ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

Model Based Groundwater System Analysis For Hayk-Ardibo Catchment

BY

Getachew Asmare

Department of Earth Sciences, Faculty of Science
Addis Ababa University, Ethiopia

Addis Ababa June 2005

ACKNOWLEDGEMENTS

I wish to thank most sincerely, the Water Resource Development Bureau of the Amhara National Regional State for granting the financing opportunity to study at the Addis Ababa University Faculty of Science, Department of Earth Science. I thank the graduate program of the Addis Ababa University for aid in conducting the research.

To Dr. Tenalem Ayenew, my thesis advisor I wish to express my deepest gratitude for his excellent advice and constructive criticism. I would like to extend my thanks to the staffs of the Earth Science Department for their assistance both during the course work and research: Dr.Tamiru Alemayehu, Dr. Dagnachew Legesse (co advisor) , Professor Sastrics, Dr.Tesfaye Kormie, and Dr. Dereje Ayalew, Chairman of the Department of Earth Science.

Particularly useful and critical reviews and suggestions were also offered during the simulation and writing of this paper from the following technical expertise: Ato Shiferew Lulu of AG Consult, professors Noaki Shibasaki of JICA and Professor Combes of International Research Institute, France.

I express special thanks to Ms Zemenay Lakew, Senior Regional Adviser of UNDP Africa, Dr. Stephen Maxwell Donkor, Senior Regional Advisor of Economic Commission for Africa and Ato Abebe G/ Hiwot, Managing Director of AG Consult for their reverent support and encouragements in moral, finance and logistic. I would like to personally thank Ato Shiferew Lule of the AG for his extraordinary sharing of his experience, and assistance.
I would like to extend my gratitude to W/t Negist Daniel and W/t Selam Daniel for their valuable secretariat support.

Finally I would like to give my appreciation and thank for my families and friends for their encouragement and extended support. Above all, God Almighty was my strength and sources of blessing and praises and glory to him forever!

TABLE OF CONTENTS

FIGURES

TABLES

ANNEX

ABSTRACT

A research was undertaken to understand better the interaction between the surface and groundwater of the Hayk-Ardibo Catchment. A two-dimensional aerial finite-difference groundwater flow model was used to simulate the groundwater flow and establish a hydro geologic budget of the region.

The Hayk-Ardibo Catchment lie on the western Afar rift escarpment, an area with a complex geologic history. The geologic history includes volcanic rocks with the major NNE-SSW fault trend in the area. Faulting have modified the distribution and thickness of volcanic rocks, their secondary porosity & permeability and the degree of weathering and fracturing which intern influence the occurrence and movement of ground-water in the region. The permeability of the aquifer which are highly weathered and fractured are associated with high hydraulic conductivity value which in most case is the typical nature of the Tertiary volcanic located in the center of the Catchment along lake area that control the gradient of the potentiometric surface and ground water flow in that region. The geology, hydrogeology and water balance of the study area has been discussed and it helped to understand the groundwater flow system in the study area. These are the basics, which helped to conceptualize and determine the type of aquifer, its aerial extent and boundaries.

A Conceptual model was first developed to decide in order to determine the modeling approach.. The model boundaries determined to represent natural hydrological boundaries incorporate (1) no-flow boundary along the western, Eastern and Southern boundaries, (2) flux boundary along Northwestern boarder of the study area (3) general head boundary on the two lakes and internal boundary along Ankerka River draining the central catchment.

Several simplifying assumptions were made for the conceptualization and simulation of flow in the Catchment: 1) Recharge to the groundwater is assumed only from precipitation with in the catchment and there is no additional subsurface inflow across boundary in any part of the study area. Recharge varies spatially, 2) single layer has been used in the model 3) Darcy's law is applicable to flow through the fractures 4) unconfined aquifer is assumed in the model, and 5) evaporation was not explicitly simulated in the model. Recharge rates were considered as 'net recharge,' and 6) discharge occurs from the aquifer along the Northern boundary where aquifers are hydraulically connected to down Catchment.

The simulated region is an area of 140.1 square kilometers. The model consists of over 62,500 cells and exercised a regular grid spacing of 250m x 250m.

Input parameters to the model included, initial hydraulic head, recharge values to the topmost model layer and hydraulic conductivity. The model was designed and calibrated to steady state conditions with heads observed at 20 springs.

The model was calibrated utilizing a manual *trial-and-error* adjustment of parameters. Horizontal hydraulic conductivity, recharge value, hydraulic conductance at the general-head boundary, and streambed conductance were adjusted during successive simulations until computed head values approximate field conditions.

Sensitivity tests were conducted on net recharge and hydraulic conductivity. Based on the results obtained from the sensitivity analysis, it is apparent that the model is highly sensitive to changes in recharge than horizontal hydraulic conductivity. The model is less sensitive to stream bed hydraulic conductivity.

The agreement between the measured and the simulated hydraulic heads obtained for the steady-state model suggests that the values assigned to the hydraulic properties that characterize the ground-water flow of fractured volcanic aquifer are reasonable.

The volumetric budget terms for the contribution to groundwater flow components for the study area simulated to be as follows: Groundwater inflow is 6.5393855E+04 m^3/d and Groundwater outflow 65389 m^3/d. This indicates that substantial amount of groundwater leaves to the adjacent catchment

CHAPTER ONE

INTRODUCTION

1.1 Background

Agriculture is the most significant sector to the nation's economy, accounting for 85% of the Country's labor force is used on agricultural activities and furthermore for the particular generating of foreign exchange. The temporal and spatial variations of rainfall distribution on the nation make irrigation an alternate solution for the extensive cultivation of crops and food security. The intention to use the two Lakes for irrigation was started long ago but the irrigation at the Hayk lake is not yet functional and limited irrigation activities has been conducted on the Ardibo lake. In order to utilize the two lakes for irrigation one has to count the sustainability of the lakes ecology and the aquifers system underlying the Hayk and Ardibo Catchment.

There fore to alleviate the growing demand for water and agricultural acreage in the region, it is essential to propose developing strategies: a scientific approach to water resources management. The scientific approach requires the use of groundwater models, to quantitatively determine the spatial and temporal trends of hydraulic parameters and to derive a hydrological budget that could help the water resources management of the region. This would include the construction of daily or weekly abstraction that would: 1) save water, 2) reduce unmet demand and 3) allow new revenue for financing the expansion of water supply system for the expansion of irrigation.

The distribution of water demand is based on the location of irrigable lands and Population concentrations. There are more extensive irrigable lands in the southern section of the Lake Ardibo and lake Hayk. The two areas with existing irrigation systems or potential irrigation area: 1) 106 ha. Plains adjacent the Hayk Catchment and 2) 72 ha Plains in the Ardibo Catchment, approximately 30.1 ha are irrigated in the Ardibo Plains, out of a potential area of 72 ha according to unpublished Co-SAERAR, 2003 report. The concentration of agriculture in the area has created a growing demand for services and labor, leading to higher population densities and consequent additional demand for water resources.

It is important to formulate plans to satisfy the projected demand of 2.434674 MCM/yr (million cubic meters per year) for agriculture during the years 2000 – 2020 according to unpublished Co-SAERAR, 2003 report. Therefore an accurate hydrologic model is essential for water managers to make informed for the decisions with regard to future conditions based on projected pumping rates (abstraction of lake water with out damaging the groundwater and lake water system).

1.2 Purposes of the study

The purpose of this thesis is to understand groundwater and surface water interaction in the Hayk - Ardibo Catchment and calculate a hydrologic budget for the region utilizing groundwater modeling soft ware. This thesis provides: 1) a scientific discussion of geologic and hydrologic characteristics of the fracture aquifer, 2) application of a three-dimensional finite-difference groundwater flow model. The groundwater flow model utilizes data collected from the field and offices (Ministry of Water Resources, Ethiopian Metrological Agency and Zone, Department of Water Resources Development Bureau of the Amhara National Regional State). This thesis is intended for the scientifically informed public and, particularly for the Amhara National Regional State Water Resources Bureau who may exercise the results to devise water resources management decisions and for researchers to build further studies and ultimately for the community, which may encourage them to ensure food security.

This modeling study includes:

1) Conceptualization of the groundwater system of the Hayk-Ardibo catchment,

2) Calibrating the model to derive optimal parameters, and

3) To establish model based groundwater resource evaluation that can be used for sustainable groundwater resource management.

1.3 Methodology

Various methods had been used to study the area. The development of model deigns and simulations of the groundwater in the study area basically require the understanding of the geology, hydrogeology, and geomorphology and hydro climatologic characteristics of the area and which intern leads to the development of the conceptual model. This will basically require gathering and organizing of primary and secondary data (point, line and polygon,) using appropriate soft wares and making analysis to gain reasonable results. Therefore varied methods were used in the above processes, these encompasses:

a. Data Collection includes existing data, reports, maps and publications.
b. Organizing data using soft ware.
c. Analysis of organized data.
d. Presentation of results using appropriate soft ware.

The whole activities accomplished could be categorized

1. Preliminary office works.
    a. Review existing works and literature
    b. Preparing maps, sections etc.

2. Main office works.

    Data Input, model calibration & simulation.

2. Field Works
    a. Site observation
    b. Water samples gathering
    c. Hydraulic conductivity measurements

In this research different data, maps and reports were utilized

1. Data and reports: well log data in the adjacent catchment which has similar hydrogeological condition, hydro metrological data collected from the Ethiopian Metrological agencies, Hayk lake level data collected from the Ethiopian Ministry of Water Resources, specific studies on soil type groundwater potential, by the Swedish Red cross society, and Commission for sustainable agriculture in Amhara Region and water balance of the Catchment studied by Molla Demelie, 2000.
2. Maps: Topo sheets, 1:50,000 (Ethiopian Mapping Agencies), Satellite Image, NASA 2002, Geological Map of Ethiopia (Tesfaye Cherent, 1988) and Geological Map of the Catchment 9 Molla Demelie, 2000).

Equipments and software

1. Equipments used.
    a. GPS-Magellan, for locating springs, water sample collected and hydraulic parameters taken
    b. Digitizing table.

c. Water quality kit for field measurement of water qualities data
d. Permeability measurement for Hydraulic conductivity measurements

2. Software used for
   a. Data preparations for the model are Arc GIS 3.2, Carta links, Surfer 8.0, and Global Mapper.
   b. Data analysis and simulation is PMWIN, Processing Mod flow Pro (the latest version of groundwater soft ware).

Conceptualization of the groundwater-flow regime is based on previous studies and hydrologic data that contain: lithologic information obtained from field observations and well logs (Hayk town wells), hydraulic heads measured in springs, lake level measurements, and hydraulic properties determined from pumping test and field measurements. The Hayk-Ardibo Catchment area has been studied using numerical model of the latest software called *Processing Modflow Pro (Version 7.0.17)*. This numerical groundwater modelling software is developed by Web Tech 360 Inc. in 2002-2003 based on the original work of W. H.Chiang & W.Kinzelbach (1991-1998). Processing Modflow *Pro (PMWIN Pro*) is an enhanced Version of Processing Modflow.

1.4 Previous Works

Different scientific research works had been conducted by different pertinent scientists for different reason. Researchers in the area of Limnology, Geology and hydrogeology had conducted studies.

The geology of the Ethiopian western escarpment in general and the surrounding area of Hayk-Ardibo in particular had been discussed by prominent scientists: Abate et al., (1968), Grananin et al., (1973), Zanettin et al., (1974) and Chorowicz et al., (1999), they had discussed on the formation, magamtology, tectonics and stratigraphy of the western rift margin, according to their study the migration of the Olig-Miocene ignimbritic volcanism in the central Ethiopian plateau from north to south west following the rift escarpment and they identified three volcanic cycles in the Afar margin and surrounding areas (Oligocene, Miocene and Plio –Palistocene in age) associated with and initiated by North trending left lateral motion .

The hydrogeology of the Hayk –Ardibo Catchment, Dessie town & Borkena Catchment and Ethiopia had been studied by different researchers: Molla Demlie (2000), Ketema Taddes (1978, 1980) and Tesfaye Cherent (1988) respectively. The outcome of their findings presents the type of aquifer and it has been used to group the hydraulic conductivity, characterize the aquifer type, groundwater flow direction and recharge value. In summery:

1. The hydraulic conductivity of this aquifer is around 3.5 $X10^{-5}$ m/s, according to Ketema Taddesse computed for wells drilled at Dessie town (1980).
2. The dominant aquifer type in the study area and the regional groundwater flow direction has been indicated in the hydrogeolgical map of Ethiopia, Tesfaye Cherenet (1988)
3. The water balance of the area and detailed geological works had been done by Molla Demlie,(2000) his findings were:
   a. Recharge values were dealt in detail by using conventional water balance method to study the water balance of Hayk-Ardibo catchment.
   b. Geological map and Hydrogeological map

   The structural trend and other relevant geological and hydrogeological description helps in characterization of aquifer and groundwater flow direction that agrees with previous hydrogeological studies and his further recommendation and conclusion for the use of groundwater modeling to simulate water budget in order to effectively make comparisons with the conventional method he used.
3. Studies conducted by different organization such as Commission for sustainable Agriculture and Environmental Rehabilitation in Amhara Region (Co-SAERAR) and the Swedish Red Cross society during the Derge regime had conducted different studies, which became a basis studies to use the lake water for irrigation. The canal structure for lake Hayk was not functional and a limited irrigation work is done in the Ardibo Lake. It was reported that the lake level of Hayk has decreased around 7.8 meter with in the past 60 years Molla Demelie et al, 2000 and there fore a reasonable pump-age of water for irrigation will be required to use in a sustainable.

CHAPTER TWO

DESCRIPTION OF STUDY AREA

2.1 Location

The Hayk-Ardibo Catchment is located around 435 km, northeast of Addis Ababa, 35km northeast of Dessie town and it is bounded between $11^0 11'$-$11^0 23'$N latitude, and $39^0 45'$-$39^0 49'$ E longitude (fig.2.1); and at an average altitude of 2100 meter above mean sea level (a.m.s.l.). The study area is part of the northwestern watershed of the A wash River basin which is found in the northwestern margin of the Afar rift escapements of the Northwestern Ethiopian plateau. It is a closed surface drainage system with a total area of 140.1 km^2.

The access to lake Hayk is relatively good, the gravel road leads to the Monastery of Hayk Istifanos and the lake is not far from the town of Hayk which is located on the main road that leads to Woldia. Where as, the dry weather road that leads to lake Ardibo is very difficult especially in the rainy season

2.2. Physiography and Drainage

The study area covers closely a total area of 140.1 km^2, of which around 37 % of the surface area is occupied by Lake Hayk and lake Ardibo and the rest plains and hills that surround the two lakes. The Hayk-Ardibo catchment is contained in the western escarpment of the Afar rift escarpment. There is a 230-meter topographic difference between the two lakes. The highest elevation is found at the southeastern and western boarder of the study area, which is around 2800 meters above mean sea level (a.m.s.l.) where as the lowest elevation is the level of lake Hayk, which is 1900 m.a.s.l. Land elevation varies throughout the study area from 1900-2800 m above mean sea level (a.m.s.l). The vegetation cover in the highlands consists of bushes, with a scattered occurrence of more valuable eucalyptus.

From geomorphologic point of view, lake Hayk looks like a subside caldera bounded in the west, north and east by very steep crater walls, while in the southeast, south and southwest, the topography gets gentler and the rim becomes flatter. On the other hand lake Ardibo, which is aligned into the NW-SE direction following the general trend of the major structures in the area, looks like a fault-bounded graben. It looks like and follows the trend of the major grabens of Brokena. The Hayk-Ardibo Catchment is a closed surface water drainage system. The distance between the two lakes is around 18 km. The drainage pattern is radial, i.e. streams drain towards the nearby lakes locally. The two lakes are connected by Ankara River, which flows with a well-defined channel in the cCatchment starting from northeast of Lake Ardibo, and then enter lake Hayk at the southeaster shore. It is a perennial stream.

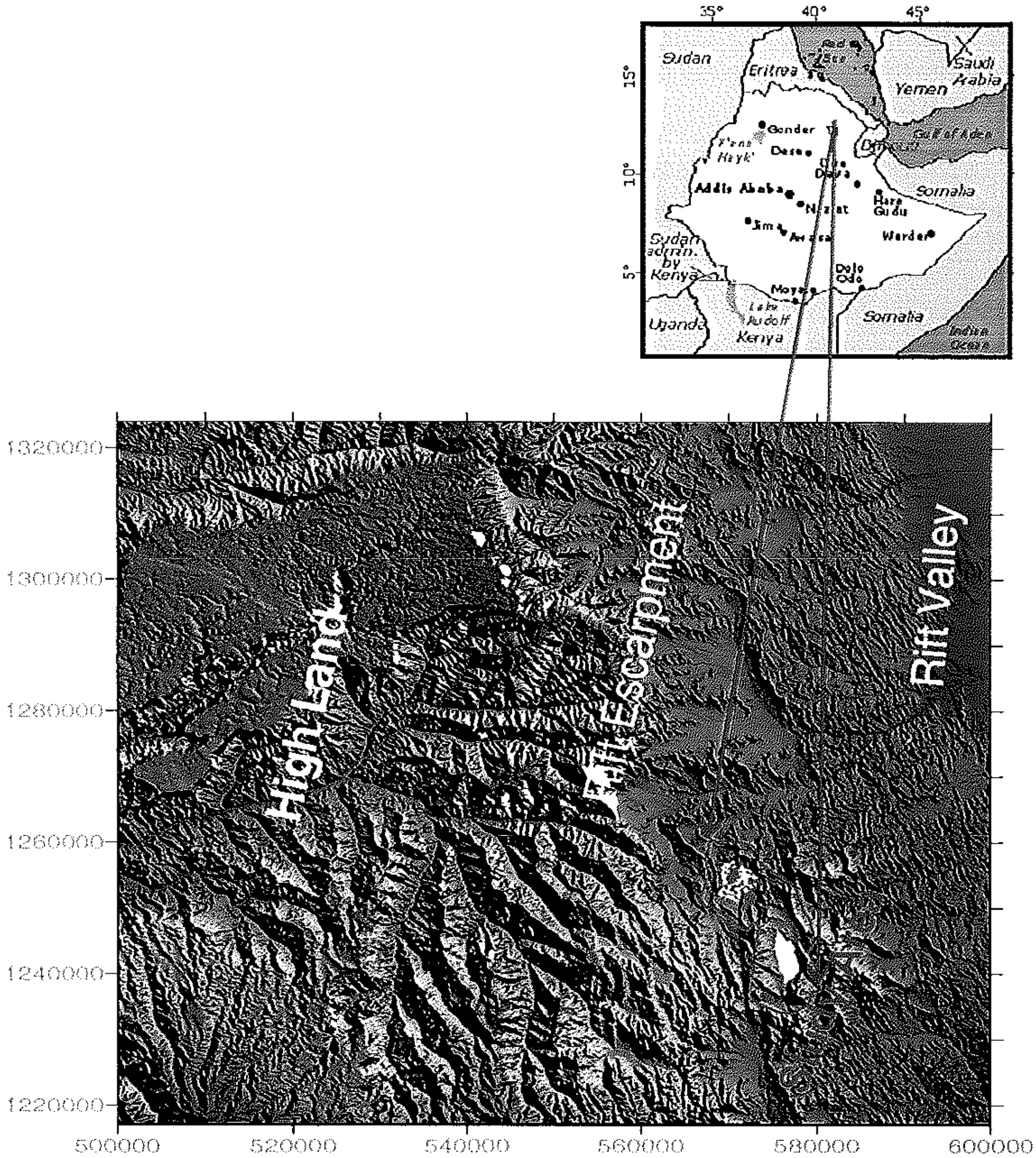


Figure 2.1a Location Map of the study area

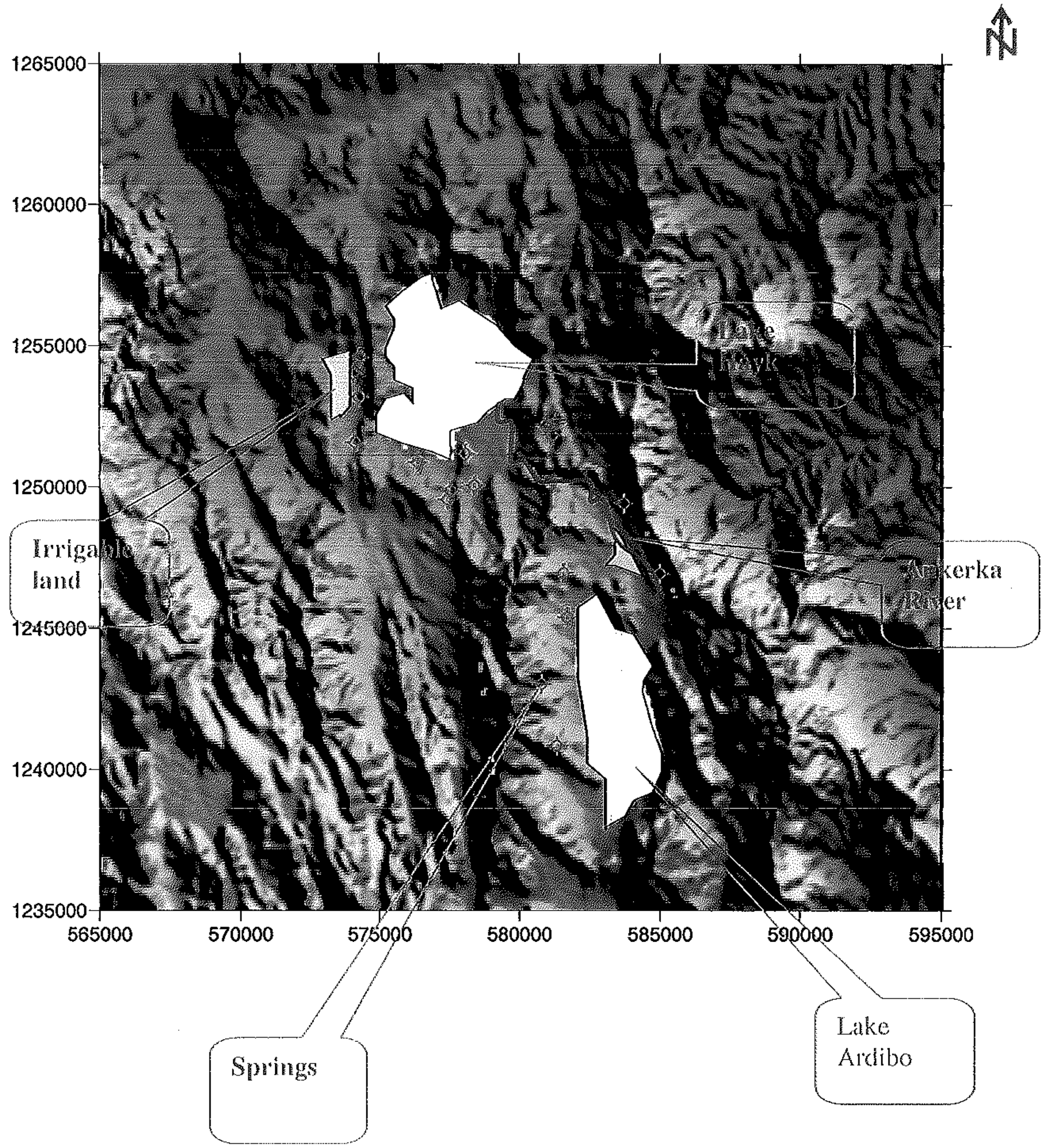


Figure 2.1b SRTM (Shuttle Radar Topography Mission) 30 of the study area

2.3 CLIMATE

Rainfall and Temperature

Temperature and rainfall patterns vary according to location, altitude and the time of year. Hayk-Ardibo catchment has a semi-arid subtropical climate traditionally classified as "Weina Dega". The rainfall in the area is bimodal. That is there are two maximal in the rainfall hydrograph of the area, which are traditionally named as "Belg" lasting from March to May, which is small in amount, and "Kermit" lasting from July to September which is big in amount.

