coordinates $4^{\circ}16'15''$ north, $34^{\circ}58'05''$ east, $1^{\circ}31'09''$ South and $33^{\circ}31'47''$ west. It is bordered in the north by Sudan, in the east by Kenya, in the west by the Districts of Kitgum, Pader, Katakwi and Kumi, form the south by Sironko and Budaka Districts. The region consists of five Districts namely, Abim, Kaabong, Kotido, Moroto and Nakapiripirit Districts.

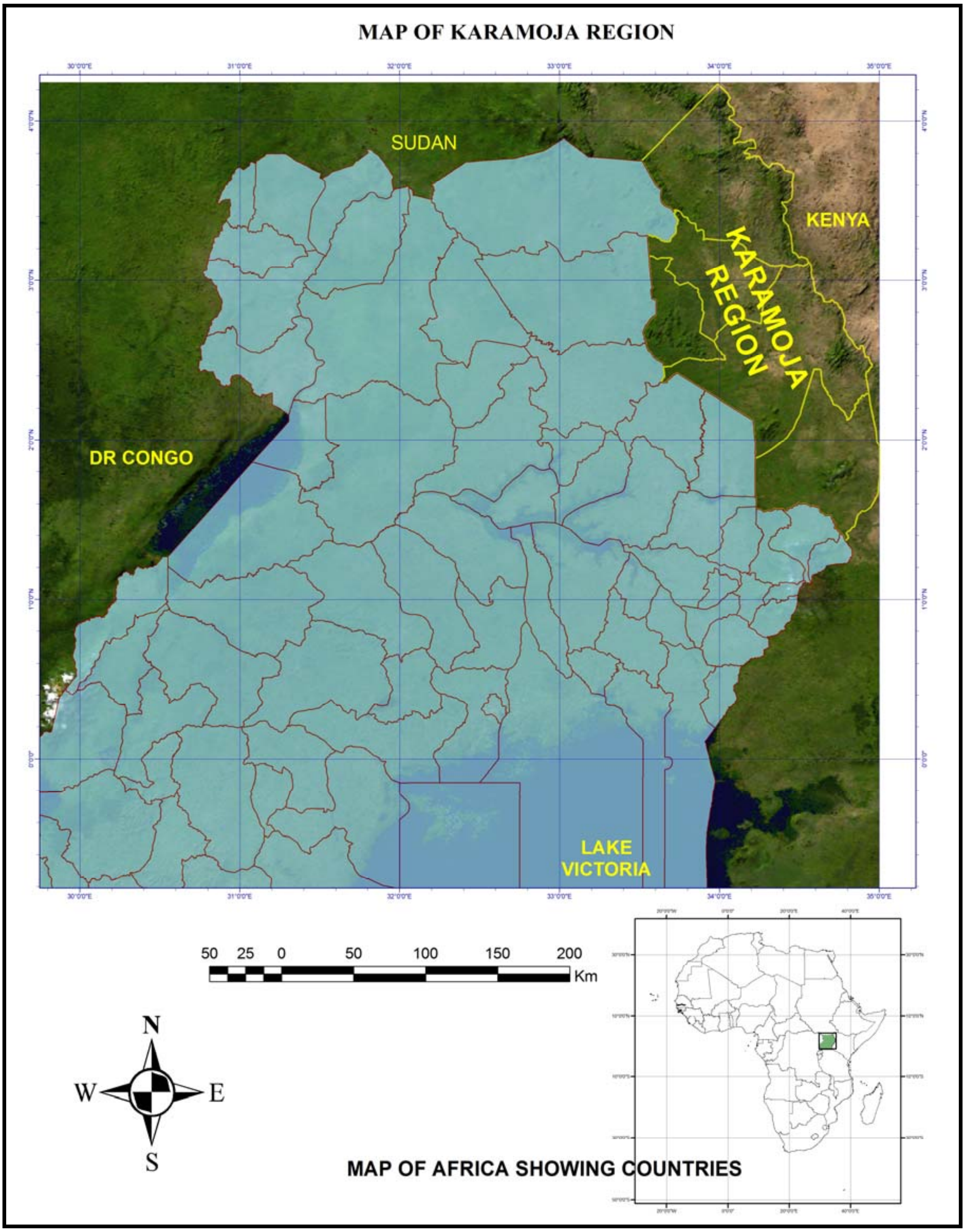

Fig 1.2-1: Map of Karamoja Region

Physiographic and Climate

The area is generally flat with intermittent outcrops of volcanic rocks and hills with semi-desert type of vegetation covered with seasonal grasses, thorned plants, and occasional small trees. From topographical maps, the average elevation of the plain of Karamoja lies at around 1400 meters above sea level. The large mountains, Mt. Kadam, Mt. Napak, and Mt. Moroto — lying at the periphery of Karamoja — have peaks reaching around 3000 meters and higher.

The rainfall regime is short and unreliable; the hydrological map indicates that rainfall ranges from 699 – 1251 mm annually from one part of the region to another. The temperature is well over 30^0C for most part of the year.

1.3 Hypothesis/Research Question

Remote sensing and GIS are playing a rapidly increasing role in the field of hydrology and water resources development with "numerous successes" *(Singh & Prakash, 2000)*. The use of GIS in hydrogeology is only at its beginning, but there have been successful applications that started to develop *(Das D. , 1997)*. These claims and many more are spreading far and wide and thus, will be assessed in the present study. The study focused on mapping potential groundwater availability and potential artificial recharge zones for sustainable development and management of the resource in the North Eastern Uganda - Karamoja region using integrated remote sensing and GIS methods. The question is therefore; to what significant level does Integrated Remote Sensing and GIS, methodology relates to the ground truth data.

1.4 Objectives of the Study

The main objective of the study is the exploration of groundwater in semi arid and mountainous terrain of Northeastern Uganda – Karamoja region.

The specific objectives of the study are:

a) Delineation of the groundwater potential zones in the area.
b) Evaluation of the relationship between delineated groundwater potential zones and aquifer characteristics.
c) Identification of suitable sites and methods for artificial recharge to augment groundwater recharge in the area.

1.5 Significance and Justification of Study

With no surface water in the region, groundwater being the only dependable water resource, groundwater resources stands central in providing fresh water resource for region. The Region also faces challenges from growing population, livestock and irrigated agriculture. Livestock and irrigated agriculture have attracted a lot of interest as potential ways of diversifying the economic income of the people in the region. However, the long-term sustainability of groundwater resources to meet all these demand has always remained unresolved given the fact that groundwater potential and aquifer characteristics has not been studied extensively.

On the other hand, groundwater development programs have been facing many challenges of dry wells. The current method of assessing groundwater in the region is using Apparent Resistivity and Vertical Electrical Sounding, which has limited coverage to some localized, usually predetermined areas. The Ministry of Water and Environment (MoWE) - Uganda specifies above 80% successes in drilling for groundwater in Government contracts, but the region has been experiencing less than 60% success –*(Karamoja Data Centre, 2003), t*his has lead to loss of resources. This therefore called for a more comprehensive study covering wider area and incorporating other parameters that influences groundwater availability in an area. Remote sensing and GIS are playing a rapidly increasing role in the field of hydrology and water resources development with numerous successes. This study provides guidelines and methods for managers and planners on the use of GIS and RS approach in delineating groundwater potential zones and related issues as an input in water development program in the region.

Scope of study

The study is focused on groundwater potential zoning and aquifer recharge site selection in the Karamoja Region. Various factors that influence the occurrence of groundwater and its recharge form the basis of the study and shall be incorporated. Sub surface strata derived from the borehole-drilling log formed part of the study. Assessment of aquifer Transmissivity will be used in the interpretation strategy thus formed part of the study.

Organization of the study

The study is presented in five chapters. Chapter 1 deals with introduction giving the background of the study, the study objectives, statement of problem, and rationale of the study, scope and brief description of the study area. Chapter 2 presents literature review with the aims of identifying contribution of other research and analytical methods. Chapter 3 discusses the analysis and methods used. Chapter 4 discusses the RS & GIS findings, and identifies key influential parameters affecting groundwater occurrence, and Chapter 5 presents the recommendation according to the findings. The outline is presented in Figure 1.7-1 below.

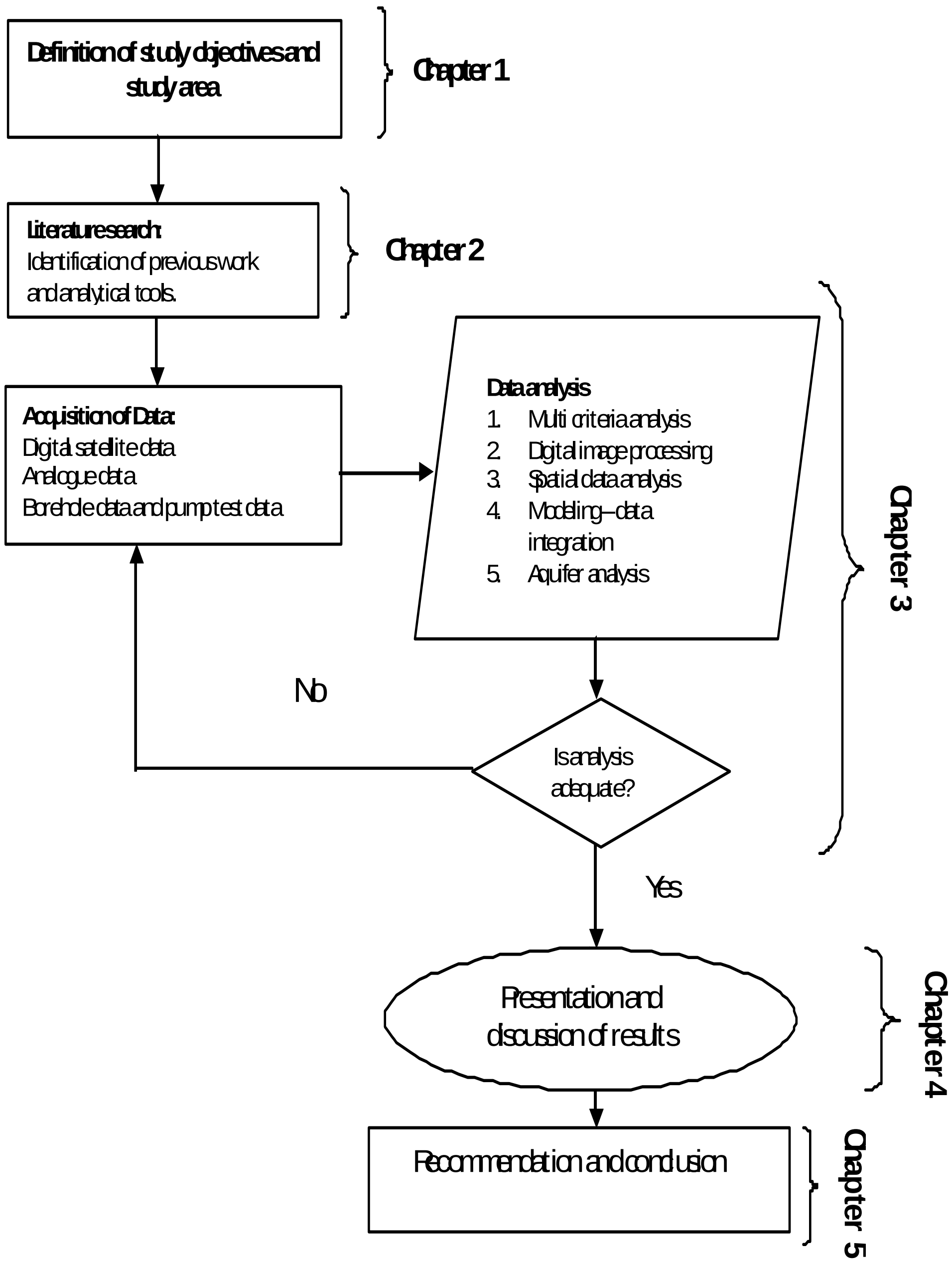

Fig 1.7-1: Schematic Representation of Research Concept

CHAPTER TWO

LITERATURE REVIEW

Karamoja Region of Northeastern Uganda is chronically drought-prone and faces acute water scarcity for both irrigation and drinking purposes. While the surface water resources in the area are non-existent or inadequate to meet the local need, the groundwater resources are not explored sufficiently *(Karamoja Data Centre, 2003).*

For optimal development of water resources, the analytical studies of hydrological investigations in relation to other existing natural resources are important. Effective methods for assessment of water resources are required to be developed which can provide the data in least possible time and cost.

The assessment of water is influenced by various factors like soil, land cover, topography, geology, climate etc., thus a large data set is required. Conventional methods of data collection are not only uneconomical and difficult, but by the time information could be compiled they are outdated. Remote sensing techniques provide basic data bank, which can be organized and controlled in near real time and can provide the desired hydrological information for water resources assessment in very short time *(Shrivastava, Sidhu, & H.S., 1992)*

2.1 Geological and Hydrogeological Conditions

The geology of the region is complex and predominantly underlain by complex basement of banded acid gneisses and undifferentiated banded acid biotite magmatic gneisses. These rocks are highly metamorphosed from north south trending forming low-lying wide ridges. The trend of the ridges indicates the axial trend of folding, which control most for the drainage system. The drainage system is almost East-West, and tends to be straight because it is controlled by the jointing.

The northern part of the region is underlain predominantly by Precambrian wholly granitised or high to medium grade metamorphic formations. These include the Karasuk series of acid gneisses, amphibolites, quartzite, marbles and granulites facies, which cover the border with Kenya and the North East. Granulites facies rocks, including charnockites and enderbites outcrop as volcanic plugs and ridges. Banded gneisses of pre-karasul series cover the central striking North-South. Pleistocene to recent sediments is in the lowlands, south and west of the region. The regolith/overburden is thin in many parts of the region *(Geotech Development Services, 2007).*

Metamorphic rocks are known hydrogeologically to have poor potential for groundwater. This is because their mechanism of formation involves high pressure and temperature, making them to flow as the mineralization changes. This makes them fail to rapture (cause fractures essential for water holding) hence poor groundwater potential.

2.2 Occurrence of Groundwater

The region is poorly drained with seasonal flowing channels and swamps, except in the southern Nakapiripirt District which tend to have few perennial streams with very low flows. Valley dams are excavated in some areas to obtain water during dry periods. Borehole forms an important source of water for the communities in the region.

Potential for shallow aquifer (for shallow wells) is very low because of unfavourable geomorphologic and geological conditions consisting mostly of lateritic-clay and sandy-clay. However, in areas bordering the western ends of the region, especially the southern part, has high potential of shallow aquifers due to occurrence of weathered regolith overlying the competent bedrock. The regolith thickness is highly variable depending on the topography of a particular area but ranges from 4m to 46m, consists mainly of sandy-clay, and highly weathered granite.

Most groundwater in the region occurs in the weathered or fractured rocks found generally deep, ranging from 41m to 125m with average depth of 72m.

2.3 GIS and Remote Sensing in Groundwater Hydrology

GIS is a tool for storing, manipulating, retrieving and presenting both spatial and non-spatial data in a quick, efficient and organized way. Since most land information features have a geographic connotation, geographically referenced data with GIS techniques come to the fore in such and application. The term 'geographic' in GIS refers to the location attributes, which define the spatial positioning of the piece of information on the face of the earth. The use of GIS in hydrogeology is only at its beginning, but there have been successful applications that started to develop *(Das D. , 1997).*

2.3.1 Database and Structure

Das (1990) indicated that, satellite data provides quick and useful baseline information on the parameters controlling the occurrence and movement of groundwater are geology, lithology/structural, geomorphology, soils, land use/cover, lineaments etc. However, all the controlling parameters have rarely been studied together because of non-availability of data, integrating tools and modelling techniques. Hence, a systematic study of these factors leads to better delineation of prospective zones in an area, which is then followed up on the ground through detailed hydro-geological and geophysical investigations.

By combining the remote sensing information with adequate field data, particularly well inventory and yield data, it is possible to arrive at prognostic models to predict the ranges of depth, the yield, the success rate and the types of wells suited to various terrains under different hydro-geological domains (*Saraf, 1999*).

Point data always considered in groundwater are water level, weathered zone thickness, saturated zone thickness, yield in the wells, rainfall, porosity of aquifer material, Transmissivity (T) and Storage co-efficient (S), which could be interpolated to fill gaps in the spatial data so that each grid cell would have valid data.

In order to assess groundwater prospect by qualitative modelling, data on geomorphology, geological structures, and lineaments would be required in addition to weathered zone thickness, saturated zone thickness and yield in the wells. Lineaments being line data has to be converted into a raster data by finding the lineament density on a coarse grid say, 1 km x 1 km. In order to assess the suitability of groundwater quality for irrigation, drinking or industrial purpose, Electrical Conductivity (EC), pH, Sodium Absorption Ratio (SAR) data etc has to be collected from the monitoring wells and interpolated to get raster data *(Novaline, Saibaba.J, & Raju, 1999).*

2.3.2 Layers Classification

When you perform a classification, you group similar features into classes by assigning the same symbol or value to each member of the class. Aggregating features into classes allows you to spot patterns in the data more easily. The definition of a class range determines which features fall into that class and affects the appearance of the map. By altering the class breaks, (the boundary between classes), you can create very different-looking maps. Classes can be created manually, or you can use a standard classification scheme.

You can choose a manual classification method or one of these standard methods:

- Manual—lets you set the class breaks. You can use this choice if, for example, you want to emphasize particular patterns by placing breaks at important threshold values or if you need to comply with a particular standard that demands certain class breaks.
- Equal Interval—the range of cell values is divided into equally sized classes where you specify the number of classes. You can use this method to emphasize the relative amount of attribute values compared to other values. It is best applied to familiar data ranges such as percentages and temperature.
- Defined Interval—you specify an interval to divide the range of cell values, and ArcMap determines the number of classes.
- Quantile—each class contains an equal number of cells. You can use this method with linearly distributed data.
- Natural Breaks (Jenks)—the class breaks are determined statistically by finding adjacent feature pairs between which there is a relatively large difference in data value.

- Standard Deviation—shows you the amount a cell's value varies from the mean.

Of importance is the Natural Break (Jenks);

Jenks-Caspall (1971)

The Jenks-Caspall (1971) algorithm is a method for improving thematic mapping as a communicative tool and, therefore, as a visualization tool. The Jenks-Caspall algorithm is an optimal classification method that can assist geographers and cartographers in creating geographic visualizations of spatial data. The objective of the Jenks-Caspall algorithm is to place similar data values in the same class by minimizing the sum of the absolute deviations about class means. The algorithm iterates through the raw data and reclassifies them based on this objective *(Michael, Williams, & Lynn, 2006).*

2.4 Recharge of Aquifer

Groundwater recharge refers to the process whereby water below the land surface is replenished by either direct infiltration of rainfall or by leakage from surface water bodies like streams and lakes. The process involves downward movement of water within the pore spaces of soil or rock until the water table is reached.

Natural recharge to an unconfined aquifer is essentially all derived from meteoric sources, but they may be direct (from precipitation) or indirect from (precipitation via surface water bodies or adjacent aquifer) other contributions known as "artificial recharge" occur where water is deliberately or incidentally recharged to aquifers through human activities. In general, terms recharge occurs by

- Direct recharge from precipitation

- Seepage from surface water storage
- Recharge and discharge via groundwater leakages.

2.4.1 Natural Recharge

Aquifer recharge occurs in nature by rainfall, seepage from canals and reservoirs and return flow from irrigation. Direct recharge from precipitation depends largely on characteristics of the precipitation itself as well as the physical characteristics of the ground surface (topography, vegetation) and the type of structure of soil and the underlying rocks as well as the antecedent soil moisture conditions.

The key factors controlling groundwater recharge are:

- Climatic, the amount and intensity of rainfall and evaporation,
- Soil and
- aquifer hydraulic properties,
- Type and amount of vegetation cover and types of land use,
- Topography, in particular the slope of the land surface
- The nature and geometry of aquifers in the catchment
- Residual (or antecedent) soil moisture stored in the soil profile from previous rainfall events
- lineaments

The geomorphic features like alluvial fans buried pediments, old stream channels and the deep-seated interconnected fractures are indicators of subsurface water accumulation *(Mukherjee et al, 1996).* These features are the natural recharge sites due to their high permeability and water holding capacity.

