ADDIS ABABA UNIVERSITY
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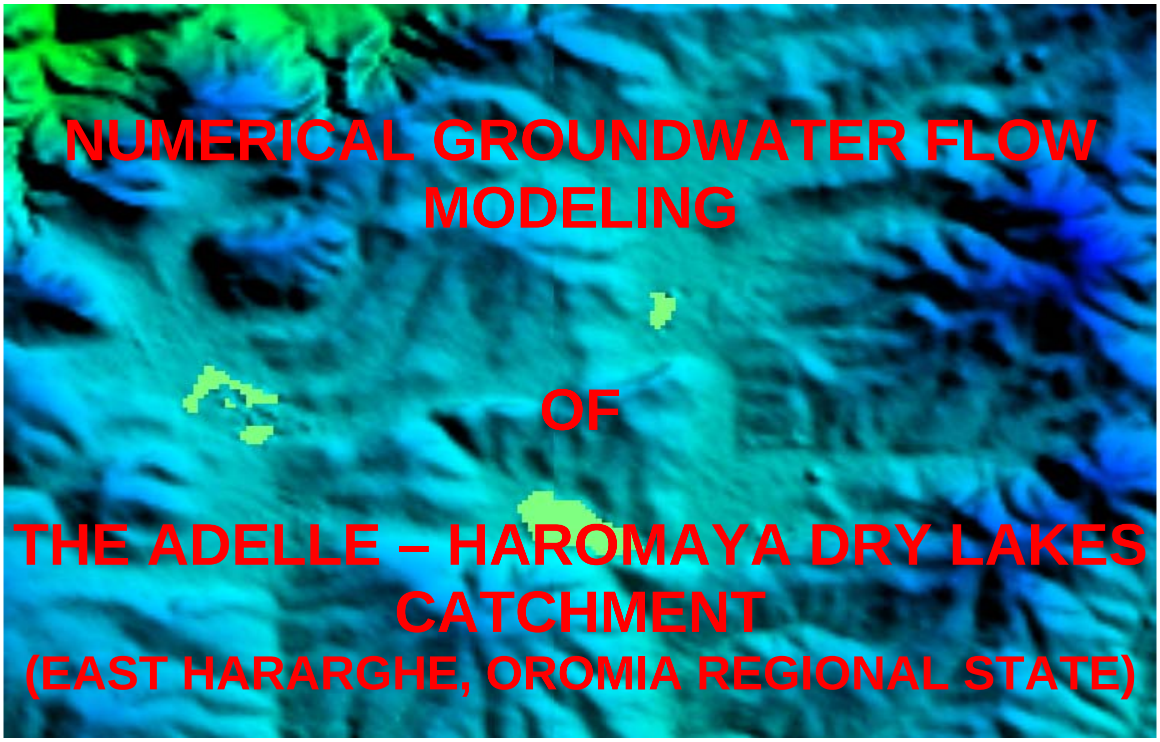
DEPARTMENT OF EARTH SCIENCES



NUMERICAL GROUNDWATER FLOW MODELING

OF

THE ADELLE – HAROMAYA DRY LAKES CATCHMENT
(EAST HARARGHE, OROMIA REGIONAL STATE)

A THESIS SUBMITTED TO THE SCHOOLOF GRADUATE
STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL
FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN HYDROGEOLOGY

GELETU BELAY

JUNE, 2006

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ADDIS ABABA, ETHIOPIA

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Abstract

Groundwater of the Adelle – Haromaya dry lakes catchment, an area of around 240km^2 in Eastern Oromia, is the primary source of drinking water for Harar, Haromaya and Awaday towns, and used also for irrigation and industrial purposes. The demand for this water source is increasing from time to time since the last few years as the surface water source became scarce and rapid population growth.

The groundwater flow system of the area was conceptualized as it consists two aquifers and one confining units, based on the geo-hydrologic properties of the sediments and rocks: the upper low permeability aquifer which includes poorly sorted alluvial sediments, weathered basement complex and weathered and fractured sedimentary formations; the lower high permeability aquifer which consists the well sorted alluvial sediment, and the confining bedrock. The well sorted sandy gravel sediment in the basin is the high yield but localized in the central part of the three watersheds. The poorly sorted alluvial, weathered basement and weathered and fractured Mesozoic formations, found at the outer part of the study area, are low yield aquifers and overlies in most parts the high yield alluvial aquifer.

Groundwater inflow to the area is mostly from infiltration of precipitation surplus left from evapotranspiration, surface runoff and soil moisture deficit to reach the water table. Groundwater outflow of the study area is mostly through withdrawals from wells for water supply, irrigation and industries. Natural discharges by two perennial springs, and seasonal outflows along the streams to the surface water bodies (seasonal lakes) also contribute to the groundwater outflow of the area. The monitored groundwater level and the information obtained from local people showed that groundwater level in Haromaya sub-basin declines starting from the development of wells in the area.

The two-layer steady-state and transient groundwater flow models were developed using the numerical modeling code MODFLOW 96 + interface with advective transport to help better understand the aquifer system, assess the long-term availability of groundwater and evaluate groundwater conditions owing to current pumping and to plan for future water needs. Boundary conditions, hydraulic conductivity, altitude of the bottom of the layers, vertical conductance, storage coefficient, recharge, and discharge were determined from the existing data and estimated from literatures. The models were calibrated to water levels of the Feb, 2006 and drilling report static water levels for steady-state simulation and 13 months water level monitoring data from Feb, 2005 to Feb, 2006 at Harar water supply observation boreholes for transient simulation.

Model calibration was accomplished by varying parameters within plausible range to produce the best fit between simulated and observed hydraulic heads. For steady-state simulation, the root mean square error for simulated hydraulic heads for all wells was 9.038m. Simulated hydraulic heads were within ±10m for observed values of 80% of the wells. For the transient simulation, the difference between the simulated and observed for the four wells was within 10m. The potentiometeric surface calculated by steady-state simulation established initial conditions for the transient simulation.

Water management alternatives were evaluated by simulating scenarios of groundwater pumping for the next five years under two pumping conditions. Result of predictive simulation indicate that in five years, if the pumping condition of Dec, 2005 continues, groundwater decline by around 6m for Haromaya sub-basin which may affect the groundwater flow system of the area.

CHAPTER ONE

1. INTRODUCTION

Adelle – Haromaya dry Lakes catchments is located in Eastern mid-land of Oromia Regional State, Eastern Ethiopia (fig. 1). In recent years, the alluvial aquifer groundwater of this basin became an important source for water supply of Harar, Awaday and Haromaya towns. It is also the source for the rural community of the catchment as water supply and local irrigation. The demand of the groundwater of this area increased from time to time, especially for the last few years. Many boreholes have been drilled in a much localized area of Haromaya Lake sub catchment located in the Eastern part of the study area (fig. 1) which may create stress on the groundwater flow condition of the area.

The reason for the increase of the groundwater demand, as information obtained from the local institutions, is due to the drying of the pre existing Haromaya Lake. This lake previously was the water supply source for the above mentioned towns and local irrigation purpose. As stated by Wagari Furi, 2005 in his “Hydrology of the Dry Lake Haromaya Basin”, the principal loss for the lake was: evaporation, abstraction of water from the lake and siltation, out of which evaporation takes the highest rank (Wagari Furi, 2005).

As the calculated water balance for Haromaya Lake basin show, annual abstraction of the groundwater is by much greater than annual recharge to the aquifer of the basin. Moreover, it was reported that the situation going on with groundwater reservoir in this lake basin is very similar with the situation that was happened to the lake. Currently, aquifers are exploited at much higher rate than their bearing capacity. The groundwater abstraction is by far higher than its recharge. This means that, groundwater is depleting at an alarming rate (Wagari Furi, 2005).

In addition to this research finding, many people including the groundwater user community now days ask questions like: what is the storage capacity of the basin aquifer? For how long can it serve under the existing pumping condition? By how much meter the groundwater of the area depletes every year?

It is this issue, the above mentioned previous work and practical problem, which is the concern of this research project. This research work describes the numerically simulated characteristics of the groundwater flow system of the study area under steady state and transient conditions. Depending on the result obtained from the two types of simulation, reasonable withdrawal system is set under different pumping condition and hydrologic stress.

1.1. Objective of the Study

General objective of the research work is to set the groundwater management system for the Adelle – Haromaya catchment's aquifers by numerical groundwater flow simulation in order to keep the environmental balance of the area. In addition to this it is also to simulate the effect of the pre existing lakes on the groundwater condition of the study area.

The specific objective of the research work was to:

- Conceptually model the aquifer parameters and the hydrologic condition of the study area. This include; estimation of the hydraulic properties of major hydro-geologic units and define and describe different hydro-geologic boundaries.
- Simulate the groundwater flow system of the study area numerically by assigning the conceptual model parameters.
- Calibrate the simulated groundwater head data with the observed head data under steady state and transient conditions.

- Analyze the sensitivity of the model to which parameter or stress the flow condition is sensitive.
- Assign different scenarios for reasonable groundwater abstraction rate.
- Recommend the best groundwater management system for the basin aquifer.
- Determine the aquifer inter-connectivity of the Adelle and Haramaya sub cathments.

1.2. Methodology

Groundwater flow system of the study area was simulated numerically by using a computer code, the U.S. Geological Survey modular three-dimensional finite difference groundwater flow model, MODFLOW (Harbough et al., 2000). MODFLOW input arrays (grided data) that describe hydraulic parameters such as hydraulic conductivity and recharge, top and bottom elevation of the aquifers and boundary conditions.

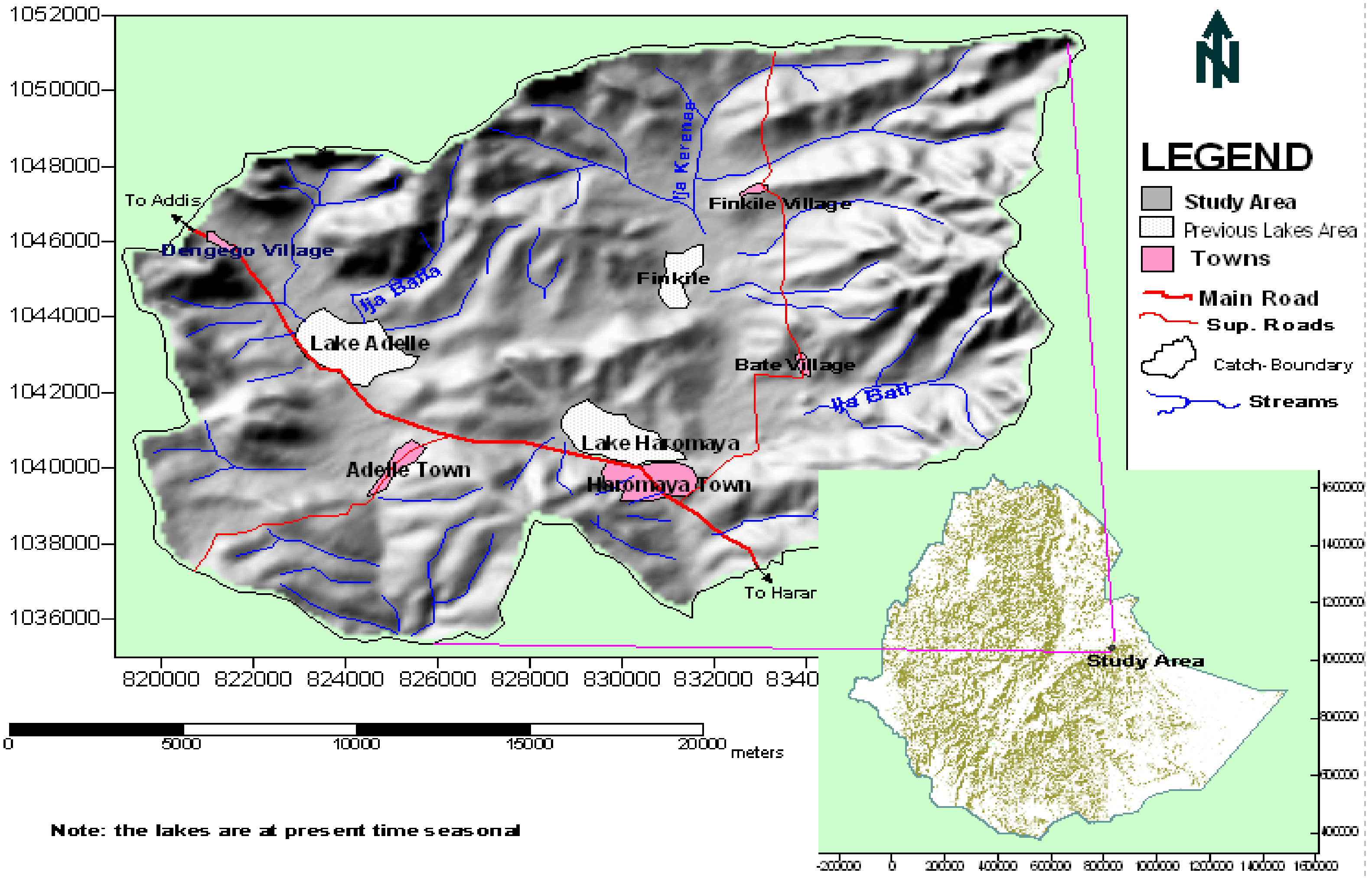
Prior to the construction of the three dimensional groundwater flow model, a conceptual model of the system was developed on the bases of the secondary data collected from different institutions, previous works, field observations and groundwater literatures. By analyzing the collected data, the input parameter for the numerical model was estimated. Different boundary conditions were estimated from physical and hydrogeologic boundaries. Hydraulic parameters such as hydraulic conductivity and storage coefficient were calculated from pumping test data whenever it is available and from literature for the others depending on the aquifer type. Hydraulic head map was established from the water level measured during field data collection and drilling reports. Groundwater recharge was modified from the previous studies and a withdrawal was obtained from daily record of the Town Water Supplies, Industrial uses and local irrigation practices.

After input of the aquifer parameters and hydrologic stresses to the numerical model, the model was calibrated using trial and error method by rearranging the input parameters and stresses within plausible range to get the best fit between the observed and simulated heads. Calibration was done under steady state and transient conditions.