The amount of rainfall at any point in Ethiopia is influenced by the location of the point relative to the source of moisture, the direction of winds and topographical relief. In summer a strong movement of air prevails form the southwest to the north east direction, i.e. from the high pressure system over the Gulf Guinea towards the low pressure of the center of Arabia, bringing the summer rain, during the summer months (June and July) the low pressure Inter-topical convergences Zone (ITCZ) is located north of the country and the area will be under the influence of the Atlantic Equatorial waterlines which ascend over the highlands from the south west and produce the big summer rain, the amount of this rainfall decreases from southwestern Ethiopia towards the study area due to topographic and altitudinal effects, since in the course of the long journey from the Atlantic to the East African highlands, the moisture of the winds decreases. The area gets moisture from the easterly and southeasterly moist air currents in spring (Belg) when the ITCZ is located south of the country. Therefore, the area gets moisture form two sources at two distinct time of the year. From the Atlantic equatorial westerlies during summer and from the southerly and easterly Indian Ocean air currents in spring. The long term mean annual rainfall for the study area is 1165.9 mm at station Hayk. The long-term average minimum and maximum temperatures is 10.7 and 25.40 ^{0}c respectively, which gives a long-term mean of 18.0 ^{0}c for the area. The average relative humidity is about 69%, minimum in the month of December and maximum in April.

Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Mean
15.5	16.7	18.1	18.9	19.6	20.7	20.3	19.7	18.8	16.8	15.6	14.9	18.0

Table2.1a Mean monthly air temperature in °c for the study area

Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
32.2	60.8	97	108.5	79.9	33.3	263.7	266.5	122.1	47.9	23.3	23.3

Table2.1 Mean monthly aerial rainfall in mm. for the study area

2.4 Soil and land use

A detailed soil survey was conducted earlier by Molla Demelie (2000). The map was prepared to estimate soil water holding capacity in the course of actual evaporation estimation using a soil-water holding capacity in the course of actual evaporation estimation using a soil-water balance approach.

The degree of weathering varies spatially, in the escarpment and in the are surrounding the two lakes, the soil material had been e roded and deposited to the central lower area. The thickness, type and distribution of soil vary with in the Catchment.

Land cover units are incorporated in the soil-water balance by way of rooting depth. The important land cover units are pasturelands, rain-fed agriculture, lakes (permanent open water bodies) bushes, shrubs, and grass lands. Most of the highlands, hills and plain areas are cultivated. L ittle irrigation is practiced in the area. The main crops are maize, teff, barley, wheat, beans, peas and lentils.

CHAPTER THREE

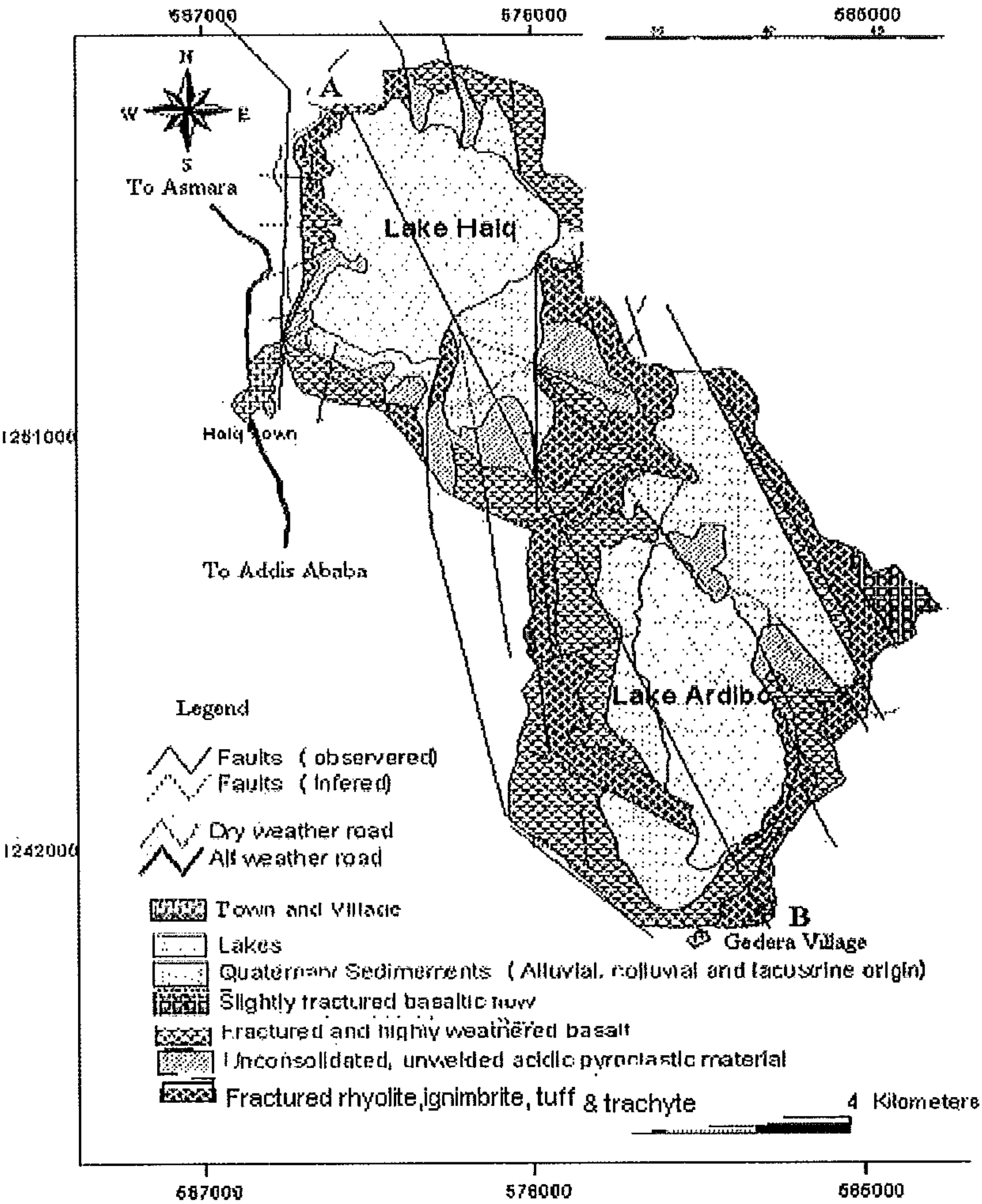
GEOLOGY OF HAYK-ARDIBO CATCHMENT

3.1 Geologic History

Hayk-Ardibo catchment has a complex geologic history during which morph tectonic processes of faulting and volcanism controlled lake formation. The geology of the studies area is mapped at a scale of 1:100,000 by Molla Demelie (2000). He tried to correlate the strartigraphy and age of the rocks to the regional strartigraphy and age the rocks outcropping in the central eastern Ethiopian plateau based on the works of Zantetin & Justin Visentin (197311974); Zanettin et al, (1974) And Zanettine et al, (1978). Based on the strategraphic successions described by Zanetine et.al. (1978), rocks outcropping in the Hayk-Ardibo catchment belong to the Alaji rhyolites and inter-bedded basalts of Oligocene age

Since the age of the Oligocene and Miocene volcanic become younger as one goes form North to South and Southeast, (Zanettin et.al., 1974, Zanettin et al, & Justin Visenttin, 1974, 1975, and Zanettin et al, 1978), the Alaji rhyolites and basalts in the area belongs more specially to the relatively older sub-unit of the northern sector, the "Alaji-Sirrio" formation which has and age range between 32-26 m.y.

According to Zanettin and Justin Visenttin (1975), the Alaji rhyolites and basalts are considered to be a product of the second cycle of volcanism and are related to a N-S fissure system which were opened since the Oligocene at Afar margin and feed the Alaji rhyoltes, zanettin et.al. (1974) described these formations to be a product of fissural Silicic volcanism linked to an approximately N-S tectonic extensive crustal movement. With in the studied area, seven phases of eruptions were recognized, each having its own typical features (fig 3.1.) these are, rhyolites a lower level, and at the top most a basaltic flow unit rate ashes on top of it. Since the rhyolities and ignimbrites exist in association and since they have similar composition (field study), they are mapped as a single unit. On the other hand, since the thin ignimbrite layer and the thin basaltic flow are small (not mapped at the working scale), these are grouped into their chemical proxy, i.e., the unwelded acidic unit and degraded basaltic unit respectively. Therefore, the volcanic outcropping in the area is mapped in to five units namely, the rhyolites and ignimbrite unit, the unwelded acidic unit, the degraded basaltic unit, and the topmost basaltic flow unit. A recent formation composed of alluvial, lacustrine and colluvial sediment is mapped covering an appreciable area of the cantonments overlying one or more of these volcanic units.



Modified Geological Map of Hayk-Ardibo Catchment (After Molla Demelie,2000)

Fig. 3.1 Simplified Geological Map of Hayk-Ardibo Catchment (After Molla Demelie, 2000)

3.2 STRATIGRAPHY

The oldest rocks in Hayk-Ardibo catchment outcrop in the south and southeast of lake Hayk and consist rhyolite and Ignimbrite. The rock types of the study area include rhyolites, ignimbrites, basalts, pyroclastic acidic materials and rare trachytes and tuffs. Quaternary sediment overly basement of volcanic rocks and they are confined to interior valleys, river floodplains, and the lakes bottom and margins. The units are described as follow according to their age:

The rhyolite and Ignimbrite unit (Tsv)

This is the oldest unit outcrop at different parts of the catchment in different stratigraphy positions. It outcrops south and southeast of lake Hayk and at this position it is the lowest and probably the oldest unit in the Catchment. When present above the degraded basaltic unit, the rhyolite becomes rare and the ignimbrite dominates and the unit gets thick (maximum thickness of more than 200m is observed northeast of lake Ardibo). The ignimbrite unit is smaller at the bottom of the succession when associated the rhyolite and in the middle it occurs distinctly individually as a thin bed extending horizontally with almost same thickness, there are rare trachytes in association with this rhyolitic and ignimbritic unit, probably with similar c omposition. The i gnimbrite unit i s m uch more d ominate w hen compared w ith t he other rock types, high degree of fracturing circulation of water within this unit. As compared to other rock outcrops in the study area, this unit is less affected by weathering.

Unwelded Acid (pyroclastic) unit (TUPS)

The unwelded acidic unit is composed by various ash and fragmental acidic vulcanite, which are loose and are highly weathered and dislocated by faults. This unit is likely a product of explosively erupted acidic magma. No welding and flow structures were observed. In most instances, it overlies the acidic rhyolitic ignimbritic rocks and undertaken by the basic degraded rock unit. Rare basic pebbles and gravel-sized materials were observed. Due to its lose and incoherent nature, high infiltration capacity is expected but due to its position is hydrogeolgically unfavorable (chapter 5), it probably serves as a recharge media than as an aquifer.

Degraded basaltic unit (Tbv)

This unit is composed of thick degraded deeply weathered; typical spheroidally weathered is characteristic of basaltic boulders. Like other units in the mapped area, this unit is also highly affected by tectonic disturbances, which will enhance the hydraulic properties of the unit. There is no observable flow structure in this unit. The columnar joints end at the contact line of the underlying unit. This basaltic unit grades upwards to slightly lighter intermediate rock, which also shows extensive fracturing and weathering.

Upper baseline unit (TBF)

This is probably the youngest unit in the Hayk-Ardibo Catchment. It is a fine-grained dark colored basaltic unit characterized by columnar jointing. Like other units, this unit is affected by high degree of fracturing. In some outcrops, this unit is associated with rare tuffaceous and volcanic ash units. The thickness and areal coverage of this unit is very small.

Recent (Quaternary unconsolidated sediments (QAC)

It is the most recent unit mapped in the study area. It includes recent sediments that occupy depressions, the foot of hills and major escarpments, the flood plain of the Ankerka river and the shore of the lakes, the composition ranges form colluvial, talus cones to alluvial and lacustrine deposits, and from fine clay fractions to gravel and sands. This Quaternary sediment covers one or more of the above volcanic unit and cover a large proportion of the studied area.

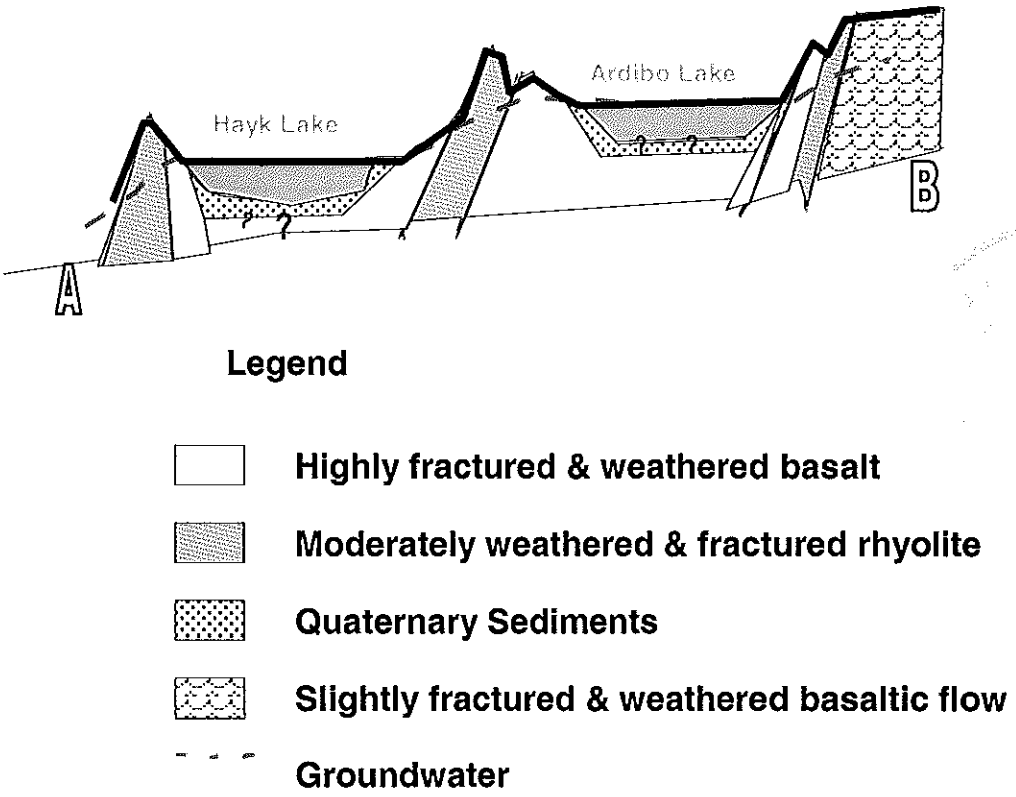


Fig 3.2 Geological Cross-Section across Lake Hayk -Ardibo(A-B)

3.4 STRUCTURE

Faults

The central western margin of the Afar rift is a tectonically affected area, where one can observe without difficulty major structures that run NNW or nearly N-S. In this area, the N-S elongated ridges, which are related probably to the regional extensional rift tectonics

Since the mid-Miocene, Hayk-Ardibo area has been affected by trans current deformation related to sinistral shear on the North Rift boundary, and the formation of a restraining bends through the eastern side of the study area. This has impacted the geometry of fault trends on the study area. Three main sets of faults define the morph-tectonic features of Hayk-Ardibo area: 1) having a trend of N300W 2) having a trend nearly E-W found to cut the NNW tending ones and are probably younger from the cross cutting relationship. The E-W trending ones are probably associated with the rift of the Gulf of Aden. According to the interpretation by Zanettin et.al. (1978), these transverse faults are mainly situated between 1100 N and 12000N, parallel to the "pre-Oligocene rift of Ashanghi" and are a rejuvenation of an old major tectonic lineament extending from the Gulf of Aden. 3) having a trend of NNE, the dominant ones, which have affected all the rock units and cross in some cases the entire study area. The major NNW sets are trending parallel to the trend of the Red Sea rift (Kroberg et. al, 1975), where as those trending NNE are due to the influence of the Ethiopian rift system or interaction of the Afar and main Ethiopian rifts The structure of Hayk-Ardibo area is characterized by numerous faults that have undergone displacement since deposition of the Mid-Tertiary Volcanic. There are two major strikes; the dominant set is about 155□, while the subordinate set is oriented about 95□. Few faults strike in a NE-SW direction. Faults and joints control the orientations drainage patterns in the Hayk-Ardibo area. Faults dissecting the Hayk-Ardibo Catchment are also oriented NNW-SSE and E-W.

There are also two dominant joints sets mapped in the study area trending on average N250W, and E-W. The spacing and aperture of these joints vary from outcrop to outcrop and are important from the perspective of water circulation with in these jointed rocks.

The presence of these faults and extensive joints contribute for occurrence and flow of groundwater with in the Catchment.

CHAPTER FOUR

HYDROGEOLOGY AND WATER BALANCE

4.1 Hydrogeology

A revised Hydrogeolgical map at the scale of 1; 100,000 was made for the study area. The mapping was prepared based on previous investigation made by different researchers, latest satellite image interpretation and field geological and hydrologic data interpretation. The field investigation includes observing the degree of weathering and fracturing of the different rock outcrops, measuring of hydro geologic properties such as infiltration capacity of the surface materials and detailed topographic and morphologic observations. The hydro geologic parameters are tried to correlate from the neighboring catchment, pump test result obtained from Hayk town well, which is found in the Northwest boarder of the study area, Hayk town. The absence of boreholes in the study area was a limitation to obtain data on the aquifer parameters such as hydraulic conductivity, transimsivity and storativity of the different rock out corps and sediments with in the study area.

The hydro geologic framework for the study area is likely consists of one aquifer system, which has a spatial variability in hydraulic conductivity. It is defined on the basis of the lithologic and hydro geologic properties of the volcanic rock and Quaternary sediments. A map of the hydrostratigraphic units of the study area is provided in Figure 4.1. The degree of weathering and fracturing varies spatially. The secondary permeability and porosity increases towards the lakes and it also follows a similar trend towards to the North. Volcanic rocks outcrops mainly in the highlands forming the principal aquifer of the Hayk-Ardibo catchment, and overly the basement rocks The Quaternary sediment covers mostly the bottom of the lakes and its shores , in a limited amount along Ankerka river.

According to the field investigation the hydro geologic characteristics vary laterally and there was no major vertical variation observed in the study area. There are generally two major hydrostratigraphic units, the first one is fractured volcanic rocks, which covers most part of the region and the others Quaternary sediments.

4.2 Rock Description

4.2.1 Fracture Volcanic Rocks

The Volcanic rocks are the principal dominant rock in the Hayk-Ardibo catchment and covers most part of the study area. It comprises both acidic and basic rocks, which includes rhyolites, ignimbrites, pyroclastic acidic materials, rare trachytes , tuffs and basalts. There is a major significant change in hydrogeological characteristics such as degree of fracturing, weathering, infiltration capacity of overlying superficial materials and the permeability of these rocks. The permeability of ignimbrites and rhyolites are relatively less than the fractured and degraded basaltic and acidic unwedded pyroclastic units. The area is highly affected by different set of faults and this was the major significant factor for the generating of secondary porosity and permeability, which in turn contributed for the occurrence and movement of groundwater in the area. Many springs emanated at the contact of the different lithostratigraphyic units in most case it was observed that the underlying rocks are rhyolite/or ignimbrite and the overlying rocks are basaltic rocks. It was observed form field that in most part of the different geologic units of the volcanic rocks primary hydrologic features are modified by secondary process of faulting and weathering.

4.2.2 Quaternary sediments

Quaternary sediments are located on the bottom of the two lakes and also around the lakeshore. The sediments in the study area are composed of gravel, sands, salt and clay. They originated from alluvial, collegial, and lacustrine processes. From field observation and investigation of this hydrostratigraphic unit, alluvial colluvial materials cover wider areas as compared to the lacustirne deposits, which are confined to the shores of the lakes. The Quaternary sediments occupy a considerable site for the recharge, infiltration, and storage of significant amount of groundwater. This is because they have high primary granular permeability and porosity of the sediments except in some points where the fine dominate. From field observation and comparison from similar geologic area this unit shows higher hydraulic conductivity in the Catchment. The aerial distribution and thickness of the sediment is so small in comparison with the volcanic rocks as a result it is very difficult to treat it as separate aquifer system in the model.