Drainage density affects the surface runoff, i.e. the higher the drainage density, the higher the runoff thus limiting infiltration. It has been observed that the terrain transmissibility is inversely proportionate to the square of drainage density (*Omar, 1990).* Das. & Kader (1996) observed that combined effect of drainage density (01.15-14.76 km/sq km), stream frequency (0.95-12.11), bifurcation ration (2-10) and granitic lithology favours high surface runoff and low infiltration.

The identification of lineaments has immense importance in hard rock hydrogeology as they can identify rock fractures that localise groundwater *(Das D. , 1990)*. The hydrogeologists usually infer subsurface hydrological condition through surface indicators, such as aerial geological features, linear structures. Most of the geological linear features are assumed zone of fractured bedrocks and the position of porous and permeable state where enhanced well yields can be expected *(Das, 1997)*. Scientists observed that yields of wells on lineaments are about 14 times than that of wells away from lineaments in the case of Gondwanas, Warangal district, A. P. India, *(Parizek, 1976)*. A study on the Relationship between fracture traces and the occurrence of groundwater in carbonate rocks have shown that wells located on fracture traces (lineaments) in the lower Palaeozoic Carbonic rocks of Pennsylvania yielded about 10-100 times more water than wells located in similar condition but away from fracture traces *(Shankar et al, 2002).*

2.4.2 Artificial Recharge

Artificial recharge, which can be conducted in a variety of ways and may be deliberate or incidental, is becoming increasingly important in groundwater management and in conjunctive use of surface water and groundwater resources

(Taigbenu, 2002). In places where the withdrawal of water is more than the rate of recharge an imbalance in the groundwater reserves is created.

Recharging of aquifers is undertaken with the following objectives:

i. To maintain or augment natural groundwater as an economic resource
ii. To conserve excess surface water underground
iii. To combat progressive depletion of groundwater levels
iv. To combat unfavourable salt balance and saline water intrusion

2.5 Methods of Artificial Recharge

There are two major form of artificial recharge, spreading and the use of pits or wells. Artificial recharge by spreading method consists of increasing the surface area of filtration by releasing water through flooding or irrigation from a source of surface of a basin, pond stream channel or a ditch and furrow system. The pit and well method of artificial recharge involve the construction of well or boreholes specifically for the purpose of encouraging recharge into the aquifers either using only the force of gravity or injection water under pressure to achieve the end. In general, terms, artificial recharge can be direct surface, direct sub surface, indirect, and combination of surface and subsurface techniques.

a) Direct Surface Techniques

- Flooding
- Basins or percolation tanks
- Stream augmentation
- Ditch and furrow system

- Over irrigation

b) Direct Sub Surface Techniques

- Injection wells or recharge wells
- Recharge pits and shafts
- Dug well recharge
- Bore hole flooding
- Natural openings, cavity fillings.

c) Combination Surface – Sub-Surface Techniques

- Basin or percolation tanks with pit shaft or wells.

d) Indirect Techniques

- Induced recharge from surface water source.
- Aquifer modification: In hard rock areas, rock-fracturing techniques including sectional blasting of boreholes with suitable techniques has been applied to inter-connect the fractures and increase recharge.

The following methods are of importance to this study;

2.5.1 Stream Channel Method – (surface technique)

In arid areas where streams are naturally, "losing streams" which recharge the aquifers beneath them, recharge may be enhanced by constructing weirs or checks dams using gabion across the width of the rivers. These structures are often "L" shaped and these have the effect of retaining water over the whole width of the river at reasonable depth. Check dams are feasible in hard rock terrain and alluvial formations. The site for these dams should have sufficient thickness of permeable bed or weathered formation to facilitate recharge of stored water.

2.5.2 Combination Surface – Sub-Surface Techniques

These are the most direct measure to recharge the ground water reservoir in both alluvial as well as hard rock formations. The efficacy and feasibility of these structures is more in hard rock formation where the rocks are highly fractured and weathered. Percolation tanks with wells and shafts can be used to recharge deeper aquifers where shallow or superficial formations are highly impermeable or clayey with certain modifications.

2.5.3 Basin Method – (Surface technique)

The basin method operates by releasing surplus surface water into artificially created shallow basins (either by digging or by constructing walls around the basin). It is important that the water directed to the basins is silt free as silts may reduce the rate of infiltration. Even so, basins do need maintenance, which might involve breaking up the bed to increase the permeability of the bed and therefore enhance infiltration capacity.

2.5.4 Recharge Well Method – (sub surface technique)

A recharge well is essentially the reverse of a pumping well and these may be used to recharge both confine and unconfined aquifers. These wells can be dug wells that have gone dry or the water level has gone down considerably.

2.6 Planning of an aquifer recharge system

To achieve the objectives of artificial recharge, it is very important to plan an artificial recharge scheme in a scientific manner. Thus, it is essential that proper scientific investigations be carried out for selection of site for artificial recharge of groundwater *(Central Water Board, MoWR, 2000)*. The proper design will include the following considerations:

2.6.1 Scientific inputs

The following studies are needed;

a) Hydro-meteorological studies

Rainfall pattern, evaporation losses and climatologically features are crucial in semi arid regions in deciding the capacity and design of the artificial recharge structures.

b) Hydrological studies

The following information will be required;

i. The quantity that may be diverted for artificial recharge.
ii. The time for which the source water will be available.
iii. The quality of source water and the pre-treatment required.
iv. Conveyance system required to bring the water to the recharge site.

c) Soil infiltration studies

Factors controlling the rate of infiltration and downward percolation of water need to be studied collectively. Factors such as soil type, moisture content, organic matter, vegetative cover, seasons, air entrapment, and formation of surface crusts or seals can control the infiltration capacity of the soil.

d) Hydro-geological studies

Data on the subsurface hydro-geological units, their thickness and depth of occurrence, and to bring out the disposition and hydraulic properties of unconfined, semi confined and confined aquifers in the area. The main stress in on knowing whether the surface rock types are sufficiently permeable to maintain high rate of infiltration during the artificial recharge.

e) Biophysical and Chemical quality of source water

The chemical and bacteriological analysis of source water is very essential, especially when the recharge water requires some sort of treatment before being used in recharge installations. Suspended solids and clogging problem are crucial in recharge augments.

2.6.2 Selection of site:

Recharge structures should be planned out after conducting proper hydro-geological investigations. Based on the analysis of this data (already existing or those collected during investigation) it should be possible to:

- Define the sub-surface geology.
- Determine the presence or absence of impermeable layers or lenses that can impede percolation
- Define depths to water table and groundwater flow directions
- Establish the maximum rate of recharge that could be achieved at the site

2.6.3 Source of water used for recharge:

The potential of rainwater harvesting and the quantity and quality of water available for recharging, have to be assessed.

2.6.4 Engineering, construction and costs

For designing the optimum capacity of the tank, the following parameters need to be considered:

a) Size of the catchment

b) Intensity of rainfall

c) Rate of recharge, which depends on the geology of the site

The capacity of the structure should be enough to retain the runoff occurring from conditions of peak rainfall intensity. The rate of recharge in comparison to runoff is a critical factor. However, since accurate recharge rates are not available without detailed geo-hydrological studies, the rates have to be assumed.

2.6.5 Operation, maintenance and monitoring

Operation and maintenance to protect the recharge zones/wells from clogging is very crucial in artificial recharge. The monitoring of water levels and water quality is of prime importance in any scheme of artificial recharge of Ground Water. The monitoring data speaks for the efficacy of structures constructed and greatly helps in taking effective measures for Ground Water Management on scientific lines.

2.7 Previous Research/ Studies Done

One of the greatest advantages of using remote sensing data for hydrological investigations and monitoring is its ability to generate information in spatial and temporal domain, which is very crucial for successful analysis, prediction and validation *(Saraf, 1999)*. The concept of integrated remote sensing and GIS integration of multi-thematic data has proved to be an efficient tool in integrating groundwater studies that open new approaches for planning and management of groundwater.

2.7.1 Studies/Research

A study on groundwater potential zone map using one climatic and seven biophysical parameters and the modified DRASTIC model was done in the Langat Basin in the South of Selangor and North of Negeri Sembilan, by *(Musa, Akhir, & Abdullah, 2000)*. The resultant map is comprised of five categories of groundwater yield – very high, high, moderate, low or very low. It was found that almost all alluvial plains have high yield of groundwater while in hard rock areas groundwater yield was high in area of lineament and low drainage densities respectively. The study used the following data; Landsat TM data, geological maps sheets of Scale 1:63360, Topographical map of scale 1:50,000, mean annual rainfall data for 18years, soil map at scale 1:150000, Hydro-geological map at scale of 1:500,000 and borehole data. These baseline data were integrated spatially in a one-system environment with standardization scale, map projection and metadata.

Spatial data analysis was done by assigning Weights *(Krishnamurthy, 1996 & 1997)* to the map units of each of the eight spatial layers generated on its contribution to groundwater as shown in Table 2.5.1 to Table 2.5.8 below;

Table 2.7.1: Drastic Weight for Slope

Scores for Slope		
Slope	Description	score
0 – 7 % (0° - 3°)	Almost Flat	50
8 – 20 % (4° - 9°)	Undulating to Rolling	40
21 – 55% (10° - 24°)	Hilly Disserted	30
56 – 140 % (25° - 63°)	Steep Dissected	20
> 140 % (> 63°)	Very Steep Mountainous	10

Table 2.7.1: Drastic Weight for Elevation

Scores for Elevation	
Elevation (m)	Score
< 20	50
20 – 100	40
100 – 500	35
500 – 1000	25
> 1000	10

Table 2.7.2: Drastic Weight for Rainfall

Scores for annual rainfall	
Annual Rainfall (mm)	Score
2500 – 2750 (Very High -VH)	70
2250 – 2500 (High - H)	60
2000 – 2250 (Moderate - M)	50
1750 – 2000 (Low - L)	40
1500 – 1750 (Very Low - VL)	30

Table 2.7.3: Drastic Weight for Soil

Scores for Soil		
Soil Series	**Soil Type**	**Score**
Keranji	Clay	10
Melaka-Durian-Muncung	Gravel clay-silty clay-clay	20
Muncung-Seremban	Fine sandy clay	20
Prang	Clay	10
Regam-Jerangau	Coarse sandy clay-clay	30
Selangor-Kangkung	Clay	10
Serdang-Bugor-Muncung	Fine sandy clay loam-fine to sandy clay-clay	30
Serdang-Kedah	Fine sandy clay loam	30
Cleared land in urban area	Sandy clay	30
Steep Land Soils	Coarse sandy clay	40
Peat Land	Clay	10
Sand Tailings (Tin Mined)	Sand	50
Telemung-Akob-Local Alluvium	Sandy loam-sandy clay	30

Table 2.7.4: Drastic Weight for Drainage Density

Score for lineament density	
Lineament Density (km/km2)	**Score**
> 0.0075 (VH)	60
0.0055 – 0.0075 (H)	50
0.0035 – 0.0055 (M)	40
0.0015 – 0.0035 (L)	30
< 0.0015 (VL)	20

Table 2.7.5: Drastic Weight for Lineament Density

Scores for Drainage density	
Drainage Density (km/km2)	**Score**
> 0.0055 (VH)	10
0.0040 – 0.0055 (H)	20
0.0025 – 0.0040 (M)	30
0.0010 – 0.0025 (L)	40
< 0.0010 (VL)	50

Table 2.7.6: Drastic Weight for Land-use cover

Scores for land-use cover	
Land use – cover	Score
Forest	20
Agriculture	40
Scrub	30
Wetland	50
Urban	10
Cleared Land	10
Water Body	60

Table 2.7.7: Drastic Weight for Lithology

Score for Lithology	
Lithology	**Score**
Alluvium	70
Limestone	40
Phylite-Schist-Quartz	20
Quartz vein	5
Volcanic	30
Granite	10

The data generated was integrated using linear summation using DRASTIC model *(Aller, 1985)* Modified,

$$GP = Rf + Lt + Ld + Lu + Te + Ss + Dd + St \qquad (2.7.1)$$

Where: Rf = mean annual rainfall

Lt = Litho logy, Ld = Lineament density

Lu = Land use, Te = Elevation

Ss = Slope steepness, Dd = Drainage density and,

St = Soil type

The model compute for each output pixel the combined Weight of the eight parameters and the pixels were then grouped into five categories using quantification based GIS classification (ESRI, 1996) – (i) very high, (ii) high, (iii) moderate, (iv) low and (v) very low for the production of the ground potential map.

Table 2.7.8: Groundwater potential Map classification

Classes of Ground water		
Groundwater Zone Classes	**Estimated Discharge Rate**	**Score/value**
Very High	> 22 m3/hour/well	> 285
High	18 – 22 m3/hour/well	260 – 380
Moderate	14 – 18 m3/hour/well	245 – 255
Low	10 – 14 m3/hour/well	230 – 240
Very Low	< 10 m3/hour/well	< 225

Musa, Akhir, & Abdullah, (2000) made several conclusions notably, The indicators of groundwater occurrences are related to the hydrological cycle, and parameter that included rainfall distribution, land use, soil types, geological structures, elevation, slope and drainage features of the area. The methods and result of this study were more suitable for groundwater zone prediction in hard terrain than for alluvium plains.

Singh & Prakash (2000) used an integrated approach of Remote Sensing, Geophysics and GIS to evaluation of Groundwater potentiality of Ojhala sub-watershed, Mirzapur district, U.P., in India. To find out the more realistic ground water potentiality map of the area, the relevant layers, which include hydro-geomorphology, lineament, slope, drainage, overburden thickness and aquifer thickness, were integrated in Arc/Info grid environment.

The thematic maps on hydro-geomorphology and lineaments were prepared using IRS 1C LISS-III data by visual interpretation on 1:50,000 scale. Drainage map was prepared from SOI toposheets & satellite data. Contour map and spot elevation map were prepared from SOI toposheets. All primary input maps (hydro-geomorphology, lineament, contour & spot elevation, drainage and geo-electrical sounding location) were digitized in Arc/Info, GIS software package and slope map was prepared from digital elevation data. Criteria for GIS analysis were defined based on ground water conditions and appropriate weightage was assigned to each information layer according to relative contribution towards the desired output.

The ground water potential zone map generated through this model was verified with the yield data to ascertain the validity of the model developed. Interpretation of geo-electrical soundings data of 68 sites. Correlation of geo-electrical parameters of drilled sites with lithology.

Finally thematic layers were converted in to grid with related item weight and then integrated and analyzed, using weighted aggregation method. The grids in the integrated layer were grouped into different ground water potential zones by a suitable logical reasoning and conditioning. The final ground water potential zone map thus generated was verified with the yield data to ascertain the validity of the model developed.

In the final thematic layer initially each one of the polygons were qualitatively visualized into one of the categories like (i) very good (ii) good to very good (iii) good (iv) moderate and (v) poor in terms of their importance with respect to groundwater occurrence and suitable weights have been assigned.

Singh & Prakash (2000) concluded that in order to delineate the groundwater potential zones, in general, different thematic layers via: hydro-geomorphology, lineaments, slope, drainage and overburden thickness can be used without considering aquifer thickness. This provides a broad idea about the groundwater prospect of the area.

The study of groundwater recharge done in south-central Kansas in USA by *(Sophocleous, 1985) in*dicated that Precipitation and evapotranspiration sequences, soil-moisture profiles and storage changes, water fluxes in the unsaturated zone and hydraulic gradients in the saturated zone at various depths, soil temperatures, water-table hydrographs, and water-level changes in nearby wells clearly depict the recharge process. Antecedent moisture conditions and the thickness and nature of the unsaturated zone were found to be the major factors affecting recharge.

In general, terms, recharge is affected by factors such as weather, soil type, surface cover (e.g., vegetation, impervious pavements), slope, and water table depth. Usually, recharge studies consider only rainfall-driven recharge. In addition to rainfall, irrigation and wastewater can also provide recharge. Recharge occurs on a wide variety of scales, from small (localized) to large (distributed). Although recharge from agricultural and natural landscapes is mostly distributed, urban settings tend to result in more localized recharge.

Land covers differ in their ability to provide recharge. While a large fraction of rainfall, falling on agricultural or natural areas can move through the soil and reach the shallow water table, localized impervious surfaces (e.g., roads and parking lots) in the urban landscape limits recharge ability because only a small fraction of rainfall can pass through a paved surface.

A study on integrated remote sensing and GIS in groundwater recharge investigation and selection of artificial recharge sites in a hard rock terrain carried out by (Saraf, Kundu, & Sarma, 1998), indicated that the information layers were combined using weighted index overlay method to give rise to zones of suitability for artificial recharge structures. The most suitable zones were along the channel fills and the flood plains in the eastern part. On the hills, suitability was poor. In order to suggest the exact location for an artificial recharge structure, Boolean logic and conditional methods were employed. Prime task in this method is to identify the criteria and to formulate the set of logical conditions to extract the suitable zones. In this case, the output will have only two classes – suitable or unsuitable. The areas in which the defined conditions of the information layers are fulfilled together, a value of one is given whereas, the remaining part will have a zero value. This analysis is suitable for objective criterion but is not suitable to show gradational values (*Kundu, 2000)*. In order to have a comparison of the results with weighted indexing method, suitability analysis was done using Boolean logic model. The criteria for site selection are:

a) The sites should be over a slope of 2°-5°.
b) The sites should be on channel fills of alluvial plains.
c) The soil should be either gravelly or alluvial in nature.
d) Geologically, the area should be covered with sand, silt or clay.
e) The sites should be on the second or third order stream.

The above studies has demonstrated the capabilities of using remote sensing, and Geographical Information System for demarcation of different ground water potential zones, as well as Groundwater recharge zoning especially in diverse geological setup.

2.8 Weighting Factors

Various researchers have proposed different way of assigning weighting factors to the different conditions of the various maps to predict the inter-map dependencies for groundwater resource.

a) Weighted Index Overlay Method for Groundwater Prospects

Weighted Index Overlay Analysis (WIOA) is a simple and straightforward method for a combined analysis of multi-class maps. The efficacy of this method lies in the fact that the human judgment can be incorporated in the analysis. A weight represents the relative importance of a parameter vis-a-vis the objective. WIOA method takes into consideration the relative importance of the parameters and the classes belonging to each parameter. There is no standard scale for a simple weighted overlay method, (Saraf, Kundu, & Sarma, 1998). Determination of the weights of each class is the most crucial in integrated analysis, as the output is largely dependent on the assignment of appropriate weightage. Consideration of relative importance leads to a better representation of the actual ground situation.

b) Multi Criteria Evaluation

Multi Criteria Evaluation technique to evaluate the interclass and inter-map dependencies for ground water resource evaluation. The most commonly used method though is Satty's Analytic Hierarchy Process, (Satty, 1980). In this method, a pair wise comparison matrix was prepared for each map using Satty's nine-point importance scale and this matrix was solved using the Eigen Vector method.

The individual class weights and map Weights were determined through this technique. These weights were applied in linear summation equation to obtain a unified weight map containing due weights of all input variables, which was further reclassified to arrive at groundwater potential zone map, *(Bharadwaj et al, 1998)*

c) Drastic Model

Other available method includes DRASTIC MODEL. Khairul, Jahari and Ibrahim (1989) used this method in the Langat Basin in the south of Selangor and north of Negeri Sembilan. All the thematic maps for various parameters were combined using the DRASTIC Model *(Khairul et al, 1989).*

Finally, it should be noted that the precise assessment of recharge and discharge of groundwater is rather difficult, as no techniques are currently available for their direct measurements. Hence, the methods employed for groundwater resource estimation are all indirect. Groundwater being a dynamic and replenishable resource is generally estimated based on the component of annual recharge, which could be subjected to development by means of suitable groundwater structures.