Prediction for future groundwater management condition was done by assigning different aquifer system conditions, hydrologic stresses, and pumping conditions under different scenarios. Finally, the best pumping condition was selected under normal hydrologic stress.

Aquifer inter-connectivity for the three sub catchments; Adelle, Finkile and Haramaya, was checked by simulating the two separately after the assigning of horizontal flow barrier of the MODFLOW package which impede the groundwater flow from one system to the other and compare the results with the existing condition.

Fig. 1 Location Map of the Study Area



Note: the lakes are at present time seasonal

CHAPTER TWO

DESCRIPTION OF THE STUDY AREA

2.1. Location and Areal Extent

Adelle – Haromaya dry lakes catchment is located in Oromia Regional State, Eastern Ethiopia at around 500km from Addis Ababa. It is part of Eastern Ethiopian plateau and extended from the hilly side of Dengego to the West to chain ridges of Damota and Sibilu to the Northeast. Geographically, the area is located between 819000E and 1035000N to 841000E and 1052000N (Datum: UTM, Adindan, Z-37). The area occupies the three lakes watersheds: Haromaya, Adelle and Finkile and covers about 240km^2 (fig. 1).

2.2. Topography and Drainage Basin

Physiographically, the study area is composed of hilly, local ridges and relatively flat terrain at the central part of the lakes basin. Altitude of the area ranges from 1971m above sea level at the floor of Lake Haromaya to 2450m above sea level at high land of Damota.

The Adelle – Haromaya lakes catchment, which is the focus of this report, is located at the upstream part of Wabi Shabale Drainage basin. The catchment area has been divided in to three sub catchments: Haromaya, Adelle and Finkile on the basis of local depressions separated by surface water divides (fig_2). Among these local sub catchments, the largest is the Adelle Lake sub catchment, which covers 40% of the study area and the least is Haromaya Lake sub catchment, which covers 27.5% of the study area; Finkile sub-catchment also covers 32.5%.

The slope, landform and the configuration of hills and peaks surrounding the study area, have created a drainage network, which takes the surface flow towards the three lakes separately. But, as information obtained from the local community and other institutions, previously there was the surface interconnection between Lakes Haromaya and Finkile by the overflow from Finkile. There are also local depressions between Adelle and Finkile and South of Haromaya which have their own surface watersheds. But, by this study, they are included in one of the major three sub basins and treated as part of the sub-basins.

The major streams of the catchment area are: Lega Ambo, Lega Bati, Lega Hida, Lega Burqa, Ija Kerensa and Ija Balla. Characteristically, all of them are seasonal streams supplied water from rain through rill lines, gully lines, ephemerals, road channels and sometimes directly from overland flows of adjacent farmlands (Wagari Furi, 2005).

2.3. Land Use and Climate

Agriculture is the primary land use within the study area where crop production is the main agricultural activity. Most land is used for crops and permanent plants which include: sorghum, maize, chat and vegetables. Most of the farmland, which located in the gentle slope alluvial cover part of the study area, is used for crops and vegetables whereas the slightly hilly side of weathered basement part is covered by chat.

The land use practice of the study area (as stated by Wagari Furi, 2005) had brought negative impact on soil conservation and management. He stated that, high population increase over the limited land area in the northern high land of the study area, including Haromaya dry Lake Basin, resulted in the indiscriminate forest clearing, overgrazing, absence of soil conservation and poor soil management and land use practice and poor land tillage that prone to siltation process coupled with the erosive nature of the land have caused much amount of soil erosion to be carried and deposited in the lakes floor.

The climate of the study area is semi arid where the average annual precipitation of 25 years (1979 – 2005) recorded at Haromaya station is 770.5mm. Maximum precipitation occurs in April, August and September with the highest peak in August (150.8mm) while the minimum in December (7.3mm). Average temperature is 16.35^0C and it ranges from 12.8^0C in December to 18.9^0C in June. Actual evapotranspiration (as estimated by Wagari Furi, 2005) is 641.1mm/year, which show that, more than 80% of the total annual precipitation goes to evapo-transpiration (table 4 and 5). The actual evapotranspiration, which calculated by another person for Haromaya sub-basin is around 594.5mm/year and shows the 77% of annual precipitation goes to evapotranspiration (table 1).

Table 1. Long term Average monthly Precipitation (1979 – 2005) and calculated AET for Haromaya Lake Catchment, recorded at Haromaya Station; units are in mm depth (from Abdulaziz, Mohammed, 2006).

	Month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
P	12.1	19.5	53.7	108.5	108.2	45.5	95.1	150.8	113.8	40.6	15.4	7.3	770.5
PET	66.1	73.4	87.5	85.5	92.2	87.9	82.8	83.9	79.3	72.8	63.5	60.5	935.5
AET	8.6	17.3	53.7	75.1	75.9	50.9	70.5	83.4	79.3	63.4	12.9	3.8	594.6

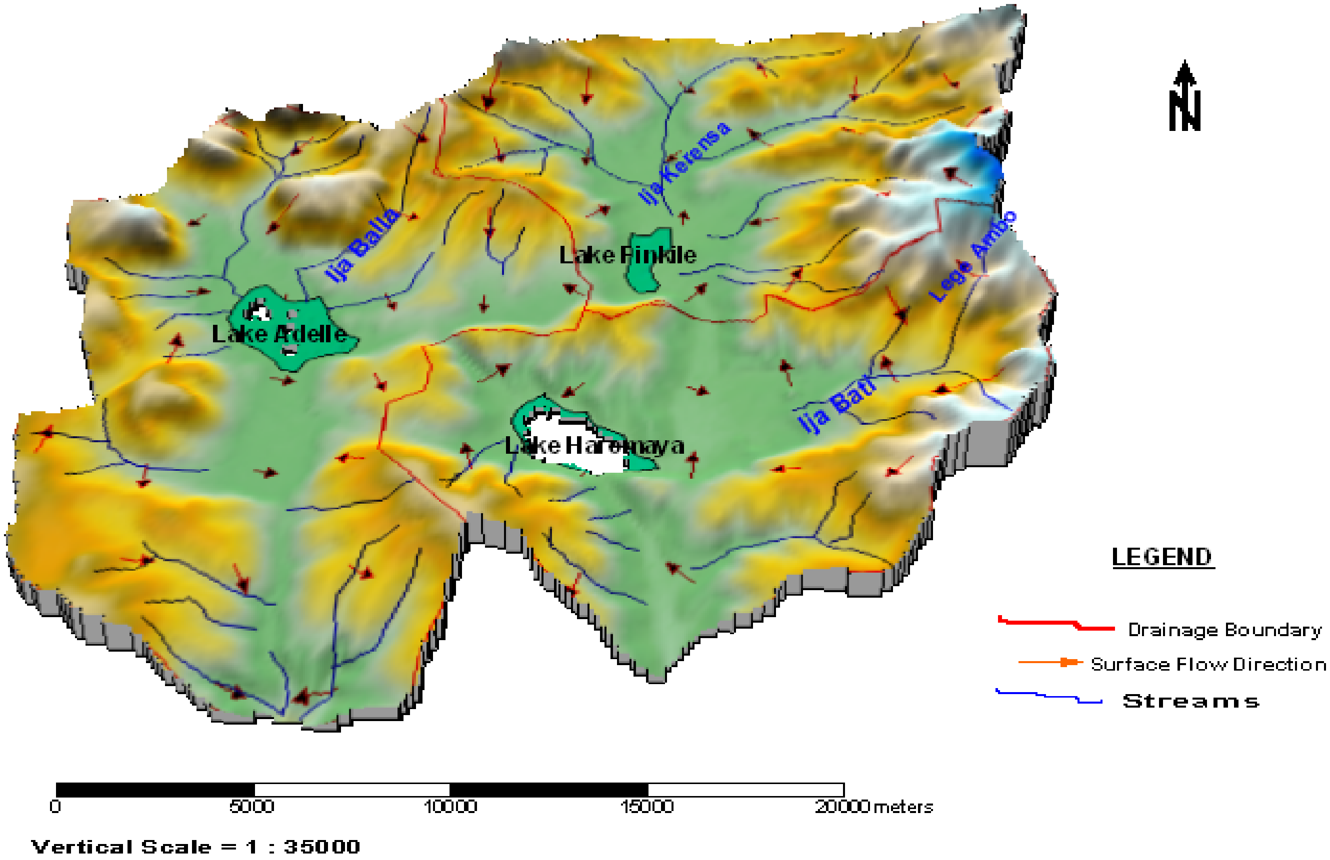


Figure 2. Drainage Map of the Study Area

Note: the lakes are at present time seasonal.

2.4. Regional Geologic Setting

The geomorphology of the regional basin (Wabi Shebele Basin) is closely linked to the nature of its geological formations, according to the Geological Map of Ethiopia and Wabi Shebele Basin Master plan study. The following large morphological regions can be identified in the basin.

- The Northwest and Northern limit of basin covered by large tabular basaltic plateaus, Garamuleta area of East hararghe Zone;
- In the North and Northeast of the basin (in the vicinity of Harar town) the formation is Precambrian mass. The erosion of these crystalline formations has resulted in the formation of important glaciers (Alemaya Region).

Generally, the stratigraphic sections from older to younger formations are as follows:-

The Archaen complex (Alghe and Mormora group), Mesozoic Sedimentary rocks (Adigrat, Hamanilei and Urandab, Amba Aradom formations) and Tertiary volcanic rocks (Ashanghe basalt).

2.4.1. Precambrian Complex

The Archaen Complex, Alghe Group(ARI), consisting of dominantly gray biotite hornblende gneiss and granulate of variable color, in part consisting well defined mass of relatively uniform ortho gneiss of granodioritic, tonalitic and diorite composition. These rocks occur in Harar region, granitic and biotitic gneiss, sometimes highly weathered is outcropped in the vicinity of Harar town (Mengesha and Berhe, 1989). Mormora Group (APRIr) is represented by several thousands of meters thick psamitic and pelitic assemblages (biotite gneiss, graphitic and micaceous schist and marble) with frequent development of kyanite, staurolite and garnet (Kazmin, 1972). Rocks of possibly early or middle proterozoic age, Wadera and Mormora groups, have been identified in Hararghe Zone (Biotite gneiss).

2.4.2. Late Paleozoic and Mesozoic Sedimentary Rocks

Medium to coarse grained yellow sandstone, grit and shale of Wayu sandstone fill channels in the Precambrian basement complex extending across the present day Jerjertu, Ramis and Soka valleys in Hararghe area (Mohr, 1963, Kazmin, 1975). These areas are located in the Southwest of the study area. The rock unit is unconformably overlain by Adigrat sandstone formation. The presence of silicified wood suggests late Paleozoic continental erosion and deposition.

The Adigrat formation (Ja) (Dow et al, 1971, Garland, 1980), which varies in thickness from few meters to 800meters, was originally named as Adigrat Sandstone after the Adigrat town in Tigray region and includes the whole succession of classic rocks resting un conformably on the Precambrian basement and overlain conformably by the Antalo formation (Jt) (Bladford, 1870). The Adigrat formation in Harar – Dire Dawa area is overlain by Hamanilei formation (Jh) (Mohr, 1965, Kazmin, 1972). This formation is cropped out in the study area forming hills. Adigrat formation chiefly comprises sandstone with minor lenses of siltstone, conglomerate and laterite up to two meters thickness (Garland, 1972). The formation typically ranges from yellowish to pink with a laterized top to a depth of 20 meters and composed of fine to medium grained well sorted cross bedded quartz sandstone.

In Harar – Dire Dawa areas, the sandstone which lies between the Precambrian basement rock and Hamanilei formation (Jh) is conglomerated and it ranges from poorly to moderately soredt. It is non calcareous except where it is the top near the contact with the overlying Hamanilei formation (Jh) where thin bed of limestone have developed. The Hamanilei Formation (Jh) is used for the fossiliferous limestone of Jurassic age of Southeastern Ethiopia. The Hamanilei formation consists of predominantly of limestone and dolomite exposed in wide areas of Hararghe. This formation has gradational contact with the underlying Adigrat formation (Ja) and overlying Urandab formation (Ju). This formation is exposed around the study area South of Harar and Garamuleta area.

A succession consisting of black shale, marl and gypsiferous limestone, Urandab formation (Ju), comparable in age with Antalo formation, occurs in Eastern part of the country. The unit consists of abundant micro fossil on the basis of which the formation is assigned on age of Oxfordian-Kimeridian. In the

East Hararghe zone 95 meters thick of brown marly limestone with alternating clay is included with the Urandab formation. The Urandab formation rests on the washed-out surface of the upper part of the Hamanilei formation.

Amba Aradom formation (Ka) occurs in Eastern Hararghe around Garamuleta area. The formation consists of sandstone, shale and marl. In this area it lies unconformably on the Jurassic sediments, namely; It and/or Ja and Ju and/or Jh (Mehade, 1968, Greitzer, 1970, Kazmin, 1975).

2.4.3. Tertiary Volcanic Rocks

The Cenozoic volcanic rocks of Ethiopia were divided to the Trap Series and Aden Series by (Mohr, 1962). Trap Series is still widely used to represent the whole pile of the tertiary flood basalt sequence with intercalation of silicic rocks (commonly on the upper part). The Ashangi basalt represents the earliest fissural flood basalt volcanism on the northwestern plateau. However, basalt flows and tuffs inter bedded in Jurassic and Cretaceous sediments have also been mapped in the Kulubi – Dire Dawa area on the Southeastern plateau (Merla et al, 1973). This rock unit is exposed widely in Garamuleta area.

CHAPTER THREE

CONCEPTUAL MODEL

A conceptual model is a pictorial representation of groundwater flow system, frequently in the form of a cross section. The nature of the conceptual model will determine the dimension of the numerical model and the design of the grid (Anderson and Woessner, 1992).

Prior to simulating the groundwater flow system, a conceptualization of the system is essential because it forms the basis for model development. The conceptualization is a necessary simplification of the natural system because inclusion of all of the complexities of the natural system in to a computer model is not feasible given the existing knowledge of the subsurface and current computer capabilities. Steps in the development of conceptual model in Adelle – Haromaya dry lakes catchment includes: 1) Definition of geologic setting, aquifer and confining units, 2) identification of the hydraulic characteristics of the aquifer, 3) identification of sources and Sinks of water and 4) identification and delineation of hydrologic boundaries encompassing the area of interest. An understanding of these characteristics is important in determining the occurrence and availability of groundwater in the given hydro-geologic basin.