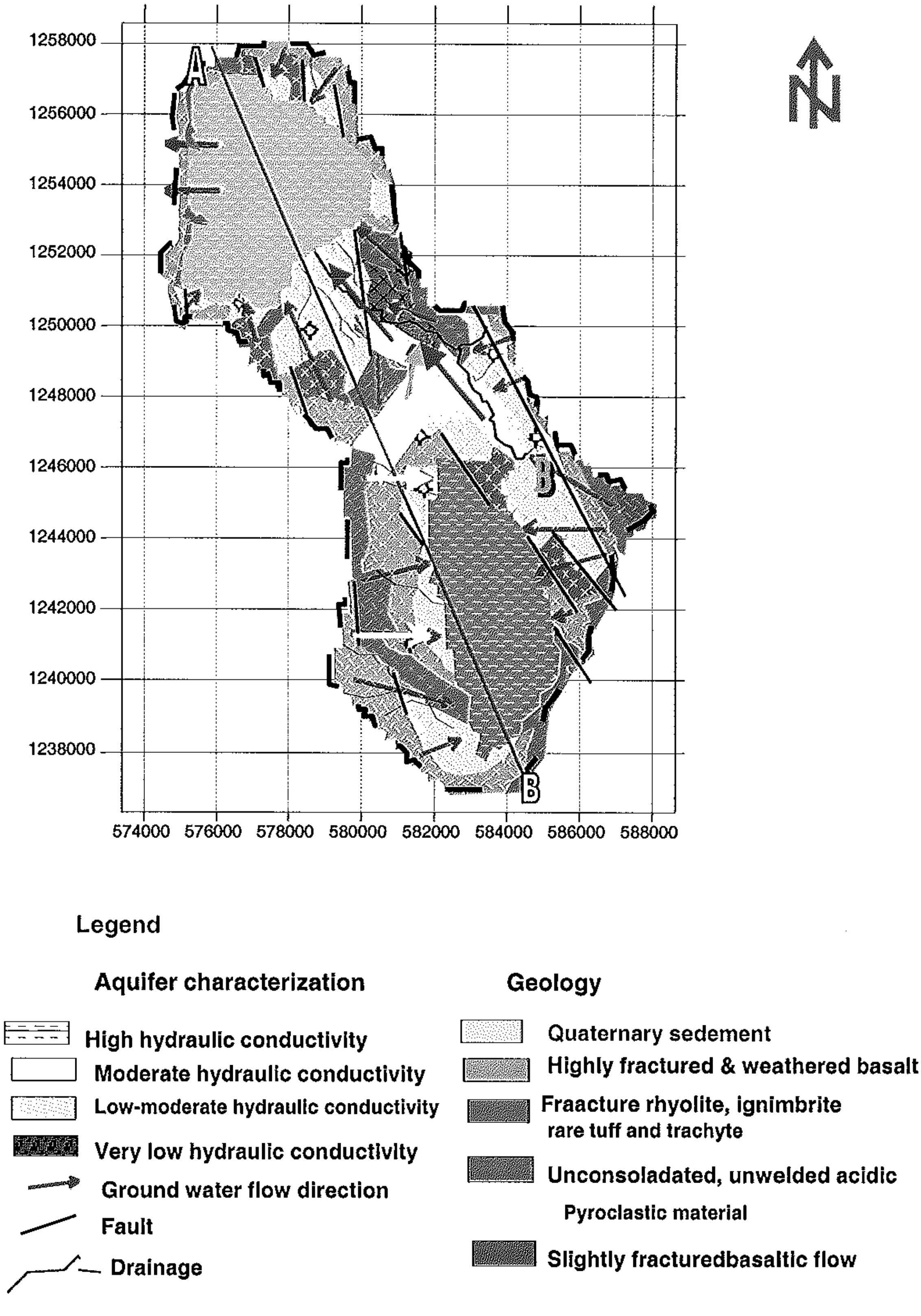


Fig 4.1 Hydrogeological Map of Hayk-Ardibo area

4.3 Aquifer Characterization

The volcanic rocks occupies larger portion of the study area. Geomorphology and the presence of springs were used to derive the thickness of hydro geologic unit used to define the top layer and bottom layer of the unconfined aquifer. The presence of Quaternary sediments with in the catchment increased the heterogeneity of aquifer hydraulic conductivity. (Refer fig 2.2 Geological section).

From the available data and the geological section, geologic logs of the near by Hayk town wells, nature of springs with in and around the Catchment and study of geomorphology, generally the aquifer can be considered as unconfined, although there are local variation.

4.3.1 Groundwater Recharge and Discharge Condition

The definition of recharge of groundwater is that: the entry in to the saturated zone of water made available at the water table surface, together with the associated flow away form the water table with in the saturated zone. On the other hand, groundwater discharge is the removal of water from the saturated zone across the water table surface, together with the associated flow toward the water table with in the saturated zone (Freezes & cherry, 1997). In recharge areas, there is often a rather deep unsaturated zone between the water table and the land surface; conversely, the water level is found either close to or at the land surface in discharge areas.

In order to describe and determine whether an area is recharge and discharge areas on the basis of field observation one has to give attention to the basic indicators such as topography, piezometiric pattern, Hydrochemical trends, environmental isotopes, and soil and land surface features such as seeps and springs. From topographic point of view, discharge areas are topographically low, where as, recharge areas are topographically high. Even though geochemical interpretation requires a large number of chemical analysis carried out on water samples, systematic samples representing the area along surface and groundwater flow paths tells recharge and discharge area, since it is a well understood fact that moving groundwater through a flow system undergoes a geochemical evolution. Generally, salinity either in terms of electrical conductivity (EC) or total dissolved solids (TDS) increases along the flow path. Therefore, recharge areas are usually with fresh water, while water in discharge areas is often relatively saline.

In order to clearly explain recharge and discharge condition and water balance of the study area, it is apparent to see the study area in sub catchment, namely Ardibo sub catchment and Hayk-sub catchment.

a). Ardibo sub catchment: The only source for Ardibo catchment to get recharge is from direct perception. The volcanic ridges, fault escarps that surround lake Ardibo and the surrounding low-lying are recharge areas. While the lake surrounding foot hill areas are discharge areas. The groundwater discharge is revealed in springs and seepage zones.

The Ardibo sub catchment is surfacially a closed drainage system, there is no a perennial stream with a well-defined channel that enters the Ardibo lake. It is evident from geologic and morphologic conditions that groundwater inflow in to this sub catchment may not be possible.

b). Hayk sub catchment: Hayk sub catchment gets its recharge from precipitation, Ankerka river, and seepage from irrigation canals and groundwater inflow from Lake Ardibo sub catchment. The ridges that surround south of lake Hayk and surrounding low-lying flat areas recharge the Hayk sub catchment. The discharge areas in the Hayk sub catchment are lake Hayk and the surrounding springs, which are located southwest of lake Hayk in the adjacent catchment.

4.4 GROUNDWATER IN THE CATCHMENT

4.4.1 Water Level

Water table gradients are relatively steep near upland areas of the Hayk-Ardibo catchment and it becomes gentle towards the two lakes. Hydraulic heads within the Quaternary sediment around the two lakes are typically lower than those of the upland areas. The source of groundwater in the volcanic aquifer appears to be from precipitation. Contoured maps of water levels recorded in the volcanic aquifers are shown in Figures 4.2

Water level data were obtained from lake Hayk located in volcanic aquifers. No well data were found in the study area. A lot of springs, which have a discharge of 0.2-2.5 l/Sec, are found in the study area and they are the sources of drinking water supply for the community. Wells drilled around the study area at Hayk town are used to correlate hydrogeologic parameters. Consequently, depth to water was extrapolated on the basis of known depths of the water level measured at lake Hayk and Ardibo and also by using known locations of spring

4.4.2 Groundwater Flow

Joints, fractures, and solution openings provide avenues through which groundwater flow is channeled (Kiersch and Hughes, 1952). Minor fault and major fracture traces are favorable sites for groundwater flow in the Hayk-Ardibo catchment.

It might be possible to deduce from field observation of geological, hydrogeological and geomorphologic evidences that the two lakes are hydraulically connected. The two lakes are surfacially connected by Ankerka River and moreover large faults trending NNE, NNW and E-W create favorable condition for groundwater movement from Ardibo Catchment towards lake Hayk. There is a 230 meter topographic difference between the two lakes, this is also an evidence that groundwater moves toward lake Hayk. Most of the springs emerge at the down side i.e. North of lake Ardibo and joins Ankerka river. From the hydrogeological map it is indicated that in the local groundwater regime flow is towards topographically low that is towards the lakes. In the intermediate flow condition, groundwater flow is from Ardibo sub catchment to the Hayk sub catchment that is recharging lake Hayk.

4.4.3 Springs

The quantity of discharge from springs is small and difficult to measure. It is speculated that these springs are formed by deep circulation of groundwater that flows along fractures; weathered section and joints. Many low discharging springs are situated immediately to the Northern part of the Catchment and one high yielding spring (50 l/sec, namely Workie spring) is found at elevation of 1750 m.a.s.l.

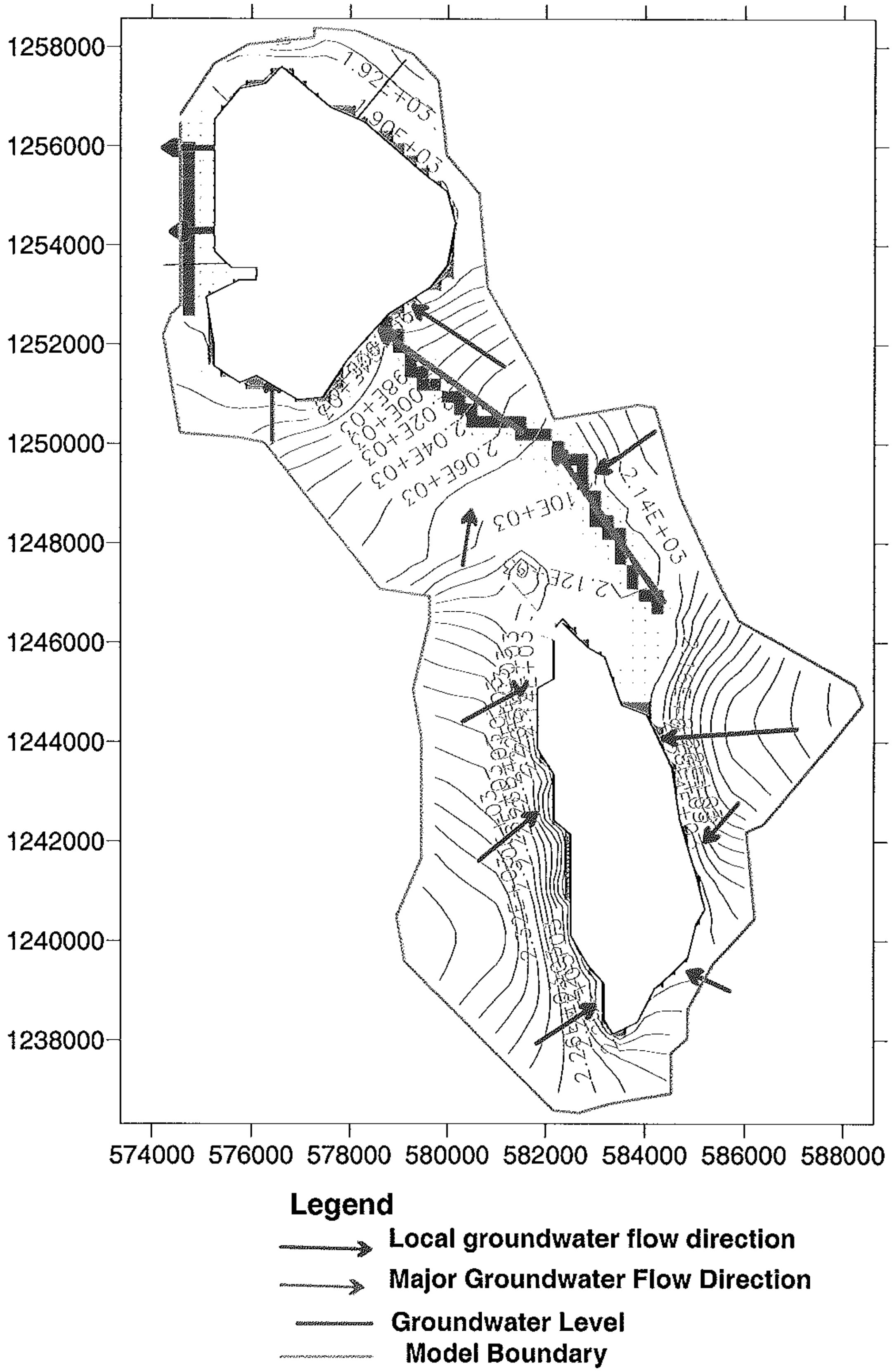


Fig. 4.2 Groundwater Table showing Flow direction

4.5 WATER BALANCE

4.5.1 Lake water balance

The water balance of Hayk-Ardibo catchment was studied previously by Molla Demelie. The water balance is one of the most important factors in understanding and development of the conceptual model in groundwater modeling. Moreover water balance study in lakes, other reservoirs and groundwater catchments is a basis for the rational use, management and control of water resource for agricultural activities and water supply; therefore it is vital to make quantitative water resource evaluation before implementing water resource evaluation.

The analysis of the water balance of the Hayk-Ardibo catchment was done by dividing the catchment in to two sub catchment namely Ardibo sub catchment and Hayk sub catchment, which are closed and independent sub catchment from surface water point of view. For each sub catchment, water balance is done independent of the other, and also the water balance of the entire catchment is treated. Abstraction of water for domestic purposes is neglected in all of the water balance analysis.

4.5.2 Water balance equation

The water balance of a given hydrologic system, such as water body (lake) or drainage catchment follows the principle of conservation of mass often referred to as the continuity equation, which states that total inputs minus outputs will be balanced by the change in storage of water in the system. Therefore, use of a water balance technique implies measurement of both storage and rates of influx and out flux for a given period of time for a given area.

The water balance for any water body of hydrologic system for any given time interval is generally represented by:

Input –Out put = Change in Storage

$$Pi + Si + Gi - E - So - Go - A = \Delta S \quad \ldots\ldots \quad 4.1$$

Where P is precipitation

Si = Surface water inflow

Gi = Groundwater inflow

E = Evapotranspiration

So= Surface water outflow

Go = Groundwater outflow

A= Abstraction

ΔS = Change in storage

Whenever the groundwater divide coincide with the surface water divide, equation 4.1 takes the form

$$P - E - A = \Delta S \quad \text{...} 4.2$$

4.5.3 Hayk-Ardibo Catchment Water balance estimation

Hayk-Ardibo catchment is a closed catchment; there is no surface water outflow from the catchment. Direct precipitation is the only measured input in the study area. From the lake level data observed for the last 20 years, it is observed that the lake level is not increased rather it shows a decreasing trend although a significant increment is observed in the last 5 years. Moreover the geological, hydrogeological and morphological condition prevails the groundwater out flow in the Northwestern part of the catchment boarder. Therefore, the water balance equation valid for the catchment of Hayk-Ardibo is:

$$P - Eo - AET - Gso = \Delta S' \quad \text{......................................} 4.3$$

P- Perception over the Catchment

Eo= Open water evaporation in the lakes

Gso = Ground outflow through springs associated with E-W ternding faults

AET =Actual evapotranspiration over the watershed.

ΔS '= Difference of groundwater inflow plus change in storage of surface water bodies

Drainage area (km^2)		**1.1 Water balance components in mcm**				
Lakes	Watershed	P	Eo	AET	Go	ΔS '
38.6	101.5	162.3	56.6	81.7	0.134	23.87

Table 4.1 Summarizes mean annual the water balance of the Hayk-Ardibo Catchment. (Molla Demelie et al., 2000)

So the residual is the groundwater outflow from the catchment i.e. the residual term is 23.87 mcm of water. The water balance for the catchment is dominated by the input term than the output term, the catchment have excess storage and this has to be reflected either in the increment of lake level (no recent lake level data found) or leave the catchment as groundwater out flow since there is no surface water out flow. The groundwater leaves the catchment through the Hayk sub catchment

4.5.3 Ardibo Sub catchment Water balance

In the Ardibo sub catchment, there are geologic, morphologic, and hydrogeology evidences that the catchment is not closed from subsurface. Therefore, there is a groundwater outflow component in the water balance. But, we can safely assume that there is no groundwater in flow from other catchments to this Catchment.

In the Ardibo sub catchment, the only input is precipitation over the Catchment. From detailed studies of the geology and hydrogeology, groundwater inflow is negligible. Outflow from this Catchment includes: evapo-transpiration from the Catchment, evaporation from lake Ardibo, groundwater out flow through springs and abstraction of water for the irrigation through a subsurface canal.

The water balance equation is given by:

$$P - E - A - Gs = \Delta s' \qquad 4.4$$

and where $\Delta s' = Go + \Delta v$, is the residual term

Gs = groundwater outflow through springs (estimated),

Go = groundwater outflow other than the observed springs,

Δv = surface water storage changes there is any, and

A =abstraction

Drainage area (km)	Water balance components of the Ardibo sub catchment					
	Volume in million cubic meters (mcm)					
	Precipitation (p)	Evaporation form lake (Eo)	Evapo-transpiration from land area	Abstraction (A)	Groundwater outflow through Springs (Gs)	Residual (s')
52.3	60.6	23.15	28.3	3.15	0.095	5.905

Table 4.2 Annual water balances for Ardibo sub catchment (Molla Demelie et al., 2000)

The abstraction amount for irrigation is measured using a current meter and a float at the canal outlet. The measured annual volume is 3.15 mcm. Groundwater out flow through springs is estimated to be (field result) 3lit/s, which is about 0.095 mcm annually (Molla Demelie et al., 2000). The residual Δs' value found therefore, is either the groundwater outflow or the change in surface water storage or both. But, from filed observation of lake Ardibo, (no recent lake level data found), the lake does not show significant rise in level, therefore, the residual term in table 4.2 that is 5.905 mcm could be considered as a component of groundwater outflow.

Water balance for Lake Ardibo

The water balance equations for a closed catchment lake where the surface water divide coincide with the groundwater of the watershed and with only ungauged surface runoff (un channalized flow) is:

$$Pi + Sr + Gi - Eo - Go - A = \Delta v' \qquad 4.5$$

Where **PI** = precipitation on the lake surface

Sr = Surface run off from the watershed

Gi = Groundwater inflow

Eo= Evaporation from the lake surface

Go= Groundwater outflow from the lake

A= Abstraction

Δv= change in volume for the water balance period.

Equation 4.5 is valid for lake Ardibo, since there's no chanalized flow that drain in to the lake and from hydro geologic observations, groundwater inflow and outflow could be possible.

Since Gi and Go are difficult to quantify, the two terms are lumped with the $\Delta\mathbf{v}$ term ad therefore, equation 4.5 becomes:

$Pi + Sr - Eo - A = \Delta v'$ 4.6

Where $\Delta v'$ is the residual for the groundwater flux and change in storage volume

Lake Ardibo		Water balance components in mcm				
Area of the lake (km^2)	Area of the Catchment without lake (km^2)	Surface inflow (Sr)	Precipitation of the lake (Pi)	Evaporation of the lake (Eo)	Abstraction From the lake for irrigation (A)	Residual ($\Delta v'$)
15.8	36.5	12.68	18.3	23.15	3.15	4.68

Table 4.3 Annual water balance of Lake Ardibo (Molla Demelie et al., 2000)

The residual term in the water balance of the lake Ardibo is 4.68 mcm. Form observation of the lake, lake level rise has not been observed on Ardibo. Therefore, the residual in equation 4.6 represent the annual net groundwater flux of this lake.

4.5.5 Hayk Sub catchment Water Balance

Following equation 4.1 the water balance for the Hayk sub catchment is:

$P + Gi + Is - E - Gs = \Delta s$ 4.7

Where, Gi = the groundwater inflow to the Catchment from the Ardibo sub catchment; Gs = groundwater outflow through springs,

$\Delta s'$ = the residual including the net groundwater out flux and charge in surface water storage; Is is water obtained from irrigation from the Ardibo sub catchment and added to Hayk sub catchment (measured using a current meter) is about 60l/s.

Drainage Area (km^2)	Precipitation Over the Catchment (p)	Evaporation From the lake surface (Eo)	Evapotranspiration form the watershed (Et)	Water added from Irrigation in to Hayk (Is)	Groundwater outflow through springs (Gs)	Groundwater Inflow into the Catchment (Gs)	Residual As'
87.8	101.7 mcm	33.4	53.4	3.15	0.134	5.905mcm	23.82

Table 4.4 Mean annual water balance of Hayk sub catchment (Molla Demelie et al., 2000)

The water balance of Hayk sub catchment (table 4.4) shows that there is a residual value of 23.8 mcm of water which accounts for the groundwater outflow and the change in storage therefore, since the change in surface water storage is small, the result shows that large amount of annual groundwater outflow from this Catchment. If additional abstraction is made on this Catchment the surface water storage will be affected.

Water Balance of Lake Hayk

A valid water balance equation for lake Hayk is written as:

$Pi + Sr + Gi - Eo - Go = \Delta V$ since the groundwater flux components are difficult to measure directly, it will be lumped with the ΔV term in the equation above. Therefore, the equation is one in the form of:

$Pi + Sr + Is - Eo = \Delta v'$ 4.8

Therefore

Lake Hayk				Water balance components in mcm		
Area of the Catchment (km2)	Area of the lake (km2)	Pi	Sr	Eo	Is	Δ v'
65	22.8	26.4	18.83	33.4	1.6	13.43

Table 4.5 Annual water balance of Lake Hayk (Molla Demelie et al., 2000)

The inflows into lake Hayk are direct precipitin on the lake surface, surface runoff from the watershed, groundwater inflow, and imported water from the Ardibo sub catchment. The out flows are evaporation and groundwater outflow. The residual, the difference in groundwater in flow and out flow plus change in the storage in the lake is 13.43 mcm. Since the change in volume of lake is in significant, the residual is the net groundwater flux.