2.9 Data resolution

The raster cell size selected for a study area depends on the cell size required for the most detailed analysis. The cell must be small enough to capture the required detail but large enough so computer storage and analysis can be performed efficiently. The more homogeneous an area is for critical variables, such as topography and land use, the larger the cell size can be without affecting accuracy.

Before specifying the cell size, the following factors should be considered:

- The resolution of the input data
- The size of the resultant database compared to disk capacity
- How close to the data you will be when visualizing it

- The desired response time
- The application and analysis that is to be performed

A cell size finer than the input resolution will not produce more accurate data than the input data. It is generally accepted that the resultant raster dataset should be the same or coarser than the input data.

If you expect to be navigating close to the raster in ArcGlobe or ArcScene, you may need to increase the raster resolution to avoid blockiness. This is especially true when converting vector features into raster data.

ArcGIS Spatial Analyst allows for raster datasets of different resolutions to be stored and analyzed together in the same database. Since ArcGIS Spatial Analyst provides this capability, the four decisions discussed above can be made separately for each dataset, rather than simultaneously for all the raster in the database.

CHAPTER THREE

METHODOLOGY

The methodology for this research revolves around the techniques of visual interpretation of satellite images and GIS operations. Different thematic maps on 50m×50m grid cell sizes were prepared from soil, rainfall, slope, elevation, Drainage density, Lithology, and lineament density maps. The thematic map of land-use was prepared using Landsat TM image data by visual interpretation on 1:50,000 scale, while lineament was prepared by digitizing an analogue geological map of scale 1:250,000. The methodology for this study is outlined in figure 3.2-1

3.1 Data and Software Used

Data: There were three sources of data: from existing maps, remote sensing and field data. Existing maps included both the digital and analogue maps. Digital maps were Soil, geomorphology, DEM, and geology; analogue map used was geological to digitise the lineaments. Satellite data used was Landsat TM image data of 30m×30m resolution. In selecting the satellite data for the study, Landsat Thematic Mapper data were preferred, due to the availability of a large spectrum of bands. These bands are mainly in the near and medium infrared portion of the electromagnetic spectrum, the most suitable for lineaments and terrain analyses, as well as in the thermal portion of the electromagnetic spectrum, which permitted the acquisition of further information. Field data used were the rainfall, lithology, drilling log and pump testing. See Table 3.1.1.

Table 3.1.1 Data Sources Used in the Study

[redacted]

Data resolution: When performing analysis between raster of different cell sizes, the raster are resampled to a common resolution, typically to the coarsest unless otherwise specified, before performing the function. Choosing an appropriate cell size is not always simple. You must balance your application's need for spatial resolution with practical requirements for quick display, processing time, and storage. Essentially, in a GIS, your results will only be as accurate as your least accurate dataset. However, in this study the data were resolved to the smallest, which is land-cover map. This was to maintain the integrity of the land-use as resolving it to a coarser size would result to loss of essential attribute features.

Software: Digital processing and GIS tasks were performed on a PC-based software. Ilwis 3.3 was used to process the RS data to obtain the land use map. ArcGIS 9.2 software was used to digitise the lineament map. It was also used to process all field data and digital maps. All the maps, in digital format, were organised in a geodatabase and a model builder was constructed for final integration. Different weights were prepared using Analytical Hierarchy Process and integrated in the model builder. AHP were solved using MATLAB 7.0 to derive the weights. AquiferTest4.2 software was used to calculate the Transmissivity of the aquifers from the borehole pump test data. These processes are outlined in the diagram 3.2-1 below.

3.2 Analysis Flow Diagram

The methodology adopted in the present study is presented schematically in figure 3.2-1 and described in the following steps:

i. In the initial stage of GIS spatial database development, analogue maps, which were in different scales obtained from different organizations (table 3.1.1), were converted into digital format by using digitization in ArcGIS software. Digital maps were registered directly to the database. Field data were compiled in database file using MS Access, interpolated into raster in ArcGIS.

ii. In the second stage, digital image processing of the satellite data were carried out for extraction of pertinent land-use information. The Landsat Thematic data were classified using supervised classification technique. The land-use maps of the year 2001 was prepared.

iii. In the third stage, all the above themes and other maps in digital forms, were delineated to the study area and were registered and stored into an ArcGIS Geodatabase file for further processing and analysis.

iv. Assigning Weight to the different themes and inter-map classes using Multi Criteria analysis (AHP).

v. The fifth stage involved the integrated analysis of multi-disciplinary data sets to construct composite information set to explain various queries in the spatial context. This was done using ArcGIS model builder. The groundwater water and recharge zones were defined at this stage.

The methodology adopted for the study is illustrated in the flow diagram below for ease of analysis.

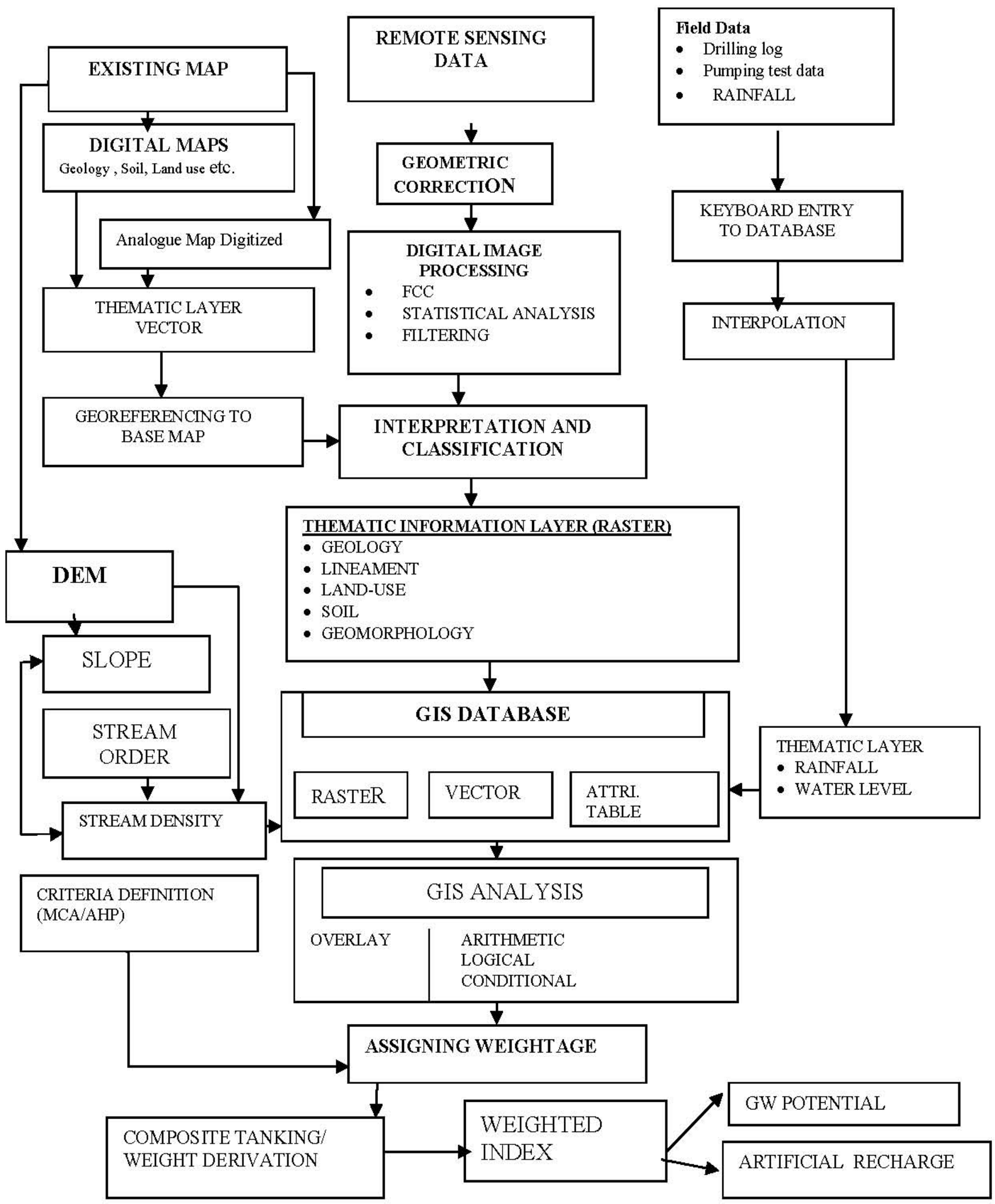

Fig 3.2-1: Flow Diagram Used For the Analysis

3.3 Delineation of Groundwater Potential Zones

In delineating the groundwater potential zones, the 90×90m DEM was downloaded from www.seamless.usgs.gov and processed using ARCGIS/INFO 9.2 software. This was used to derive various thematic layers such as drainage density and slope as in the following subsections.

Satellite and ancillary data was acquired from http://edcsns17.cr.usgs.gov, and the data was essentially used for the location of land-cover occurring in the area.

3.3.1 Weighting using Multi Criteria Analysis Method.

Individual class weights and map Weights was assessed based on Satty's Analytic Hierarchy Process. Analytic Hierarchy Process (AHP) is one of Multi Criteria decision-making method that was originally developed by Satty in 1980. In short, it is a method to derive ratio scales from paired comparisons.

In this study, a pair-wise comparison square $n \times n$ matrix (Fig 3.3.1) was prepared

for each map using Satty's nine-point importance scale and this matrix was solved using Eigen Vector and Eigen Value method using MATLAB 7.0.

Table 3.3.1 Number of Comparisons

Number of things	1	2	3	4	5	6	7	n
No of comparisons	0	1	3	6	10	15	21	$\frac{n(n-1)}{2}$

Note: For qualitative data such as preference, ranking and subjective opinions, it is suggested to use the full scale 1 to 9.

Applying the AHP procedure involved three basic steps:

- Decomposition, or the hierarchy construction - this decomposition into a hierarchy was based on previous studies and empirical experiences.
- Comparative judgments, or defining and executing data collection to obtain pair wise comparison data on elements of the hierarchical structure, the prioritization procedure was to determine the relative importance of the elements in each level.
- Synthesis of priorities, or constructing an overall priority rating was done by following the procedure by *Teknomo (2006)*.

3.3.2 Layers Classification

The classification method adopted for study was ArcGIS Natural Breaks (Jenks) classifier method. This was chosen because classes are based on natural groupings inherent to the data. Grouping is done by picking the class breaks that best group similar values and maximizes on the differences between classes i.e. classes are set where there are relatively big jumps of the data values.

3.3.3 Generation of Thematic Layers

The different map layers were prepared and relative weights calculated for integration in the delineation process in the following sub headings. The different themes of maps and the classes of the themes were coded for easy reference

(i) Slope Map Layer

The slope layer was derived from the DEM Fig 3.3-1, in its raw form to maintain the general integrity of the slope aspects. The slope was calculated in percentage and classified as Flat, Rolling, Hilly, Steep and Very Steep following a process determined by Khairul et al (1989)

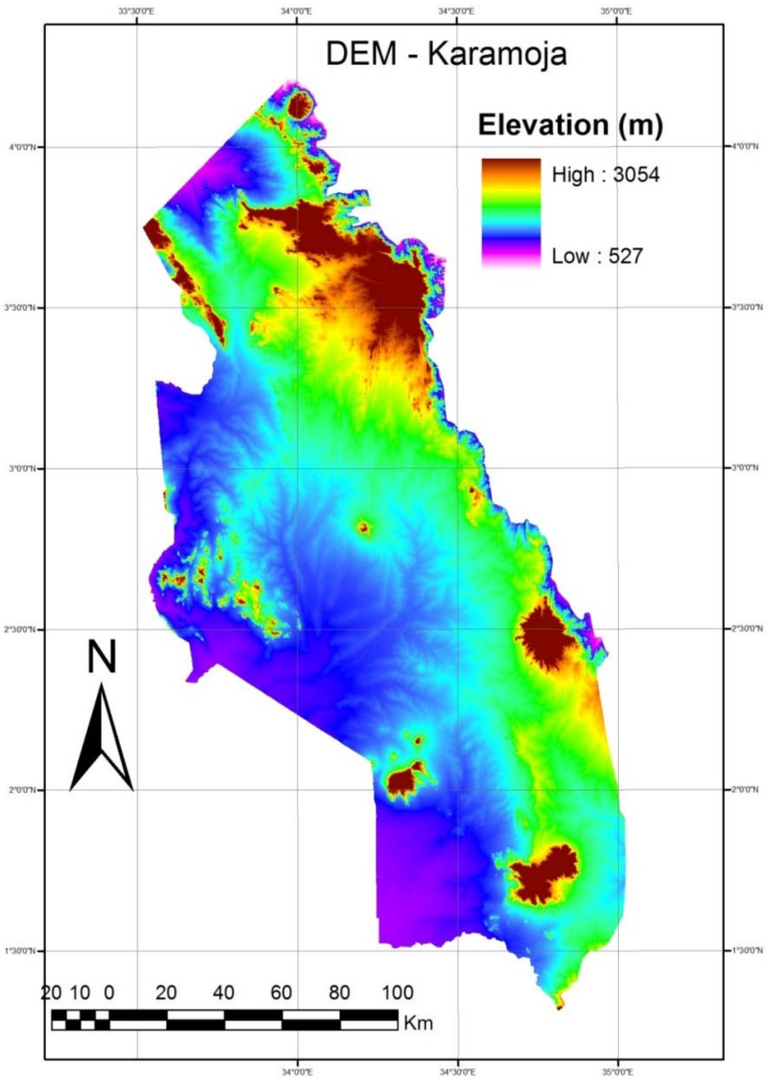

Fig 3.3-1: Digital Elevation Model for Karamoja Region

The Weight was assigned using AHP, the process of which is described below. This was then applied for all the other layers

Analytical Hierarchy Process - AHP

a) Reciprocal Matrix – the process started by preparing the pair wise analyses for the slope category by developing a comparison matrix, Table 3.3.2, at each level of the hierarchy. Elements in each level are compared in pairs with respect to their importance to an element in the next higher level. Starting at the top of the hierarchy and working down, the pair-wise comparisons at a given level was reduced to a square matrix, which was then solved to get the relative weights.

Table 3.3.2: Reciprocal Matrix

Reciprocal matrix					
Criteria	Flat	Rolling	Hilly	Steep	Very Steep
Flat	1.00	2.00	5.00	7.00	9.00
Rolling	0.50	1.00	3.00	6.00	7.00
Hilly	0.20	0.33	1.00	3.00	5.00
Steep	0.14	0.17	0.33	1.00	2.00
Very Steep	0.11	0.14	0.20	0.50	1.00
Sum	1.95	3.64	9.53	17.50	24.00

b) Computing the Relative Weights

This was calculated using Eigen values and Eigen vectors properties of matrices.

Principal Eigen Value, λ_{max} = 5.1256 and the corresponding Principle Eigen Vector was solved for, using MatLAB software and the values were as in Table 3.3.3 below,

Table 3.3.3: MATLAB Weight calculation results for Slope Map

MATLAB Calculations	
Principle Eigen vector	**Priority vector**
0.7835	0.43
0.5299	0.29
0.2805	0.15
0.1402	0.08
0.0837	0.05

The Principle Eigen was then normalized to Vector priority vector (Normalized Principle Eigen Vector). This was the weights used in the map analysis. However, the solution for the matrix was checked for consistency.

a) Estimating the Consistency

This weighting was checked for consistency. . Satty proved that for consistent reciprocal matrix, the largest Eigen value is equal to the number of comparisons, or $\lambda_{max} = n$. Then he gave a measure of consistency, called Consistency Index as deviation or degree of consistency using the following formula

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \text{(3.3.1)}$$

Where ***CI*** = consistency index

He proposed that we use this index by comparing it with the appropriate one. The appropriate Consistency index is called Random Consistency Index (***RI)*** as shown in the Table 3.3.1 below.

Table 3.3.1: Random Consistency Index (*RI)*.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Then, he proposed what is called Consistency Ratio, which is a comparison between Consistency Index and Random Consistency Index, or in formula

$$CR = \frac{CI}{RI} \quad \text{(3.3.2)}$$

If the value of Consistency Ratio is smaller or equal to 10%, the inconsistency is acceptable. If the Consistency Ratio is greater than 10%, we need to revise the subjective judgment. In this case

lambda max, λ_{max}	5.1256
consistency index (CI)	0.0314
consistency ratio (CR)	0.0280

This was then use to calculate the consistency ratio using equation (3.3.2) and was found to be $CR = 0.0153$ which is less than 0.1 (or 10%), showing the inconsistency is acceptable. Thus the normalised priority vector was used as map weight as in Table 3.3.4 below. This was done for the rest of the map layers.

Table 3.3.2: Slope Aspect Thematic layer Weights

Slope	**Description**	**Code**	**Weight**
0-7%	Almost Flat	FL	43
8-20%	Undulating to Flat	UD	29
21-55%	Hilly Disserted	HD	15
56-140%	Steep Dissected	SD	08
>140%	Very Steep Mountainous	VS	05
TOTAL			100

Satty's Consistency Ratio, CR = 0.0153

(ii) Drainage Density Map Layer

A surface drainage map was prepared from 90m×90m DEM. The drainage layer was processed using ARCHYDRO 2.0 extension, and the drainage of order five, Fig 3.3-2 was processed and the layer labelled.

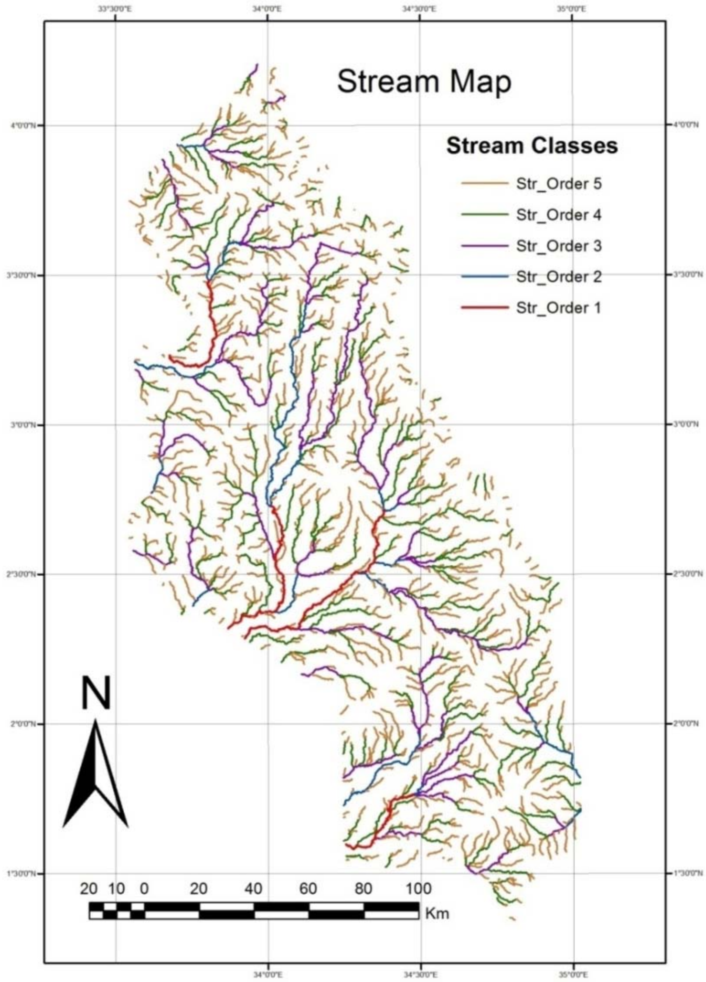

Fig 3.3-2: Drainage map of Karamoja Region – Stream order 5

The drainage density Fig 3.3-3, was calculated using Kernel's method. The drainage density in km/sq.km was categorized in five classes using Natural Breaks (Jenks) classification method of the ArcGIS.