3.1. Local Geologic Setting

Geology of the study area can be grouped in to three types of formations: Precambrian basement Complex which is exposed as a bed rock, Mesozoic Sedimentary Formation which composes sandstone and limestone and valley filled alluvial sediments (fig. 3 and 4).

The Precambrian basement rock of the study area consist granite pegmatite rocks that penetrate gneissic rocks and cover the hilly side of the area which has 56.7sq. km area coverage. This rock unit underlies the unconsolidated alluvial materials and the Mesozoic formation. As it is observed at outcrops and from drilling samples, the formation has weathered thickness not more than 20m but, in some areas, as information obtained from hand-dug well logs in west of Haromaya town, the weathered thickness reaches 40m. The degree of fracturing is less in most of the formation except the local fractures.

The Mesozoic formation of the area consist two types of rocks: the lower Sandstone unit (Adigrat Sandstone) and the Limestone unit (Hamaniel formation).

The lower sandstone unit (Adigrat formation) is formed during the beginning of Mesozoic era when subsidence of landmass and uplift of sea floor occurred. This caused the inflow of sea water in to the landmass transporting surface materials from which this rock unit was formed. The unit is characterized by having quartz as cementing material with variegated quartz sandstone, intercalation of laminated shale, bedded siltstone and intra-formation of conglomeratic beds. The rock is found overlying unconformable the basement complex and exposure is well identified as a hill forming in the Western, Northern and Northeastern part of the study area. At the study area, the thickness of this formation ranges from 20m in the Northern part to 60m in the north Eastern part. At its top part, where it contacts with Hamanielei formation, the formation ranges to siltstone and marl. The areal coverage of this rock is 22.3sq.km.

The Hamaniel formation has an areal coverage of 25.7sq.km at the study area. The major rock of this formation is limestone which outcrops at the mountainous part of the study area.

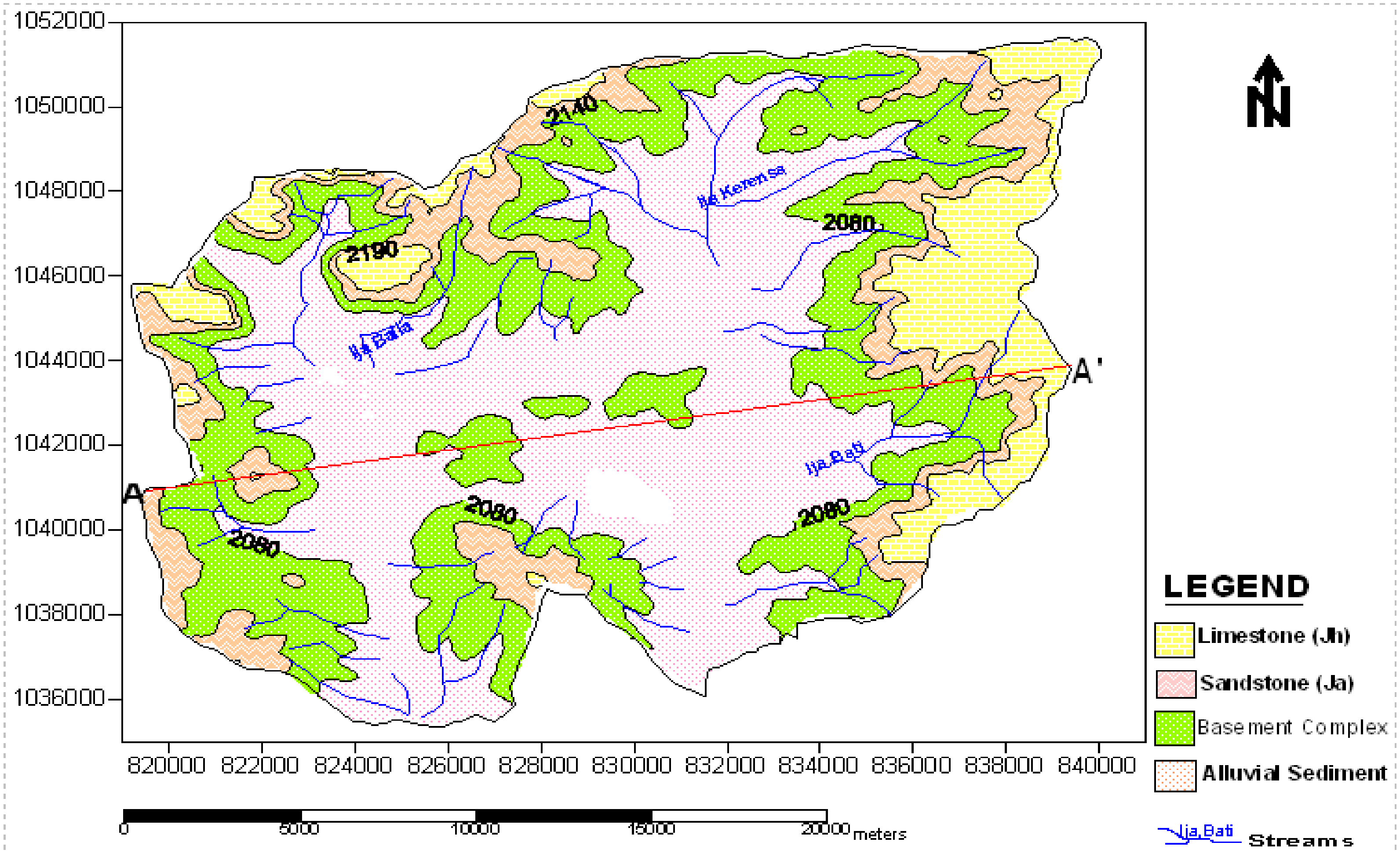


Fig. 3 Surficial Geologic Map of the Study Area

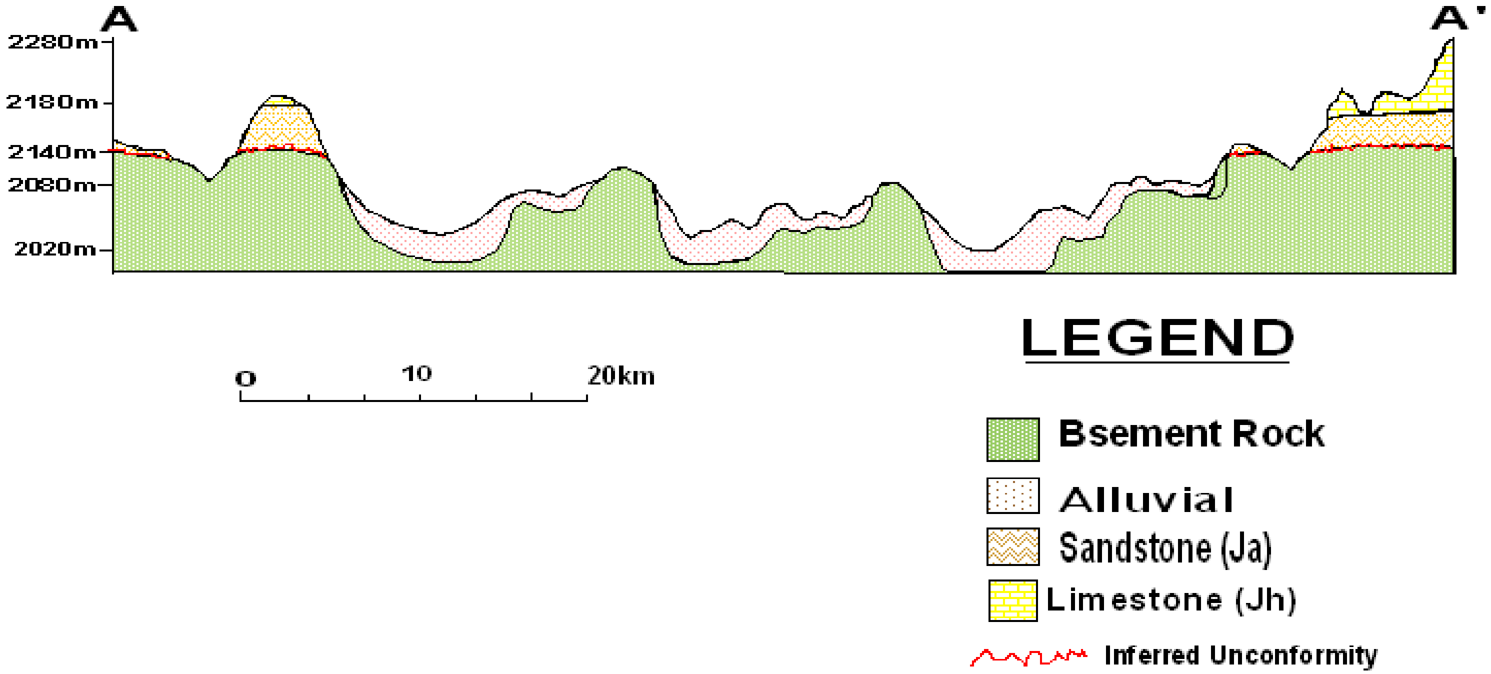


Figure 4. Geological Cross-section of the Study Area along Line A-A' of figure 3.

The alluvial and lacustrine sediment of the area covers the flat surface of the lakes basin. The unit consist mostly of stratified silt, sand, sandy gravel and minor amount of clay at the dry lakes floor. The thickness of this unit generally ranges from 1m at the hilly parts to 60m at the center of the lakes basin. The unit covers an area of 140.4sq.km.

In the study area, there is no identified geological structure except the stratification of the Mesozoic sedimentary rocks which is horizontal. But, some local fractures are observed on weathering resistant basement complex and hill forming limestone.

3.2. Hydrogeologic Setting

The surface geologic units described previously and the deposits at depth were differentiated in to aquifers and confining units on the basis of areal extent and general water bearing characteristics. An aquifer is a saturated geologic material that is sufficiently permeable to yield water in significant quantities to a well or spring, whereas a confining unit has low permeability that restricts the movement of groundwater and limits the usefulness of the unit as a source of water supply. Permeability generally is higher in well sorted, coarse grained deposits than fine grained or poorly sorted deposits.

Igneous and metamorphic rocks (Granite, gneiss etc.) yield reasonable (but still moderate) amount of groundwater only when fractured by faulting or weathering. Davis and Turk (1964) found that most of the interstitial openings in various types of jointed and faulted crystalline rocks occurred within a depth of about 30m.

Aquifers of unconsolidated or non indurate materials, such as alluvial, glacial or Aeolian deposits, are among the most common sources of groundwater. In alluvial or glacial deposits, buried valleys or old stream beds offer the best groundwater potential. These are ancient stream beds or valleys, primarily consisting of sand and gravel that have been covered by finer sediments (glacial till for example). Because of erosion, bed rock tends to be depressed below unconsolidated sediments of ancestral streams (Bouwer, 19780).

In the Adelle – Haromaya dry lakes catchment, saturated coarse grained deposits form high productivity aquifers whereas, the poorly sorted silty sand and clay materials as well as the fractured and weathered basement including fractured and weathered sandstone and limestone, form low productivity aquifers. The un-weathered part of the basement rock is taken as confining unit due to its very low to no permeability.

Based on the lithologic description obtained from 12 borehole logs, different hand dug wells and 10 Vertical Electrical Sounding geophysical survey results in the study area, three principal hydrogeologic units are recognized by grouping lithologies of similar permeability. These are:

- The Upper Low Permeability Aquifer (ULPA)
- The Lower High Permeability Aquifer (LHPA)
- Bed Rock (BR)

The Upper Low Permeability Aquifer (ULPA) comprises mostly of clay and silty sand which is poorly sorted, and highly to moderately weathered and fractured basement complex with Mesozoic formations. This hydrogeologic unit almost covers the surface part of the study area including the hilly parts, where limestone and sandstone are exposed. Vertical thickness of the unit ranges from 4 meters at the dry lakes floor to 300 meters where the weathered basement complex is underlain the Mesozoic formation. Even though the permeability is different for silty, clayey sand which is poorly sorted and weathered and fractured rocks, it is grouped as a single hydogeologic unit since both have low permeability. Many hand dug wells were constructed in this aquifer unit which used for water supply and some for irrigation purposes. All hand dug wells have very low yield which ranges from 0.1 to

0.5 lit/sec. But, the two springs emerged from the Limestone of the Damota area have around 2 lit/sec. discharge.

The Lower High Permeability Aquifer (LHPA) of the study area generally comprises saturated gravely sand and sandy gravel, which is well sorted. It is assumed to be confined as analyzed from the pumping test data of the boreholes drilled in the area. The unit is underlain by the regional bed rock and overlain by the upper low permeability aquifer in most areas. The aquifer unit is extended in the study area from dry Lake Haromaya to Finkile where many high productivity deep wells were drilled and to some part of Adelle. The groundwater of this aquifer unit is used for many town water supplies and industries. The estimated average thickness of this unit is around 80 meters.

The Bed Rock (BR) unit underlies all the above described hydrogeolocic units in the study area is granitic nature. This unit is slightly to moderately weathered at its upper part where it is exposed to the surface and assumed as low permeability aquifer unit whereas, in areas where it underlies the upper and lower hydrogeologic units, as observed from drilling geologic logs, is mostly fresh granite, it is assumed to be the lower confining unit.

The lithologic and hydrologic characteristics of the hydrogeologic units are summarized in (fig. 6) and a simplified conceptual model of the hydrogeologic system of the study area is presented in (fig. 5).