4.5.6 Lake level fluctuation and chemistry

4.5.6.1 Lake level fluctuation

It has been observed that from the lake level data obtained from the Ministry of water Resources and actual field observation, lake level fluctuation had been ocurred in both lakes. Lake Hayk has experienced a minimum lake level fluctuation of about 7.8 meters for the last 60 years, which is evident on the bathymetric map of Morandini (1941) and Molla Demelie (2000). As it is clearly shown in fig. 4. the main rainfall begins at June and the highest rainfall is observed in mid July and apparently the lake level starts to rise in September and reaches maximum lake level in October and November, this shows that the impact of groundwater in feeding the lake Hayk is more important than the run off feeding the lake. In addition as it can be observed from the water balance the net out put or the reserve is much higher than the one lost through evaporation and this gives a clue that excess water will leave the catchment through groundwater out flow since the lake level is not increasing with equal proportion. The recent lake level rise in the last five years is likely due to excess water from Ardibo irrigation.

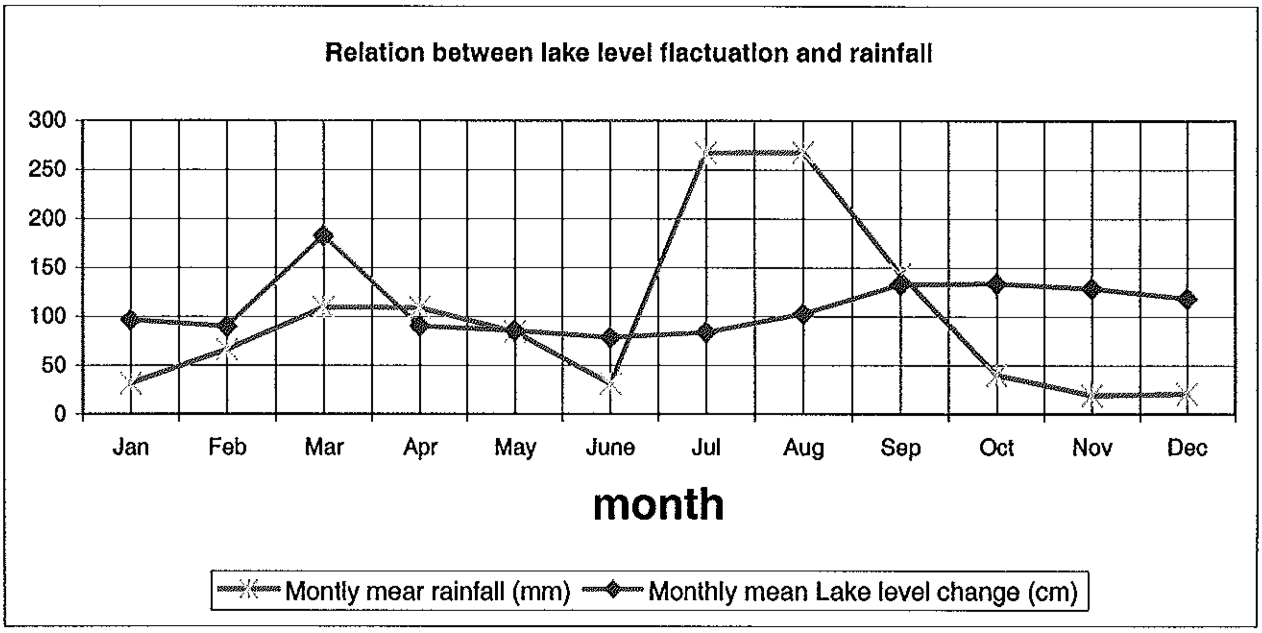


Fig. 4.1 Lake level Fluctuation and Rainfall (monthly)

In general actual field observation of the area shows that

1. Appreciable amount of groundwater is lost: by evapotranspiration, through irrigation and springs.
2. A small increase of lake level, especially lake Hayk for the past five years due to excess water from Ardibo irrigation.
3. Groundwater leaves the catchment as subsurface out flow due to the high tectonic activity in the area.

These all contribute loss to the residual term of the 23.87 mcm of water. Since the water balance for the catchment is dominated by the groundwater out flow term than the groundwater inflow term, the catchment will be sensitive to a small addition and abstraction of water, the main groundwater outflow form the catchment is through the Hayk sub catchment which is almost the same as the amount of groundwater outflow to that of the entire catchment.

Summary water balance

Name	Change in storage (m^3/d)	Change in storage (l/s)	Remark
Lake Hayk	36794.5	425.86	
Hayk Catchment	65260.27	755.32	
Lake Ardibo	12821.9	148.4	
Ardibo Catchment	16178	187.24	
Hayk-Ardibo Catchment	65397.26	756.9	

Fig. 4.6 Summery of water balance

4.5.6.2 Chemistry of the lakes

The relation between the pattern of flow and hydrochemistry is valuable both in the study of the genesis of hydrological and hydrogeological phenomena and in recognizing the distribution and movement of subsurface waters. The concentrations, relative proportions and rates of transport of dissolved material in subsurface water sample reflecting their sources, paths and interactions with different subsurface rock. Hydrochemical data were collected from different springs, lake Hayk, Lake Ardibo and Ankerka River. The field measurement taken at different points on the two lakes is closely related to the chemistry of the surrounding springs, which shows the interaction between groundwater and lake water as the ground water moving from lake Ardibo towards lake Hayk. Even though geochemical interpretation requires a large number of chemical analysis carried out on water samples, systematic samples representing the area along surface and groundwater flow paths tells recharge and discharge area, since it is a well understood fact that moving groundwater through a flow system undergoes a geochemical evolution. Generally, salinity either in terms of electrical conductivity (EC) or total dissolved solids (TDS) increases along the flow path. Therefore, recharge areas are usually with fresh water, while water in discharge areas is often relatively saline.

The water moving from Lake Ardibo to Lake Hayk also recharges most of the springs located North of Lake Ardibo. Table 4.7 shows the water quality variable measured in the field, and it is indicated that the TDS and salinity at lake Hayk is relatively higher than that of lake Ardibo and this shows evaporation to infiltration ratio at lake Hyk is higher than at Ardibo lake. In general the chemistry indicates that the two lakes are not closed but they are flushed lakes and the lake water is in a continuous interaction with the groundwater and the resident time is short. In addition the low EC and TDS values of the two lakes indicate that the groundwater in these area is mainly consists of meteoric water, which originates from direct recharge of precipitation circulating at a shallow depth.

No	Sample	Conductivity	Salinity	TDS (mg/l)	Ph	Remark
A. Springs						
1	OBS1	599	0.3	289	6.9	
2	OBS2	435	0.2	206	6.54	
3	OBS3	579	0.3	275	6.74	
4	OBS5	454	0.2	212	6.1	
5	OBS7	616	0.3	293	7.31	
6	OBS9	681	0.3	326	1.9	
7	OBS10	733	0.4	354	1.8	
8	OBS11	558	0.2	263	1.55	
9	OBS12	714	0.3	348	1.56	
B. Lakes						
1.	Hayk	935	0.4	431.88	8.6	
2.	Ardibo	569	0.3	272	8	
C. River						
1	Ankerka	356	0.2	169	7.5	

Table 4.7 Summery of water quality variables measure in the field

CHAPTER FIVE

SIMULATION OF GROUNDWATER FLOW

5.1 Modeling Objectives

Detailed water balance study was conducted by convectional method by a researcher from Addis Ababa University and he had recommended using numerical method. In addition irrigation development activities were conducted especially in the Lake Ardibo area. There fore the use of groundwater modeling is very important in understanding the hydrgeologic conditions and evaluation of the groundwater by applying numerical groundwater flow model. The aim of this thesis is to simulate groundwater flow in the Hayk-Ardibo Catchment. In order to achieve this aim, the following objectives have been identified: 1) Develop a conceptual model based on the available geological, hydrogeological and water balance of the study area. 2) Use the conceptual model to develop a two-dimensional aerial finite difference groundwater flow model of the area. The conceptual model will be used to identify the appropriate hydrostratigraphic layers to use with homogeneous or heterogeneous feature, which can be incorporated in the numerical model. 3) Establish suitable concepts to model sensitive hydrologic parameter, 4) Quantify the hydrologic parameters and hydrologic budget for the Hayk-Ardibo catchment under steady-state conditions, 5) simulate the distribution of hydraulic head in the catchment, 6)) finally determine the overall water budget.

5.2 Development of Conceptual Model

Models are conceptual descriptions or approximations that describe physical systems using mathematical equations—they are not exact descriptions of physical systems or processes. The applicability or usefulness of a model depends on how closely the mathematical equations approximate the physical system being modeled and it also depend on a thorough understanding of the physical system and the assumptions embedded in the derivation of the mathematical equations. These equations are based on certain simplifying assumptions, which typically involve: the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer. It is because of these assumptions, and the many uncertainties in the values of data required by the model, that a model must be viewed as an approximation and not an exact duplication of field conditions. The equations that describe the groundwater flow may be solved using different types of models. Some models (e.g. analytical models) may be exact solutions to equations, which describe very simple flow, or transport conditions and others (such as numerical models) may be approximations of equations that describe very complex conditions. The model conceptualization aids in determining the modeling approach and which software to use.

5.2.1 Defining Hydrostratigraphic unit

The available hydrogeological data are used to describe the hydrogeological conditions of the site. The degree and intensity of weathering and fracturing affect the spatial variability of hydrogeological parameters that prevails in the study area. The presence of major and minor faults in the study area clearly shows that the occurrence and movement of groundwater will be limited highly on the fracture aquifer. The hyrogeological characteristics of the highland Ethiopia shows that groundwater occurs at shallow depth mainly with in a fracture aquifer in which the intensity and distribution decreases with increasing of depth. From the limited data obtained unconfined aquifer is more prevailing in the area although there is local variation. The hydraulic conductivity is higher around lakes and it becomes lower towards the boarder.

5.2.2 Establishing Water Budget For The Model

The recharge to the entire study area is from precipitation and there is no both surface and subsurface inflow at the adjacent catchments. The water budget calculation was made by dividing the Hayk-Ardibo Catchment in to Hayk and Ardibo sub catchments. There is excess recharge from lake Ardibo sub catchment that flows in to Lake Hayk sub catchment. Ankerka River and excess water from Ardibo irrigation also contributes 1.89MCM each year to Hayk sub catchment. The net out put from Hayk sub catchment is around 23.82 mcm and this amount of water leaves the catchment through subsurface.

5.2.3 Defining the Flow System

The groundwater movement as observed from the hydrogeological and geomorphologic condition, ground water moves towards the lakes at the shallow groundwater movement regime and it moves from South to Northwest direction at the intermediate level, and thus the level water movement is dominantly or characterized as two-dimensional aerial. The ground water leave the catchment through the Northwestern border of the study area and this assumption is supported by different evidences: a) the chemistry of the lake water shows that it is fresh and have similar hydrochemistry with that of the near by springs this means that the lakes are open and there is a continuous interaction with the groundwater. b) There is no significant lake level rise observed at the two lakes rather the lake level data shows that there is a gradual decrement in the past 60 years with an amount of 7.8 meter according (Molla Demelie et al., 2000) although the water balance shows there is an additional water 36000m^{3}per annum, which can increase the lake Hayk by 20mm each year. c) There are a number of springs in the adjacent lower catchment near the study area, which indicates that groundwater, is moving in the same direction.

5.3 Modeling Approach

A three-dimensional model grid was used to represent a two-dimensional aerial flow through a single layer. Groundwater in the aquifer was simulated using *Processing Modflow Pro (Version 7.0.17)*. This numerical groundwater modelling software is developed by Web Tech 360 Inc. in 2002-2003 based on the original work of W. -H.Chiang & W.Kinzelbach (1991-1998). Processing Modflow *Pro (PMWIN Pro*) is an enhanced version of Processing Modflow

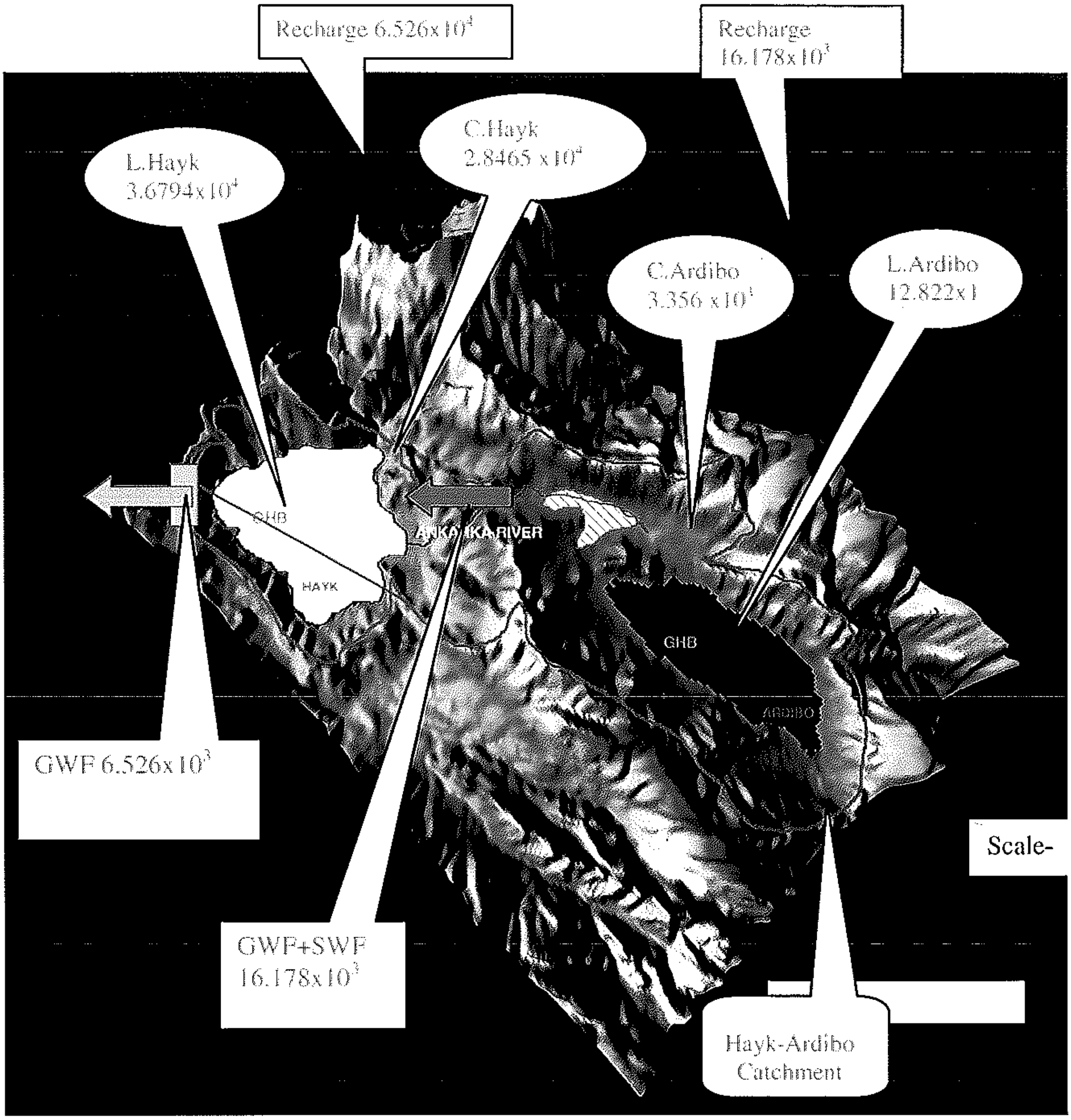


Fig 5.1 Conceptualization of Hayk-Ardibo catchment

5.3.1General Assumptions

Several general simplified assumptions are used in the simulation of ground water flow, and the development and calibration of the model:

- Fractures and weathered zones through which water flows may be considered, as porous medium to which Darcy's Law is assumed applicable.
- Spring discharge does not significantly affect the level of hydraulic heads; therefore, springs are not simulated.
- Net recharge from precipitation is not spatially uniform because there is heterogeneity in the spatial distribution of hydraulic conductivity, variations in geology, total precipitation, slope, and vegetation.
- Aquifer heterogeneity, vertical anisotropy, and the presence of fracture and faults impact the spatial distribution of hydraulic conductivity. Consequently, a zonation approach is adopted where similar K values assigned to specific regions on the basis of above factors.
- Vertical flow is assumed to be zero since one aquifer system is considered.
- Evapotranspiration was not directly simulated in the model. Recharge rates were considered as "net recharge" implying that the effects of evapo-transpiration were already accounted for in the net precipitation rates.
- Subsurface discharge occurs from the aquifer along the Northern boundary where the aquifers are hydraulically connected to the adgacent catchment.
- Different boundary conditions are assumed in the model: head dependent boundary is used on the lakes and flux boundary is used at the Northwestern boarder.

5.3.2 Selection of Computer Code

A groundwater flow model for the Quaternary sediment and volcanic aquifers is based on MODFLOW, the USGS modular three-dimensional finite-difference computer code commonly used to simulate groundwater flow and determine hydrologic budgets in various physiographic regions (McDonald and Harbaugh, 1988). Many versions of this code have been created since 1988 and version MODFLOW96+ INTERFACE TO MT 3D AND LATER was used in this modeling study.

MODFLOW was used for many reason, among it is well suited to simulate three-dimensional groundwater flow in heterogeneous and anisotropic systems such as Hayk-Ardibo catchment and it is a well documented and widely used public domain.

MODFLOW was originally developed to simulate flow through porous media. However MODFLOW has been applied to regional fracture systems (Hunttoon, 1994; Mercer and Faust, 1981). The computer program uses finite-difference techniques and a block-centered formulation to solve the groundwater flow equation for two-dimensional aerial, steady state flow in anisotropic, heterogeneous, porous media of the Hayk-Ardibo catchment. In order to use a finite-difference approximation, a grid is superimposed over the study area, and aquifer hydraulic parameters necessary to solve the flow equation are averaged over the area of cell or grid block and assigned at a node at the center of the block. Finite-differences compute the average head value for a cell at the node. In the block-centered formulation, the nodes for which water levels are simulated are located at the center of the grid cells. These cells are the smallest volumetric units over which the hydraulic properties are assumed constant.

5.3.3 MODFLOW Pro (PMWIN Pro)

MODFLOW Pro (PMWIN Pro) is an enhanced version of processing MODFLOW for Windows. Now it supports MODFLOW-2000, PEST-ASP, and others. PMWIN has professional graphic user interface, the supported codes and other useful modeling tools.

The Main Features of PMWIN Pro are

a) Data Input Facilities:

- Support models with up to 1,000 stress periods, 200 layers and 250,000 cells in each model layer.
- Graphical grid design tools.
- Specify model parameters using cell-by-cell, zones, and poly line tools.
- Interactive model display in both plan view and cross-sectional view.
- Rotate and align the model grid over the site base map.
- Overlay maps in AutoCAD (.dxf), SURFER BLN, or bitmap image (.bmp) formats.
- Imports existing MODFLOW files.
- Import / export model parameters from/ to SURFER AND ASCII files.
- Interpolation of discrete data to model grid by means of Inverse Distance Telescopic Mesh Refinement for creating a local scale refined model from a large-scale model. Both steady state and transient models can be created.
- Customizable display colors of model features, such as rivers, well, and drains.
- Weighting, kriging, or Triangulation.

b) Simulation:

- Support MODFLOW-88/96/2000, MT3D, MT3DMS, MT3D99, RT3D, MOC3D, PMPATH, UCODE, and pest-asp.
- Support the stream flow-Routing package, Horizontal-Flow Barrier package, Reservoir package, and Time-Variant Specified Head package.

c) Model Calibration

- Parameter estimation (often referred to as automatic calibration) using MODFLOW-2000, PEST-ASP OR UCODE.
- Detailed summaries of model calibration results (scatter plots and time series plots) and statistics (estimated parameter values and sensitivity values).

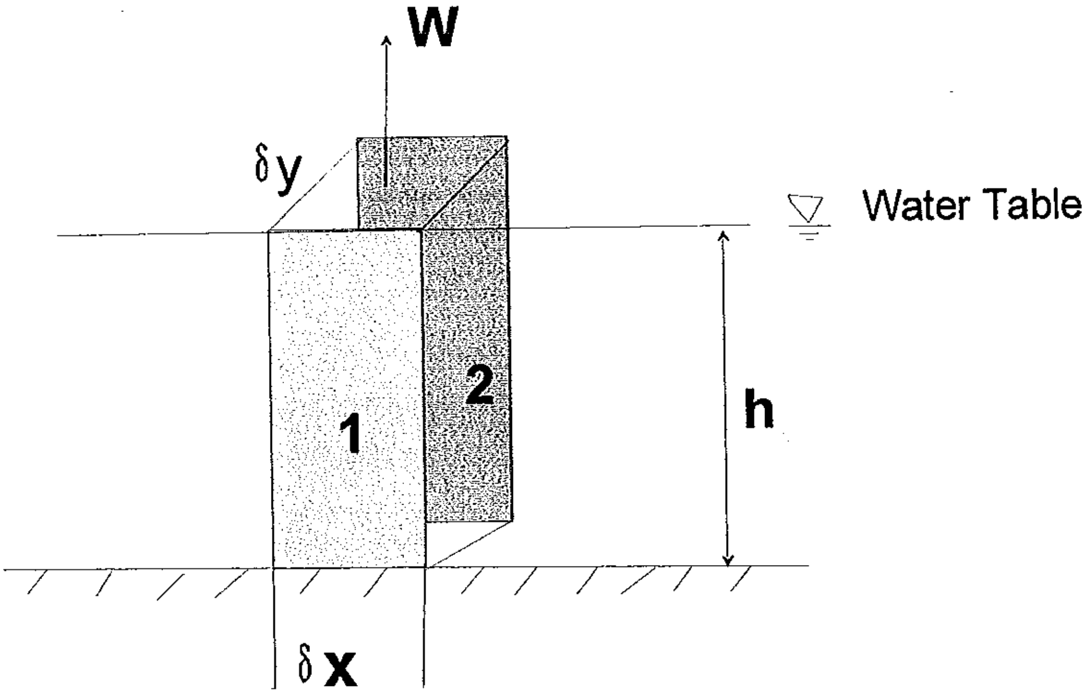
5.3.4 Governing Flow Equation

A three-dimensional finite-difference groundwater flow model developed by McDonald and Harbaugh (1998) was used for the computer simulations. The mathematical model simulates flow indirectly by means of a governing equation thought to represent the physical processes that occur in the system. This model is based on the governing equation for anisotropic, heterogeneous steady flow expressed as follows:

Two dimensional, anisotropic media, steady state flow equation for unconfined aquifer:

$$\frac{\partial}{\partial x}\left(Kxx\ h\ \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kyy\ h\ \frac{\partial h}{\partial y}\right) - W = 0 \qquad \ldots\ldots 1$$

Since the upper surface of the aquifer is determined by the water level elevation, the aquifer thickness is variable as a result of fluctuation in the water table. Therefore, taking into account the water table elevation h with a datum at the lower impervious layer and unit width in the x and y direction as shown on the figure the equation for horizontal flow of unconfined aquifer can be derived.