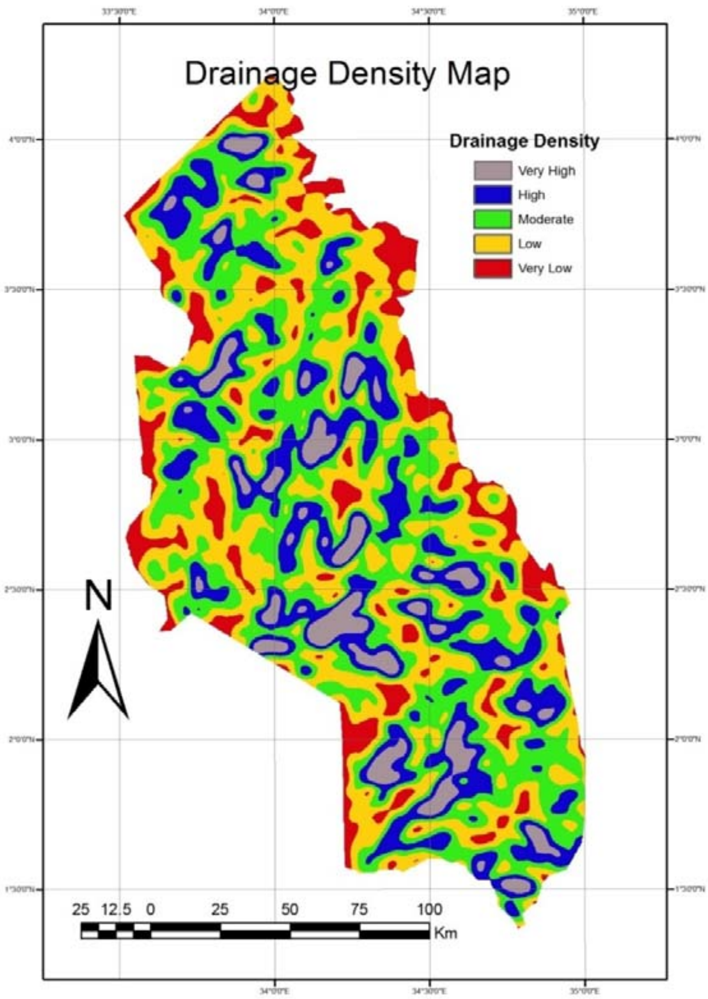

Fig 3.3-3: Classified Drainage Density Thematic Layer

The corresponding Weights derived using Analytical Hierarchy Process (AHP) as listed in Table 3.3.5 below

Table 3.3.3: Drainage Density Thematic Layer Weights

Drainage density Km/Km^2	**Theme Category**	**CODE**	**Weight**
< 0.6	Very Low	VL	41
0.6 – 1.5	Low	LW	27
1.5 – 3.0	Moderate	MD	16
3.0 – 4.5	High	HG	10
4.5 <	Very High	VH	07
TOTAL			100

Satty's Consistency Ratio, CR = 0.0228

(iii) Geomorphology Thematic Layer

A geomorphologic map of scale 1:250,000 were got form the Ministry of Energy and Minerals, Department of Geology – Uganda Government Fig 3.3-4. On the basis of specific relief and characteristic nature, the geomorphologic features, present in study area were classified into (i) Swamp (ii) Floodplains (iii) Lower alluvial fan (iv) Upper alluvial fans (v) Lower fan terrace (vi) upper fan terrace (vii) Denudated/Dissected slope (viii) Hills.

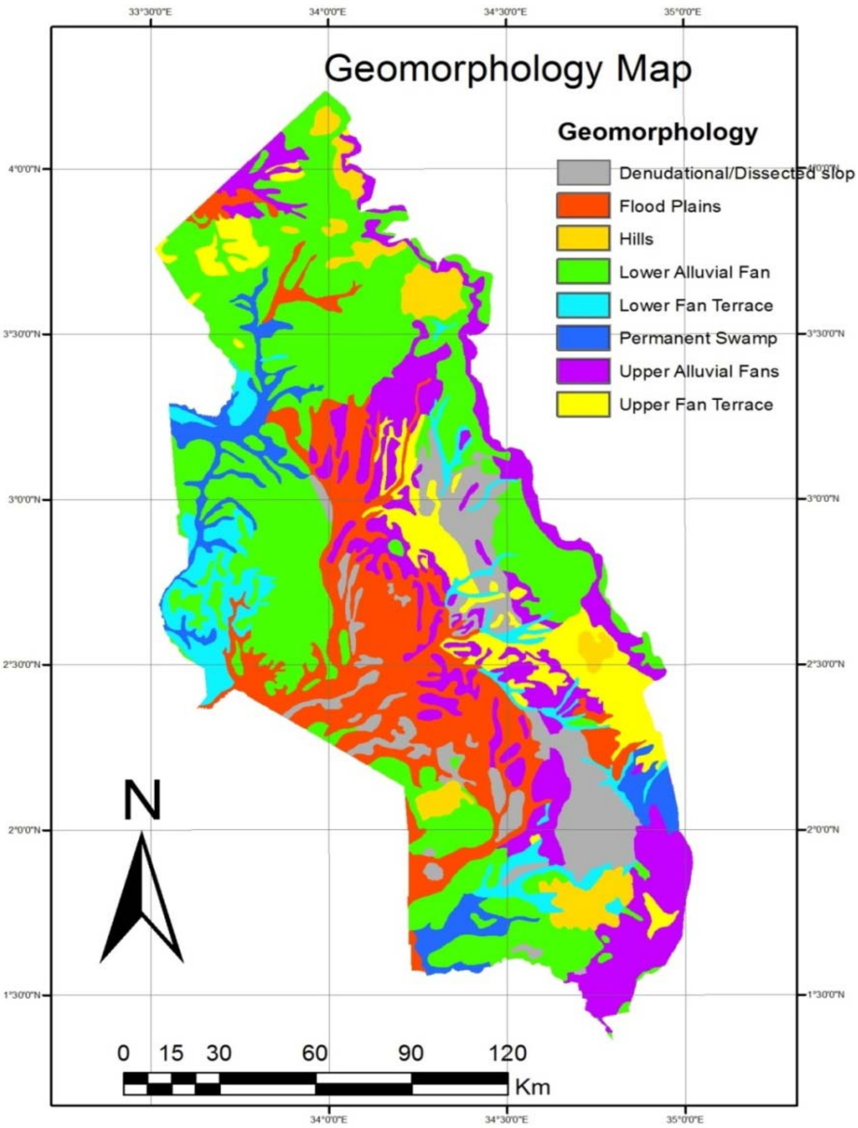

Fig 3.3-4: Classified Geomorphologic Thematic Layer

These were assigned Weights as in Table 3.3.6 below

Table 3.3.4: Geomorphologic Thematic Layer Weights

Geomorphology type	CODE	Weights
Permanent Swamp	PSW	31
Floodplains	FLP	23
Lower alluvial fan	LAF	16
Upper alluvial fans	UAF	11
Lower fan terrace	LFT	8
Upper fan terrace	UFT	5
Denudated/Dissected slope	DDS	4
Hills.	HLL	3
TOTAL		100

Satty's Consistency Ratio, CR =0.0340

(iv) Soil Thematic Layer

The soil map was got from the Ministry of Forestry – the Government of Uganda, processed by the Ministry Fig 3.3-5. The soil classified to the normal soil nomenclature based on the parent Rock from which the soils came from, FAO soil description and Ugandan soil series.

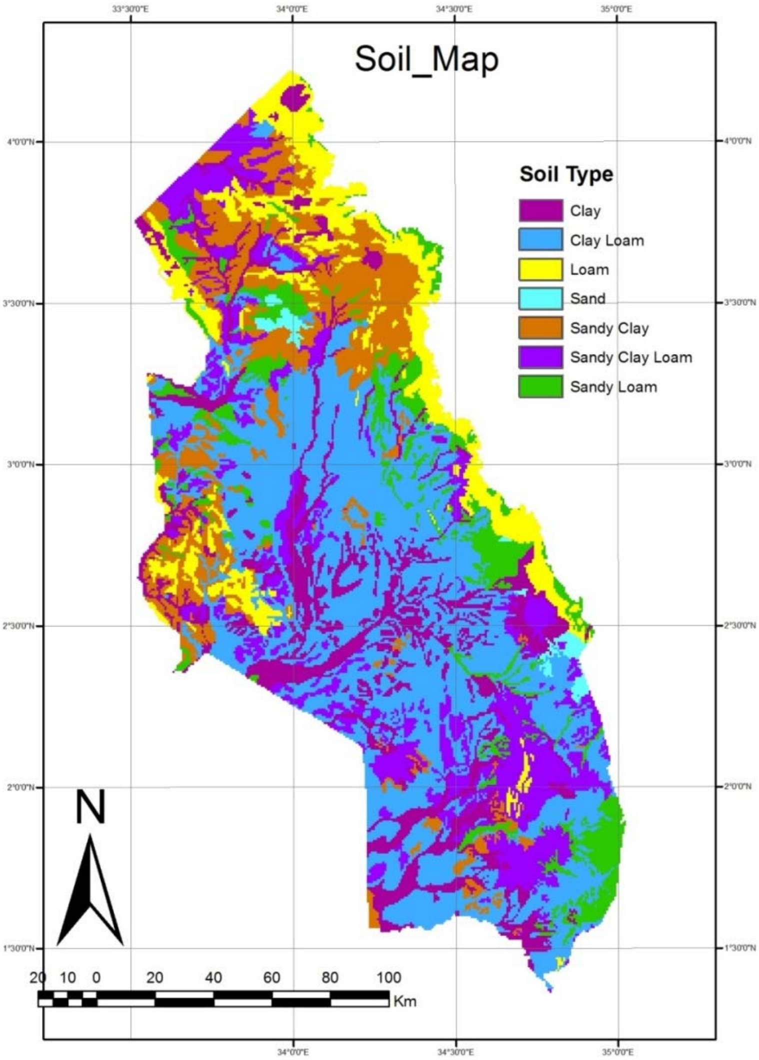

Fig 3.3-5: Classified Soil Layer Thematic Layer

Assignment of the Weights was related to basic infiltration rate for commonly occurring soils adopted from a study made by *Brouwer (1990)*, Table 3.3.5. It has been interpolated to suit the analysis criteria.

Table 3.3.5: Basic Infiltration Rates (*Brouwer et al. 1990*).

Soil type	Basic infiltration rate (mm/hour)
sand	>30
sandy loam	20 - 30
loam	10 - 20
clay loam	5 - 10
clay	1 - 5

Basic infiltration rates for the commonly occurring soil types (*Brouwer et al. 1990*) – interpolated and weights assigned using AHP and result in Table 3.3.6 below.

Table 3.3.6: Soil Thematic Layer Weights

Soil Type	Basic Infiltration Rate (mm/hr)	CODE	Weight
Sand	>30	SD	36
Sandy Loam	20-30	SM	25
Loam	15-20	LM	16
Sandy clay Loam	10-15	SCL	11
Clay Loam	5-10	CM	6
Sandy Clay	2-5	SC	4
Clay	<2	CL	3
TOTAL			100

Satty's Consistency Ratio, CR = 0.0238

a) Land-use Thematic Layer

The land cover map was obtained by processing the landsat image of the study area of 27th Nov 2001. Land-use Classification using remotely sensed imagery requires suitable imagery. Defining mapping classed is often an iterative process. A balance was struck between the classes that were desired, often based on the map's purpose, and the classes that can be accurately and economically delimited. Spatial image enhancement was carried out by applying High pass filters normally known as edge enhancement filter; this was done to enhance the images for visual interpretation, and extracting features using ILWIS software. Laplace user defined high pass filter was used. The applied filter 3x3 edge enhancement filter with a central value of 16, eight surrounding values of -1 and gain of 0.125, set for the images.

Optimum Index Factor (OIF): The maps were prepared in a map list and the Optimum Index Factor (OIF), which is a statistic value that can be used to select the optimum combination of three bands in a satellite image with which you want to create a colour composite, was calculated. The optimum combination of bands out of all possible 3-band combinations is the one with the highest amount of 'information' (= highest sum of standard deviations), with the least amount of duplication (lowest correlation among band pairs). The highest was BRG 147 combination and was used. The classification and the fusion were done and the confusion matrix gave the result as shown in Table 3.3.7 below.

Table 3.3.7: Confusion Matrix of Land Cover Classification

[redacted]

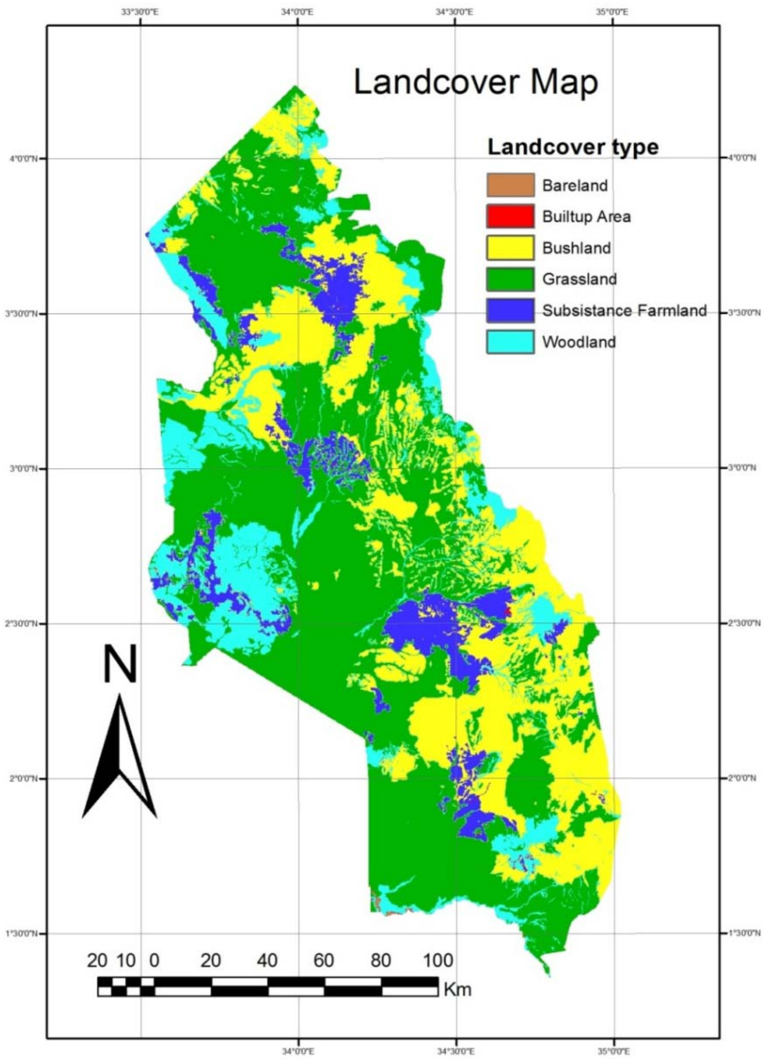

Fig 3.3-6: Classified Land-cover Thematic Layer

The classed land-cover was then analyzed using AHP and the weights were assigned, see Table 3.3.10 below,

Table 3.3.8: Land Thematic Layer Weights

Land-use	CODE	Weight
Subsistence Farmland	SF	31
Grassland	GL	24
Bush land	BL	20
Woodland	WL	12
Bare land	BR	8
Built-up Area	BA	5
TOTAL		100

Satty's Consistency Ratio, CR=0.0077

b) Lineament Thematic Layer

Lineament analysis for ground water exploration was started by digitizing geological map of the study area Fig 3.3-7 below.

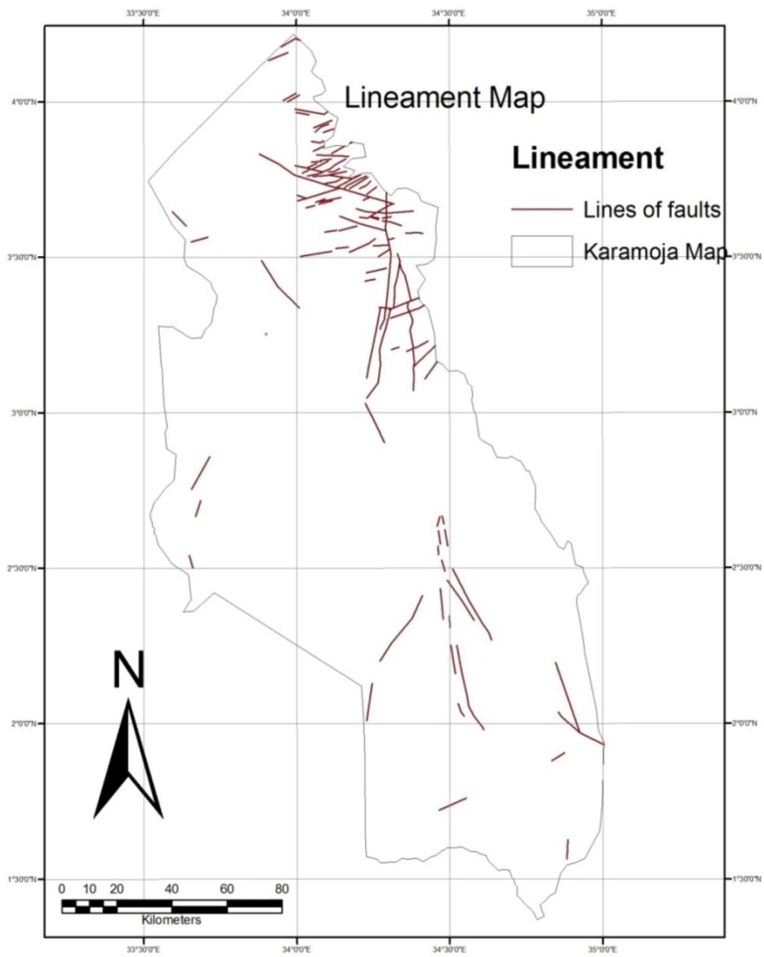

Fig 3.3-7: Digitised Lineament Map

The lineament density was then calculated in ArcGIS using Kernel density method – to fit a smoothly tapered surface to each polyline. The output cell size was 50m (the smallest size of all layers). This was classified into five classes with high density areas preferred as shown in Fig 3.3.8.

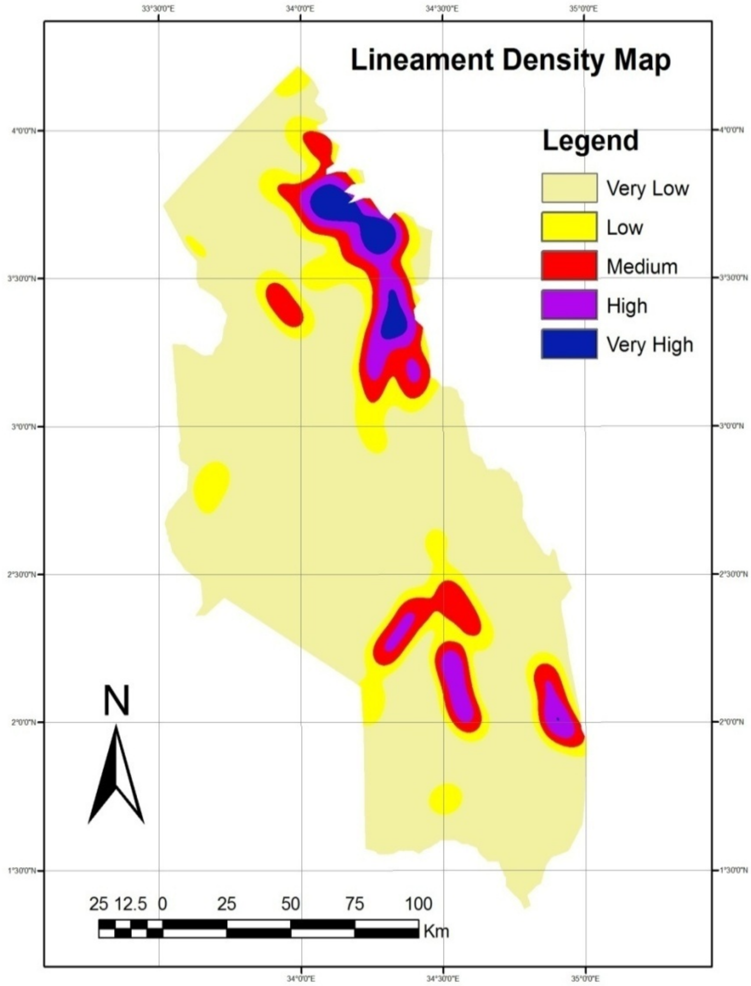

Fig 3.3-8: Classified Lineament Density Thematic Layer

The weights were then assigned using AHP and results displayed in Table 3.3.9

Table 3.3.9: Classification of lineament and Thematic Layer Weights

Classes	Description	CODE	Weights
< 0.5	Very Low	VL	4
0.5 – 1.8	Low	LW	7
1.8 – 3.4	Medium	MD	13
3.4 – 5.4	High	HG	27
5.4 <	Very High	VH	49
TOTAL			100

Satty's Consistency Ratio, CR=0.0190

c) Geology Thematic Layer

The geology map obtained was already classified and no modification was made. The classes were Fig 3.3-9

- Banded gneisses – Karasuk series of Pre-karasuk age with metamorphic rock type.
- Acid gneisses, quartzite - Karasuk series of Precambrian age with metamorphic rock type
- Carbonatite – Tertiary and Mesozoic of tertiary to cretaceous age grouping with intrusive rock type
- Cataclasites – No form name identified but the rock is of Precambrian age group with metamorphic rock type.
- Granulites facies rocks – Watian Series of Precambrian age group. it's a charnokites, enderbites and retrograded derivatives with metamorphic rock type
- Highly granitized rocks – no form name indentified but it is of Precambrian age group with metamorphic rock type.
- Sediments/alluvium – no form name identified but is of Pleistocene to recent age group. It is a sedimentary rock type associated with alluvium, black soils and moraines.
- Undifferentiated gneisses – it is a basement complex from of Precambrian age group with metamorphic rock type. It is undifferentiated gneisses and in the north granulites facies rocks.
- Volcanic rocks – it is a tertiary from of tertiary and Mesozoic age group. It is associated with volcanic type of rock and associated sediments.