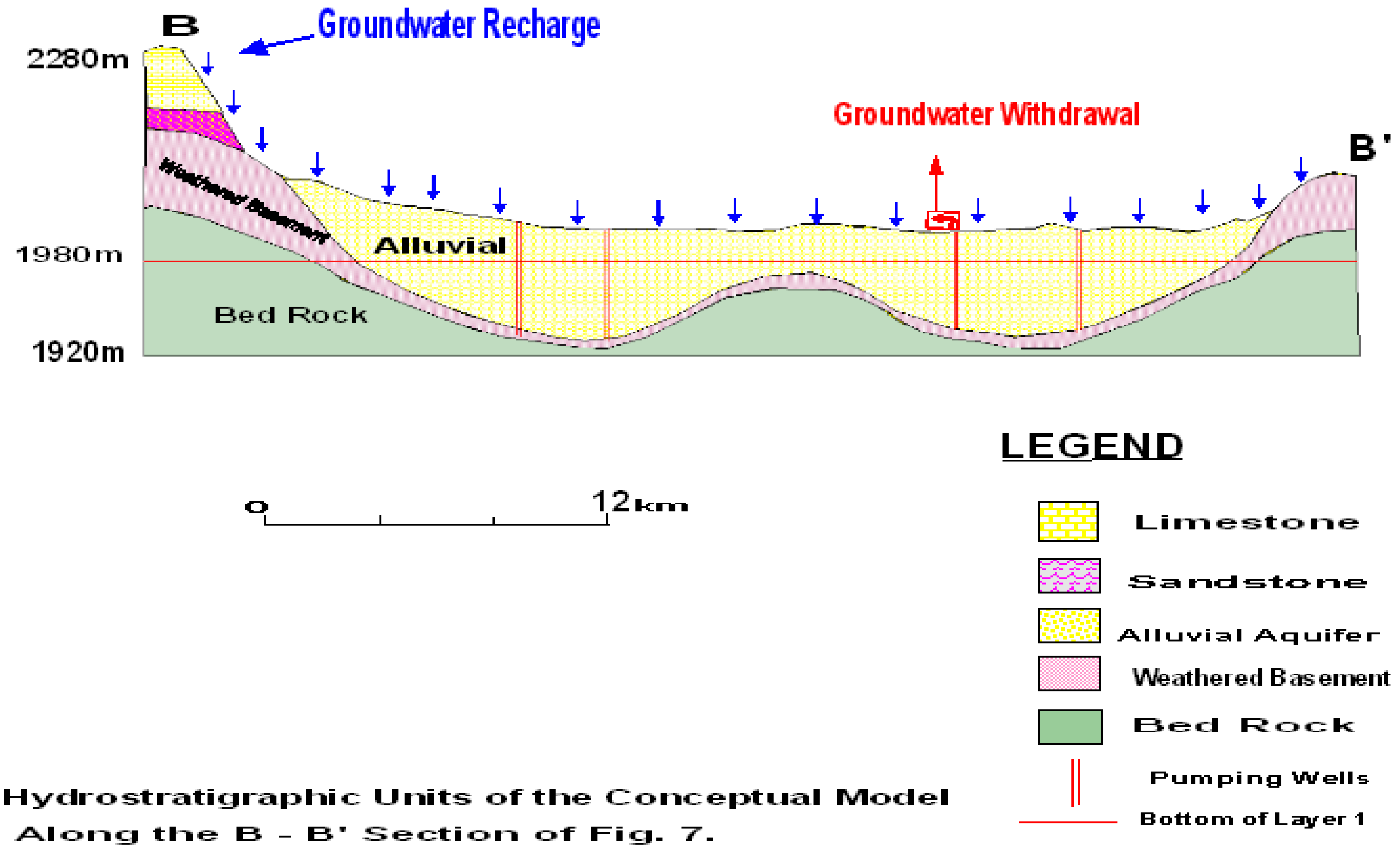


Fig 5. Hydrostratigraphic Units of the Conceptual Model Along the B - B' Section of Fig. 7.

S/N	Hydrogeologic Unit	Unit Lable	Range of Thickness (m)	Lithologic and Hydrogeologic Characteristics
1	The Upper Low Permeability Aquifer	ULPA	4 – 32 [20] for alluvial And 20 – 250 for weathered rocks with average 50	Unconfined low permeability aquifer consisting of poorly sorted clay, silt and sand for alluvial sediments and slightly to moderately weathered granite. The unit generally covers most part of the study area where the central part is covered by alluvial sediments and the weathered granite covers the hilly sides following the limestone and sandstone formations.
2	The Lower High Permeability Aquifer	LHPA	40 – 80 [60]	High permeability, probably confined aquifer consisting of mostly of sand and gravel with some silt. The unit occurs in the central part of the study area underlying the upper low permeability aquifer of alluvial sediment. It is elongated between the two dry lakes of Haromaya and Finkile where the thickness is gradually increases towards north except with few interruption near the surface divides of the two lakes. The unit becomes shallow and minimum in thickness at Adelle dry lake watershed.
3	Bed Rock	BR	-	The unit consists of weathered, fractured and fresh granite.

Fig. 6 Aquifer units and their lithologial description

3.3. Hydraulic Properties

The hydraulic conductivity of the material in an aquifer or confining unit is a measure of the ease with which water can move through the material. It is a function of properties of both the matrix and fluid. Water in the regional flow system was assumed to have a uniform density and viscosity, and thus the hydraulic conductivity only varies as the grain size, shape, sorting and packing vary (Freeze and Cherry, 1979). Because matrix properties may vary over short distances, the hydraulic conductivities also may vary over short distances.

Horizontal hydraulic conductivities generally were greater than vertical hydraulic conductivities, as a result of the depositional history of the sediments. Horizontal hydraulic conductivity may be determined from single or multiple – well aquifer tests. Horizontal hydraulic conductivity was estimated for the hydrogeologic units of the study area on the base of available groundwater literature and analysis of existing pumping test records of aquifer tests.

The hydraulic property of the upper low permeability aquifer of the study area is estimated from literature. The hydraulic conductivity, transmissivity and Specific Yield and/or storage coefficient of poorly sorted alluvial aquifers and fractured as well as weathered rocks is estimated by different literatures such as Davis and De Wiest, 1966; Driscoll, 1986; Freeze and Cherry, 1979; Fetter, 1994; Todd, 1980; Zekai Sen, 1995; Heath, 1983 and others.

Large number of studies has been made of water bearing properties of alluvium from normal system valleys. Fine grained sediments are rarely impermeable if judged by the standards used by petroleum industry. Silts and loosely compacted clays will have permeabilities of at least few millidarcy and in many sediments the permeability will be several milli darcys (1 darcy = 0.987cm^2).

Some of the permeability can be explained on the basis of an open structure of original clay and silt aggregates. Most of the permeability, however, is probably owing to secondary structures such as root holes, warm burrows and desiccation cracks. Most test of water bearing zones with in alluvial sediments indicates permeability of between 10 to 100 Darcy's (Davis and De Wiest, 1966). The range of hydraulic conductivity for unconsolidated materials of silt, sandy silt, clayey sand and till is from 10^{-6} – 10^{-4} cm/sec. (1 cm/sec = 864 m/day) (Fetter, 1994). Hydraulic conductivity varies over a very wide range for different geological materials. The range of conductivity for unconsolidated deposits of silt and clayey sand is from 10^{-5} -10^{-2} cm/sec. and for fractured and weathered igneous and metamorphic rocks is from 10^{-6} – 10^{-2} cm/sec. (Freeze and Cherry, 1979). Ranges of values of hydraulic conductivity for silty sand silt loess is from 10^{-3} - 1 m/day and for fractured igneous and metamorphic rocks is from 10^{-4} – 10^{-1} (Heath, 1983).

From the above ranges of hydraulic conductivity for poorly sorted alluvial materials and weathered basement, it is concluded that the value ranges from 10^{-5} - 10^{0} m/day for unconsolidated material with mean of 10^{-2} m/day and for fractured and weathered basement complex, it is estimated that the range is from 10^{-5} – 10^{-1} m/day with mean of 10^{-3} m/day; for carbonate rocks and sandstone the value ranges from 10^{-3} to 10^{3} (table. 2).

Table 2. Horizontal Hydraulic Conductivity for Clay, Silt, Sand, Gravel, Carbonate rocks, Sandstone and Igneous and Metamorphic rocks.
[Freeze and Cherry, 1979; Driscoll, 1986; and Heath, 1983; units in meter/ day]

Lithology	Horizontal Hydraulic Conductivity Ranges in meter per day
Clay	10^{-7} to 10^{-4}
Silt	10^{-4} to 1
Sand	10^{-2} to 10^{3}
Gravel	10^{2} to 10^{5}
Carbonate Rocks	10^{-4} to 10^{3}
Sandstone	10^{-5} to 1
Igneous and metamorphic rocks	10^{-8} to 10^{1}

Generally, the average hydraulic conductivity of the upper low permeability aquifer in the study area is estimated as 10^{-1} m/day for unconsolidated poorly sorted alluvial sediment and 10^{-3} m/day for the weathered and fractured basement complex and for limestone and sandstone it was assumed to be 10^{1}m/d.

The specific yield of the first layer of the aquifer is also estimated from literature. Two important properties of an aquifer that are related to the storage function are porosity and specific yield. The porosity of water bearing formation is determined by that part of its volume consisting of openings or pores.

Porosity is an index of how much groundwater can be stored in a saturated medium is usually expressed as a percentage of the bulk volume of the material. Although of water contained in a particular segment of aquifer is of interest, of more concern is how much water can be actually released from storage per unit area of aquifer, per unit change in head. Whereas porosity represents the volume of water an aquifer can hold, it does not indicate how much water the aquifer is yield. When water is drained from a saturated material under a force of gravity, the material releases only part of the total volume stored in its pores. The quantity of the water that a unit volume of an unconfined aquifer gives up by gravity is called its specific yield. The specific yield of alluvial material of clay type ranges from 0.01 – 0.1 (Driscoll, 1986). The specific yield of the different rock materials was estimated from Heath, 1987 (table 3).

Table 3. Selected Values of Porosity, Specific Yield, and Specific Retention different materials.[units are in percent by volume]. (Taken from Heath, 1987).

Material	Porosity	Specific yield	Specific retention
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone (semi-consolidated)	11	6	5
Granite	0.1	0.09	0.01
Basalt (young)	11	8	3

The horizontal hydraulic conductivity for the second hydrogeologic unit, the Lower High Permeability alluvial Aquifer, was estimated from pumping test data of 12 boreholes in the study area which were recorded during drilling. Even if there are around 21 boreholes in the area, which yield water for town supply and industries, only 12 are considered for estimation of hydraulic conductivity of the unit. This is because, it was only these wells which have drillers log containing discharge rate, time of pumping, drawdown, static water level, well construction data and lithologic logs. The recorded data for these wells was used for calculating the transmissivity, and horizontal hydraulic conductivity.

As observed from the records of the pumping test data of the above wells, recorded at different construction time, the wells are pumped under different pumping rates for different pumping time. Discharge rates range from 172 m^3/d to 1296 m^3/d depending on the yield capacity of the wells for 8hrs. to 36hrs. pumping duration. The maximum and minimum drawdown was recorded at HBH-2 and HBH-6, which are 13.5m and 8m, respectively.

The pumping test data for different wells were analyzed by plotting water level versus time using aquifer test software ‘Aquitest’ and the aquifer parameters (transmissivity and hydraulic conductivity) were obtained for the hydrogeologic unit. The hydraulic conductivity value of the aquifer unit ranges from 1.5 m/d to 10 m/d. It was found that the horizontal hydraulic conductivity of the aquifer unit varies spatially based on topography, nature of the alluvial sediment and its thickness. In the Southeastern part of the study area, where the Harar town water supply boreholes are found (e.g. HBH-7), the hydraulic conductivity reaches 10 m/d since the area is topographically low, thick alluvial sediment and well sorted sandy gravel. In the areas where the boreholes are close to the hill sides (e.g. AUBH-3), the hydraulic conductivity becomes low and reaches 1.5 m/d due to the less alluvial thickness and high topography.

Generally, as boreholes are evident, the Eastern half side of the study area which extend from dry Lake Hromaya to Finkile sub-catchment, have high groundwater potential than the western part (Adelle dry Lake sub-catchment). The horizontal hydraulic conductivity of the Lower High Permeability Aquifer unit of Adelle dry lake sub-catchment is extrapolated from its other side spatial distribution. The hydrogeologic unit hydraulic parameters and related data for the analyzed boreholes are summarized in (table 4).

Transmissivity is the ability of the aquifer to transmit water. Its definition as it stands in the groundwater literatures falls in to one of the following categories.

- The rate of flow under unit hydraulic gradient through a cross section of unit width over a whole saturated thickness of aquifer (Bear, 1979).
- The product of the thickness of the aquifer and the average value of hydraulic conductivity (Davis and De Wiest, 1966; Freeze and Cherry, 1979).
- The ratio at which water prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of the property of the fluid, the flow media and thickness of the media (Fetter, 1980; Todd, 1980).

Transmissivity of the selected boreholes is also summarized in the table–4 for the second hydrogeologic unit.

Storage coefficient for the unit is estimated from literature like Todd, 1980; that storage coefficient is defined as the volume of water that aquifer releases from or takes in to storage per unit surface area of aquifer per unit change in the component of head normal to that surface. In most confined aquifers, values fall in the range $0.00005 \leq S \leq 0.005$ indicating that large pressure changes over extensive areas are required to produce substantial water yields (Todd, 1980).

Table-4. Hydraulic properties for the second layer of the aquifer system as calculated from the pumping test of the 12 Boreholes found at the study area. (Source: from drilling and pumping test reports obtained from different institutions).

S/N	Geographic Coordinate (UTM) (Z-37N, Adindan)		BH CODE	Total Depth (m)	Static Water Level(m)	Screen length (m)	Water Column (m)	Q L/s	T (m^2/day)	K (m/day)
	Easting	Northing								
1	832105	1040754	HTBH-1	47.00	2.20	24.00	44.80	10.30	124.85	2.79
2	832551	1040269	HTBH-2	65.00	13.99	27.00	51.01	4.46	122.54	2.40
3	831774	1041150	HTBH-3	39.00	3.78	18.00	35.22	10.00	106.13	3.01
4	832446	1040863	HTBH -4	52.30	3.95	18.00	48.35	18.00	269.28	5.57
5	832149	1040439	HTBH -5	53.00	2.89	24.00	50.11	18.00	336.96	6.72
6	832329	1041370	HTBH -6	44.00	4.86	33.00	39.14	16.60	174.24	4.45
7	832217	1041860	HTBH -7	44.00	5.52	26.00	38.48	22.00	411.84	10.70
8	832432	1045791	HBBH-65	64.00	2.00	34.00	62.00	8.00	51.68	1.52
9	832300	1045792	HBBH-59	59.00	2.60	12.00	56.40	3.50	26.76	2.23
10	832140	1047901	HBBH-51	51.00	1.00	18.00	50.00	6.70	45.38	2.52
11	831498	1047365	HBBH-85	85.00	1.45	24.00	83.55	8.00	57.25	2.39
12	833430	1041804	AUBH -4	58.00	10.25	21.61	47.75	7.00	103.68	4.80

3.4. Aquifer System Boundaries

For groundwater system of the given area, there are two types of aquifer boundaries which control the groundwater flow direction (Anderson and Woessner, 1992). These boundaries are; 1) Physical boundaries of groundwater flow system which are formed by physical presence of an impermeable body of rock or a large body of surface water. 2) Other boundaries form as a result of hydrologic conditions. These invisible boundaries are hydraulic boundaries that include groundwater divides and streamlines.