Figs 5.2 A water table aquifer with thickness h and unit width and length

5.3.5 Application of Finite-Difference Equations

The partial differential equation representing groundwater flow (Eq.1) may be closely approximated by finite-difference equations, which are sets of algebraic expressions that are solved simultaneously in MODFLOW (PMWIN Processing Mode flow Pro) using the strongly implicit procedure. The set of algebraic equations that result when approximating a groundwater flow model using the method of finite differences is normally solved using a combination of matrix and iterative solution techniques (Anderson and Woessner, 1992).

5.4 MODEL DESIGN

5.4.1 Spatial Discretization of Model Grid

The geographic boundaries of the model grid were determined by using a map created in AutoCAD Drawing Exchange Format (DXF) covering the extent of Hayk-Ardibo catchment. The DXF map was projected in a Geographic Information System (GIS) using metric coordinates (UTM) and then imported into MODFLOW. The map represents the areal extent of the physiographic region. A finite-difference grid superimposed over a 140.1-km^2 study area was designed and constructed based on the simplification of a conceptual model representing the physical properties of the groundwater system (Figure 4.2). The grid network has a constant spacing of 250 m by 250 m. A total of 89 rows and 61columns and 62,500 cells are used to cover the study area, figure 5.3.

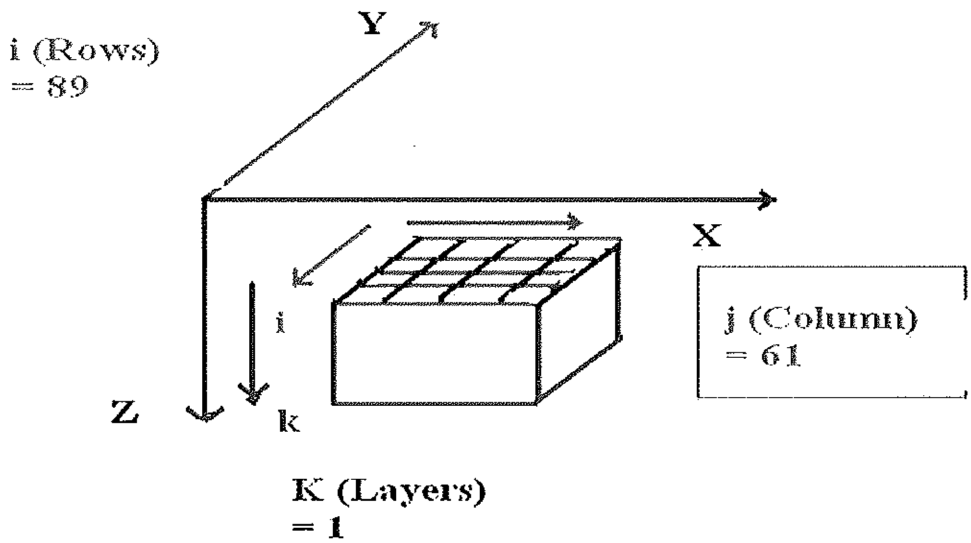


Fig.5.3 Model Frame work

The aquifer structure had been determined by preparing DEM, which was used to construct the top elevation of the aquifer. The bottom elevation of the aquifer had been prepared by taking in to account of the elevation difference between the highest topographic elevation to that of Lake Ardibo, between Lake Ardibo and lake Hayk, which is 230, and between lake Hayk and Workie Spring, which is 200. One-model layer was used to represent the study region extending vertically from 1 882 meters above mean sea level to 2800 meters below mean sea level. The one-model layers slope with the land surface and thickness is highly varied

5.4.2 Discretizing Time

The model was simulated for a steady state condition. The time unit used is day.

5.4.3 Boundary Conditions

Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the domain. Both physical boundaries and hydraulic boundaries types were used to define the area domain. Boundaries are defined in both the vertical and horizontal planes.

Boundary conditions are specified for the upper surface, sides and bottom of the model area. No-flow boundaries were used at the boarder of the study area except at the Northwestern part where flux boundary is used based on the assumption that ground water does not flow across Eastern, Southern and Western boundary. In addition, topographic divides are also groundwater divides figure 5.4.

The base of the volcanic aquifer is the basement volcanic rock where groundwater flow is negligible. Because no flow is assumed to the bottom of the volcanic aquifer, it is a specified-flux (no-flow) boundary. A general-head boundary was assigned on the Hayk and Ardibo lakes. Ankerka River is simulated as head-dependant boundaries where the river stage and riverbed conductance are specified. Although the contribution of major and minor faults are significant for the occurrence and movement of groundwater in fractured volcanic aquifer, no flow boundary has been assumed in the model so that groundwater inflow is considered to be negligible from the adjacent catchments in to Hayk-Ardibo catchment. Moreover Fractures and weathered zones through which water flows may be considered, as porous medium to which Darcy's Law is assumed applicable.

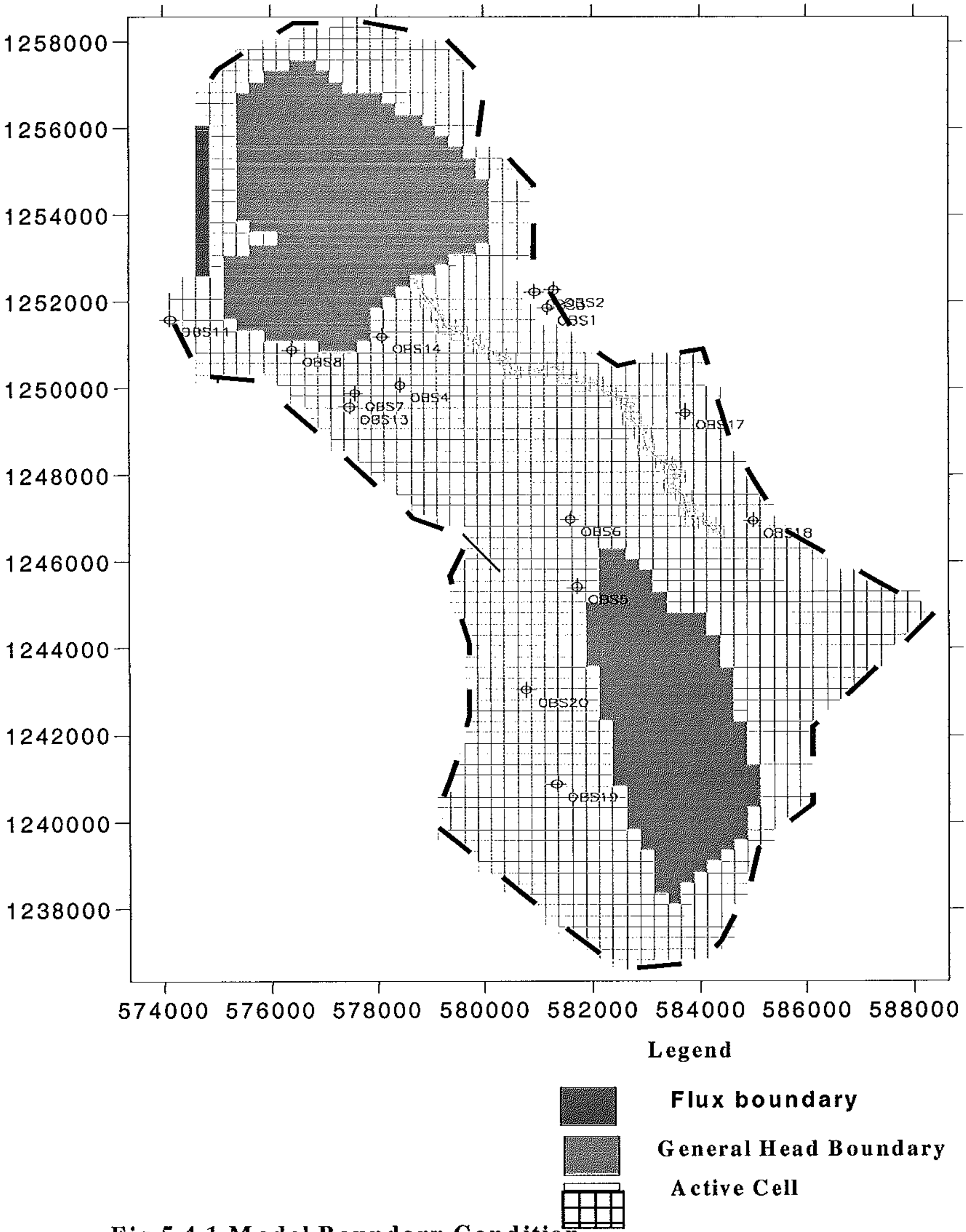


Fig 5.4.1 Model Boundary Condition

5.5 Model Data Input

The finite-difference model was developed by incorporating geologic data with hydrologic data. The model must generally have values specified initially for all necessary parameters. Input parameters to the model included lakebed conductance along the general head boundary, initial hydraulic head, recharge values to the topmost model layer and hydraulic conductivity. Each active grid cell was assigned values according to its location within the study area. In the study area the input parameters for the steady state simulation for the unconfined aquifer were the following,

5.5.1 Initial Hydraulic heads

Hydraulic heads distribution in the study area, i.e. initial condition, was obtained form the data of 20 springs and lake level data in the area. The hydraulic heads distribution was imported to PMWIN, MODFLOW at the beginning of the model run. This initial data were interpolated using kriging method and each cell in the model was assigned its head value.

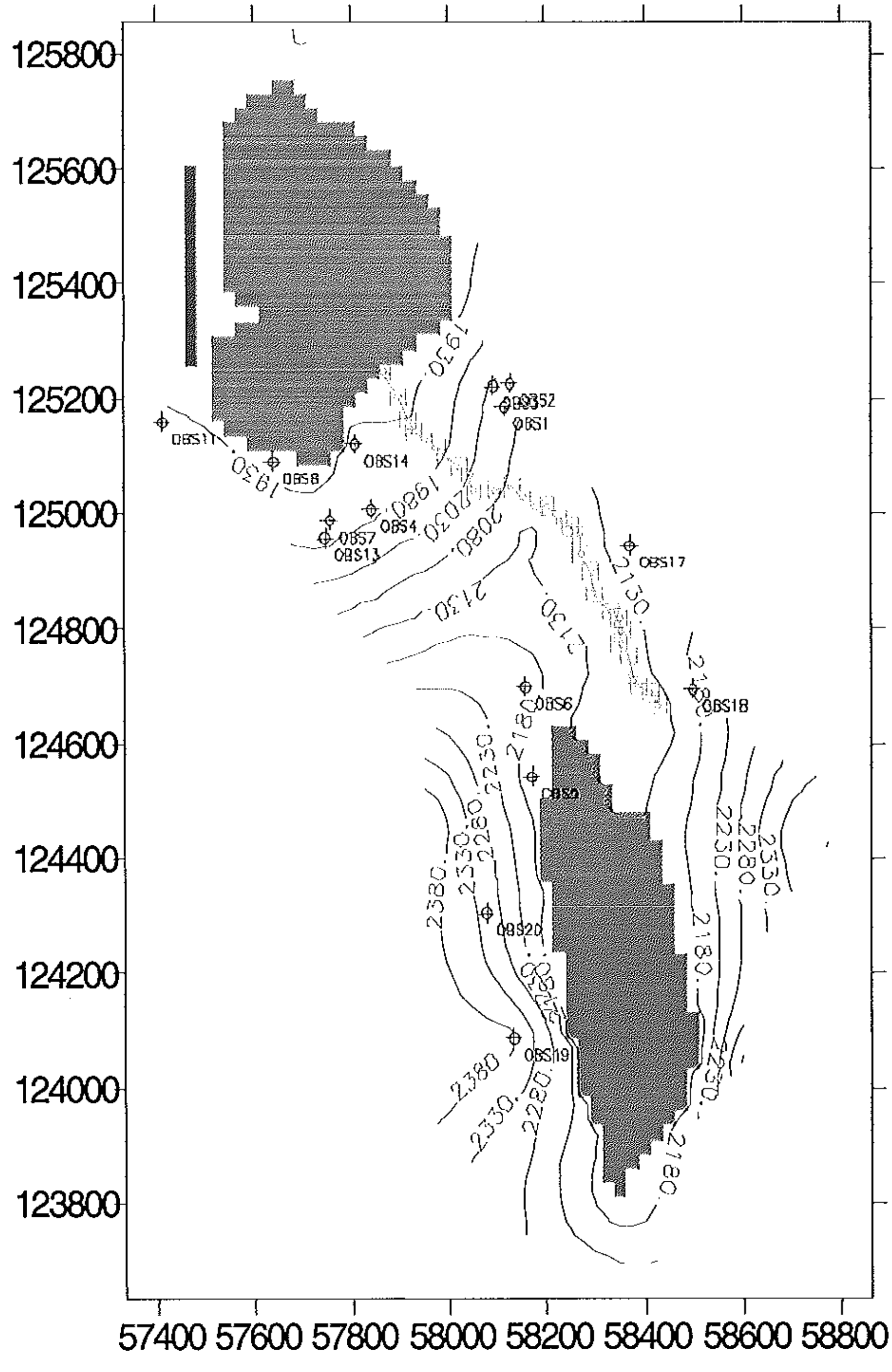


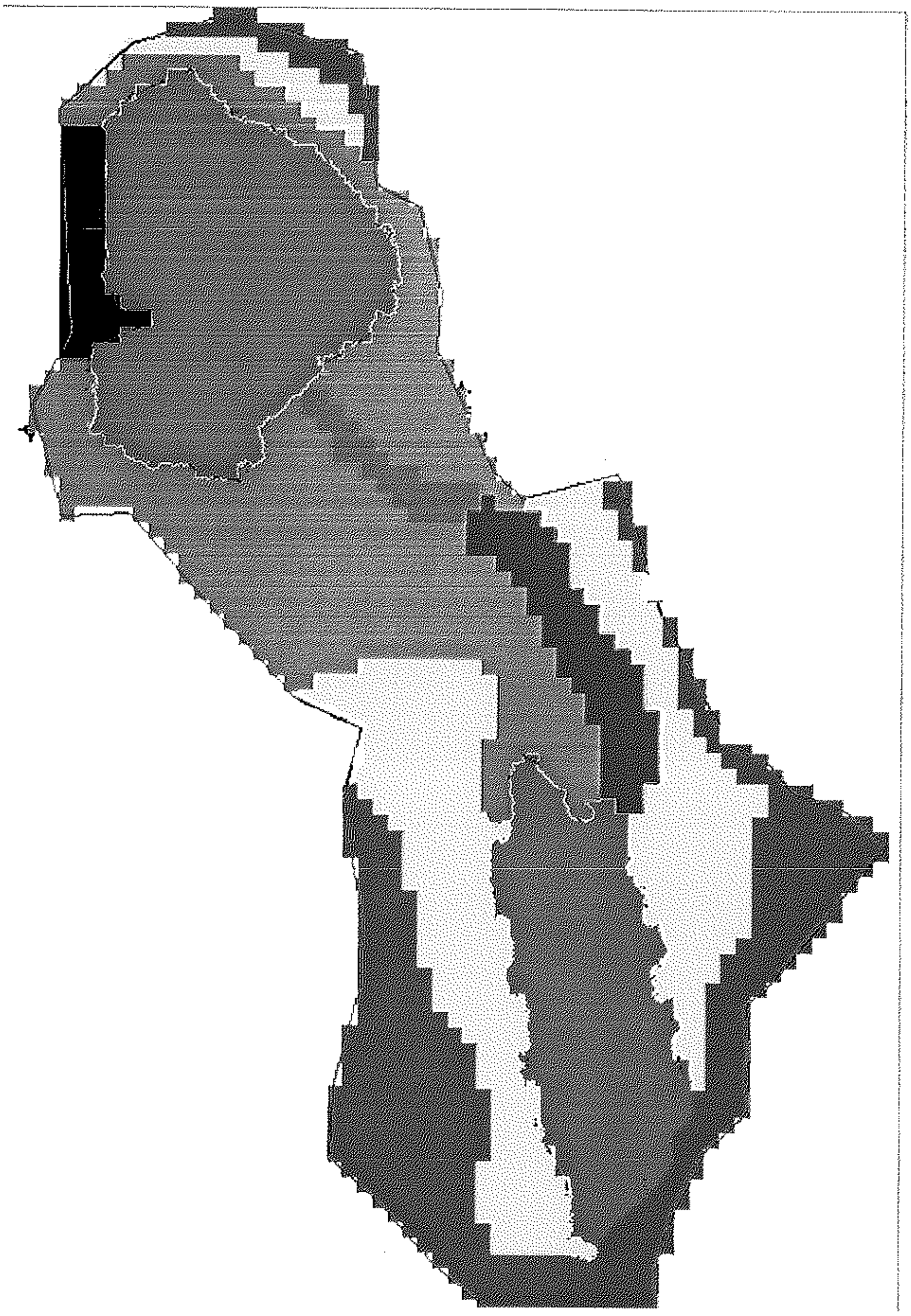
Fig. 5.5 Map showing the Distribution of Initial Hydraulic Head

5.5.2 Horizontal Hydraulic conductivity

The hydraulic conductivity data were assigned in ten zonation based on the geology, hydrogeologic and geomorphologic conditions. Initial hydraulic data were gathered from field measurement, pumping test (one well data was used in comparison) and reviewing literature from areas with similar geology.

Zone	Description	Range input of Hydraulic Conductivity (M/day)	Calibrated Hydraulic Conductivity (M/day)
1	Lake Hayk	1.0-4.0	1.375
2	Transitional area	0.01-0.04	0.01375
3	Plain area in Hayk-sub catchment	0.1-1.4	0.59417
4	Steep area in Hayk-sub catchment	0.0001-0.001	0.00044
5	Lake Ardibo	1.0-4.0	1.375
6	Transitional area	0.0001-0.002	0.00055
7	Plain area in Ardibo-sub catchment	0.0001-0.0025	0.00055
8	Steep area in Ardibo – sub catchment	0.0001-0.001	0.00044

Table 5.1 Summery of model input parameter-Hydraulic conductivity



Legend

1.0-4.0	0.0001-0.001
0.01-0.04	0.5-1.0
0.0001-0.002	1.0-1.5
	0.1-1.4

Fig 5.6 Map showing the Distribution of Hydraulic Conductivity

5.5.3 Recharge

Natural recharge to the saturated zone in a groundwater reservoir comes form vertical percolation of precipitation. Direct recharge refers to precipitation that contributes to soil moisture content and crosses the water table and becomes part of the groundwater flow system. The recharge assigned to the unconfined part of the aquifer in the model area is both direct from precipitation and indirect recharge, which has been dealt in detail on water balance. The recharge input assigned was assumed to be spatially variable and eight zones were used to in the model. (Figure 5.7).

Zone	Description	Range of Recharge (m/day)	Calibrated Recharge (m/day)
1	Lake Hayk	0.0014-0.0016	0.001477
2	Transitional area	0.0003-0.0004	0.000322
3	Plain area in Hayk sub-Catchment	0.00052-0.000568	0.000524
4	Steep area in Hayk sub-Catchment	0.0.00002-0.00003059	0.0000282
5	Lake Ardibo	0.0007-0.0008	0.000749
6	Transitional area	0.00007-0.000077	0.0000712
7	Plain area in Ardibo sub-Catchment	0.00005-0.000055	0.0000509
8	Steep area in Ardibo sub-Catchment	0.000008-0.00000919	0.00000848

Table 5.2 Summery of model input parameter-Recharge

Legend

0.0016
0.0003496
0.0003059
0.0005681
0.0000811
0.000077196
0.00000919
0.00005514

Fig 5.7 Map showing the Distribution of Recharge in the Study area

5.5.4 River hydraulic conductance

Field measurements on river width, riverbed hydraulic conductance, riverbed thickness and riverbed elevation were taken. The hydraulic conductance increases from Lake Ardibo towards lake Hayk and it is in the range of 0.0001m/day to 0.01m/day.

Zone	Layer, Row, Column	Hydraulic Conductivity of river bed (m/day)	Width of the river	Thickness of the river bed	Remark
1	1,25,22	0.01	18	0.5	The difference in head in the river & elevation of the riverbed bottom for the river cells is taken as 0.5 meter.
2	1,27,23	0.01	13	1.5	
3	1,28,24-1,33,29	0.01-0.001	5	1.5	
4	1,33,31-1,36,37	0.001-0.0001	2.5	2.5	
5	1,36,38-1,48,44	0.0001-000001	1.5-1.9	0.5-1	

Table 5.3 Summery of model input parameter for Ankerka River

CHAPTER SIX

MODEL CALIBRATION AND RESULTS

6.1 MODEL CALIBRATION

Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. This requires that field conditions at a site be properly characterized. Lack of proper site characterization may result in a model that is calibrated to a set of conditions, which are not representative of actual field conditions. The calibration process typically involves calibrating to steady state and transient conditions. Transient simulations involve the change in hydraulic head or contaminant concentration with time (e.g. aquifer test, an aquifer stressed by a well-field, or a migrating contaminant plume). These simulations are needed to narrow the range of variability in model input data since there are numerous choices of model input data values which may result in similar steady-state simulations. At a minimum, model calibration should include comparisons between model-simulated conditions and field conditions for the following data:

- Hydraulic head data (there are around 20 springs used for calibration), assuming that the spring levels represent the regional static water level.
- Groundwater-flow direction.
- Hydraulic-head gradient.
- Water balance.
- Horizontal hydraulic conductivity.

A graphical comparison between measured and computed heads is shown in Figure 6.1 in this example, the closer the heads fall on the straight line, the better the calibration is.

6.1.1 Calibration Strategy

A two-dimensional aerial finite-difference groundwater flow model was designed and calibrated to: 1) quantify the hydrologic parameters representing the hydrogeologic units of the study area, 2) establish the role of the two lakes on the discharge and recharge condition of the catchment, 3) provide the overall hydrologic budget of the catchment and 4) produce a map of the potentiometric surface in the volcanic aquifer.