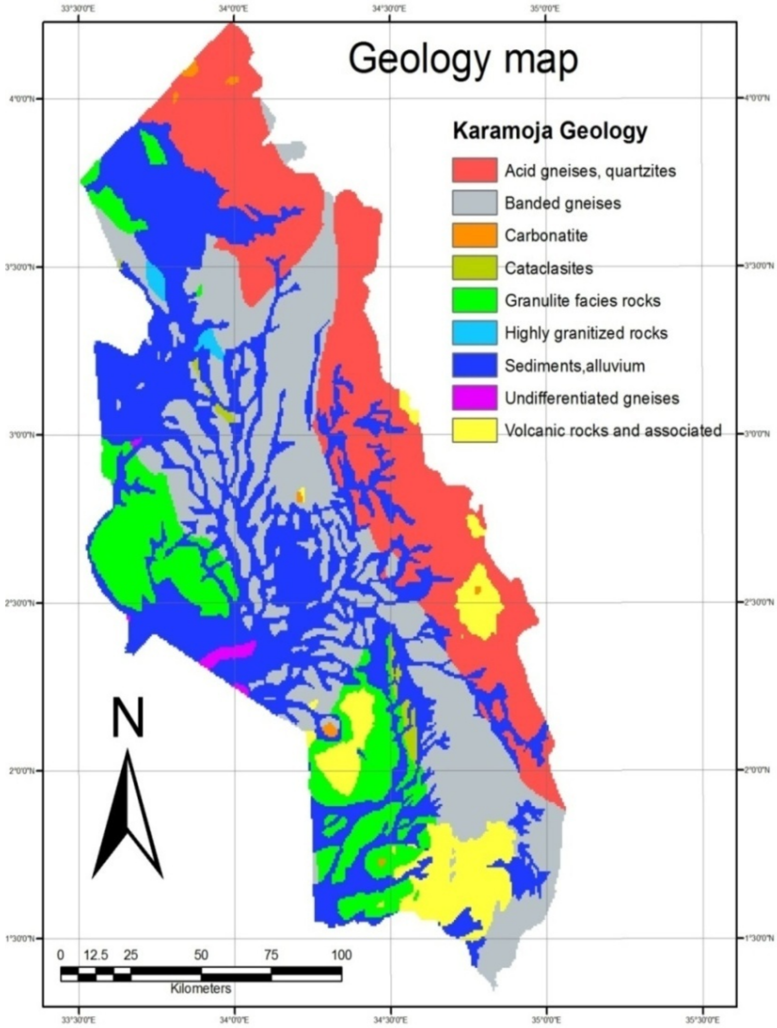

Fig 3.3-9: Geological Thematic Layer

The rocks were classified based on their water bearing potential and AHP applied, the results as shown in the table 3.3.10 below

Table 3.3.10: Geology Thematic Layer Weights

Rock Category	CODE	Weights
Highly quartzied rocks	HQ	30
Volcanic Rocks	VR	22
Acid Gneisses	AG	15
Sediment Alluvium	SA	11
Carbonatite	CB	8
Cataclasites	CT	5
Banded Gneisses	BG	4
Granulites Facies rocks	GF	3
Undifferentiated gneisses	UG	2
TOTAL		100

Satty's Consistency Ratio, CR=0.0292

d) Rainfall Thematic Layer

Orographic information was collected from global rainfall data sets for 18 stations around the region for a period of eighteen years as the region is poorly covered by rainfall station and average annual rainfall estimated. The range of the mean annual rainfall of the region obtained 699mm to 1251mm/year. The rainfall data was interpolated using Inverse Distance method in ArcGIS. The resultant raster was classified using Natural Break (Jenks) classifier in six classes in Very Low, Low, Moderate, Moderately high, High, Very High, Fig 3.3-10.

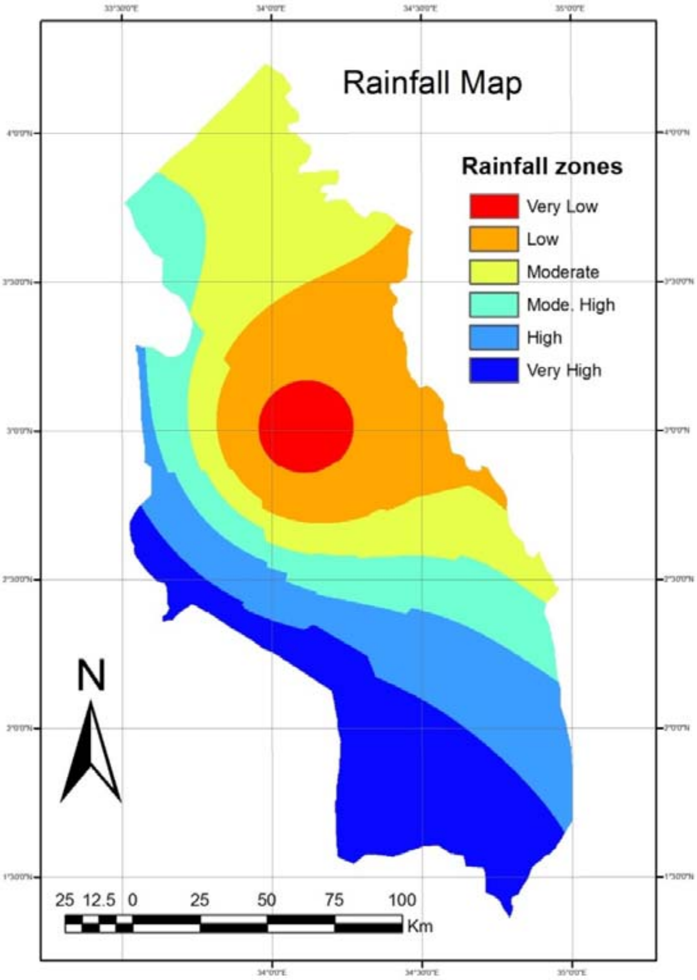

Fig 3.3-10: Classified Rainfall Thematic Layer

Weights for modelling were assigned using AHP as shown in Table 3.3.11 below

Table 3.3.11: Rainfall Thematic Layer Weights

Range of Rainfall (mm)	Description	CODE	Weight
Less than 750	Very Low	VL	4
750-890	Low	LW	7
890-975	Moderate	MD	12
975-1056	Moderately High	MH	20
1056-1139	High	HG	24
Greater than 1139	Very high	VH	33
TOTAL			100

Satty's Consistency ratio, CR=0.0027

3.3.4 Integration of Thematic Layers and Modelling through GIS

After understanding their behaviour with respect to groundwater control, the different classes were given with suitable weights, according to their importance with respect to other classes. This weights were assigned using AHP and the results are as in Table 3.3.12 below,

Table 3.3.12: Inter-Map Weights

Thematic Map Category	Weight	Remarks
Geomorphology	25	Mge
Geology	22	Mgl
Rainfall	20	Mrf
Soil	13	Msl
Slope	07	Msp
Lineament	06	Mln
Landover	04	Mlu
Drainage Density	03	Mdr
TOTAL	100	

Satty's Consistency ratio, CR=0.0340

3.3.5 Groundwater Potential Map Production

All individual class weights were multiplied with inter-map Weights and kept in linear summation equation to result in a unified weighted map. This was done using ArcGIS model builder, Fig 3.3-11, and the result classified into five potential zones from High Potential zone to negligible potential zones according to Alexandru (1972)

$$GWP = Mgp * Gp + Mge * Ge + Mso * So + Mrf * Rf + MLu * Lu + Mdd * Dd + Msl * Sl + MLd * Ld$$

…………………………………………………………………………….. (3.3.3)

Where:

Gp – geomorphology

Ge – geology Thematic Map

So – Soil Thematic Map

Rf - mean annual rainfall

Lu – Land use Thematic Map

Dd – Drainage density Thematic Map

Sl – Slope Thematic Map

Ld – Lineament Thematic Map

Mgp – geomorphology map coefficient

Mge – geology Map coefficient

Mso – soil Thematic Map coefficient

Mrf – rainfall map coefficient

Mlu – land use map coefficient

Mdd – Drainage map coefficient

Msl – Slope map coefficient

Mld – Lineament map coefficient

ArcGIS model builder window

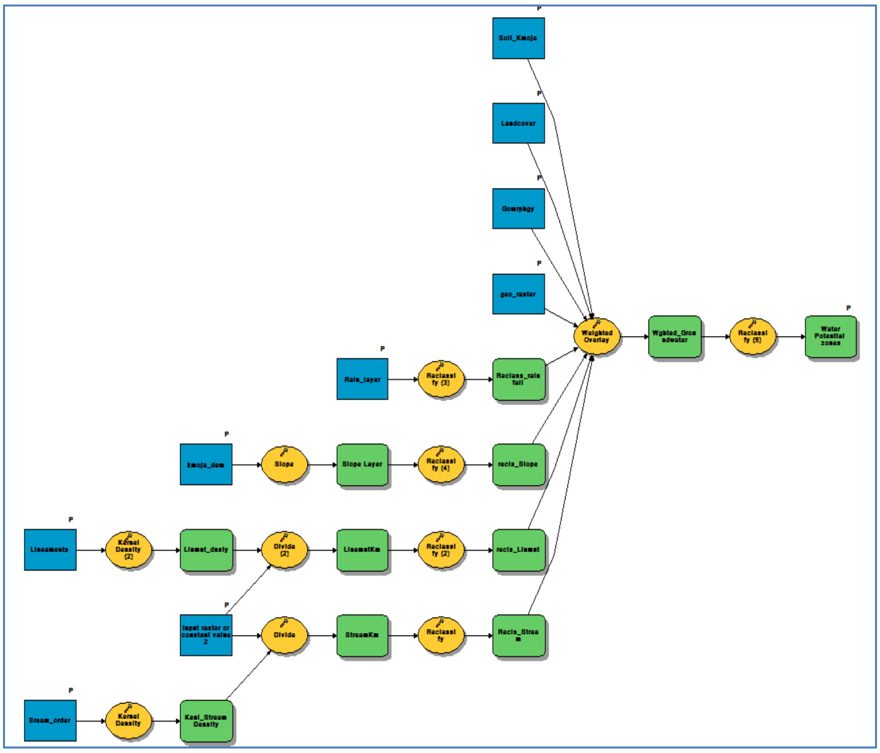

Fig 3.3-11: ArcGIS Model Builder Window.

The model was executed and the results were as displayed in the map Figure 4.1-1. This result was compared with the Transmissivity values calculated from the pump testing data and the results as in table Appendix A.

3.4 Relationship between Potential Zones and Aquifer Characteristics

The evaluation of the relationship between the GIS potential zone and Borehole data is seen as a validation of the Integrated RS & GIS in the preceding sub section 3.3. In the evaluation borehole drilling logs and pumping test data were collected as point data. This included static water level, weathered zone thickness, saturated zones thickness, yields, aquifer materials, Transmissivity; T the compilation is as in Appendix A.

3.4.1 Aquifer Parameters

The aquifer parameter used in this study was the Transmissivity, T in m^2/day. Transmissivity (T) is the volume of water flowing through a cross-sectional area of an aquifer that is unit aquifer thickness (b), under a unit hydraulic gradient in a given amount of time (usually a day). In this study the Transmissivity of the aquifers were used as they explain aquifer characteristics better in terms of yield and productivity. Samples of forty-four boreholes across the region were done for boreholes drilled and tested from year 2000 to 2007. The pump tests were done for 180 minutes (three hours), with about 90% recovery observed.

Groundwater flow in confined aquifer can be expressed by a differential (mass conservation) equation as

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-S_o\frac{\partial h}{\partial t} \quad \text{.................. (3.4.1)}$$

Where

$K_{xx,yy,zz}$ - Hydraulic conductivities in the x, y and z directions with

$\frac{\partial h}{\partial x}$, $\frac{\partial h}{\partial y}$ and $\frac{\partial h}{\partial z}$ the respective temporal hydraulic gradients

S_o - The specific storativity for confined aquifer.

$\frac{\partial h}{\partial t}$ - Temporal derivative of the hydraulic head.

For isotropic but heterogeneous aquifer $K = K_{xx} = K_{yy} = K_{zz}$ that is

$$\frac{\partial^2 h}{\partial x}+\frac{\partial^2 h}{\partial y}+\frac{\partial^2 h}{\partial z}=\frac{S_o}{K}\frac{\partial h}{\partial t} \quad \text{...................................... (3.4.2)}$$

For steady flow and assuming that water and porous matrix are incompressible, the right hand side of the above equation becomes zero, thus

$$\frac{\partial^2 h}{\partial x}+\frac{\partial^2 h}{\partial y}+\frac{\partial^2 h}{\partial z}=0=\nabla^2 h \quad \text{............................... (3.4.3)}$$

Where, $\nabla^2 h$ - is the Laplace equation.

Combining the above equation with Darcy's give, for homogeneous and isotropic medium,

$$T\nabla^2 h = S\frac{\partial h}{\partial t} \quad \text{... (3.4.4)}$$

Where T - Transmissivity

s - Slope

The solution to the above equation 3.4.4 has been provided by many Scientist. In this study, the Jacob method was used. The Jacob (1946) method was found to be more valid for confined aquifer, and small drawdown in well penetrating unconfined aquifers and for fractured rock aquifer (*Kheva et al, 2003*). This method was suggested by *Howard et al (1989), Kheva et al (2003), and Adil et al, (2004)* as most convenient methods for most available field data from pumping tests. The basic formula of the method assumes conditions that are sufficiently met at borehole scale of investigation.

In general, terms, Jacob Solution assumes the following:

- The aquifer is confined and has an "apparent" infinite extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping
- The pietzometric surface was horizontal prior to pumping
- The well is pumped at a constant rate
- The well is fully penetrating
- Water removed from storage is discharged instantaneously with decline in head
- The well diameter is small, so well storage is negligible
- The values of *u* are small (rule of thumb $u < 0.01$) the well function

Jacob method stems from examining the series expansion of the well function that is the drawdown, s is expressed as

$$H - h = s(r,t) = \frac{Q_W}{4\pi T} W(u) \quad \text{.....................................} \ (3.4.5)$$

Where, s = the drawdown

Q = pumping rate of the borehole

T = Transmissivity

t = time at which the drawdown was measured

H and h are initial water level and water level at time t, $W(u)$ in the groundwater

literature is the Well Function for confined aquifers.

In mathematical texts, it is the exponential integral $E(u)$ – Euler's function, which

is given by

$$W(u) \equiv E(u) = \int_u^{\infty} \frac{e^{-z}}{z} dz \quad \text{.. (3.4.6)}$$

Where, $u = \frac{Sr^2}{4Tt}$

S – Storativity, The drawdown *s* depends both on the radial distance from the well *r* as well as time *t*,
Jacob linearised the above expression to come with;

$$W(u) = -\gamma - \ln u - \sum_{n=1}^{\infty} \frac{(-1)^n u^n}{nn!} \quad \text{............................ (3.4.7)}$$

Where, $\gamma = 0.5772$ – is the Euler's constant,

W (u) = well function

for small values of *u*, the well function can be approximated as

$$W(u) \approx -0.5772 - \ln u = \ln(\frac{2.25Tt}{Sr^2}) = 2.3 \log(\frac{2.25Tt}{Sr^2}) \quad \text{...... (3.4.8)}$$

The resulting equation for the drawdown by substitution is:

$$s = \frac{2.3Q}{4\pi T} \log(\frac{2.25Tt}{Sr^2}) \quad \text{... (3.4.9)}$$

For measurements of drawdown taken in the same pump well, the radius $r = r_w$ (r_w=*well radius*), at two different times t_1 and t_2, the above equation becomes,

$$s_1 - \frac{Q_w}{4\pi T}\ln\left(\frac{2.25Tt_1}{Sr_w^2}\right) \ldots\ldots\ldots\ldots\ldots\ldots \text{(3.4.10)}$$

$$s_2 = \frac{Q_w}{4\pi T}\ln\left(\frac{2.25Tt_2}{Sr_w^2}\right) \ldots\ldots\ldots\ldots\ldots\ldots \text{(3.4.11)}$$

Subtracting the two equations *(3-10 and 3-11),* the Transmissivity becomes;

$$T = \frac{Q_w}{4\pi(s_2 - s_1)}\ln\left(\frac{t_2}{t_1}\right) \ldots\ldots\ldots\ldots\ldots\ldots \text{(3.4.12)}$$

3.4.2 Determination of Transmissivity, T from Pump Testing

A pump test consists of pumping a well at a certain rate and recording the drawdown (decline) of water level in the pumping well and in nearby observation wells over a certain period. The responses of the water levels at and near the pumping well reflect the aquifer's ability to transmit water to the well. The response allows hydro geologists to determine the aquifer's characteristics. Water levels will drop less in more permeable aquifers than in aquifers of lower permeability. “The size” of the drawdown cone depends on several factors: the pump rate, the length of time the well is pumped, and aquifer characteristics of permeability and Transmissivity. In order to interpret the results of the pump test, hydro geologists need data such as aquifer thickness, screened interval, pumping rate, static water level before pumping, and dynamic water level during pumping. These data are input into a computer program and the computer generates aquifer parameters such as the specific capacity of the well, hydraulic conductivity, and Transmissivity. The aquiferTest software, was used to analyze the pump test data sample shown in fig 3.4.1 below

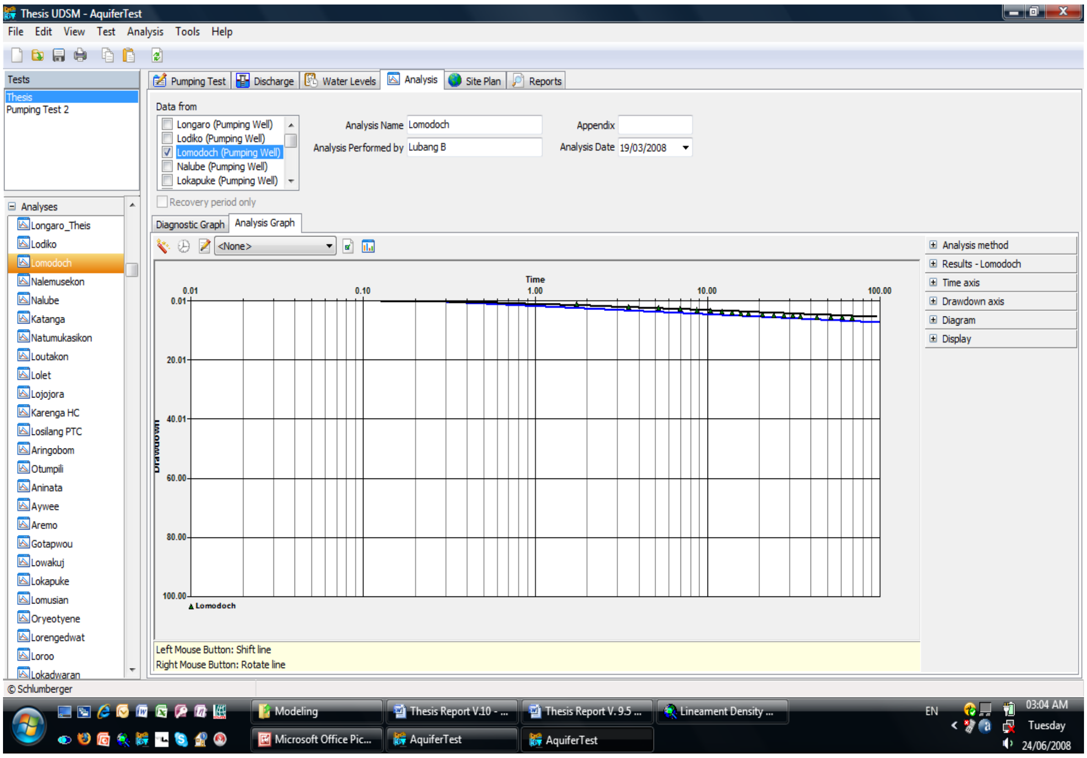

Fig 3.4-1: Aquifer analysis using Transmissivity - Lomodoch

The whole results are listed in Appendix A

3.5 Recharge Zone Delineation

Recharge zones delineation will incorporate the previous steps of layers preparation in the first methodology. This will be analyzed together with well-data inventory to delineate the recharge zones. The layers that were used included;

a) Geomorphology layer

b) Slope

c) Over-burden thickness

d) Rainfall layer

e) Soil type

f) Surface cover – land use

g) Weathered zone depth.

h) Drainage layer

3.5.1 Subsurface Lithology

The top layer thickness varies from 0 m to 8.0 m, which indicates the variable nature of surface soil (loose and moist, dry and hard). The second layer is predominantly clay / clay with thickness varies between 1.0 m to 42.0 m. The third layer consisted of weathered / fractured sandstone, which is, water bearing and forms the aquifer zone in the area. The thickness of aquifer zone varies from between 10m to 50m. Depth to the hard rock varies from 66m to 126m below ground surface. Wells locations and details of the drilling results are in (Appendix A).