The conceptual model of the aquifer system of Adelle – Haromaya groundwater basin utilized a litho-stratigraphic approach to divide the basin sediments and weathered rock units in to two major aquifer units. These are; the upper low permeability aquifer (Layer-1), which consists poorly sorted clay, silt, and sand, weathered basement complex, sandstone and limestone. The lower high permeability aquifer (Layer-2), which consists well sorted sandy gravel.

The lateral and vertical boundaries of the aquifer system of the groundwater basin are formed, in most cases, by hydraulic boundaries as groundwater divide and physical boundaries where the aquifers are in contact with the bed rock. In most areas of the groundwater basin, the lateral boundary of the layer-1 of the aquifer system is the groundwater divide, which in most areas assumed to be coinciding with the major surface water divides. The bottom boundary of Layer-1 is the physical boundary where it contacts with the basement complex along the outer edges of the study area. In these areas, the second layer of the aquifer system is missed as the elevation of the basement complex is higher than the top of the layer and the second layer is punch-out. In central part of the study area, the bottom contact of the Layer-1 is the top contact of Layer-2 so that there is no bottom boundary for the layer. The top boundary of Layer-1 is the ground surface.

The lateral boundary of Layer-2 of the aquifer system, in most areas, is the physical boundary (basement complex), where the aquifer pinch-out. The bottom boundary of this aquifer layer is also the bed rock. In most areas, this aquifer unit underlies the upper aquifer (Layer-1) so that there is no boundary between the two layers except the permeability difference. But, in some areas near the Haromaya dry lake, the second layer is exposed to the surface since the bottom elevation of the Layer-1 is above the ground surface at this locality. At this area, the top boundary of the Layer-2 is ground surface.

3.5. Groundwater Recharge

Groundwater recharge is defined in general sense as the downward flow of water reaching the water table, forming an addition to groundwater reservoir. A clear distinction should thus be made, both conceptually and for any modeling purposes between the potential amount of water available for recharge from the soil zone and the actual recharge. Quantification of the rate of natural groundwater recharge is a basic prerequisite for efficient groundwater resources management, and is particularly vital in arid and semi-arid regions where such resources are often the key to economic development (David and Lerner, 1990).

Groundwater recharge can not be measured directly and is difficult to accurately estimate. Indirect recharge estimate can be subjected to large errors and therefore, when possible, more than one method should be used to verify the estimates. A common indirect method for hydrologic system under equilibrium condition is to equate groundwater recharge to groundwater discharge. In the Adelle – Haromaya dry lakes catchment (the study area), groundwater recharge occurs naturally through direct percolation from precipitation when it exceeds the soil moisture deficit and evapotranspiration. Previously, groundwater recharge of the area was estimated by surface water balance method by Wagari Furi and other researchers for the basin.

As concluded by Wagari Furi, 2005, the land use land cover of the study area is divided in to two: 1) clay soil with shallow rooted plants having available water field capacity 75mm and covers 23.9% of the study area; 2) soil of fine sand with shallow rooted plants having available water field capacity of 100mm with estimate root depth of 1m. This soil covers 76.1% of the study area. From this condition, annual groundwater recharge is estimated as 52.5 mm/year for the clay soil cover and 58.4 mm/year for the sandy soil cover. Detail calculation for both soil types is summarized in (table 5 and table 6).

On the other hand, the surface runoff for the Haromaya sub-basin calculated by Solomon Muleta, 2003 was 6,731,614m^3/year which is around 134.5mm/year. The 25 years average actual evapotranspiration for Haromaya sub-basin was computed as 594mm/year (Abdulaziz Mohamed, 2006). Based on the annual average precipitation recorded at Haromaya station, which is 770.5mm/year, the annual average groundwater recharge for Haromaya sub-basin is calculated to be 42mm/yr. It was this annual recharge value which was taken as the conceptual model recharge for the Haromaya sub-basin.

The two sub-basins of the study area (Finkile and Adelle) do not have any estimated groundwater recharge. Both sub-catchments have more or less similar hydro-meteorological condition with the Haromaya sub-basin, but have less groundwater outflow by pumping. Due to this condition, the sub-basins might have less groundwater recharge. For these sub-basins, the groundwater recharge for the conceptual model was assumed as recharge is equals to discharge on the annual basis and calculated from inflow-outflow balance. Generally, the whole study area was assumed, as estimated from surface water balance and inflow-outflow balance, to have groundwater recharge which ranges from 20 – 42mm/yr on an average.

Table 5. Long term average monthly water balance of Haromaya dry lake basin, for a soil with an available water field capacity of 75mm. The soil is **clay** under shallow rooted with estimated rooting depth of 0.25m. This type accounts 23.9% of the total land cover. All values in tables are in millimeters.

(MM)	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	YEAR
P	11.7	19.95	65.8	102.75	94	45.35	98.75	149.3	103.65	37.55	12.25	10.15	751.2
PET	**43**	**51.7**	**63.3**	**70.3**	**74.4**	**77.6**	**68.3**	**67.9**	**65.3**	**51.3**	**44.6**	**37.5**	**715.2**
P-PET	-31.3	-31.8	2.5	32.5	19.6	-32.3	30.5	81.4	38.4	-13.8	-32.4	-27.4	36.0
AccPWL	-135.7	-167.5	-165.0			(-9.3)				-44.7	-77.1	-104.4	
S_m	9.2	4.9	5.1	37.6	57.2	30.0	60.5	75.0	75.0	57.0	29.8	17.3	
ΔSM	-8.0	-4.3	0.3	32.5	19.6	-27.2	30.5	14.5	0.0	-18.0	-27.1	-12.6	
AET	19.7	24.3	63.3	70.3	74.4	72.6	68.3	67.9	65.3	55.6	39.4	22.7	643.8
D	23.3	27.4	0.0	0.0	0.0	5.1	0.0	0.0	0.0	-4.3	5.2	14.8	71.4
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.9	38.4	0.0	0.0	0.0	**105.2**

Table 6. Long term average monthly water balance of Haromaya dry lake basin, for a soil with an available water field capacity of 100mm. The soil is **fine sand** under shallow rooted (chat, sorghum, and some grasses) with estimated rooting depth of 1m. This type accounts for 76.1% of the total land cover. All values in tables are in millimeters.

(MM)	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	YEAR
P	11.7	19.95	65.8	102.75	94	45.35	98.75	149.3	103.65	37.55	12.25	10.15	751.2
PET	**43**	**51.7**	**63.3**	**70.3**	**74.4**	**77.6**	**68.3**	**67.9**	**65.3**	**51.3**	**44.6**	**37.5**	**715.2**
P-PET	-31.3	-31.8	2.5	32.5	19.6	-32.3	30.5	81.4	38.4	-13.8	-32.4	-27.4	36.0
AccPWL	-135.7	-167.5	-165.0			(-9.3)				-44.7	-77.1	-104.4	
S_m	35.1	25.5	26.2	58.6	78.2	66.6	97.0	100.0	100.0	87.2	63.1	48.0	
ΔSM	-12.9	-9.5	0.6	32.5	19.6	-11.7	30.5	3.0	0.0	-12.8	-24.1	-15.1	
AET	24.6	29.5	63.3	70.3	74.4	57.0	68.3	67.9	65.3	50.4	36.3	25.2	632.6
D	18.4	22.2	0.0	0.0	0.0	20.6	0.0	0.0	0.0	0.9	44.3	12.3	82.6
S	0	0	0	0.0	0.0	0.0	0.0	78.4	38.4	0.0	0.0	0.0	**116.8**

(Tables 5 and 6 are taken from Wagari Furi, 2005.)

3.6. Groundwater Discharge

Groundwater use of the Adelle – Haromaya dry lakes catchment was steadily increasing from time to time as the population increased and surface water source became scarce. The groundwater discharge from the two aquifer units of the area is mostly by withdrawals from wells. Groundwater discharges from the system by evapotranspiration, where the water table is shallow. The total discharge by groundwater evapotranspiration is unknown but is presumed to be insignificant compared to groundwater pumpage from the system.

The pumping system of the groundwater from the two aquifer system of the study area is divided in to three;

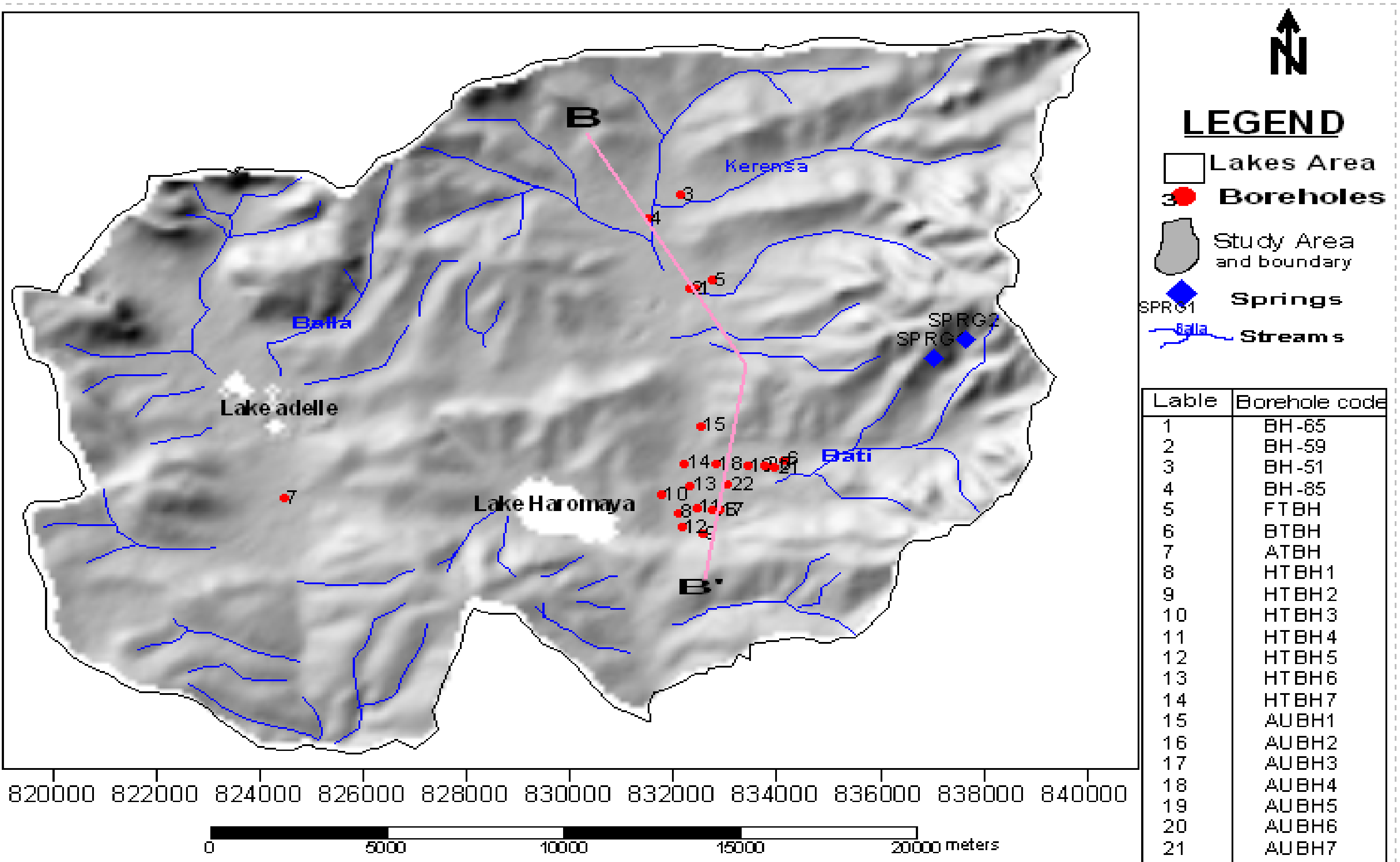
1. The shallow hand-dug wells, which were dug in the upper low permeability aquifer, are used for irrigation purposes by collecting the water in to the local surface reservoirs. As the data obtained from the Haromaya woreda irrigation development office, there are 262 hand-dug wells in the Adelle sub-catchment, 200 in Finkile subcatchment and 60 in Haromaya sub-catchment. The hand-dug wells are pumped for around 40 minutes a day at 2 lit/sec. pumping rate and the wells serve for six months of a year during dry seasons. Generally, the groundwater abstraction rate by this method as computed from the above was $619m^3/d$, $418m^3/d$ and $144m^3/d$ from Adelle, Finkile and Haromaya sub-basins respectively. The groundwater pumpage by this system was assumed to be directly goes to evapotranspiration after irrigating the crops.
2. The shallow drilled wells, which were drilled in most cases in layer one of the aquifer system and in part in layer two, are fitted with hand pumps and used for rural water supply of the area community. As the data collected from Haromaya Rural Water supply development office, there are 29 hand pumps in Adelle area, 20 hand pumps in Haromaya area and 14 hand pumps in Finkile area. The hand pumps yield on average around 0.5 lit/sec. and serve for eight hours a day for the whole year. Based on this, it was assumed that the groundwater

abstraction by these hand pumps is 417m^3/d area, 288m^3/d for Haromaya area and 201m^3/d for Finkile sub-catchment.

3. The relatively deep wells, installed with submersible pumps, abstract water mostly from layer two of the aquifer system and some from layer one. The water is used for towns' water supply and industrial purposes. There are 15 wells in Haromaya sub-basin, 5 wells in Finkile sub-basin and 1 well in Adelle sub-basin (fig. 7). The amount of daily discharge of these wells was obtained from the water meter reading of the wells owners and summarized in table-7A and B.