Calibration of the model is a process of updating selected model parameters based on the results of previous simulations to derive a close match between the observed steady-state water levels and calculated hydraulic heads in the model. A steady-state simulation of hydraulic head was used to calibrate the model. Steady-state conditions imply that the system is in equilibrium, such that total inflow is equal to total outflow.

A reasonable calibration target of six meter was set as the accepted margin of difference between calibrated and observed heads for each spring observation point used to calibrate the model. The model was calibrated using initial *trial and error* adjustments.

Adjustments were made in: 1) recharge 2) the hydraulic conductivity 3) lakebed conductance values at the general-head boundary and 4) streambed vertical hydraulic conductivity until an acceptable match between calculated and observed hydraulic heads was achieved. A map of the distribution of hydraulic head observation points used to calibrate the model is presented in Figure 6.2. There are two notable conditions or strategies that were crucial to the final development and calibration of the model: 1) the simulation of a general-head condition along the two lakes and 2) The successive adjustment of hydraulic conductivity to the volcanic aquifer. Recharge rates were assigned to vary in regions by weight based on steepness of slope by considering the direct and indirect recharge as revealed from model simulation. During model calibration, applied groundwater recharge was adjusted according to topographic features (Figure 5.7).

The assignment of a general-head boundary at the two lakes was assumed appropriate to provide stability to the model allowing it to calculate the distribution of hydraulic heads in the catchment and also provide a way to estimate the upland subsurface inflow that may be occurring through the upper boundary. Specifying a hydraulic conductance value to a higher number was aimed to bring the two lakes to the level of constant head boundary.

The most effective calibration technique for the adjustment of the hydraulic conductivity field in the model was to initially delineate fewer conductivity zones and then gradually increase the number of zones based on the geology and permeability of the hydrogeologic unit in the region.

Ten hydraulic conductivity zones were assigned to the area based on the variation in geology (Table 5.1). Two of the eight hydraulic conductivity zones simulated earlier in the model calibration included a zone of cells representing the two lakes in the Hayk-Ardibo Catchment (Figure 5.6). A higher average hydraulic conductivity value of $1.375m^3/d$ was assigned in the two lakes.

Hydraulic conductivity was continually adjusted during calibration according to the geology and permeability in each hydraulic conductivity zone.

The adjustment of streambed vertical hydraulic conductivity was constrained to the range of values obtained from literatures on similar geology. Although streambed vertical hydraulic conductivity may vary locally, the same initial value was assigned to all hydrogeologic units because of lack of data. Calibration of the streambed hydraulic conductivity was accomplished by adjusting the initial value of streambed hydraulic conductivity in the same manner for all stream reaches overlying the same hydrogeologic unit. An initial value of 0.0001 m/d was assumed for streambed sediments in this study and finally the calibrated value reach in the range of 0.01-0.0001m/d.

6.1.2 Calibration Criteria

The criteria used to determine acceptable match between calculated and measured hydraulic heads are subjective, despite the goal of minimizing the difference between calculated and measured heads. The calibration criteria involved a fairly good visual comparison between the measured and simulated heads. The model was considered calibrated when the following criteria were met:

1) Simulated flow directions agreed with those represented in the water table map constructed from the static water level measurements of 20 springs.
2) The calculated heads reasonably matched measured or inferred heads
3) Visual inspection of the areal distribution of the residuals or differences between heads interpolated from the water level map and simulated heads indicated no consistent pattern of positive and negative high or low values.

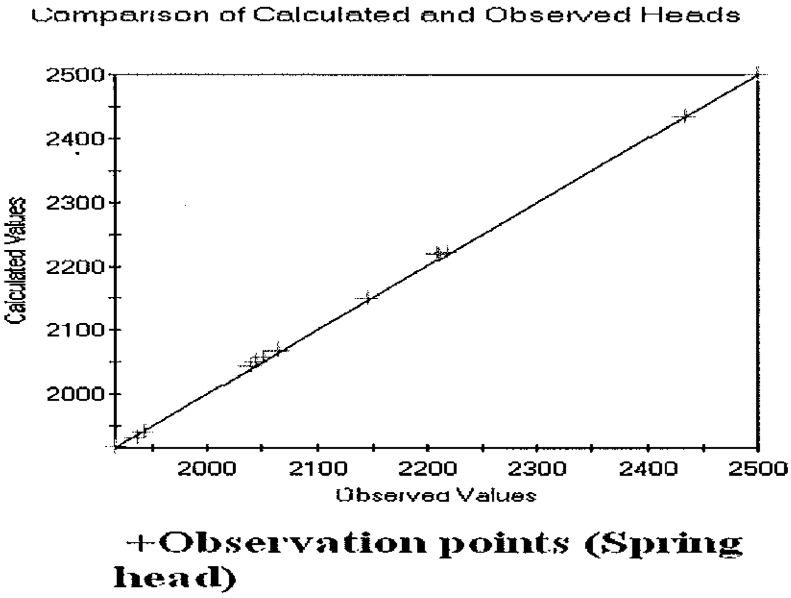


Fig 6.1 A graph showing Calculated Head verses Observed Head.

6.2 SIMULATION RESULTS

The model was most responsive to the general-head boundary assigned to the upper boundary on the two lakes. This was the first significant calibration strategy for the model development. The amount of inflow expected to occur through precipitation is based on volume of recharge calculated for the region with in the study area. It is evident that there is no upland subsurface inflow across the boundary, which can be considered, as is a secondary source of recharge to the study area.

Hydraulic gradient became gentle and a more agreeable match between the calculated and observed heads observed in the catchment. The water table slopes in a general northwest-southeast direction that coincides with the major fault trend in the Catchment. The topography facilitates a steep water table gradient in the southwest region of the study area, and a gentle water table surface over the immediate area of the lower Ardibo catchment. It may be inferred from this modeling study that the NNW trending fault works in conjunction with the Tertiary volcanic in controlling the water table gradient and flow regime in the Hayk-Ardibo catchment. Hydraulic heads from several spring observation points used to calibrate within reasonable differences between calibrated heads and observed heads.

The groundwater flow direction is from North to south, i.e. from lake Ardibo towards Lake Hayk, which agrees in the conceptual model development. The flow is towards the two lakes at the shallow ground water level. The presence of low permeability rock between the two lakes had contributed for the presence of the lake Ardibo, although there is a significant elevation difference between the two lakes, which is around 230 meter. The contribution of Ardibo catchment has been reflected in the model simulation and it agrees with the assumption of the conventional method. The Ankerka River gains water from the ground water, which is around 4895m^3/day.

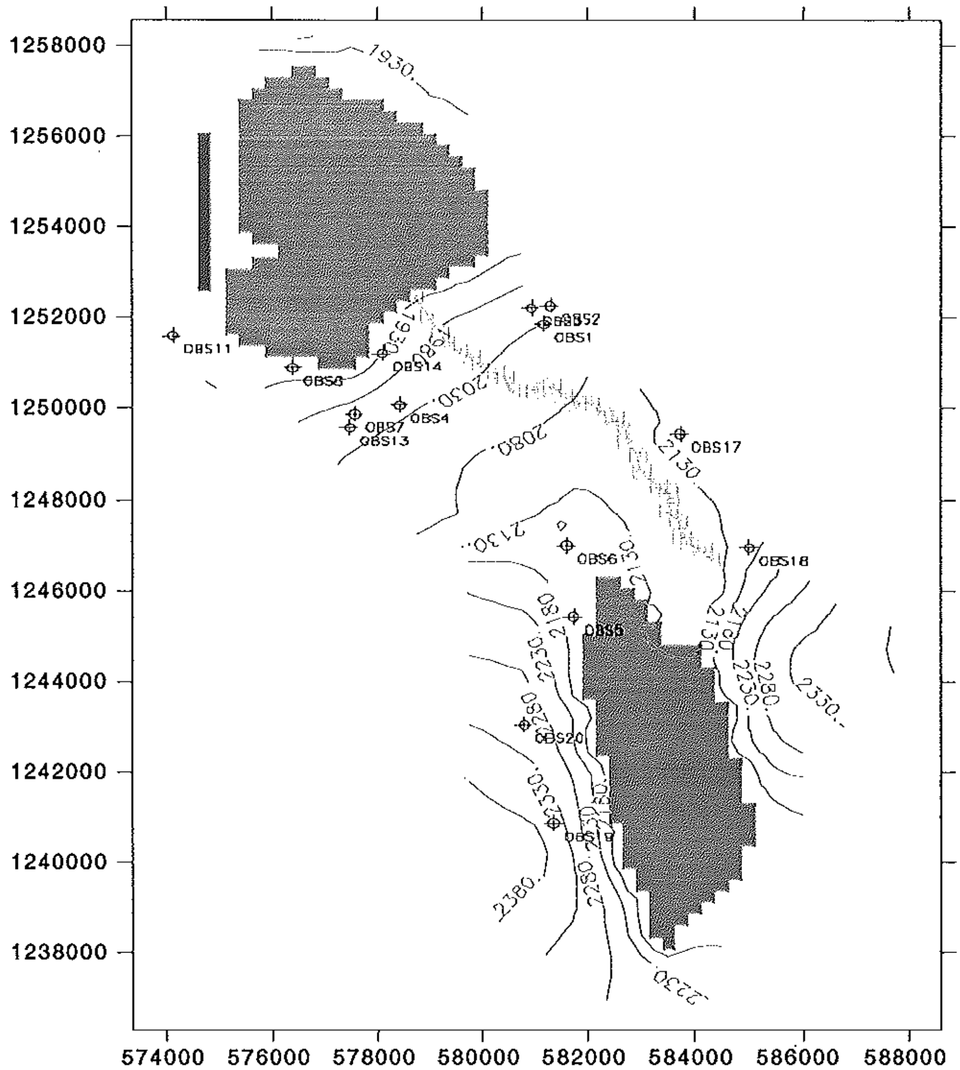


Fig. 6.2 Map showing the Distribution of simulated head

6.2.1 HYDROLOGIC BUDGET

Zone Budgets

The groundwater budget for steady-state simulation of flow in the Hayk-Ardibo catchment gives an accounting of recharge to the catchment, discharge from the catchment, and flow between hydrogeologic units in the catchment. The continuity equation establishes that inflows are equal to outflows. One of the main benefits of using PMWIN Pro is that mass balance calculations provide a very useful way to examine the source of water provided to a system of hydrologic stresses like recharge and discharge. The main objectives of this study were the estimation of groundwater flow budget and determination of groundwater flow directions. Four budget zones were assigned throughout the Hayk -Ardibo catchment using PMWBLF (SUBREGIONAL WATER BUDGET) to determine the overall hydrologic budget for the region (Figure 6.3).

Zone one includes Lake Hayk and the recharge to lake Hayk is not only from direct precipitation but also groundwater inflow from Ardibo sub catchment. Zone two is Hayk sub catchment with out lake Hayk and this Zone get recharged from precipitation as well as from the Ardibo sub catchment. This zone included areas where discharge may be taking place such as in the adjacent catchment, where the aquifers are hydraulically connected. Zone three is Lake Ardibo, which receive recharge from direct precipitation and the surrounding area. Zone four is Ardibo sub catchment, which receives recharge from rainfall only. Water budget outflows calculated in this modeling are presented in Table 6.

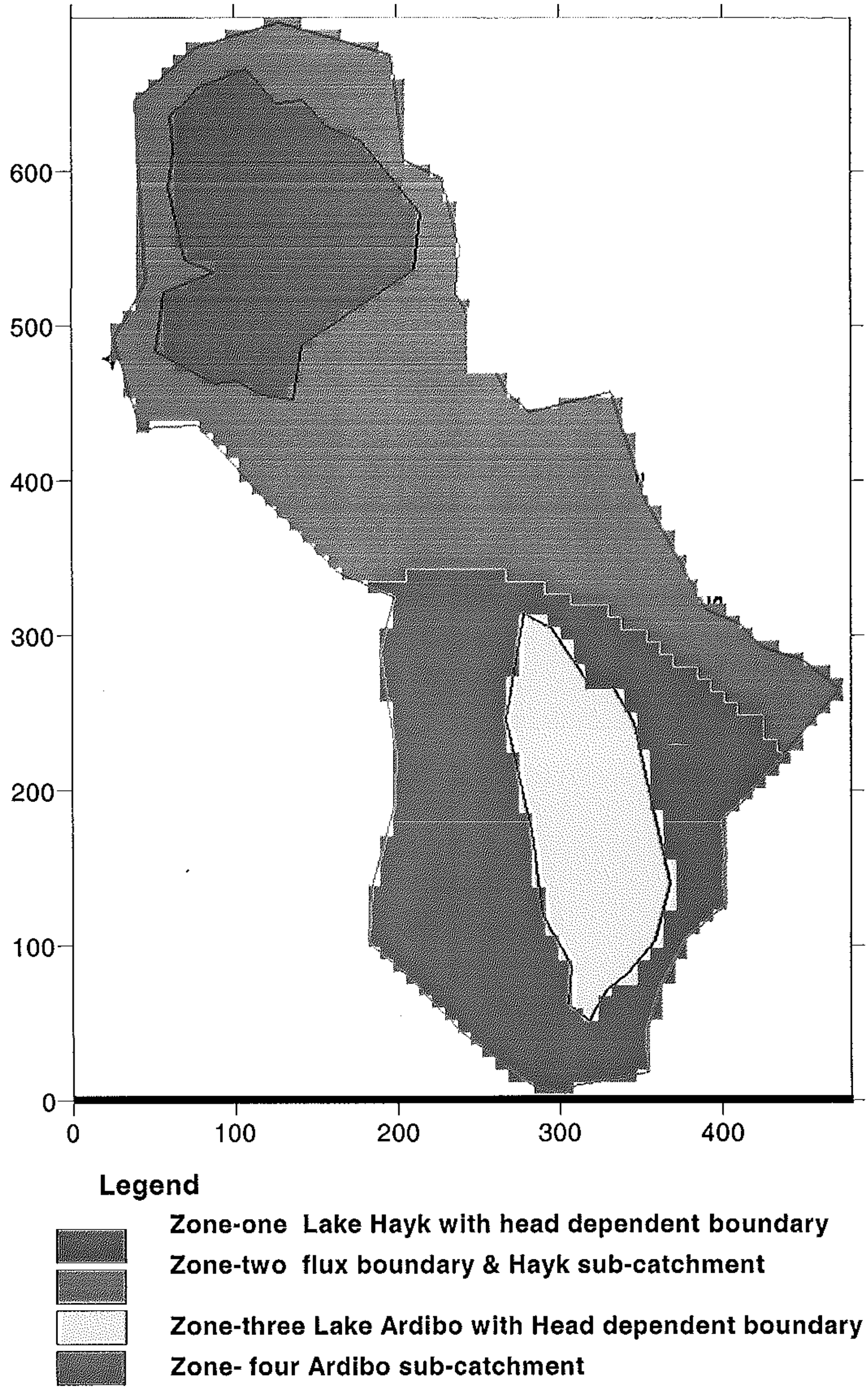


Figure 6.3 Assigned hydrologic zones in Zone budget

I) Model result Zone budget

==

WATER BUDGET OF THE WHOLE MODEL DOMAIN:

==

FLOW TERM	IN	OUT	IN-OUT
TORAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
CONSTANT HEAD	0.0000000E+00	0.0000000E+00	0.0000000E+00
Flux Boundary (wells)	0.0000000E+00	6.0494727E+04	-6.0494727E+04
DRAINS	0.0000000E+00	0.0000000E+00	0.0000000E+00
RECHARGE	6.5393855E+04	0.0000000E+00	6.5393855E+04
ET	0.0000000E+00	0.0000000E+00	0.0000000E+00
RIVER LEAKAGE	0.0000000E+00	4.8957607E+03	-4.8957607E+03
HEAD DEP BOUNDS	5.6526242E+04	5.8126313E+04	-1.6000703E+03
STREAM LEAKAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
INTERBED STORAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
RESERV. LEAKAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
SUM	1.2192009E+05	1.2351680E+05	-1.5967031E+03

DISCREPANCY [%] -1.30

WATER BUDGET OF THE WHOLE MODEL DOMAIN

6.2.2 Sensitivity Analysis

The overall performance of a groundwater model may be better analyzed through a sensitivity analysis of its aquifer parameters. The process of model development and sensitivity analysis allows the groundwater investigator to better understand the system's response to changing hydrologic parameters. Sensitivity analyses were used during model calibration to refine initial estimates of input parameters and after model calibration to determine which input parameters had the largest effect on simulated head values. The model is considered sensitive to an input parameter when small changes in the value of that parameter result in large changes in simulated head values. Conversely, if large changes in the value of an input parameter result in little or no change simulated in the simulated head, then the model is not sensitive to that parameter, and the model is not useful for refining the initial estimate of the parameter. If the model is sensitive to an input parameter, additional data on that variable can help improve calibration. Increments and decrements of 10 percent were applied to horizontal hydraulic conductivity and rainfall recharge. Sensitivity analyses conducted for horizontal hydraulic conductivity and recharge verify a satisfactory level of calibration. The effect is not the same if net recharge to the area is increased by 10%. Increments and decrements of 10% to any one hydraulic parameter improve neither model calibration nor development. Sensitivity analyses of these parameters indicate simulated heads are mostly sensitive to changes in aquifer recharge and relatively least sensitive to hydraulic conductivity as it is indicated in fig. 6.4.

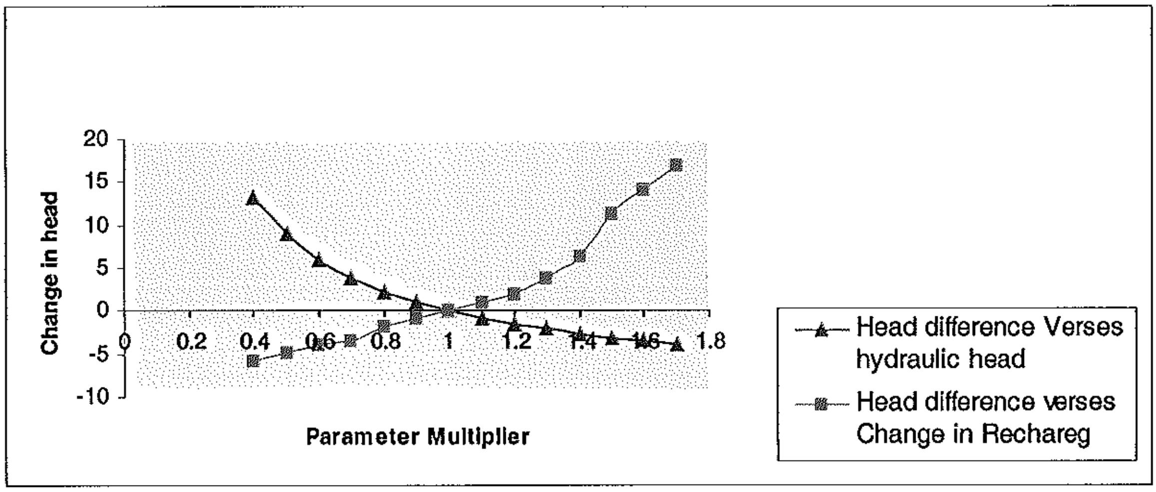


Fig. 6.4 Simulated change in hydraulic head resulting from change in Parameter value

The above fact is strengthening by observing the effect of increasing or decreasing horizontal hydraulic conductivity and recharge against Ankerka river leakage. As the input of horizontal hydraulic conductivity increases the head decreases and less water flows from groundwater to the river but when the recharge input increases the head rises and as a result leakage increases. It is clearly indicated in fig. 6.5 the model is more sensitive to recharge than horizontal hydraulic conductivity.

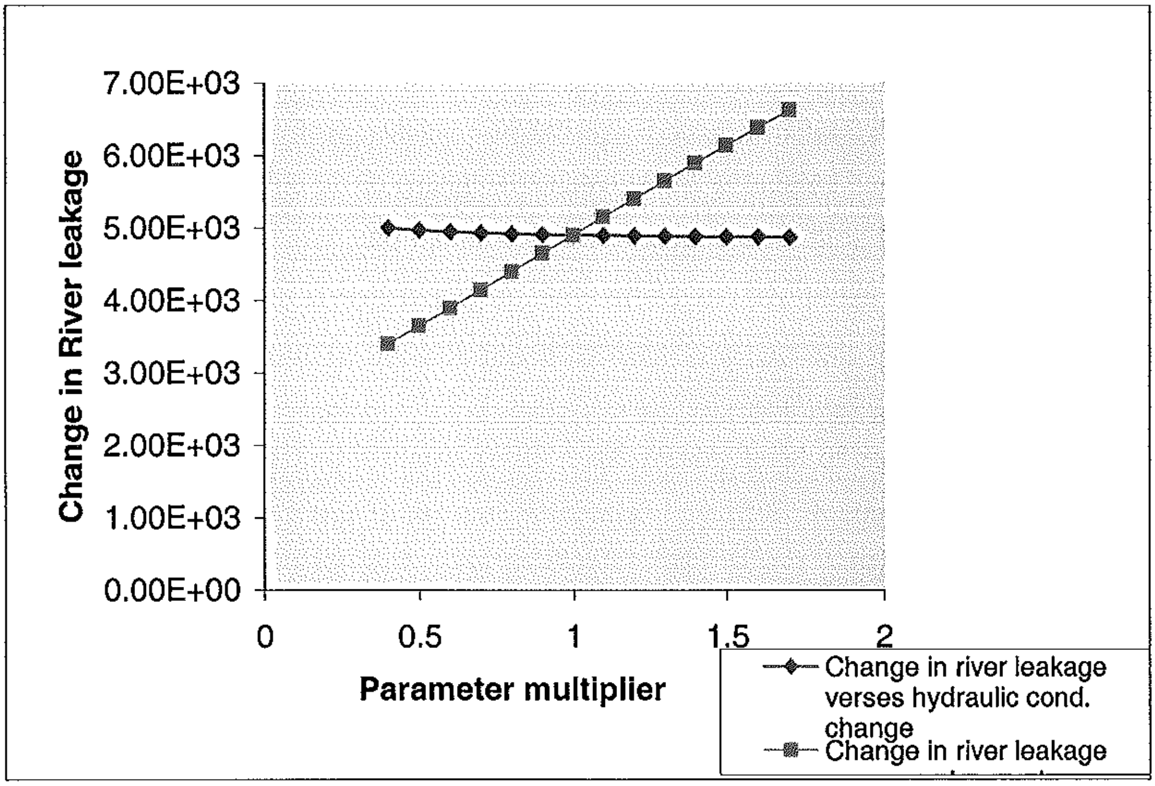


Fig 6.5 Simulated change in River leakage resulting from change in parameter value

6.3 Additional Data Needs and Model limitations

Steady-state simulations do not represent changes in the flow system over time. Annual, seasonal components of flow in response to fluctuations in evapotranspiration and stream flow relate to climatic changes. Some of the data requirements needed to apply the finite-difference numerical analysis are still needed. Future investigations need to include a broader database. The hydrologic analysis of the data limitations includes the lack of information on wells.