3.5.2 Thematic Maps Layers

From the above-inferred lithology, the weathered zone thicknesses were interpolated using Inverse Distance method to form spatial data. This was then classified into five classes using Natural Breaks (Jenks) method to generate the weathered zone depth Thematic Maps as shown in Fig 3.5.1

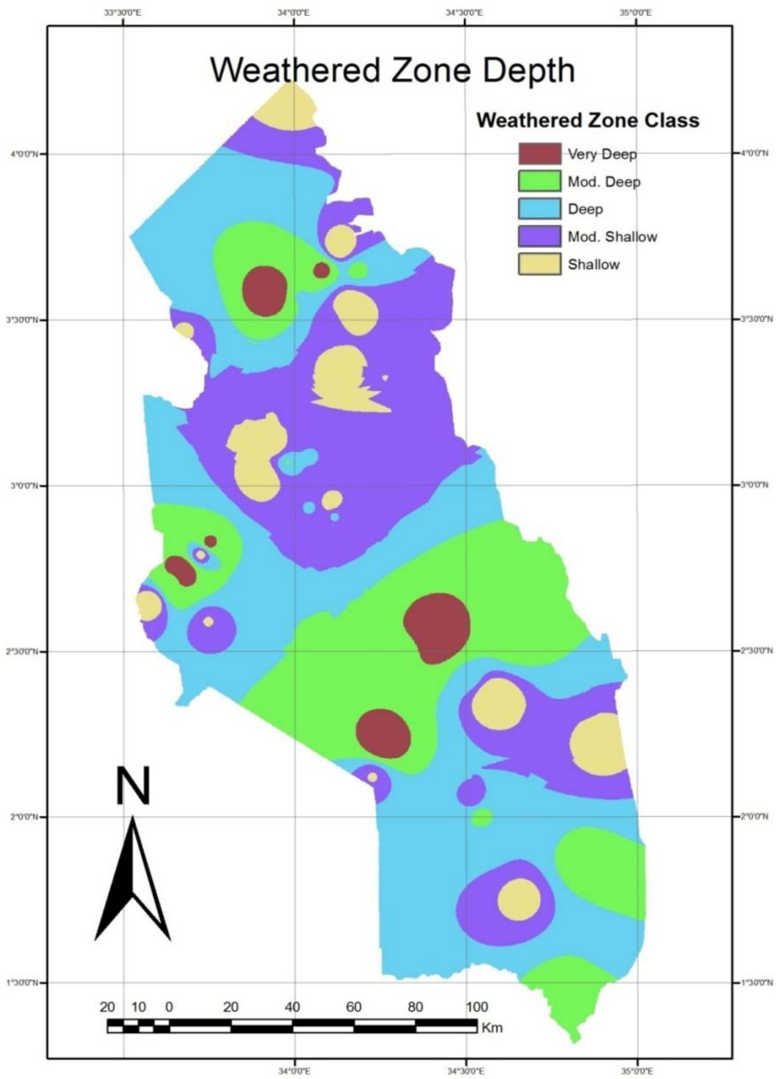

Fig 3.5-1: Weathered Zone Thickness Thematic Layer

From the same inferred lithology, overburden thickness was interpolated using Inverse Distance method to form spatial data. This was then classified into five classes using Natural Breaks (Jenks) method to generate the clay (top impermeable layer) thickness Thematic Map shown in Fig 3.5.2

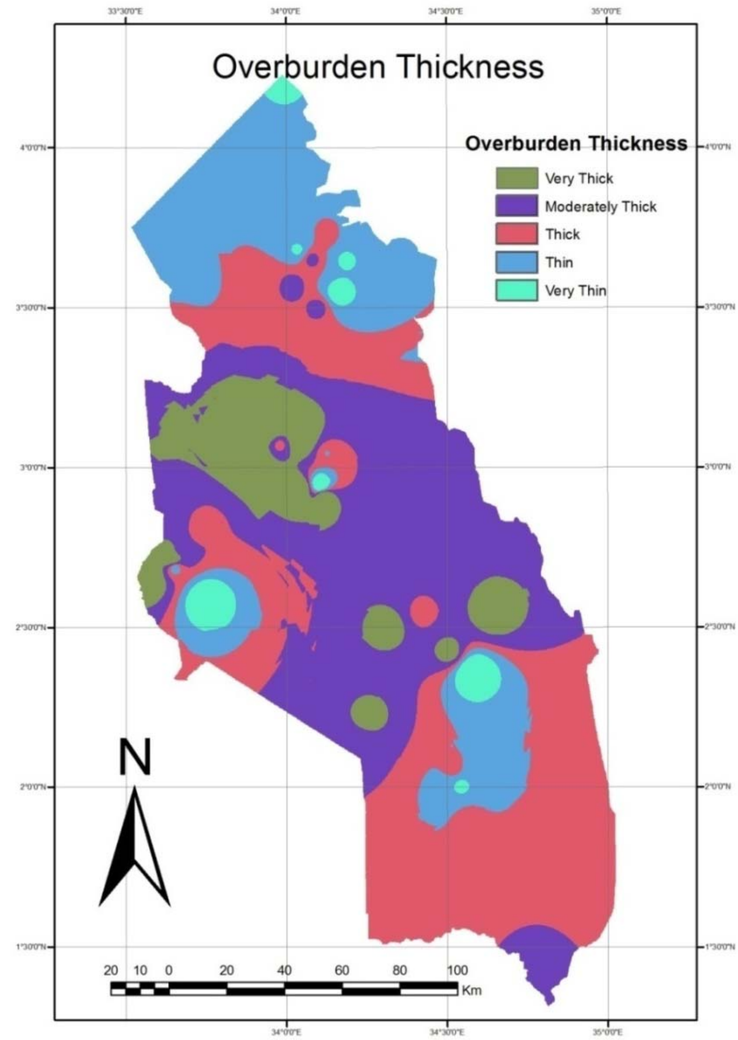

Fig 3.5-2: Top Impermeable Layer Thematic Map

The Analytical Hierarchy Process was applied to these layers to obtain the weights to the classes as shown in Table 3.5.1 and Table 3.5.2 below;

Table 3.5.1 Weathered Zone Depths Thematic Layer Weights

Weathered zone classes	Description	CODE	Weights
< 11	Shallow	SH	42
11 – 17	Moderately shallow	MS	30
17 – 22	Deep	DP	14
22 – 28	Moderately deep	MD	9
28 <	Very deep	CD	4
TOTAL			100

Satty's Consistency Ratio, CR = 0.0208

Table 3.5.2: Overburden Thickness Thematic Layer Weights

Overburden thickness classes	Description	CODE	Weights
< 1.5	Very thin	VT	42
1.5 – 2.8	Thin	TH	26
2.8 – 3.2	Thick	TK	16
3.2– 3.7	Moderately thick	MT	10
3.7 <	Very thick	VT	6
TOTAL			100

Satty's Consistency Ratio, CR = 0.0128

3.5.3 Integration of Thematic Layers and Modelling through GIS

After understanding their behaviour with respect to infiltration, the different classes were given with suitable weights, according to their importance with respect to other layered map in the modelling for recharge zoning. This was analyzed through the Analytical Hierarchy Process to come with the class Table 3.5.3 below,

Table 3.5.3: Inter-Map Dependency for GWR Zones Weights

Thematic Map Category	Weight	Remarks
Geomorphology	34	Mge
Overburden	23	Mob
Soil	16	Msl
Weathered zone thickness	10	Mwz
Rainfall	07	Mrf
Drainage Density	05	Mdr
Land-cover	03	Mlu
Slope	02	Msp
TOTAL	100	

Satty's Consistency ratio, CR=0.0247

The mathematical expression used to design the groundwater recharge model is as shown below;

$$GWRZ = Mgp * Gp + Mob * Ob + Mso * So + Mrf * Rf + MLu * Lu + Mdd * Dd + Msl * Sl + Mwz * Wz \quad \ldots\ldots (3.5.1)$$

Where:

Gp – geomorphology , Mgp – geomorphology map coefficient

Ob– overburden Thematic Map Mob – Overburden map coefficient

So – Soil Thematic Map Mso – soil map coefficient

Rf - mean annual rainfall Mrf – rainfall map coefficient

Lu – Land use Thematic Map Mlu – land use map coefficient

Dd – Drainage density Thematic Map Mdd – Drainage map coefficient

Sl – Slope Thematic Map | Msl – Slope map coefficient

Wz – Weathered zone Thematic Map | Mwz – Weathered map coefficient

The model was executed and the results were as displayed in the map Figure 4-2.

3.6 Boolean Analysis for Artificial Recharge Sites Selection

The Potential Recharge zone developed in the preceding section was used to analyse the final recharge sites. Information layers consisting of geomorphology, Stream order 2 and 3, groundwater recharge zones, soil and slope are analysed using Boolean logic criteria.

The main task in this method is to identify the criteria and to formulate the set of logical conditions to extract the suitable sites. Suitability analysis using Boolean logic model for the site selection have the objective criteria for site selection as follows:

i) The sites should be over a slope of less than 5°.
ii) The sites should be on channel fills in the flood plains, alluvial plains and alluvial fan terraces (geomorphology layer)
iii) The soil should be Sand, sandy loam, or sandy clay loam.
iv) The sites should be in the good or better groundwater recharge zones
v) The sites should be on the second or third order stream.

In this case, the output will have only two classes – suitable or unsuitable (fig 4.4-3). The areas in which the defined conditions of the information layers are fulfilled together, a value of one (1- suitable) is given whereas, the remaining part will have a zero (0- unsuitable) value.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

Integration of thematic layers and modelling through GIS yielded the groundwater potential mapping in Figure 4.1-1 which was classified as High Potential, Moderate Potential, Low Potential, Very Low Potential, and Negligible Potential according to Alexandru (1972), as having Transmissivity of 500 <, 50-500, 5-50, 0.5-5, and <0.5 m^2/day respectively.

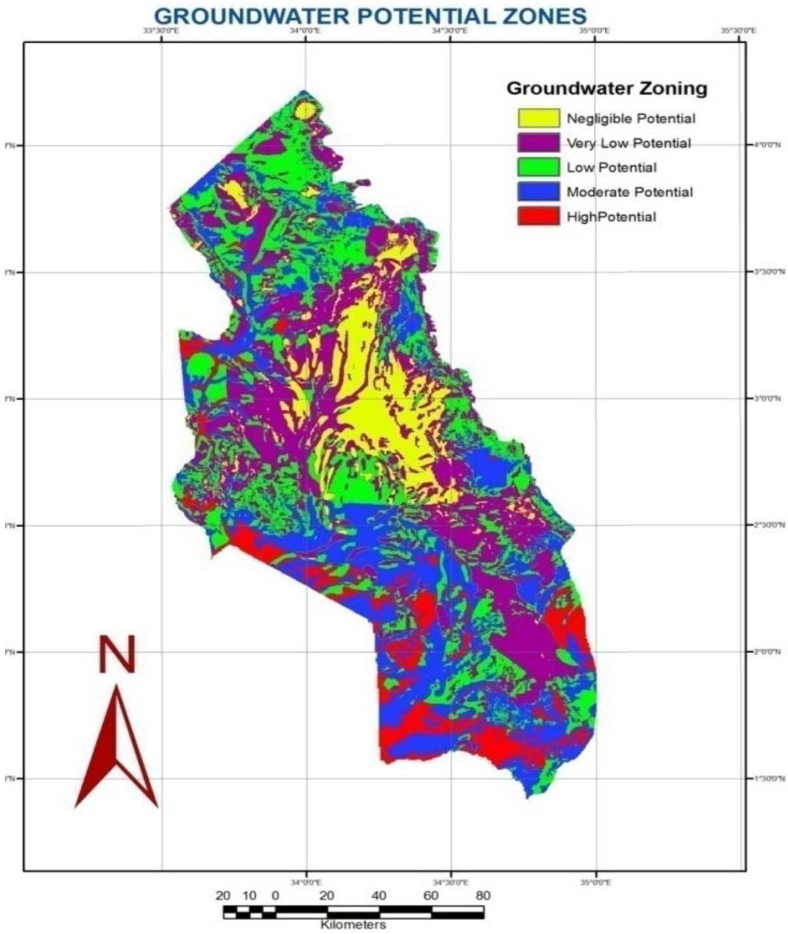

Fig. 4.1-1: Groundwater Potential Zones

4.2 Groundwater Potential Zoning

The GIS classification in Table 4.2.1 has been derived from the classification in Fig 4.1-1 above. The proportions of different layers available in these zones were identified.

Table 4.2.1: Biophysical Characteristics of Groundwater Potential Zones

BIOPHYSICAL CHARACTERISTICS GROUND WATER POTENTIAL (GWP) ZONES										
Classification of Groundwater potential - Alezandru (1972) using Transmissivity Values	High Potential	Moderate Potential		Low Potential			Very Low Potential			Negligible Potential
	500< m^2/day	50-500 m^2/day		5-50 m^2/day			0.5-5 m^2/day			<0.5m^2/day
Rainfall (mm)	VH	VH	VH	VH	MD	MD	VL	MH	VL	VL
Landuse	SF	SF	BL	SF,GL	SF	GL	GL	SF	WL	GL
Soil Type	CL	SC	CL	CM	SC	SC	CM	CM	SM	CM
Geomorphology	LAF	LFT	LAF	LAF	LAF	LAF	UAF	LAF	HLL	UFT
Lineament (km/km2)	MD	VL	LW	MD	VL	LW	MD	VL	VL	VL
Slope (%)	FL	FL	FL	FL	FL	FL	FL	FL	FL	FL
Drainage density (Km/Km^2)	MD	LW	VL	MD	HG	MD	MD	LW	HG	VH
Geology	SA	GF	BG	GF,AG	SA,AG	BG	BG	SA,GF	BG	AG

Note: the coding used in the table above is as presented in the weighting tables in chapter three.

It has been observed that groundwater potential zone has been influenced as follows,

4.2.1 High Potential Zone

This is characterized by very high rainfall and subsistence farming land use. Soil layer is clay type and the geomorphology is of alluvial fans in the lower deposits where the slope is described as flat. The lineament and drainage densities are moderate and the geology of the area is sediment alluvial. It should be noted here that this descriptions tends to concur with numerous literature especially Mukherjee et al (1996) who stated " the geomorphic features like alluvial fans, buried pediments, old stream channel and deep seated interconnected fractures are indicators of subsurface water accumulation".

4.2.2 Moderate Potential

This region has been characterized by very high rainfall and subsistence farming with bush land cover. The region fall in the alluvial fan and lower fan terraces, these regions are known for their high infiltration rates. They are in the flat terrain with very low lineament and drainage densities. This is typical of an anticline and its worth mentioning here that over 90% of the boreholes are in this region. See map Fig 4.2.1 below,

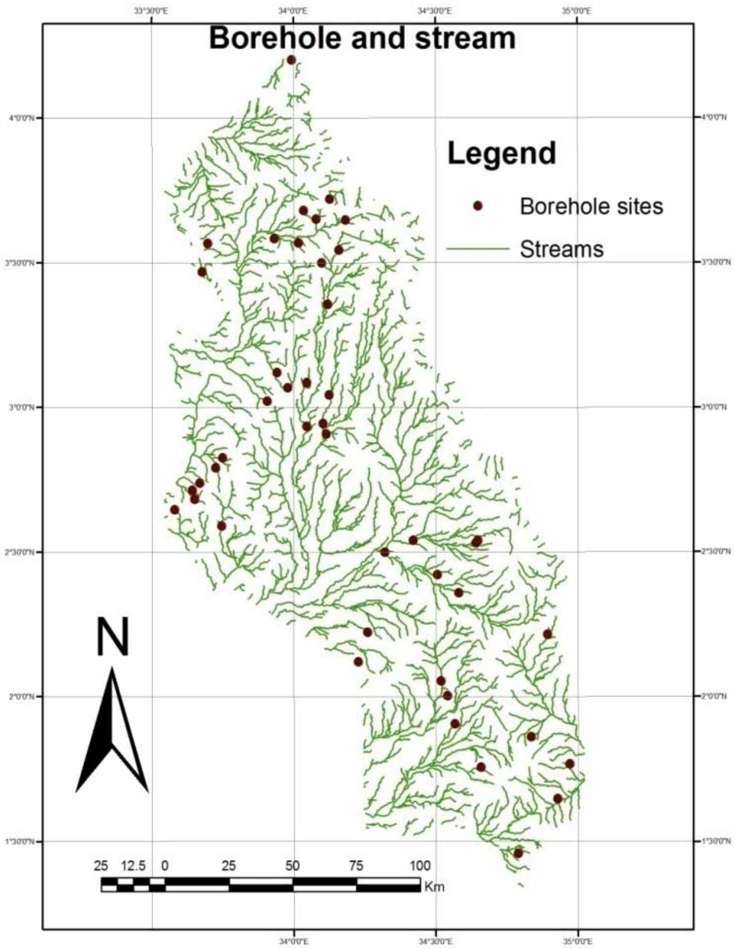

Fig 4.2-1 Borehole Location and Valleys

4.2.3 Low Potential

The low potential is found in the moderate rainfall region with greater proportion of land use being grassland with subsistence farming blended in several places. The soil is predominantly sandy clay with alluvial fan geomorphology in a flat terrain. The drainage density is moderate and the geology of the area is predominantly Acid gneiss. Lineament density ranges between moderate to high.