There is no surface perennial river in the study area to discharge groundwater from the system except two springs (Lege Hidha and Lege Masno) and the average yield of these springs is around 420m^3/d. The springs are located in Haromaya sub-catchment. The other seasonal springs drain groundwater to the three seasonal lakes along the stream channels temporarily. The amount of the groundwater discharged by these seasonal springs was not quantified by this study which may cause discrepancies between inflow and outflow of the groundwater balance.

There is no groundwater outflow out of the study area since the area is almost bounded catchment. But, small seepages are observed at the topographically low catchment boundaries around Dangago and Balla Bakalcha areas. These seepages are also not quantified by the conceptual model. Generally, among the groundwater discharge of the study area, 74.4 % is from Haromaya sub-basin, 14.6% is from Finkile sub-basin and 11% is from Adelle sub-basin.



Lable	Borehole code
1	BH-65
2	BH-59
3	BH-51
4	BH-85
5	FTBH
6	BTBH
7	ATBH
8	HTBH1
9	HTBH2
10	HTBH3
11	HTBH4
12	HTBH5
13	HTBH6
14	HTBH7
15	AUBH1
16	AUBH2
17	AUBH3
18	AUBH4
19	AUBH5
20	AUBH6
21	AUBH7
22	AUBH8

Fig. 7 High Groundwater Pumping Areas of the Study Area and the Well Locations

Note: The Lakes are at present time seasonal

Table 7A. Summary of Daily Groundwater Abstraction Rates from Deep Wells of the study area and names of the Boreholes and their codes. (Source Water meter reading of the boreholes owners).

SUMMARY OF DEEP WELLS FOUND IN THE STUDY AREA AND THEIR DISCHARGE CONTRIBUTION FOR TOWN WATER SUPPLY AND INDUSTRIES.			
Name of the Boreholes	Well Code	Number of Boreholes	Average Total Daily Discharge (m3/d)
Harar Town Boreholes	HTBH	7	3456
Harar Brewery Boreholes	HBBH	4	700
Alemaya University Boreholes	AUBH	7	1628.4
Finkile Town Borehole	FTBH	1	50
Bate Town Borehole	BTBH	1	40
Adelle Town Borehole	ATBH	1	33
Total		21 Wells	5907.4

Table 7B. Daily Groundwater Abstraction Rates from Deep Wells of the study area and Discharge Contribution of each well with geographic locations of the wells and the ground elevation at the boreholes.

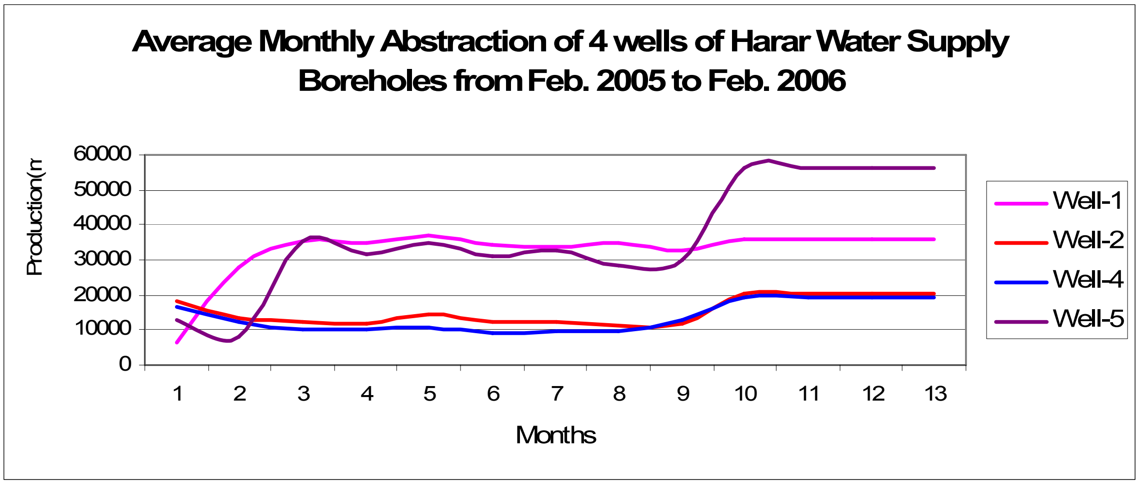
Average Daily Discharge Contribution of the Harar town Water Supply Deep Wells:					
Borehole Code	Geographic Coordinate		Ground Elevation (m)	Each well Daily Discharge (m3/d)	% contribution
	Easting	Northing			
HTBH1	832105	1040754	2018	784.512	22.7
HTBH2	832551	1040269	2023	435.456	12.6
HTBH3	831774	1041150	2015	186.624	5.4
HTBH4	832446	1040863	2013	480.384	13.9
HTBH5	832149	1040439	2014	784.512	22.7
HTBH6	832329	1041370	2011	369.792	10.7
HTBH7	832217	1041860	2020	414.72	12.0
Total				3456	100.0
Average Daily Discharge Contribution of the Harar Brewery Deep Wells:					
Borehole Code	Geographic Coordinate		Ground Elevation (m)	Each well Daily Discharge (m3/d)	% contribution
	Easting	Northing			
HBBH65	832432	1045791	2008	215.6	30.8
HBBH59	832300	1045792	2008	94.5	13.5
HBBH51	832140	1047901	2026	175	25
HBBH85	831498	1047365	2020	214.9	30.7
Total				700	100.0

Table 7B Continued

Average Daily Discharge Contribution of the Alemaya University Deep Wells:					
Borehole Code	Geographic Coordinate		Ground Elevation (m)	Each well Daily Discharge (m3/d)	% contribution
	Easting	Northing			
AUBH1	832513	1042715	2024	87.9336	5.4
AUBH2	832750	1040816	2021	431.526	26.5
AUBH3	832831	1041841	2028	258.9156	15.9
AUBH4	833430	1041804	2032	306.1392	18.8
AUBH5	833776	1041821	2034	389.1876	23.9
AUBH6	833963	1041778	2037	130.272	8
AUBH7	833055	1041378	2030	24.426	1.5
Total				1628.4	100
Average Daily Discharge Contribution of the three small towns Deep Wells:					
Borehole Code	Geographic Coordinate		Ground Elevation (m)	Each well Daily Discharge (m3/d)	% conjtribution
	Easting	Northing			
ATBH	824465	1041067	2040	33	100
BTBH	834140	1041944	2036	40	100
FTBH	832300	1045990	2026	50	100

Table 8. Monthly Abstraction Rates of the Four Boreholes of the Harar Water Supply wells from February 2005 to February 2006 (source Harar Water Supply and Sewerage Authority).

Month	Abstraction from HBH-1 (m3/month)	Abstraction from HBH-2 (m3/month)	Abstraction from HBH-4 (m3/month)	Abstraction from HBH-5 (m3/month)
1	6630	18058	16849	12853
2	27747	13135	12411	79220
3	35250	12230	10192	35250
4	34700	11992	10292	31570
5	37035	14296	10669	34700
6	34133	12558	8943	30811
7	33607	12081	9484	32420
8	34924	11345	9581	28158
9	32939	11548	13023	29964
10	36113	20472	19517	56379
11	36113	20472	19517	56379
12	36113	20472	19517	56379
13	36113	20472	19517	56379



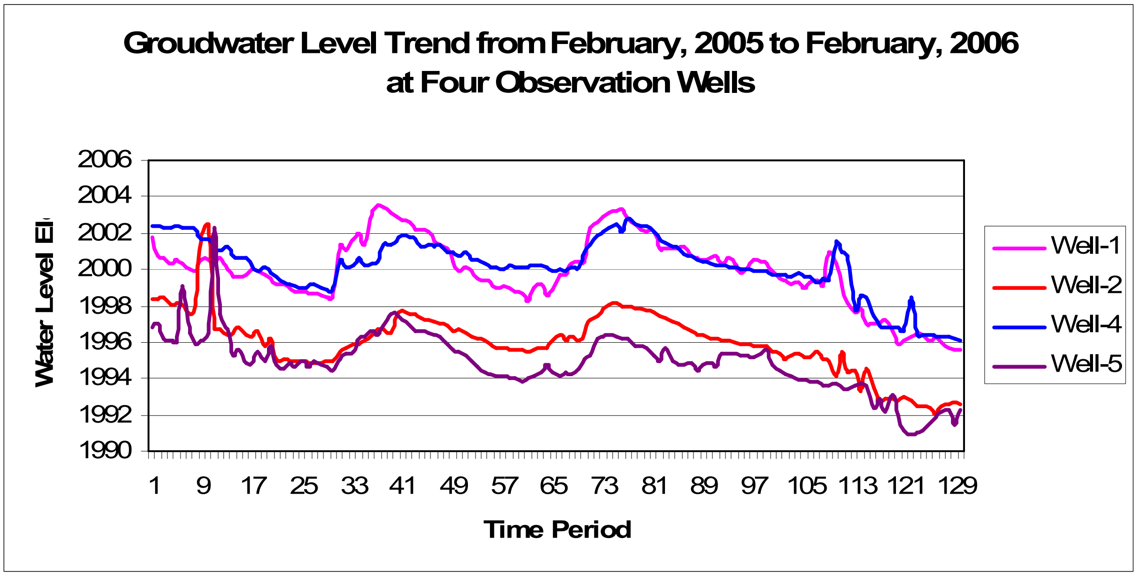


Fig 8. Comparison of Average Monthly Abstraction and Groundwater Level Trend of the Four Wells of Harar Water Supply Observation Boreholes.

3.7. Groundwater Level and Movement

Groundwater levels in Adelle – Haromaya dry lakes catchment were measured during the investigation time in February, 2006 in the shallow wells and deep wells to determine the direction of groundwater flow for the study area. The water level elevation data collected from 51 wells in the study area was used to develop a 2006 water table map shown in (fig. 9). The map shows that groundwater flows to the local depressions of the lakes bottom and to the high groundwater pumping localities. The general direction of the groundwater movement for the study area is mostly towards the Harar water supply well field, which is found in the Haromaya sub-basin. The flow starts from topographical highlands and from Adelle subcatchment to Finkile subcatchment and then finally to Haromaya subcatchment

where the well field is found. Groundwater divide coincides with surface water divide at the area south of Haromaya town where it flows towards south.

The groundwater level data, prior to the development of seven boreholes of the Harar town water supply, three boreholes of the Alemaya University in the Haromaya subcatchment and four boreholes of the Harar Brewery boreholes in the Finkile subcatchment is collected from drilling reports and mapped to compare with the 2006 groundwater level data. As the static water level data from 14 boreholes in two subcatchments (Haromaya and Finkile) shows, the general groundwater movement of the subcatchments is towards south with some local movement to the lakes. The water level data for the 14 boreholes were combined with the water level data of Feb, 2006 and the contour map of water level was produced (fig. 9).

Generally, when the groundwater level of pre development of wells is compared with the groundwater level of February 2006, there is an average of 5m decline of groundwater level which might be the effect of groundwater withdrawal from the two sub-cathments. The water level data from well monitoring site of Harar water supply borehole (HTBH-1) also indicate that there is a decline of water level in the borehole by 5m from February 2005 to February 2006 (fig. 8).

3.8. Conceptual Groundwater Balance

A steady state groundwater balance for the Adelle – Haromaya dry lakes catchment (the study area) describes alluvial aquifer system and provides a conceptual framework for the groundwater flow model (table 7). In the steady state water balance, inflow to and outflow from the aquifer system are identified and quantified on an average annual basis. The water balance described here includes the components simulated in a groundwater flow model.

Inflow for the groundwater of the study area is the groundwater recharge from precipitation. Outflow includes, spring outflow in the study area, withdrawals from supply, industries and irrigation wells, groundwater evapotranspiration (not considered for balance) and subsurface outflow from the study area at topographically low outlets (not quantified). Seasonal groundwater outflow to the lakes along the streams was not quantified.

Groundwater recharge from precipitation is assumed to be the only source for the groundwater inflow. Precipitation recharge rate, which was estimated by surface water balance method by different researchers, was used for groundwater balance. Basin wide precipitation recharge rate has been estimated from long-term average precipitation data record was 42 mm/year for Haromaya sub-basin and fro the other sub-basins inflow-outflow balance was used. Finally, the recharge rate ranges from 20mm/yr to 42mm/yr for all the sub-basins.