Other information required to improve future modeling studies are:

1) Additional water level information in the two lakes and especially for Ardibo lake,

2) The hydraulic head along the southwestern boundary should be taken, and so that the lack of calibration of some water points will be improve.

parameters had the largest effect on simulated head values. The model is considered sensitive to an input parameter when small changes in the value of that parameter result in large changes in simulated head values. Conversely, if large changes in the value of an input parameter result in little or no change simulated in the simulated head, then the model is not sensitive to that parameter, and the model is not useful for refining the initial estimate of the parameter. If the model is sensitive to an input parameter, additional data on that variable can help improve calibration. Increments and decrements of 10 percent were applied to horizontal hydraulic conductivity and rainfall recharge. Sensitivity analyses conducted for horizontal hydraulic conductivity and recharge verify a satisfactory level of calibration. The effect is not the same if net recharge to the area is increased by 10%. Increments and decrements of 10% to any one hydraulic parameter improve neither model calibration nor development. Sensitivity analyses of these parameters indicate simulated heads are mostly sensitive to changes in aquifer recharge and relatively least sensitive to hydraulic conductivity as it is indicated in fig. 6.4.

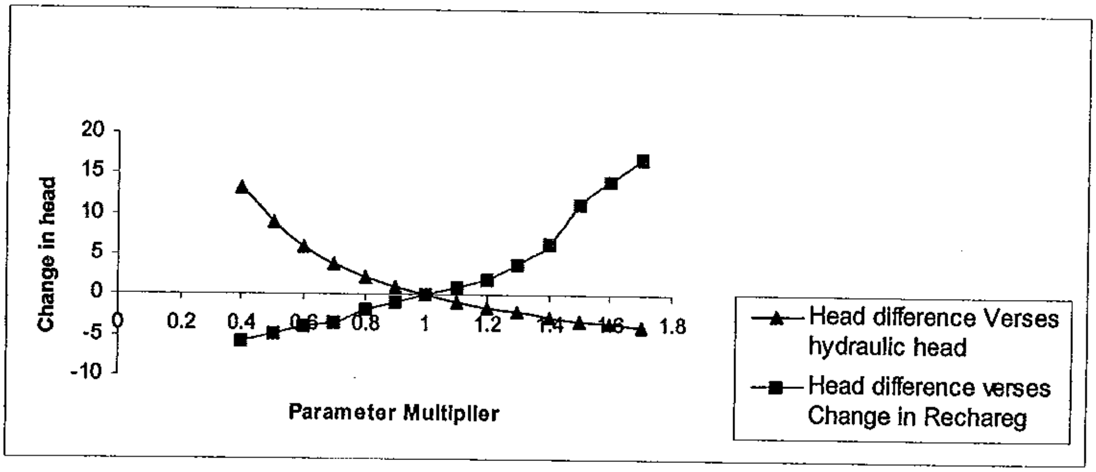


Fig. 6.4 Simulated change in hydraulic head resulting from change in Parameter value

The above fact is strengthening by observing the effect of increasing or decreasing horizontal hydraulic conductivity and recharge against Ankerka river leakage. As the input of horizontal hydraulic conductivity increases the head decreases and less water flows from groundwater to the river but when the recharge input increases the head rises and as a result leakage increases. It is clearly indicated in fig. 6.5 the model is more sensitive to recharge than horizontal hydraulic conductivity.

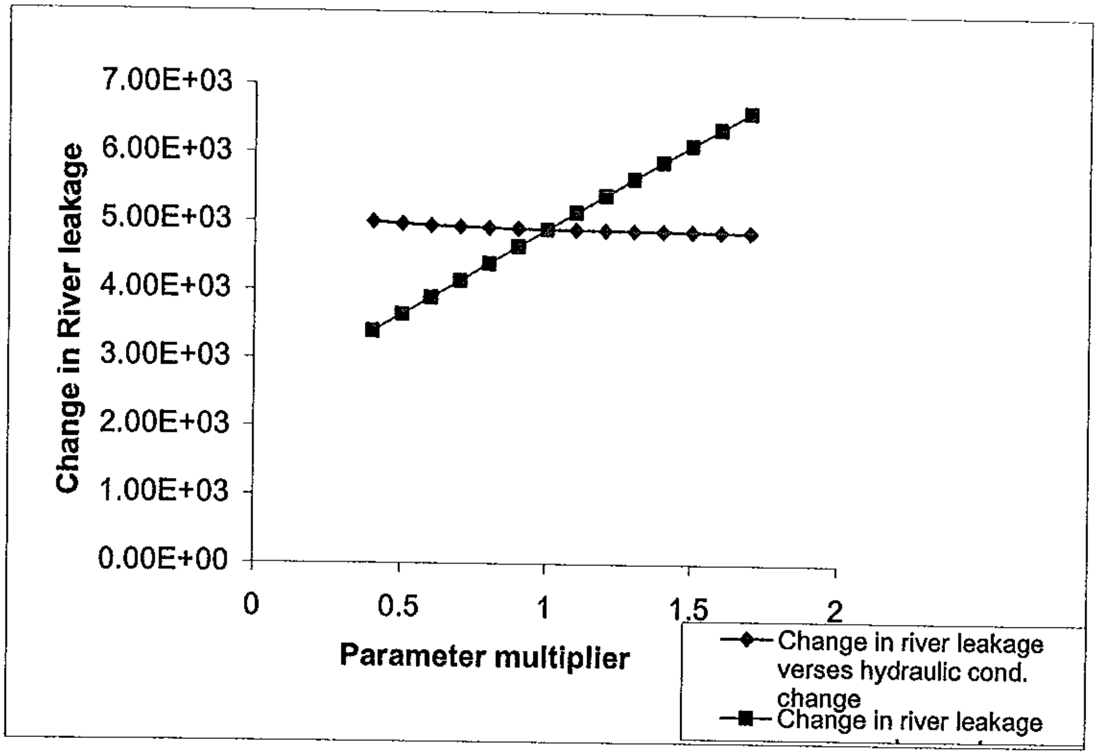


Fig 6.5 Simulated change in River leakage resulting from change in parameter value

6.3 Additional Data Needs and Model limitations

Steady-state simulations do not represent changes in the flow system over time. Annual, seasonal components of flow in response to fluctuations in evapotranspiration and stream flow relate to climatic changes. Some of the data requirements needed to apply the finite-difference numerical analysis are still needed. Future investigations need to include a broader database. The hydrologic analysis of the data limitations includes the lack of information on wells.

Other information required to improve future modeling studies are:

1) Additional water level information in the two lakes and especially for Ardibo lake,

2) The hydraulic head along the southwestern boundary should be taken, and so that the lack of calibration of some water points will be improve.

3) Hydraulic conductivity data should be collected from wells (if possible).

4) If it is not possible to drill wells , it is advisable to drill shallow wells and dug wells to take water level measurements

5) Measurement should be taken at Ankerka River at different points during the dry season and wet seasons.

6) Spring inventory should be taken out side the study area.

7) Spring discharge should be measured at different season of the year.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

8.1 CONCLUSION

The research was undertaken to better understand the hydrogeologic framework of the Hayk - Ardibo catchment. A two-dimensional aerial finite-difference groundwater flow model was used to conceptualize flow conditions and establish a hydrogeologic budget of the region. The catchment is found on the western Rift escarpment, an area with a complex geologic history.

Aquifer recharge areas are generally affiliated with topographic high region of the study area while aquifer discharge areas are found topographically low areas. The depth and extent of groundwater circulation depends on topographic relief.

A Conceptual model was first developed to decide in order to determine the modeling approach. The model boundaries determined to represent natural hydrological boundaries incorporate (1) no-flow boundary along the western, Eastern and Southern boundaries, (2) flux boundary along Northwestern boarder of the study area (3) general head boundary on the two lakes and internal boundary along Ankerka River draining the central catchment

Several simplifying assumptions were made for the conceptualization and simulation of flow in the catchment: 1) Recharge to the groundwater is assumed only from precipitation with in the catchment and there is no additional subsurface inflow across boundary in any part of the study area. Recharge varies spatially, 2) single layer has been used in the model 3) Darcy's law is applicable to represent flow through the fractures and weathered zone in the region, 4) unconfined aquifer is assumed in the model, 5) evaporation was not explicitly simulated in the model. Recharge rates were considered as 'net recharge,' and 6) discharge occurs from the aquifer along the Northwestern boarder of study area where the aquifer is connected to the neighboring aquifer. However, this approach should not be considered as a final tool for interpretation of the simulation results of the Catchment.

e) A summary for the volumetric budget terms for the contribution to groundwater flow components for the study area simulated to be as follows:

Groundwater inflow terms are

Zone 1 Lake Hayk	33803.6 m3/d
Zone 2 Hayk Catchment	17107.9 m3/d
Zone 3 Lake Ardibo	11547.7 m^3/d
Zone 4 Ardibo Catchment	2934.1 m^3/d,
Total	6.5393855E+04 m^3/d

Groundwater outflow terms are:

Flux boundary (Wells)	6.0494727E+04 m^3/d and
River Ankerka	4.8957607E+03 m^3/d
Total	65389 m^3/d

f) Calibrated stream vertical hydraulic conductivity is between 0.01- 0.0001 m/d

g) Sensitivity tests were conducted on net recharge and hydraulic conductivity. Based on the sensitivity analyses performed for this investigation it is apparent that the model is sensitive to changes in recharge and horizontal hydraulic conductivity and, but least sensitive to streambed vertical hydraulic conductivity.

h) From the modeling result the out flow can be assumed that water leaves the Catchment through subsurface and it is around 65389 m^3/day. The irrigation water demand at Hayk lake and Ardibo lake is that 1987.5 m^3/day for 106 ha (18.75 m^3/day /ha) command area and 1350.6 m^3/day for 72 ha irrigable land respectively. There fore the amount of draw dawn from the Lake Hayk and Lake Ardibo is 3.18cm and 3.12 cm respectively, which is 5% of the total annual out put.

I) The model indicates that significant amount of groundwater leaves the lake catchment through its northern ends. If this groundwater is developed somewhere downstream by tracing its flow direction, the output from the lakes catchment can be utilized. However, this requires further investigation in the future including availability of irrigation area. The use of this groundwater will have very low environmental impact as compared to utilizing directly the lake water.

7.2 Recommendations

The results of this modeling study should be used as a guide to the conceptual understanding of the groundwater surface interaction of the Hayk– Ardibo catchment. Future applications of this model depend on its ability to describe the hydraulic behavior of the Hayk–Ardibo catchment. The understanding of the hydrogeologic system was improved substantially after construction and analysis of the groundwater flow model. This approach should not be considered unique or a final tool for interpretation of any hydrogeologic analysis that may follow.

Models are representations useful for guiding further study (Oreskes et al., 1994). Modeling results may be used to indicate where additional data are needed to improve predictions and strengthen conclusions or recommendations to authorities on water resources management issues. The model itself can be utilized as a prediction tool to simulate alternative remedial actions and assist in the long-range management of the region's water resources and increased agricultural acreage in the Hayk-Ardibo catchment. Further investigation into the groundwater flow of the region is required for ongoing improvement of future water resources decisions. The following is a discussion with suggestions for any development entities to improve and propose the water resources management of the Hayk –Ardibo catchment.

a) Drilling of monitoring well and measuring Hydraulic head

In order to fully understand the groundwater model it would be preferable to enrich the model with relevant data, among which the head measurements and hydraulic conductivity test are most important. Wells should be drilled at three places if possible: the first preferred place is on the Northern part of lake Ardibo, the second place is between Lake Hayk and Lake Ardibo and the third is on the Northern part of lake Hayk which would help to get information on the water level and also help to get clues on the direction of groundwater flow with in the catchment.

b) To undertake transient state simulation after collecting all the important data mentioned in recommendation (a) and study how the lake level fluctuation will be affected with season and abstraction of water from the lakes for irrigation, this will help to predict the groundwater system and lake water under different scenario.

c) To conduct further study to trace the outflow direction by using different techniques such as hydrogeological, geophysical and drilling.

d) Investigate the availability of areas to develop the groundwater.

e) After enriching with data to conduct further groundwater modeling including transient simulation in order to understand the lake water and groundwater interaction and to predict the impact of pumping water from the lakes.

f) Scheduling of pumping from lakes

Regulated pumping may be used to control the current extraction of water from lakes in the Catchment to avoid further decline in groundwater and lake level. Systematic pumpage of water from lakes can create favorable condition that would increase the efficiency of using irrigation in the area.

References

1. Admasu Gebeyhue (1996): Hydrological regions in Ethiopia –In Water Resources Management in Drought Prone areas, Italian Cultural Institute. Addis Ababa.
2. Anderson, Marry p., Woessner, William W., 1992, Applied Ground water Modeling, Simulation flow and Advective Transport, Academic press Inc.
3. Fetter, C.W., Jr., 1988, Applied Hydrogeology, Second Edition, University of Wisconsin Oshkosh, Charles E. Merrill Publishing Company, a Bell & Howell company.
4. Freeze, R. Allan / Cherry, John A., 1979, Groundwater. Prentice-Hall, Englewood Cliffs New Jersey 07632..
5. James W. Mercer /Charles R.,- Faust, Geo Trans, Inc. Reston, Virginia 220901981, Groundwater Modeling, National Water Well Association.
6. Ketema Tadesse, (1980): Hydrogeology of the Borkena river catchment: Unpub. M.Sc. Thesis Addis Ababa University, Addis Ababa.
7. Michael G. McDonald and Arien W. Harbaugh, 1988, A Modular three-dimensional Finite Difference Groundwater Flow Model.
8. Molla Demlie, (2000): Hydrology, Hydrogeology and Hydrochemistry of the Lakes system Hayk-Ardibo, Northern Ethiopia. Unpub. M.Sc. Thesis, Addis Ababa, Ethiopia.112pp
9. Neven Kresic, 1977, Quantitative Solutions in Hydrogeology and Groundwater Modeling, America.
10. Ourgie Zeleke, 2002, Three- Dimensional transient groundwater modeling of the Southern Unit of Hanxing Catchment. Unpub. M.Sc. Thesis, Hohai University, china, 81pp
11. Phillip B. Bedient, Hanadi S. Rifai, Charles J. Newell, 1994, Groundwater Water contamination, Transport and Remediation, PTR Prentice Hall, Englewood cliffs, New jersey 07632.
12. Ragunath, H.M, 1996 Ground Water, New Age International Publishers.
13. Ralph C. Heath, 1984, Basic Ground water Hydrology, U.S. Geological Survey Water Supply Paper 2220.

14. Richard L. Cooly, 1974, Finite Element solutions for the equations of Groundwater Flow, Technical report Series H-W, Hydrogeology and Water Resources Publication No.18.

15. Tenalem Ayenew Tegaye, (1998): The hydrogeological systems of the lakes District Catchment, central main Ethiopian rift. PhD. Thesis. ITC, The Netherlands, 256pp.

16. Tesfaye Cherent, (1985): Hydrogeology of Ethiopia Institute of geological surveys, Addis Ababa.

17. Todd.D.K. ((4980) Groundwater hydrogeology 2nd ed John Willey & Sons, Inc. New York, 535pp.

18. UNESCO, (1974) Methods for water balance computations: An international guide for research and practice. The UNESCO press, Paris, 127pp.

19. Zanettin,B., & Justin-Visentin, E., (1974a): The volcanic successionin central Ethiopia. The volcanics of the western Afar and Ethiopian rift margins. Mem. 1st. geo.miner.univ.Padova.31: 20pp.

20. Zanettin,B., & Justin-Visentin, E., (1975):Tectonical and volcanological evolution of western Afar margin(Ethiopia): Pilger, a. & roseler, a. (edit), Afar Depression of Ethiopia. Stuttgart (Schwezerbart).

21. Zanettin,B., Gregnanin, A., & Justin-Visentin, Enicoletti, M., Petrucciani, C., Piccirillo, E.M. & Tolomeo, L., (1974): Migration of the Oligocene-Miocene ignimbritic volanism in the central Ethiopian plateau. N.Jb. Geol.palaont., Mh., 1974:567-574.

22. Zanettin,B., Justin-Visentin, Enicoletti, M., & Piccirillo, E.M., L., (1978):Volcanic succession ,tectonics and magmatology in central Ethiopia. Mem. Acc. Patavina SS. LL.AA.v.90:1-9

Annex

Annex I. Hydrochemistry data

1. Hydrochemistry data of Hayk Lake

No	Easting	Northing	Conductivity	Salinity	TDS (mg/l)	Ph	Remark
1	575087	1252290	868	0.4	415	8.8	
2	575433	1251809	904	0.4	436	8.3	
3	576106	1251954	919	0.4	439	8.5	
4	577578	1251185	900	0.4	431	8.3	
5	579251	1253158	854	0.4	415	8.3	
6	579531	1254925	882	0.4	429	8.4	
7	579236	1256140	888	0.4	422	8.4	
8	578039	1256482	896	0.4	429	8.4	
9	578020	1257042	883	0.4	431	8.4	
10	577076	1255006	895	0.4	426	8.5	
11	575109	1252049	894	0.4	427	8.7	
12	574985	1252535	914	0.4	440	9	
13	575551	1253285	909	0.4	439	9	
14	576244	1253675	905	0.4	435	9	
15	575869	1253777	900	0.4	436	8.9	
16	575487	1254433	900	0.4	436	9	
17	575368	1255204	898	0.4	431	8.9	
18	575323	1256739	900	0.4	433	8.5	
19	575866	1257362	898	0.4	434	8.5	
20	577031	1257717	897	0.4	430	8.5	
21	577785	1256899	908	0.4	437	8.5	
22	577611	1255845	893	0.4	437	8.5	
23	577129	1254060	899	0.4	427	8.5	
24	576893	1252981	904	0.4	434	8.4	
25	576527	1252053	904	0.4	435	8.4	
26	575564	1252026	904	0.4	438	8.5	
Average			935	0.4	431.8	8.6	

2 Hydrochemistry data of Ardibo Lake

No	Easting	Northing	Conductivity	Salinity	TDS (mg/l)	Ph	Remark
1	583081	1245946	567	0.3	277	7.6	
2	582866	1246232	575	0.3	278	7.5	
3	582638	1246463	565	0.3	267	8.1	
4	582437	1247334	575	0.3	277	8.1	
5	582013	1243985	575	0.3	272	7.9	
6	582480	1242166	572	0.3	276	7.9	
7	582634	1240739	577	0.3	257	7.9	
8	583145	1239909	575	0.3	274	7.8	
9	583195	1238408	472	0.2	229	8.4	
10	583846	1239411	575	0.3	277	7.9	
11	585033	1240143	573	0.3	275	8.1	
12	584532	1241022	553	0.3	265	8.2	
13	584848	1242477	579	0.3	277	7.9	
14	584059	1242917	580	0.3	279	8	
15	584159	1243665	580	0.3	277	8	
16	584178	1244642	580	0.3	278	8	
17	583221	1245231	582	0.3	278	8	
18	582908	1245598	584	0.3	280	8	
19	582703	1246042	583	0.3	280	7.9	
Average			569	0.3	272	8	

Annex II. Spring Head Observation and Location data

No	Spring Code	X(Easting)	Y (Northing)	Head Observation	Remark
1	OBS1	581179	1251856	2068	
2	OBS2	581300	1252263	2049	
3	OBS3	580951	1252211	2037	
4	OBS4	578428	1250073	1967	
5	OBS5	581734	1245420	2148	
6	OBS6	581602	1246985	2209	
7	OBS7	577572	1249877	1936	
8	OBS8	576405	1250894	1920	
9	OBS9	574304	1254587	1869	
10	OBS10	574293	1253203	1882	
11	OBS11	574144	1251591	1941	
12	OBS12	574073	1254022	1869	
13	OBS13	577475	1249573	1967	
14	OBS14	578100	1251200	1951	
15	OBS15	574335	1254597	1869	
16	OBS16	574288	1253194	1888.4	
17	OBS17	583727	1249442	2160	
18	OBS18	584992	1246945	2195	
19	OBS19	581352	1240857	2339	
20	OBS20	580798	1243037	2312	

Annex III. Ankerka River-Data Input for river package

No.	Reference	Head in the river in meter	Elevation of the riverbed bottom in meter	Hydraulic conductivity of the river bed in m/day	Width of the rive in meter	Thick ness in meter	Remark
1	1,25,22	1904.5	1904	0.01	18	0.5	
2	1,27,23	1918.5	1918	0.01	13	1.5	
3	,1,28,24,	1926.5	1926	0.0035	13	1.5	
4	1,29,24	1935.5	1935	0.001	13	1.5	
5	1,30,25	1948.5	1984	0.001	5	1.5	
6	1,30,26	1963.5	1963	0.001	5	1.5	
7	1,31.27	1975.5	1975	0.001	5	1.5	
8	1.31.28	1986.5	1986	0.001	5	1.5	
9	1..32..29	2005.5	2005	0.001	5	1.5	
10	1..33..29	2013.5	2013	0.001	2.5	1.5	
11	1.33.31	2034	2033.5	0.0001	2.5	2.5	
12	1.33.32	2040.5	2040	0.00001	2.5	2.5	
13	1,34,33	2048	2047.5	0.0001	2.5	2.5	
14	1,34,34	2055	2024.5	0.0001	2.5	2.5	
15	1,34,35	2062.5	2062	0.0001	2.5	2.5	
16	1,35,36	2070	2069.5	0.0001	2.5	2.5	
17	136,37	2076.5	2076	0.0001	1.9	2.5	
18	1,36,38	2080.5	2080	0.00001	1.9	1	
19	1,38,38	2086.5	2086	0.0001	1.9	1	
20	1,39,39	2090.5	2090	0.0001	1.9	1	
21	1,40,39	2094.5	2094	0.0001	1.9	1	
22	1,41,40	2100.5	2100	0.0001	1.5	1	
23	1,42,41	2102.5	2102	0.00001	1.5	0.5	
24	1,43,41	2104.5	2104	0.0001	1.5	0.5	
25	1,44,41	2107.5	2107	0.0001	1.5	0.5	
26	1,45,42	2110.9	2110	0.0001	1.5	0.5	
27	1,46,42	2111.5	2111	0.0001	1.5	0.5	
28	1,47,43	2114.9	2114.4	0.0001	1.5	0.5	
29	1,47,44	2114.5	2114	0.0001	1.5	0.5	
30	1,48,44	2116	2115.5	0.0001	1.5	0.5	

Annex IV Calculated verses observed head

OBS name, calculated value, observed value,

OBS1	2065.446	2065
OBS2	2056.603	2051
OBS3	2044.019	2040
OBS4	2066.831	2065
OBS5	2147.884	2147
OBS6	2222.416	2218
OBS7	2049.987	2045
OBS8	1918.551	1916
OBS11	1931.444	1936
OBS13	2069.608	2065
OBS14	1941.661	1944
OBS18	2218.059	2212
OBS19	2498.907	2500
OBS20	2432.926	2435

Annex IV. Sensitivity analysis data

Data Observed at OBS8

Parameter multiplier	Head difference due Hydraulic Change	Head difference due Recharge Change
0.4	13.154	-5.806
0.5	8.896	-4.824
0.6	5.99	-3.845
0.7	3.879	-3.474
0.8	2.275	-1.91
0.9	1.016	-0.952
1	0	0
1.1	-0.837	0.944
1.2	-1.538	1.887
1.3	-2.134	2.773
1.4	-2.647	3.751
1.5	-3.093	11.443
1.6	-3.484	14.163
1.7	-3.83	17.011

Head difference observed by varying horizontal hydraulic conductivity and recharge at OBS8.