4.2.4 Very Low Potential

The rainfall in this region fall in the very low category the land use is predominantly woodland with some grassland here and there. The soil type is clay loam with alluvial fan in the upper terrace and hilly geomorphology. The topography can be described as flat with drainage densities ranging from high to moderately high. This is expected following the argument advanced in section 4.2.1.

The geology of the area is banded gneiss and granulites facies rocks. These rocks are highly metamorphosed and metamorphosed rocks are known hydro-geological to have very poor potential for groundwater. This explains the poor groundwater potential of the region as whole.

4.2.5 Negligible Potential Zones

The rainfall in these areas is in the class of moderately high. The areas are characterized with high drainage density and acid gneiss geological formations, which are known to have high water bearing potential. This thus, tries to explain the high effect of drainage density on groundwater occurrences.

In general terms, the groundwater potential is influenced highly by subsistence farming as land use. This can be attributed to the loosening of the land surface during farming, which encourages the infiltrations. The geomorphology category that featured predominantly is the alluvial both in the lower and upper fans; these are known to have very high water transmitting capabilities to the underground water systems.

The region's geological formation stems from the rift valley formation. The folds produced causes trends of ridges, which controls most of the drainage systems, which are NE-SW trending. These tend to be straight because the joining controls them. These caused the formation of Pleistocene to recent sediments in the lowlands of south and west regions; thus the high occurrences of groundwater potentials in these areas.

4.3 Aquifer Characteristics and Delineated Groundwater Zones Evaluation

The evaluation of the relationship between the delineated groundwater potential zones and aquifer characteristics can be seen as a validation of the GIS groundwater potential exploration method. It started by evaluating the general aquifer potentiality from boreholes Transmissivity.

4.3.1 Groundwater Classification by Borehole Data

This classification was derived from categorizing the borehole Transmissivity in to the five potential zones according to Alezandru (1972) and the proportion of each class expressed in percentage as shown in Table 4.3.1 below,

Table 4.3.1: Groundwater Classification by Borehole Data

Transmissivity, m2/day	Number of boreholes	Percentage
Negligible potential, < 0.5	3	6.8%
Very low potential, 0.5-5	24	54.5%
Low potential, 5-50	16	36.4%
Moderate Potential, 50-500	1	2.3%
High potential >500	0	0%
TOTAL	44	100%

The region can be said to have Low (36%) to Very Low (55%) groundwater potential. This confirms what was seen in the literature that the region has low groundwater potential Geotech Development Services (2007) that was attributed to the geological formations of the region.

4.3.2 Groundwater classification by comparing borehole data with GIS data.

The proportion of boreholes correctly classified were analyzed and summarized in Table 4.3.2 below, for example, in Low potential zones according to GIS, 63% of the boreholes falling in that zones were actually low potential boreholes, 25% were very low potential and 12% negligible potential. That mean the last two were actually wrongly classified by GIS.

Table 4.3.2: Characteristic groundwater potential zones

[redacted]

4.3.3 Model Evaluation and Results

The validity of the model developed was checked against the borehole Transmissivity data, which reflects tested groundwater potential. Appendix B shows that groundwater potential zones prepared through this model are in good agreement with borehole data. Out of 44 sampled boreholes, 31 of them has their Transmissivity correctly classified using GIS (Natural Break – Jenks classifier method), giving overall accuracy of 70.5%. This is the correlation efficiency of the GIS method. This confirms the hypothesis made at the beginning of this research that GIS has made numerous successes in water studies over the years. With 70.5% correlation with ground truth data, the research question made at the beginning of this report as been answered as significant.

4.4 Groundwater recharge zone

The recharge zoning was processed in a similar manner to the groundwater potential delineation. In a similar way, the potential zone was classified in five zones using Natural Breaks (Jenks) classifier.

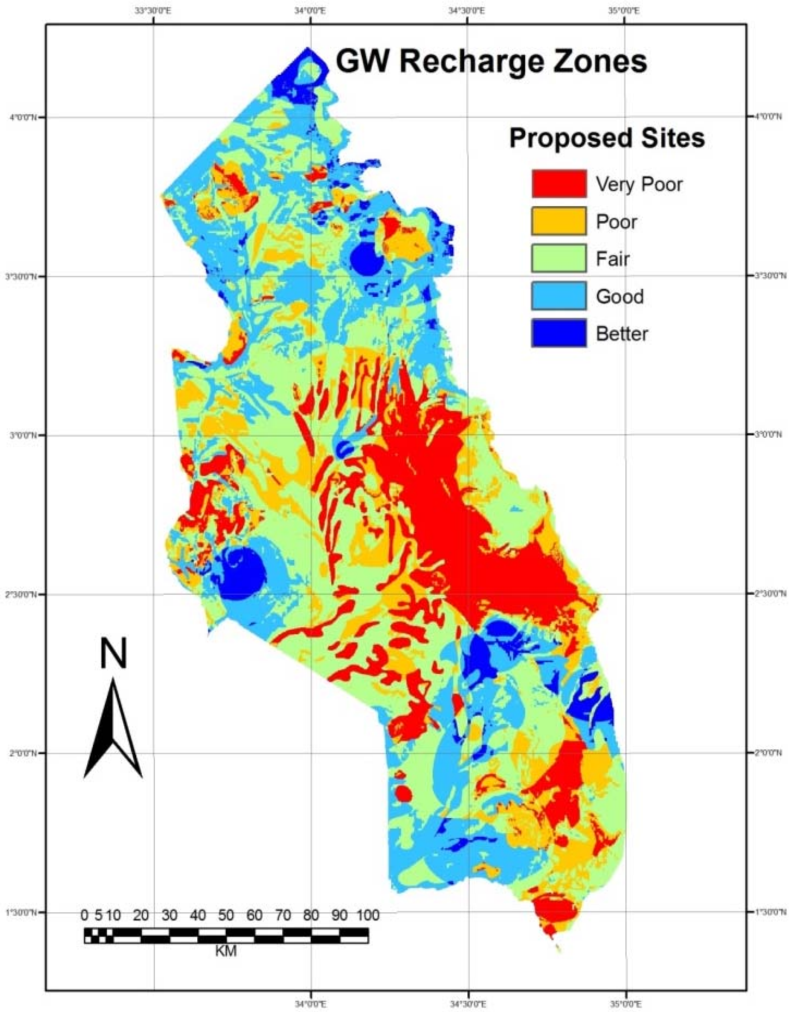

Fig 4.4-1: Recharge Potential Zones

From the map, Fig 4.4-1 above, the recharge positions can be located at the following locations; 3°33′N 34°10′E, 2°57′N 34°06′E, 2°34′N 33°45′E, 2°19′N 34°32′E. These locations occur on or along the third order streams Fig 4.4.2. This was previously suggested by *Saraf, Kundu, & Sarma, P. (2000),* who did similar research on artificial recharge sites in hard rock terrain. They indicated that recharge sites should be on channels fill of alluvial and flood plains. These sites, especially channel fills of alluvial fans are quite suitable due to their high infiltration rates.

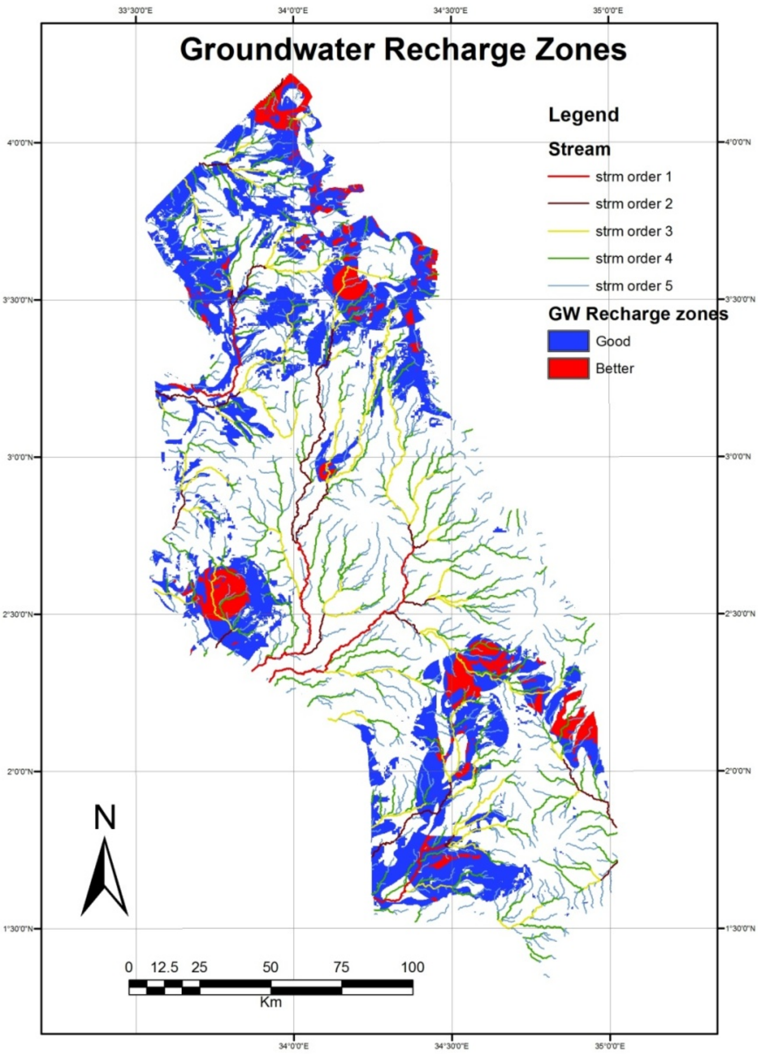

Fig 4.4-2: Groundwater and stream order relationship

4.4.1 GIS Site Selection

Site selection is purely based on GIS output, literature review was only used to analyse and confirm them.

Site 3°33′N 34°10′E – North of region

This site is located in the northern part of the region. This site has several lines of faults, which would give ease of infiltration. This would then be recharging both the northern and central region. The suggested recharge method is stream channel method.

Site 2°57′N 34°06′E – Central Region

The site at the central region is a flood plain where two streams joins. It has a characteristic of swampy area. This is more or less, a natural recharge site. This would then be recharging both the central, south, and southwest regions. The suggested recharge method is Flooding method.

Site 2°34′N 33°45′E – Western region

This site is somehow in the periphery of the region; however, if water management is to be done in integrated manner, this recharge site will benefit the local but especially the neighbouring Districts in the west of the region. The suggested recharge method is Flooding method.

In general, the pietzometric level of water slopes from NE towards the Central SW, which indicates the general trend of groundwater flow in the Northern sub-region *Martin (2006).* The above mentioned sites were suggested previously in an independent study of aquifer in the region by *Martin (2006), a*nd I quote "there are therefore, three basic groundwater recharge zones; central Kotido areas in around Jie county [2°57′N 34°06′E][1], south west of Kotido areas around Abim border with Lira District [2°34′N 33°45′E][2] and northern Kotido in areas of Kathile and Kapedo slightly west of [3°33′N 34°10′E][3]. This still go a long way to show how relevant GIS in groundwater recharge zoning.

[1] Compared to suggested in this study – Central region
[2] Compared to suggested in this study – Western region
[3] Compared to suggested in this study – Northern region

Site 2°19′N 34°32′E – Southern region.

This site is located in the southern part of the region. It is served with few lines of faults, which could be used to influence infiltration. The suggested recharge method is stream channel method.

It should be noted that several ‘fertile’ areas for recharge exists in the north and south of the region Fig 4.4-2.

4.4.2 GIS Recharge Zones Characteristics.

Factors considered influential by GIS classification have been listed in the Table 4.4.1 below. As can be seen from the table below, good weathered zone depth, shallow to moderately shallow, and very thin overburden are good for recharge zones.

Table 4.4.1: Table of GIS Recharge Zones Characteristics.

[redacted]

The presence of flood plain and alluvial fans as geomorphological formation is quite encouraging, as these formations are known to aid natural groundwater recharge. The occurrences of sediment alluvial in these sites have strong indication of good hydraulic properties for groundwater recharge. The aquifer thickness, especially at Northern region coupled with Acid Gneiss rock type, which is known to have high groundwater potential, points to the fact that this is a good site for recharge. All sites, however, needs to be confirmed during site investigations.

4.5 ARTIFICIAL RECHARGE SITES SELECTION

Although selection of sites for artificial recharge by an integrated GIS and RS analysis through a combination of multi criteria analysis in the GIS platform gave the recharge zones, Fig 4.4-1, Boolean logic method discussed in section 3.6, is necessary to improve on the site selection criteria. Detailed site selection information and geophysical data analysis of the proposed sites greatly improved the results of this recharge site selection Fig 4.5-1. The analysis was purposefully performed on 650m×650m grid to cater for the different methods of recharge.

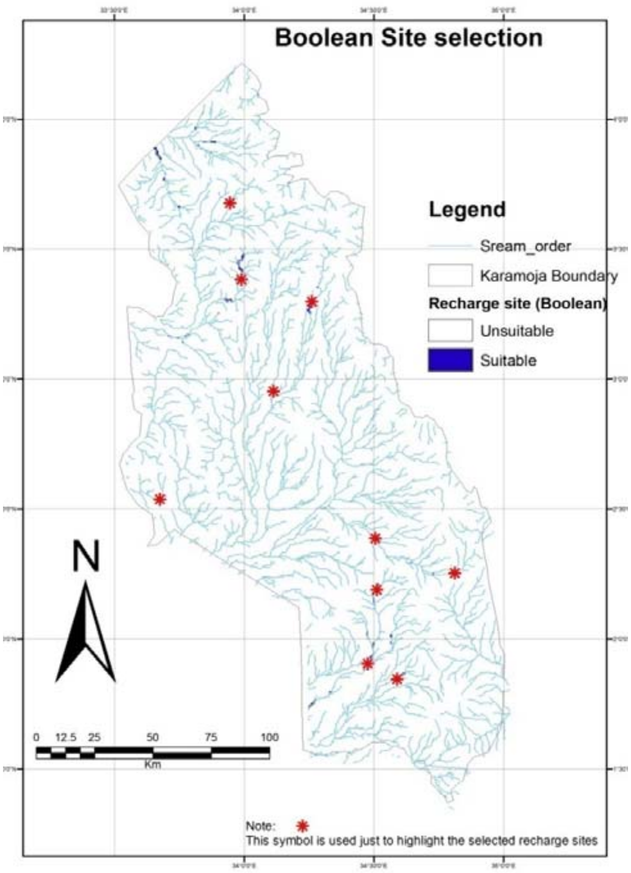

Fig 4.5-1: Boolean criteria for Recharge Site selection

The overlay of the Boolean criteria with aquifer thickness, Fig 4.5-2 and Transmissivity, Fig 4.5-3, is to verify the selection suitability.

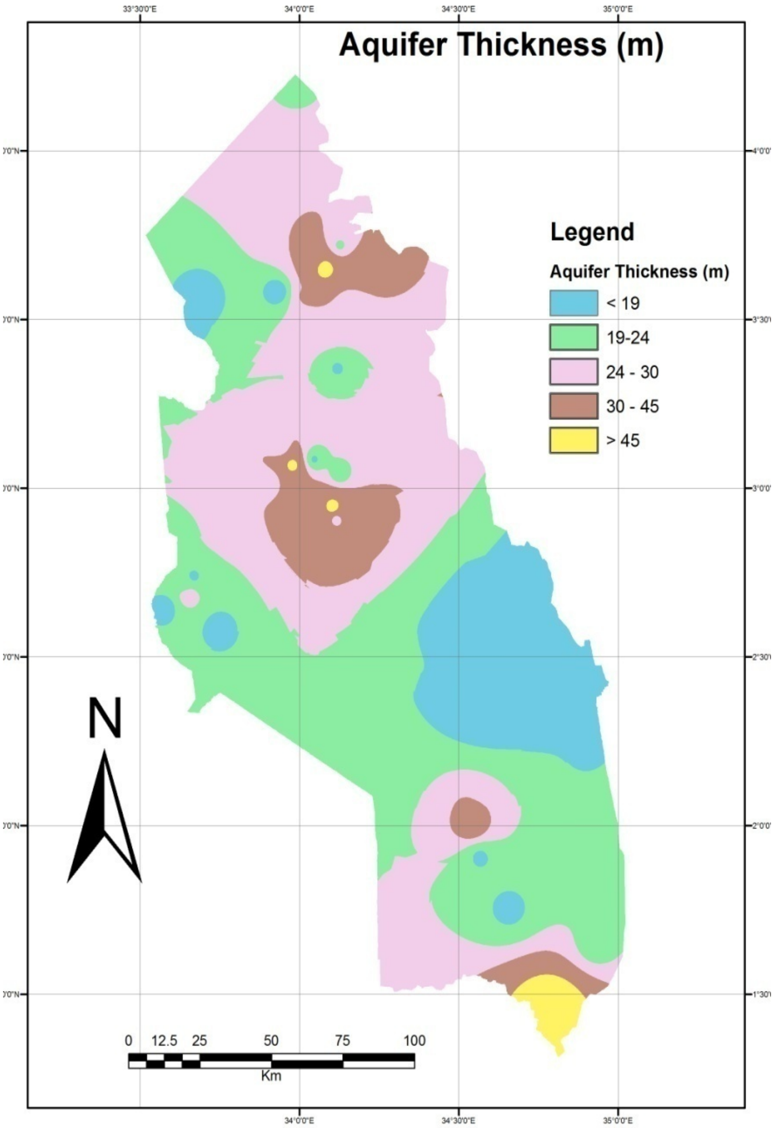

Fig 4.5-2: Groundwater Recharge sites and Aquifer Thickness

As can be seen in Fig 4.5-2, the site selection cuts across the region without clear trend on the aquifer thickness. However, since recharge has more to do with groundwater movement, the objective analysis of the Transmissivity indicates the recharge sites in normally distributed on the 'prime[4]' aquifer of the region. Remember it was earlier shown section 4.3.1 that the region can be classified as low to very low groundwater potential region due to geological formation.

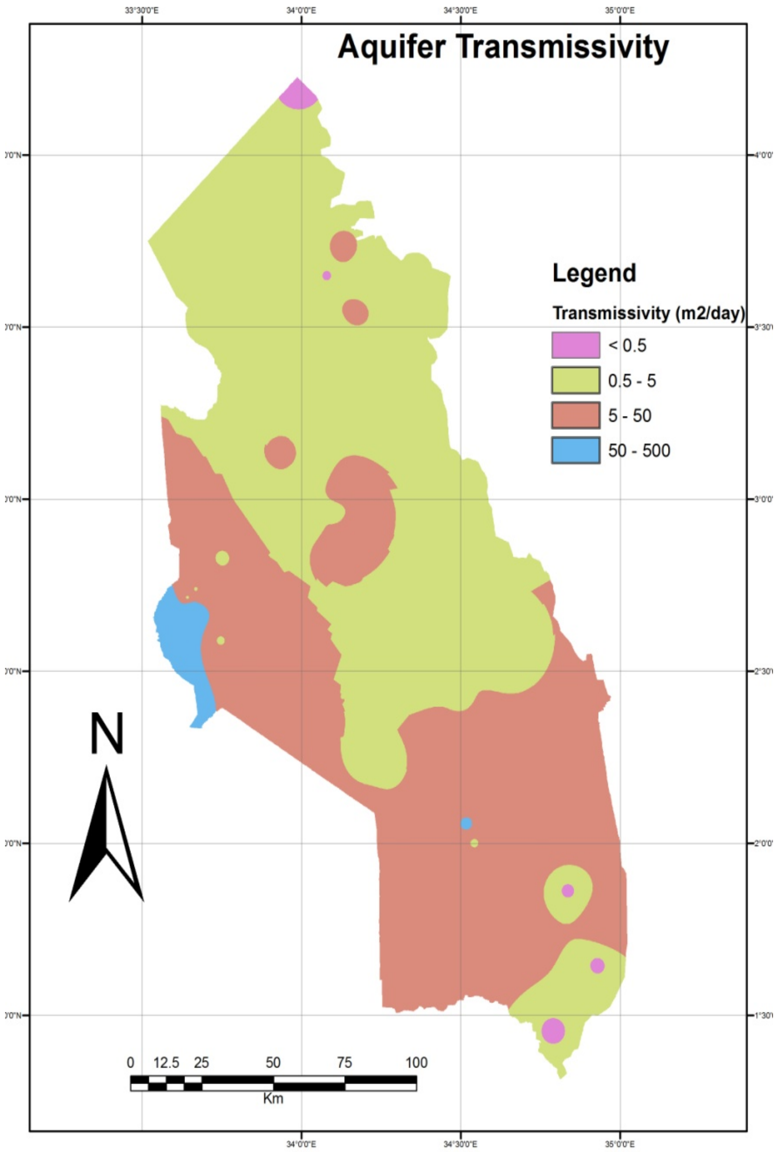

Fig 4.5-3: Groundwater Recharge sites and Aquifer Transmissivity

---

4 Prime aquifer in the sense that over 90% of the region is covered with low to very low potential aquifer.

It follows, therefore, that the artificial recharge methods seen earlier can be selected as follows seen below.