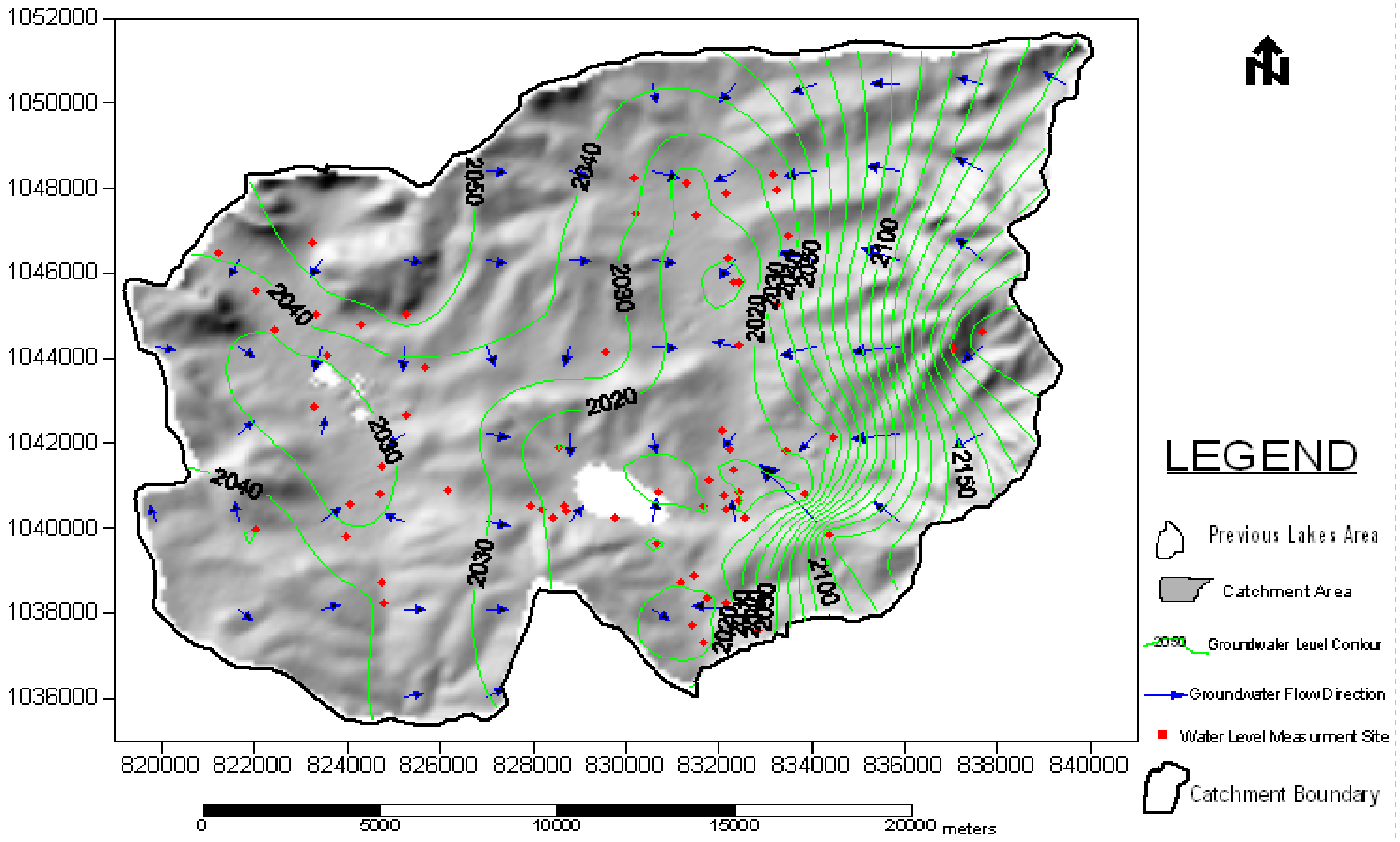


Fig. 9. Groundwater Level and Its Flow Direction of the Study Area including Water Level Measured points.

Note: the Lakes are at present time seasonal

The primary outflow from the study area is through groundwater withdrawals from shallow and deep wells. Total groundwater withdrawal from the wells is around 2,940,586m^3/year. Groundwater outflow from Lege Masno and Lege Hidha springs is 153,300m^3/year. Underflow through the topographic low areas and evapotranspiration from groundwater including the seasonal outflow to the lakes through the streams was not quantified for the study area. Estimated average annual groundwater balance of the study area is summarized in (table. 9).

Table 9. Estimated Average Annual Water Balance for the three sub-basins of the Study Area calculated from existing data conceptually.

Water Balance Component	Rate of Flow	
	Cubic meter per Day	Cubic meter per year
Inflow		
Recharge from Precipitation	**13,150 – 27,616**	**4,800,000 – 10,080,000**
Outflow		
From Springs	420	153,300
From Hand-dug Wells	1,243	453,695
From Hand Pumps	906	330,690
From Deep well	7635.0	2,786,775
Total Outflow	**10,240**	**3,093,886**
Inflow (minimum) minus Outflow	+2,946.0	+1,075,290

CHAPTER FOUR

NUMERICAL SIMULATION OF GROUNDWATER FLOW

A numerical groundwater flow model of the Adelle – Haromaya dry lakes catchment is developed to better understand the aquifer system of the basin and to determine the long-term availability of groundwater by simulating groundwater condition at present and predict the future condition under different hydrologic and pumping scenarios for various groundwater management alternatives. The model was developed using assumptions and approximations to simplify the actual aquifer system. The model idealizes the complex geo-hydrologic relations of the actual system, thus, it is a simplification based up on the data and the assumptions used to develop it. Limitations of the model are discussed in a later section of this report.

4.1. Modeling Approach

Groundwater flow of the study area aquifer system is simulated using the USGS three-dimensional finite-difference groundwater flow model MODFLOW (Harbaugh and other, 2000). MODFLOW-96 is a modified version of MODFLOW (Mc Donald and Harbaugh, 1988) that incorporates the use of parameters to define model input, the calculation of parameter sensitivities and the modification of parameter values to match observed heads, flows or advective transport using the observation, sensitivity and parameter estimation processes described by Hill and others (2000).

The equation used in the computer model to describe groundwater flow is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = Ss\frac{\partial h}{\partial t} \qquad (1)$$

Where:

K_x, K_y and K_z : are the values of hydraulic conductivity along x, y and z coordinate axes and are assumed to be parallel to the major axes of hydraulic conductivity, in meters per day;

h : is potentiometric head, in meters;

W : is a volumetric flux per unit volume and represents sources or sinks or both of water, such as well discharge, recharge and water removal from the aquifer by drains, per day;

Ss : is the storage coefficient of the porous materials, per meter;

t : is time, in days.

The flow equation was solved by using solver – Slice successive over relaxation Package (SSOR) of the MODFLOW.

The groundwater flow system of the study area is numerically simulated in three dimensions using the MODFLOW to determine the hydraulic head distribution in the aquifer system around the pumping well fields where there is vertical flow component of the groundwater. The flow system is also defined by, descritizing the aquifer system in to finite difference grid and layers, determining the boundary conditions for the aquifers, estimating the rates and distribution of recharge and discharge and estimate the aquifer properties within the model. The accuracy of these input data, in part determines the accuracy of the model.

The model was calibrated in the steady-state mode with drilling report static water levels and the water level of February, 2006, and transient calibration was done using drawdown measured for monitoring wells. Hydraulic parameters were iteratively adjusted by trial and error between steady state and transient modes of the model until satisfactory matches to measured variables were achieved in the steady state and transient simulations.

4.2. Model Description

4.2.1. Grid Design

The modeled area is 22 by 17 km and contains the entire study area shown in figure 10, A. The model uses a uniform grid size of 100m by 100m and contains 74,800 cells in two layers, 220 columns and 170 rows. The irregular shape and the locally bounded nature of the two aquifers of the study area reduced the number of active cells in the model to 43,678 with 24,933 active cells in layer-1 and 18,745 active cells in layer-2. Layer-2 has fewer active cells than Layer-1 because some of the cells, along the outer edge of the study area at Damota ridges and Dangago localities, are in areas of basement complex that are higher in elevation than the top of the Layer-2 (1980m above sea level); thus, there is no Layer-2 in these areas (fig. 10, C). The regular grid spacing facilitated data input from DEM and surfer files. The aquifer was descritized vertically in to two layers (layer-1 and layer-2) (fig 10 B and D). Layer-1 corresponds the upper part of the aquifer where poorly sorted clay, silt and sand are predominant in the central part of the study area and weathered and fractured basement complex at the hill sides and weathered sandstone and limestone along the border of the study area.

Thickness of the layer-1 is adequate to account for the anticipated range of water level variation within the aquifer during groundwater flow simulation and was modeled using both confined and unconfined aquifer hydraulic properties. Layer-2 corresponds to the lower part of the aquifer where sand and gravely sand predominates. This layer was assumed to be confined, in most areas during conceptual model, but during simulation it was modeled using unconfined and confined aquifer hydraulic properties.

The two layers of the aquifer system of the study area have variable thicknesses depending on the geologic type and permeability differences. The height of each cell in the model was equal to the estimated formation thickness, which was determined based on the USGS 90-meter resolution Shuttle Radar Terrain Model (SRTM) of the land surface. Layer-1 represents the Upper unconfined Low Permeability aquifer and has thickness ranging from 10m near the lakes bottom to 380m at the top of the limestone hills. The top altitude of layer-1 represents ground surface elevation above sea level. The bottom altitude of this layer (the bottom of the upper aquifer) is 1980m above sea level throughout the study area, which was conceptualized from the bottom of poorly sorted alluvial sediments as observed from borehole logs and geophysical survey results. Layer-2 represents the confined lower high permeability aquifer, underlies layer-1 in most areas, and has variable thickness which range from 10m to 150m depending on the elevation of the underlying basement complex, which was assumed to be the replica of the topographic surface. The top of layer-2, which is the bottom of layer-1, is 1980m above sea level and the bottom of layer-2 is the altitude of the underlying basement complex.

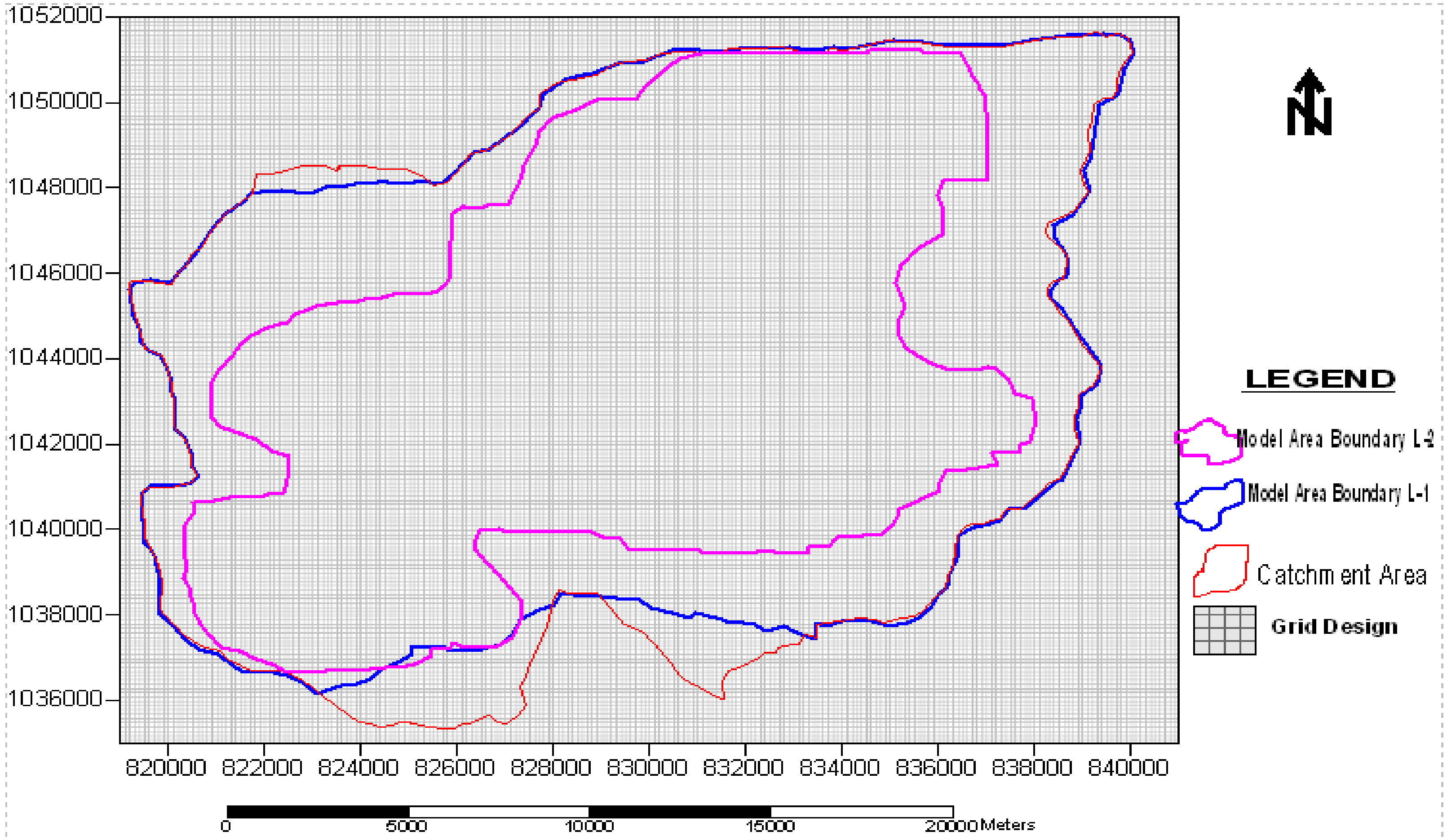


Fig. 10 A Groundwater Model Grid Design of the study Area.

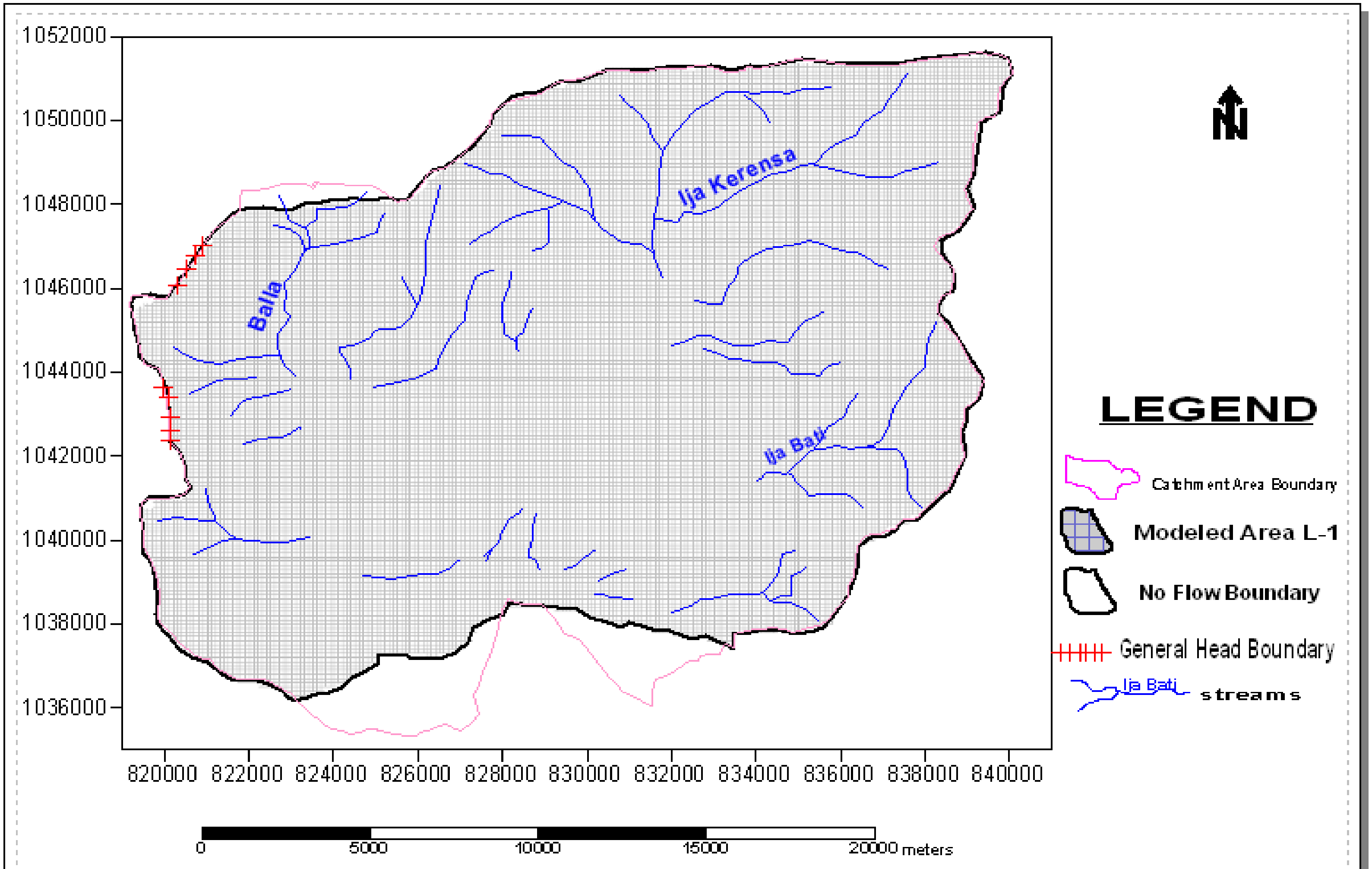


Fig. 10 B Groundwater Model Area Grid Design to the Catchment Area of Layer-1 and Lateral Bundary Conditions