River leakage

	IN	OUT	IN-OUT		IN	OUT	IN-OUT
0.4	0.00E+00	5.00E+03	-5.00E+03	RIVER LEAKAGE	1.56E+00	3.40E+03	-3.40E+03
0.5	0.00E+00	4.96E+03	-4.96E+03		1.54E+00	3.64E+03	-3.64E+03
0.6	0.00E+00	4.94E+03	-4.94E+03		1.49E+00	3.89E+03	-3.89E+03
0.7	0.00E+00	4.93E+03	-4.93E+03		1.38E-01	4.14E+03	-4.14E+03
0.8	0.00E+00	4.91E+03	-4.91E+03		0.00E+00	4.39E+03	-4.39E+03
0.9	0.00E+00	4.90E+03	-4.90E+03		0.00E+00	4.64E+03	-4.64E+03
1	0.00E+00	4.90E+03	-4.90E+03		0.00E+00	4.90E+03	-4.90E+03
1.1	0.00E+00	4.89E+03	-4.89E+03		0.00E+00	5.15E+03	-5.15E+03
1.2	0.00E+00	4.88E+03	-4.88E+03		0.00E+00	5.39E+03	-5.39E+03
1.3	0.00E+00	4.88E+03	-4.88E+03		0.00E+00	5.64E+03	-5.64E+03
1.4	0.00E+00	4.88E+03	-4.88E+03		0.00E+00	5.89E+03	-5.89E+03
1.5	0.00E+00	4.87E+03	-4.87E+03		0.00E+00	6.13E+03	-6.13E+03
1.6	2.98E-01	4.87E+03	-4.87E+03		0.00E+00	6.38E+03	-6.38E+03
1.7	5.51E-01	4.87E+03	-4.87E+03		0.00E+00	6.62E+03	-6.62E+03

River leakage observed by varying horizontal hydraulic conductivity and recharge

0.4Hyd-OBS			
obsnam,	calculated	value,	Difference
OBS1	2070.594	2024.761	45.833
OBS2	2061.774	2016.621	45.153
OBS3	2049.092	2005.725	43.367
OBS4	2076.155	2009.611	66.544
OBS5	2155.908	2140.237	15.671
OBS6	2233.034	2159.388	73.646
OBS7	2060.434	1991.708	68.726
OBS8	1924.405	1911.251	13.154
OBS11	1934.067	1914.604	19.463
OBS13	2080.962	2003.863	77.099
OBS14	1944.14	1929.507	14.633
OBS17	2230.396	2145.395	85.001
OBS18	2226.992	2160.421	66.571
OBS19	2536.485	2338.775	197.71
OBS20	2466.589	2295.698	170.891
0.5HYDCON_OBS			0
obsnam,	calculated	value,	#VALUE!
OBS1	2056.29	2024.761	31.529
OBS2	2047.658	2016.621	31.037
OBS3	2035.5	2005.725	29.775
OBS4	2055.413	2009.611	45.802
OBS5	2150.827	2140.237	10.59
OBS6	2210.179	2159.388	50.791
OBS7	2039.022	1991.708	47.314
OBS8	1920.147	1911.251	8.896
OBS11	1928.098	1914.604	13.494
OBS13	2057.062	2003.863	53.199
OBS14	1939.442	1929.507	9.935
OBS17	2204.299	2145.395	58.904
OBS18	2206.222	2160.421	45.801
OBS19	2477.898	2338.775	139.123
OBS20	2415.719	2295.698	120.021
0.6HYd			0
obsnam,	calculated	value,	#VALUE!
OBS1	2046.258	2024.761	21.497

OBS2	2037.771	2016.621	21.15
OBS3	2025.997	2005.725	20.272
OBS4	2040.857	2009.611	31.246
OBS5	2147.365	2140.237	7.128
OBS6	2194.092	2159.388	34.704
OBS7	2023.991	1991.708	32.283
OBS8	1917.241	1911.251	5.99
OBS11	1923.725	1914.604	9.121
OBS13	2040.225	2003.863	36.362
OBS14	1936.218	1929.507	6.711
OBS17	2185.787	2145.395	40.392
OBS18	2191.662	2160.421	31.241
OBS19	2435.438	2338.775	96.663
OBS20	2379.03	2295.698	83.332
0.7HYD			0
obsnam,	calculated	value,	#VALUE!
OBS1	2038.815	2024.761	14.054
OBS2	2030.442	2016.621	13.821
OBS3	2018.965	2005.725	13.24
OBS4	2030.051	2009.611	20.44
OBS5	2144.853	2140.237	4.616
OBS6	2182.119	2159.388	22.731
OBS7	2012.83	1991.708	21.122
OBS8	1915.13	1911.251	3.879
OBS11	1920.519	1914.604	5.915
OBS13	2027.687	2003.863	23.824
OBS14	1933.864	1929.507	4.357
OBS17	2171.924	2145.395	26.529
OBS18	2180.629	2160.421	20.208
OBS19	2403.013	2338.775	64.238
OBS20	2351.138	2295.698	55.44
0.8Hydr			0
obsnam,	calculated	value,	#VALUE!
OBS1	2033.07	2024.761	8.309
OBS2	2024.789	2016.621	8.168
OBS3	2013.546	2005.725	7.821
OBS4	2021.7	2009.611	12.089
OBS5	2142.947	2140.237	2.71

OBS6	2172.848	2159.388	13.46
OBS7	2004.201	1991.708	12.493
OBS8	1913.526	1911.251	2.275
OBS11	1918.076	1914.604	3.472
OBS13	2017.97	2003.863	14.107
OBS14	1932.068	1929.507	2.561
OBS17	2161.138	2145.395	15.743
OBS18	2172.532	2160.421	12.111
OBS19	2377.311	2338.775	38.536
OBS20	2329.125	2295.698	33.427
0.9Hyd			0
obsnam,	calculated	value,	#VALUE!
OBS1	2028.494	2024.761	3.733
OBS2	2020.289	2016.621	3.668
OBS3	2009.236	2005.725	3.511
OBS4	2015.044	2009.611	5.433
OBS5	2141.451	2140.237	1.214
OBS6	2165.446	2159.388	6.058
OBS7	1997.323	1991.708	5.615
OBS8	1912.267	1911.251	1.016
OBS11	1916.154	1914.604	1.55
OBS13	2010.21	2003.863	6.347
OBS14	1930.653	1929.507	1.146
OBS17	2152.49	2145.395	7.095
OBS18	2165.897	2160.421	5.476
OBS19	2356.363	2338.775	17.588
OBS20	2311.255	2295.698	15.557
1.0Hydr			0
obsnam,	calculated	value,	#VALUE!
OBS1	2024.761	2024.761	0
OBS2	2016.621	2016.621	0
OBS3	2005.725	2005.725	0
OBS4	2009.611	2009.611	0
OBS5	2140.237	2140.237	0
OBS6	2159.388	2159.388	0
OBS7	1991.708	1991.708	0
OBS8	1911.251	1911.251	0
OBS11	1914.604	1914.604	0

OBS13	2003.863	2003.863	0
OBS14	1929.507	1929.507	0
OBS17	2145.395	2145.395	0
OBS18	2160.421	2160.421	0
OBS19	2338.775	2338.775	0
OBS20	2295.698	2295.698	0
1.1Hydro			0
obsnam,	calculated	value,	#VALUE!
OBS1	2021.658	2024.761	-3.103
OBS2	2013.572	2016.621	-3.049
OBS3	2002.809	2005.725	-2.916
OBS4	2005.091	2009.611	-4.52
OBS5	2139.245	2140.237	-0.992
OBS6	2154.349	2159.388	-5.039
OBS7	1987.036	1991.708	-4.672
OBS8	1910.414	1911.251	-0.837
OBS11	1913.327	1914.604	-1.277
OBS13	1998.573	2003.863	-5.29
OBS14	1928.56	1929.507	-0.947
OBS17	2139.468	2145.395	-5.927
OBS18	2155.991	2160.421	-4.43
OBS19	2323.975	2338.775	-14.8
OBS20	2283.249	2295.698	-12.449
1.2Hydro			0
obsnam,	calculated	value,	#VALUE!
OBS1	2019.036	2024.761	-5.725
OBS2	2010.997	2016.621	-5.624
OBS3	2000.348	2005.725	-5.377
OBS4	2001.27	2009.611	-8.341
OBS5	2138.415	2140.237	-1.822
OBS6	2150.085	2159.388	-9.303
OBS7	1983.085	1991.708	-8.623
OBS8	1909.713	1911.251	-1.538
OBS11	1912.257	1914.604	-2.347
OBS13	1994.095	2003.863	-9.768
OBS14	1927.765	1929.507	-1.742
OBS17	2134.438	2145.395	-10.957
OBS18	2152.194	2160.421	-8.227

OBS19	2311.253	2338.775	-27.522
OBS20	2272.584	2295.698	-23.114
1.3Hydro			0
obsnam,	calculated	value,	#VALUE!
OBS1	2016.791	2024.761	-7.97
OBS2	2008.793	2016.621	-7.828
OBS3	1998.242	2005.725	-7.483
OBS4	1997.996	2009.611	-11.615
OBS5	2137.707	2140.237	-2.53
OBS6	2146.426	2159.388	-12.962
OBS7	1979.7	1991.708	-12.008
OBS8	1909.117	1911.251	-2.134
OBS11	1911.348	1914.604	-3.256
OBS13	1990.254	2003.863	-13.609
OBS14	1927.087	1929.507	-2.42
OBS17	2130.114	2145.395	-15.281
OBS18	2148.944	2160.421	-11.477
OBS19	2300.073	2338.775	-38.702
OBS20	2263.104	2295.698	-32.594
1.4Hydr			0
obsnam,	calculated	value,	#VALUE!
OBS1	2014.847	2024.761	-9.914
OBS2	2006.884	2016.621	-9.737
OBS3	1996.418	2005.725	-9.307
OBS4	1995.159	2009.611	-14.452
OBS5	2137.095	2140.237	-3.142
OBS6	2143.25	2159.388	-16.138
OBS7	1976.766	1991.708	-14.942
OBS8	1908.604	1911.251	-2.647
OBS11	1910.566	1914.604	-4.038
OBS13	1986.921	2003.863	-16.942
OBS14	1926.502	1929.507	-3.005
OBS17	2126.356	2145.395	-19.039
OBS18	2146.08	2160.421	-14.341
OBS19	2290.19	2338.775	-48.585
OBS20	2254.544	2295.698	-41.154
1.5Hydro			0
obsnam,	calculated	value,	#VALUE!

OBS1	2013.146	2024.761	-11.615
OBS2	2005.215	2016.621	-11.406
OBS3	1994.825	2005.725	-10.9
OBS4	1992.677	2009.611	-16.934
OBS5	2136.566	2140.237	-3.671
OBS6	2140.473	2159.388	-18.915
OBS7	1974.199	1991.708	-17.509
OBS8	1908.158	1911.251	-3.093
OBS11	1909.886	1914.604	-4.718
OBS13	1984.002	2003.863	-19.861
OBS14	1925.992	1929.507	-3.515
OBS17	2123.061	2145.395	-22.334
OBS18	2143.623	2160.421	-16.798
OBS19	2281.461	2338.775	-57.314
OBS20	2247.231	2295.698	-48.467
1.6Hydr			0
obsnam,	calculated	value,	#VALUE!
OBS1	2011.647	2024.761	-13.114
OBS2	2003.744	2016.621	-12.877
OBS3	1993.421	2005.725	-12.304
OBS4	1990.486	2009.611	-19.125
OBS5	2136.102	2140.237	-4.135
OBS6	2138.021	2159.388	-21.367
OBS7	1971.934	1991.708	-19.774
OBS8	1907.767	1911.251	-3.484
OBS11	1909.289	1914.604	-5.315
OBS13	1981.424	2003.863	-22.439
OBS14	1925.544	1929.507	-3.963
OBS17	2120.146	2145.395	-25.249
OBS18	2141.5	2160.421	-18.921
OBS19	2272.905	2338.775	-65.87
OBS20	2240.605	2295.698	-55.093
1.7Hydr			0
obsnam,	calculated	value,	#VALUE!
OBS1	2010.312	2024.761	-14.449
OBS2	2002.434	2016.621	-14.187
OBS3	1992.171	2005.725	-13.554
OBS4	1988.537	2009.611	-21.074

OBS5	2135.692	2140.237	-4.545
OBS6	2135.838	2159.388	-23.55
OBS7	1969.919	1991.708	-21.789
OBS8	1907.421	1911.251	-3.83
OBS11	1908.761	1914.604	-5.843
OBS13	1979.129	2003.863	-24.734
OBS14	1925.147	1929.507	-4.36
OBS17	2117.545	2145.395	-27.85
OBS18	2139.571	2160.421	-20.85
OBS19	2265.671	2338.775	-73.104
OBS20	2234.823	2295.698	-60.875
			0

0.4Rech-OBS			0
obsnam,	calculated	value,	#VALUE!
OBS1	1995.988	2024.761	-28.773
OBS2	1988.472	2016.621	-28.149
OBS3	1978.83	2005.725	-26.895
OBS4	1972.955	2009.611	-36.656
OBS5	2133.511	2140.237	-6.726
OBS6	2122.826	2159.388	-36.562
OBS7	1956.119	1991.708	-35.589
OBS8	1905.445	1911.251	-5.806
OBS11	1904.059	1914.604	-10.545
OBS13	1963.651	2003.863	-40.212
OBS14	1920.232	1929.507	-9.275
OBS17	2100.415	2145.395	-44.98
OBS18	2128.132	2160.421	-32.289
OBS19	2227.482	2338.775	-111.293
OBS20	2202.768	2295.698	-92.93
0.5Rech-obs			0
obsnam,	calculated	value,	#VALUE!
OBS1	2000.966	2024.761	-23.795
OBS2	1993.34	2016.621	-23.281
OBS3	1983.476	2005.725	-22.249
OBS4	1979.346	2009.611	-30.265

OBS5	2134.665	2140.237	-5.572
OBS6	2129.241	2159.388	-30.147
OBS7	1962.329	1991.708	-29.379
OBS8	1906.427	1911.251	-4.824
OBS11	1905.843	1914.604	-8.761
OBS13	1970.702	2003.863	-33.161
OBS14	1921.807	1929.507	-7.7
OBS17	2108.358	2145.395	-37.037
OBS18	2132.123	2160.421	-28.298
OBS19	2248.661	2338.775	-90.114
OBS20	2220.91	2295.698	-74.788
0.6REch			0
obsnam,	calculated	value,	#VALUE!
OBS1	2005.887	2024.761	-18.874
OBS2	1998.152	2016.621	-18.469
OBS3	1988.07	2005.725	-17.655
OBS4	1985.65	2009.611	-23.961
OBS5	2135.782	2140.237	-4.455
OBS6	2135.51	2159.388	-23.878
OBS7	1968.45	1991.708	-23.258
OBS8	1907.406	1911.251	-3.845
OBS11	1907.615	1914.604	-6.989
OBS13	1977.64	2003.863	-26.223
OBS14	1923.376	1929.507	-6.131
OBS17	2116.147	2145.395	-29.248
OBS18	2139.256	2160.421	-21.165
OBS19	2268.502	2338.775	-70.273
OBS20	2235.942	2295.698	-59.756
0.7Rech			0
obsnam,	calculated	value,	#VALUE!
OBS1	2010.714	2024.761	-14.047
OBS2	2002.873	2016.621	-13.748
OBS3	1992.58	2005.725	-13.145
OBS4	1991.807	2009.611	42.611
OBS5	2136.91	2140.237	-7.763
OBS6	2141.655	2159.388	-11.418
OBS7	1974.429	1991.708	-1.91
OBS8	1908.377	1911.251	-3.474
OBS11	1909.378	1914.604	-26.396
OBS13	1984.399	2003.863	36.863

OBS6	2170.729	2159.388	11.341
OBS7	2002.754	1991.708	11.046
OBS8	1913.138	1911.251	1.887
OBS11	1918.039	1914.604	3.435
OBS13	2016.254	2003.863	12.391
OBS14	1932.508	1929.507	3.001
OBS17	2159.176	2145.395	13.781
OBS18	2170.538	2160.421	10.117
OBS19	2369.876	2338.775	31.101
OBS20	2322.79	2295.698	27.092
1.3Rech			0
obsnam,	calculated	value,	#VALUE!
OBS1	2038.292	2024.761	13.531
OBS2	2029.865	2016.621	13.244
OBS3	2018.401	2005.725	12.676
OBS4	2026.567	2009.611	16.956
OBS5	2143.512	2140.237	3.275
OBS6	2176.264	2159.388	16.876
OBS7	2008.126	1991.708	16.418
OBS8	1914.024	1911.251	2.773
OBS11	1919.471	1914.604	4.867
OBS13	2022.267	2003.863	18.404
OBS14	1933.993	1929.507	4.486
OBS17	2165.885	2145.395	20.49
OBS18	2175.495	2160.421	15.074
OBS19	2384.643	2338.775	45.868
OBS20	2335.42	2295.698	39.722
1.4Rech			0
obsnam,	calculated	value,	#VALUE!
OBS1	2042.698	2024.761	17.937
OBS2	2034.179	2016.621	17.558
OBS3	2022.532	2005.725	16.807
OBS4	2032.066	2009.611	22.455
OBS5	2144.589	2140.237	4.352
OBS6	2181.718	2159.388	22.33
OBS7	2013.463	1991.708	21.755
OBS8	1915.002	1911.251	3.751
OBS11	1921.437	1914.604	-19.563
OBS13	2028.233	2003.863	61.233
OBS14	1935.471	1929.507	-15.529

OBS17	2172.484	2145.395	12.484
OBS18	2180.296	2160.421	-14.704
OBS19	2398.99	2338.775	5.99
OBS20	2347.721	2295.698	35.721
1.5Rech			0
obsnam,	calculated	value,	#VALUE!
OBS1	2078.319	2024.761	53.558
OBS2	2069.06	2016.621	52.439
OBS3	2055.969	2005.725	50.244
OBS4	2075.917	2009.611	66.306
OBS5	2153.522	2140.237	13.285
OBS6	2225.222	2159.388	65.834
OBS7	2055.854	1991.708	64.146
OBS8	1922.694	1911.251	11.443
OBS11	1935.484	1914.604	20.88
OBS13	2075.38	2003.863	71.517
OBS14	1947.678	1929.507	18.171
OBS17	2224.776	2145.395	79.381
OBS18	2219.495	2160.421	59.074
OBS19	2507.889	2338.775	169.114
OBS20	2441.84	2295.698	146.142
1.6Rech			0
obsnam,	calculated	value,	#VALUE!
OBS1	2090.599	2024.761	65.838
OBS2	2081.088	2016.621	64.467
OBS3	2067.512	2005.725	61.787
OBS4	2090.848	2009.611	81.237
OBS5	2156.687	2140.237	16.45
OBS6	2240.014	2159.388	80.626
OBS7	2070.263	1991.708	78.555
OBS8	1925.414	1911.251	14.163
OBS11	1940.461	1914.604	25.857
OBS13	2091.324	2003.863	87.461
OBS14	1951.989	1929.507	22.482
OBS17	2242.44	2145.395	97.045
OBS18	2233.016	2160.421	72.595
OBS19	2543.193	2338.775	204.418
OBS20	2472.571	2295.698	176.873
1.7Rech			0
obsnam,	calculated	value,	#VALUE!

OBS1	2103.313	2024.761	78.552
OBS2	2093.543	2016.621	76.922
OBS3	2079.471	2005.725	73.746
OBS4	2106.22	2009.611	96.609
OBS5	2160.009	2140.237	19.772
OBS6	2255.237	2159.388	95.849
OBS7	2085.087	1991.708	93.379
OBS8	1928.262	1911.251	17.011
OBS11	1945.677	1914.604	31.073
OBS13	2107.691	2003.863	103.828
OBS14	1956.502	1929.507	26.995
OBS17	2260.571	2145.395	115.176
OBS18	2247.215	2160.421	86.794
OBS19	2578.831	2338.775	240.056
OBS20	2503.673	2295.698	207.975

Head difference observed by varying horizontal hydraulic conductivity and recharge at different springs