4.6 Proposed recharge methods

4.6.1 Stream channel method:

recharge can done by constructing sand dams since those region has lineaments and the presence of alluvial terraces and fans that provides good infiltration media. It should also be noted that, not only will the sand dam provide conducive environment for groundwater recharge but provide the much needed water by pumping or other methods.

4.6.2 Flooding method:

In the central region and south western, the flooding is suggested since the areas are relatively flat. The land use in the areas should be restricted to encourage natural or enhanced natural conditions that facilitate infiltration.

4.6.3 Combination Surface – Sub-Surface Techniques

This method can be used in combination with the first two methods. These are the most direct measure to recharge the ground water reservoir. Percolation tanks with wells and shafts can be used to recharge deeper aquifers where shallow or superficial formations are highly impermeable or clayey with certain modifications.

These methods should, however, go hand in hand with groundwater level monitoring for maximum output.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The findings noted and discussed previously were used in principle, to assess the performance of integrated Remote Sensing and GIS application in groundwater exploration.

Groundwater potential zones: The delineation of groundwater potential zones was achieved using the Integrated RS and GIS. Classification of the final zones was related to Alexandru (1972) classification, which categorises groundwater potential according to the aquifer characteristics, thus the potential zones. The study provided information on long-term practicability of groundwater development in the region by categorizing its potential zones.

Analysis of the borehole data indicated that the region has low groundwater potential especially in the central region. The borehole data analysed for aquifer Transmissivity was used to evaluate the groundwater potential zoning using GIS. This indicated 70.45% correlation showing the effectiveness of GIS application in the field of groundwater exploration.

In applying GIS analysis in groundwater zoning, the weighting became crucial, as assigning wrong weights would provide wrong output. In this sense, multi criteria analysis with Analytical Hierarchy Process (AHP) suggested by Satty (1988) proved very effective as decisions were checked for consistence before being applied. Besides, the weights normalization provided common platform of comparison and analysis of the GIS data. The use of Natural Break (Jenks) in the classification proved to be ideal, as classes are based on natural groupings inherent to the data.

Objective of groundwater delineation has been achieved as the groundwater potential zones defined. This confirms the hypotheses stated at the beginning of this report that Integrated RS and GIS have made a lot of successes in groundwater hydrology over the years. The research question “to what significant level does Integrated Remote Sensing and GIS methodology relates to the ground truth data” have been determined with 70% correlation, which shows good significance of its application in groundwater exploration.

However, underfunding of the research became apparent when it came to data purchase. Good quality data of high resolution are very expensive. It is my believe that if quality data was used better correlation could have been achieved.

Groundwater Recharge: as seen for the groundwater potential zones, this was also achieved. Over the years increasing population, urbanization and expansion in Agriculture called for intuitive water resources management, in particular groundwater, development program that can cope with prevailing situations, effective and efficient techniques for its assessment.

Low values of aquifer parameter, poor distribution of the good aquifer, thin productive mantles and difficult terrains suggest that long-term sustainability of groundwater is compromised. This calls for alternative ways to argument the groundwater recharge to replenish the resource. Artificial recharge comes in handy for this purpose.

To ensure long-term resources sustainability proper management plan should be developed. The principle behind this plan should be that coordinated and planned operations of both ground and surface water in such a manner that water requirements are met and water is conserved. The separate firm yields of both resources are replaced by a larger and more economic joint yield of the two resources.

For judicious use of groundwater resource, I suggest that;

i. Low yield wells are pumped for duration such that undesirable drawdown is not created in the wells since the region has low groundwater potential.
ii. Recharge zones areas should be managed carefully or be subjected to restricted use to avoid pollution of the entire groundwater.
iii. Hydro-fracturing technique is adopted when developing boreholes in fractured rock aquifers so that discontinuous fractures are opened to improve the yields of the wells.

In conclusion, the present study demonstrated that integrated Remote sensing and GIS based methodology has been developed and tested for evaluation and exploration of groundwater resources in semi arid and mountainous terrain. It should be mentioned here that the amount of time and cost invested in this research compared to the size of the region (27,900Km2) also points out how effective and efficient is the GIS method.

5.2 Recommendations

Following the result discussions and discussions in the preceding chapters and sections above, I recommend that;

i. Multi criteria analysis with Analytical Hierarchy Process (AHP) suggested by Satty (1988) proved very effective because decisions were checked for consistence before being applied. Besides, the weights normalization provided common platform of comparison and analysis of the GIS data. Thus should be used to assign weights in this kind of analysis.
ii. The use of Natural Break (Jenks) in the classification proved to be ideal, since classes are based on natural groupings inherent to the data, thus it is recommended for data classification in this type of analysis.
iii. Classification of groundwater potential zone as High Potential, Moderate Potential, Low Potential, Very Low Potential, and Negligible Potential according to Alexandru (1972), as having respective Transmissivity, T of 500 <, 50-500, 5-50, 0.5-5, and <0.5 m^2/day proved ideal thus recommended for this kind of study.
iv. The methodology developed may be applied to similar terrain conditions, with some local considerations and modifications. Further incorporation of geophysical data can enrich the interpretation for groundwater management

5.3 Way forward

To understand the groundwater hydrology of Karamoja region and the quality of water in region, further research in the following areas is required;

i. Map the suitability of groundwater quality for irrigation, drinking or industrial purpose, Electrical Conductivity (EC), pH, Sodium Absorption Ratio (SAR) data etc.

ii. Aquifer storage and zoning to estimate groundwater quantities and storage capacities. This is crucial before planned developments are initiated.

iii. Groundwater recharge and discharge estimation coupled with groundwater flow path zoning, should be subjected to development of suitable groundwater structures for monitoring.

iv. Studies on longer scale, changes in climate change can have significant impact on groundwater and should not be overlooked.

REFERENCES

Bharadwaj et al, R. J. (1998) *Multi Criteria Analysis using GIS for groundwater Resource evaluation in Rawasen and Pili Watershed, U.P.* Indian Institute of Remote Sensing, Dehradun. Remote Sensing Application Centre, Bhopal, M.P.

Central Water Board, MoWR. (2000, May) Guide on Artificial Recharge to Ground Water. New Dehli, India.

Das,D (1997) Enhancement analysis of geological linear features for groundwater information extraction. *International Conference on Management of Drinking Water*, (p. pg 9). India.

Das, D (1997) "*GIS application in Hydrological Studies",* Dehli, India: GIS development.

Das, D (1990) Satellite remote sensing in subsurface water targeting. *ACSM-ASPRS annual Convention*, (pp. pgs 99-103). Singapore.

Das, D and Kader, A (1996) "A Geomorphological approach for selecting the sites for artificial recharge of groundwater in the upper catchment ara of the Kumari River basin". (pp. pgs 67-115). Dhanbad, India: *Springer Journals.*

Geotech Development Services. (2007). *Hydrogeological Survey Report.* Kotido District Local Government. Kotido: Unpublished.

Gupta. (25 Oct 1980) "*Correlation of Landsat and Airborne Magnetic anomaly data of a part of the Bihar mica belt", Porc Symposium*, (pp. pp23-30). Bangalore, India.

Karamoja Data Centre. (2003) *Situational Analysis and Sector Plans.* Kotido Distirct Local Government. Kampala: Prime Ministers Office, Karamoja Affairs.

Khairul, A. M., Juhari, M. A., and Ibrahim, A. (1989). *Groundwate potential zoning in Langat basin using the integrated remote sensing and GIS* http://www.gisdevelopment.net/aars/acrs/2000/ps3/ps318pf.htm. retrieved on Sunday, 13th April, 2008

Martin, N. (2006) *Study of Characteristics of Kotido Aquifers.* Unpublished.

Michael, P. F., Williams, M. S, and Lynn, U. E. (2006) "An Implementation of the Jenks-Caspall Algorithm for Optimal Classification of Data for Geographic Visualization," *USGS, Science of a Changing World* , 11 to 26.

Mukherjee et al, A. D. (1996). Aquifer Characteristics and groundwater management in Eastern India. In J. University (Ed.), *Seminar* (pp. pgs 36-42). Culcutta, Inda: GIS development.

Musa, K. A., Akhir, J. M., & Abdullah, I. (2000) "Groundwater potential zoning in Langat Basin using the Integration of Remote Sensing and GIS," *SpringerLink Journal*

Novaline, J., Saibaba.J, & Raju, P. (1999) "Groundwater modeling for sutainable development using GIS techniques," *Geoinformatics Beyond 2000*, (pp. Abstract pgs 5-11). Dehradun, India.

Parizek, R. (1976) "Relationship between fracture traces and the occurance of groundwater in Carbonate rocks," *Hydrology Journal*

Saraf, A. K., Kundu, P., and Sarma, B. (1998) "Integrated Remote Sensing and GIS groundwater Recharge Investigation Selection of Artificial Recharge sites in Hard Rock terrain," *GIS explorer.* Indian Institute of Technology, Roorkee, Department of Earth Sciences. ROORKEE

Satty, L. T. (1980) *The Analytic Hierarchy Process.* McGraw Hill, New York.

Shankar , N. (2002) Relationship between fracture traces and the occurance of groundwater in Carbonate Rocks. *Hydrology*

Shrivastava, R., Sidhu, R., and H.S., M. (1992). *Integrated Water Resources Planning and Development using Remote Sensing Techniques.* Institute of Technology & Science,, Dept of Civil Engineering, S.G.S. Indore (M.P) India: GIS development.

Singh, A. K., & Prakash, S. R. (2000) "An integreted approach of Remote Sensing, Geophysics and GIS to evaluation of Groundwater," *Gis development Journal* , Abstract, pgs 4-9.

Sophocleous, M. (1985, Nov 15) "Experimental studies in Natural Groundwater-Recharge Dynamics The Analysis of Observed Recharge Events," *Journal of Hydrology JHYDA7 Vol. 81, No. 3/4,* gs 297-332.

Akpofure, E.Taigbenu, Ron Chaoka, Brian K. Rawlins, Richard Owen and Simon Mkhandi., (2002). "Introduction to Hydrogeology. Ground Module", *Lecture Notes for M.Sc.* (IWRM), University of Dar es Salaam – Tanzania.

Teknomo, K. (2006). *People Revoledu*.http://people.revoledu.com/kardi Retrieved May 15-28, 2008

APPENDICES

Appendix A: Aquifer analysis - for Transmissivity

ID	BH NAME	X-CORD	Y-CORD	ELEVATION (m)	AQU1_TUKNE	Discharge	Static Water Level (m)	Overburden thickness (m)	Weathered zone depth (m)	Aquifer Thickness (m)	Transmissivitv T,(m)
1	Amudat	719410	195431	1234	24.00	360	2965	3.00	25.00	24 (X)	10 60
2	Aninata	571467	300025	1184	21.04	0.73	28.88	5.00	24.20	21.04	2.47
3	Aremo	583010	286241	1166	16.00	1.70	11.00	2.10	8.20	15.80	3.00
4	Aringobomb	583420	312400	1205	30.00	2.08	10.50	3.10	30,76	25.60	1..34
5	Aywee	572481	296589	1205	30.00	3.52	14.49	2.40	27,60	30.00	96.10
6	Chepkarat	699216	161127	1325	66.70	0.00	42.70	6.00	27.00	34.00	2.00
7	Gotapwou	564535	292535	1130	16.00	3.52	4.90	4.80	4.80	16.46	284.00
8	Iriri	636448	234370	1259	21.00	1.50	4.33	3.50	12.50	21.00	6. 06
9	Kaelemiiye	616228	324359	1196	37.00	1.00	24.68	5.00	18.00	37.00	3.71
10	Kaleketyo	714739	1 82097	1341	22.00	1.55	38.15	3.00	19.00	22.00	2.30
11	Kamaret	704321	205875	1147	21.00	0.80	34.50	3.00	27.00	35.00	3.40
12	Kamor	622730	325543	1219	50.16	0.72	21.86	0.35	9.35	50.16	3.33
13	KarengaHC	577467	394280	1417	15.60	0.95	22.30	2.50	20.00	15.60	4,50
14	Katanga	682581	280034	1337	1 0.00	0.80	36.38	4.11	26.00	10,70	1.62
15	Kathile East	619909	403574	1542	52.30	0.00	30.00	5.00	33.00	52.30	0.30
16	Kidepo	610242	464438	1576	0.00	1.10	14.00	2.10	8.00	23.00	3.10
17	Kokwiwaum	604611	345022	1224	27.00	1.50	13.75	5.00	9.00	27.00	6.06
18	Lodiko	628853	391855	1601	25.00	2.40	34.16	1.50	2.00	2470	7,35
19	Lojqj ora	646924	276255	1149	21.70	1.50	39.94	4.11	25.51	21.70	2.18
20	Lokadwaran	674359	210684	1146	18.00	1.20	28.15	3.00	18.00	1 8.00	5.01
21	Lokapuke	575409	383401	1258	18.80	1.00	4.00	3,00	12.00	18.80	4.50
22	Lokitela-Diida	684594	194109	1147	1700	1.20	13.00	3.00	9.00	17.00	8.18
23	Lokwakaramoi	625232	411236	1751	23.80	0.82	31.63	3.00	3.00	23.80	7.35
24	Lolet	667568	267807	1211	15.89	1.00	10.41	4.21	19.91	1589	4.04
25	Lomodoch	613092	394541	1482	31.00	1.50	29.90	6.00	21.00	30.60	2.84
26	Lomusian	622183	386931	1557	30.00	0.53	21.31	3.50	15.00	30.00	0.62
27	Longaro	624428	370955	1435	18.70	0.50	42.77	3.00	9.15	18.70	1.54
28	Longaroi	669003	227081	1163	30.70	3.00	25.97	3.00	15.00	30.70	5590
29	Lopotha	624027	321463	1 196	28.02	2.50	22.32	5.00	18.00	18.02	9.11
30	Lorengechora	640121	245686	1182	23.01	1.00	63.84	3.99	36.76	23.01	091
31	lorengedwat	675951	260828	1263	12.00	6.20	8.14	0.50	0.50	34.00	8.18
32	Loroo	710586	244930	1437	1900	3,00	34.43	3.00	9.00	19.00	34.20
33	Losilang PTC	625140	336448	1293	21.00	1.22	31.28	8.00	13.00	20.60	6.75
34	Louton	658097	280916	1208	18.28	0.60	66.38	3.00	41.14	18.28	1.10
35	Lo\\aku|	603500	396065	1438	14.50	0.74	32.52	3.00	42.00	14.50	4.12
36	Miniyang	608765	339229	1191	84.00	0.70	57.75	5.00	22.00	34.00	4.50
37	Nalemusekon	63 1449	403277	1650	37.00	1.25	32.50	2.00	24.00	36.60	1.64
38	Nalube	614982	406849	1621	30.70	0.47	40.10	2.00	24.00	30.70	280
39	Napongae	671557	221413	1166	36.70	5.00	1293	2.00	24.00	3670	2 75
40	Natir	600888	333978	1211	27.00	070	20.38	5.00	5.50	27.00	2.58
41	Natumukasikon	683379	280824	1343	11.40	0.80	33.28	4.11	25,51	1 1.40	0.91
42	Oryeyotyene	574351	302732	1144	18.04	1.63	1569	3.50	42.50	18.04	3.71
43	Otumpili	580700	308553	1160	20.60	0.73	16.32	3.10	10.40	2060	6,71
44	Urn Urn	616382	341091	1172	18.34	1.50	25.14	5.00	18.00	18.34	3.40

Appendix B: Zoning of GIS and Borehole classes correlation

ID	BH NAME	X COOD	Y COOD	ELEVATION (m)	Alexandru, 1972 zoning		Correct clasification	Calculated Traiismissivity T, (m)
					Zone as per GIS	Zone as per Borehole		
7	Gotapwou	564535	292535	1 130	4	4	1	284.00
5	Ay wee	572481	296589	1205	2	3	0	96.10
29	Eopotha	624027	321463	1196	2	3	0	9.11
31	lorengedwat	675951	260828	1263	2	3	0	8.18
33	Losilang PTC	625140	336448	1293	2	3	0	6.75
1	A mud at	719410	195431	1234	3	3	1	10.60
10	Kaleketyo	714739	182097	1341	3	3	1	2.30
17	Kokwiwaui	60461 1	345022	1224	3	3	1	6.06
18	Lodiko	628853	391855	1601	3	3	1	7.35
20	Lokadwaran	674359	210684	1146	3	3	1	5.01
22	Lokitela-Diida	684594	194109	1147	3	3	1	8.18
23	Lokwakaramoi	625232	41 1236	1751	3	3	1	7.35
28	Longaroi	669003	227081	1163	3	3	1	55. 90
32	Loroo	710586	244930	1437	3	3	1	34.20
37	Nalemusekon	631449	403277	1650	3	3	1	1.64
43	Otumpih	580700	308553	1160	3	3	1	6.71
8	Iriri	636448	234370	1259	4	3	0	6.06
14	Katanga	682581	280034	1337	1	2	0	1.62
2	Aninata	571467	300025	1184	2	2	1	2.47
3	Aremo	583010	286241	1 166	2	2	1	3.00
4	Aringobomb	583420	312400	1205	2	2	1	1 34
9	Kaelemuye	616228	324359	1 196	2	2	1	3 71
12	Kamor	622730	325543	1219	2	2	1	3 33
13	Karenga HC	577467	394280	1417	2	2	1	4 50
16	Kidepo	610242	464438	1576	2	2	1	3.10
19	L.ojqj ora	646924	276255	1 149	2	2	1	2.18
24	Lolet	667568	267807	1211	2	2	1	4.04
27	Longaro	624428	370955	1435	2	2	1	1.54
30	Lorengechora	640121	245686	1182	2	2	1	0.91
34	Louton	658097	280916	1208	2	2	1	1.10
35	Lowakuj	603500	396065	1438	2	2	1	4.12
36	Miniyang	608765	339229	1191	2	2	1	4.50
38	Nalube	614982	406849	1621	2	2	1	2.80
40	Nalir	600888	333978	1211	2	2	1	2.58
41	Natuinukasikon	683379	280824	1343	2	2	1	0.91
42	Oryeyotyene	574351	302732	1144	2	2	1	3.71
44	Urn Urn	616382	341091	1172	2	2	1	3.40
21	Lokapuke	575409	383401	1258	3	2	0	4.50
25	Lomodoch	613092	394541	1482	3	2	0	2.84
26	Lomusian	622183	386931	1557	3	2	0	0.62
39	Napongae	671557	221413	1166	5	2	0	2.75
11	Kamaret	704321	205875	1147	2	1	0	3.40
6	C hep karat	699216	161127	1325	3	1	0	2.00
15	Kathile East	619909	403574	1542	3	1	0	0.30
						44	31	

TOTAL BOREHOLES ASSESSED 440
TOTAL BOREHOLES CORRECTLY CLASSIFIED BY GIS 310
PERCENTAGE OF CORRECT CLASSIFIED (MODEL EFFICIENCY) 70.5%