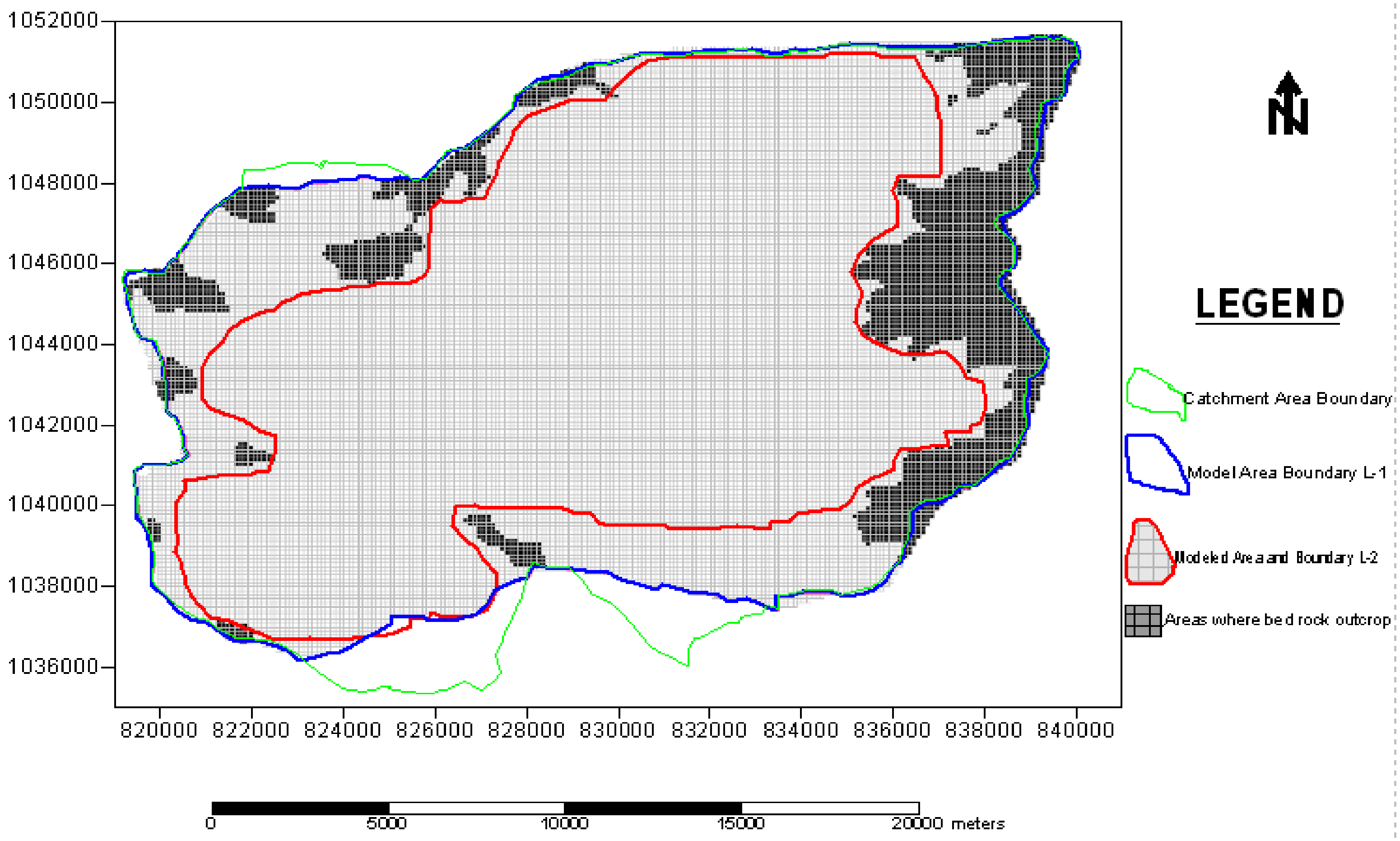


Fig 10 C. Groundwater Model Grid and Outcrop Areas of Basement Rock for Layer-2

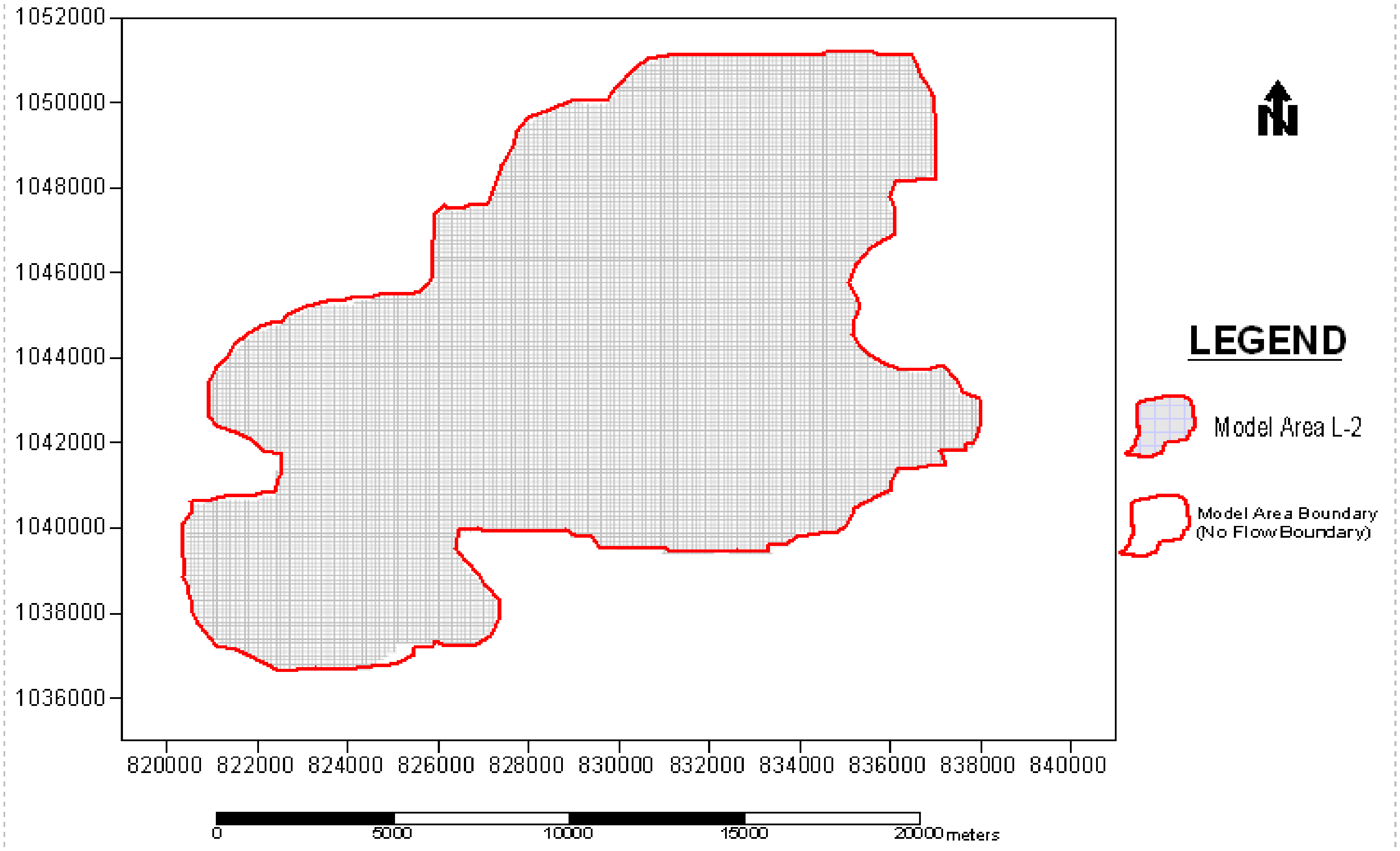


Fig. 10 D. Model Areal Extent of Layer 2 of the Aquifer System and Lateral Boundary Conditon

4.2.2. Boundary Conditions

Boundary conditions are mathematical statement specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain (Anderson and Woessner, 1992). The choice in the type and location of model boundaries is important, as this may affect the simulation results. Ideally, model boundaries represent actual hydrologic boundaries, but this objective can not always be met. If model boundaries do not represent actual hydrologic boundaries, it is important that they are located far enough away from the area of interest so they do not affect the simulation results (Marijke and Smith, 2002).

Boundary conditions may be of three general types. One type is a specified-flux boundary, of which no flow boundary is a special case. A second type is a specified-head boundary, which was not used in this study. The third type is a head-dependent flux boundary, for which the boundary flux is the product of a specified factor and the difference between the simulated head at the boundary and specified head of an external source/sink.

The lateral boundaries of the model area (fig.10) are either no-flow or head dependent flux boundaries. No water enters or leaves the system at no-flow boundaries. The lateral no-flow boundaries are located at the surface water divide of the study area by assuming that groundwater divide coincides with surface water divide for layer-1. For the second layer of the model aquifer system, the lateral no-flow boundary is located at the contact between the alluvial aquifer and the bed rock. The location of head-dependent flux boundary for the study area is assumed at the localities of topographically low surface water divides. At these localities (Balla Bakalcha and Dangago areas), water can enter or leave the system depending on the gradient of the water level at the boundaries. The head-dependent flux boundary of the model is simulated with the General-Head-Boundary (GHB) module of the MODFLOW.

The top boundary of the model, the upper boundary of layer-1, was simulated as a free surface boundary, which include specified-flux and head-dependent flux boundary cells. The specified-flux boundary is the areally applied groundwater recharge and the head-dependent boundary represents springs. Recharge was specified and simulated with the recharge (RCH) module, Lege Hidha and Lege Masno springs were simulated with drain (DRN) module. The bottom boundary of the model is a specified no-flow boundary. This no-flow boundary is located where the aquifer comes in to contact with bed rock. In areas where the second aquifer of the model is missing, layer-1 contacts the bed rock and the contact between layer-1 and the bed rock is the no-flow boundary. In other areas where layer-2 exists, the contact between the layer-2 and the bed rock is the no-flow boundary.

4.3. Model Input Parameters

Simulation of groundwater flow and fluxes requires specifying aquifer system properties and stresses. Aquifer system properties can vary considerably both horizontally and vertically and thus, cannot be precisely represented in a numerical model. The aquifer system properties specified for each active cell in the model are estimates of the average conditions in the area represented by the cell. Similarly, stress applied to the system (recharge and discharge) are estimates for the area represented by each cell. The initial aquifer system properties of the study area were conceptually modeled from different groundwater literatures and analysis of pumping test. Areal recharge estimation was obtained from Wagari Furi (2005) and other researchers, and pumpage was estimated, as described in the conceptual model, from daily pumping records and estimation of hand-dug wells and shallow drilled well discharges. Selected properties and stresses were modified during model calibration.

4.3.1. Initial and Prescribed Hydraulic Heads

Water table surface used to define initial head in the model are based on the DEM land surface data source for each model cell. The land surface value of the DEM data are adjusted to the water table depth by subtracting the depth to the water table from land surface at measured points of water level during this study and from drilling reports. By analyzing the elevation difference between the land surface and the water level for 63 shallow and deep wells, it was assumed that the level varies depending on the topography of the area. The difference increases as topography increases. Based on this, the initial and prescribed hydraulic head for the model was assigned for each cell of the model layers by the following methods:

- areas where land surface elevation ranges from 1970m – 2000m hydraulic head was assigned by land surface minus 10m,
- areas where land surface elevation ranges from 2000m – 2178m hydraulic head was assigned by land surface minus 12m,
- areas where land surface elevation ranges from 2178m – 2450m hydraulic head was assigned by land surface minus 30m.

4.3.2 Hydraulic Conductivity and Transmissivity

Groundwater flow within the model layers was assumed to be horizontal. Hydraulic conductivity and transmissivity are properties that, in conjunction with the horizontal hydraulic gradient, control horizontal flow of groundwater. Hydraulic conductivity is a measure of the water transmitting properties of aquifer material; coarse and well sorted materials have a higher hydraulic conductivity than fine and poorly sorted materials. Transmissivity is the product of hydraulic conductivity and saturated thickness and represents the water transmitting properties of the saturated section of the aquifer.

Hydraulic conductivity for the aquifer system of the study area was estimated from different materials. The hydraulic conductivity for layer-1 was estimated from groundwater literatures depending on the geologic and hydrogeologic properties of the aquifer unit. The layer-1 of the model consist different geologic units (poorly sorted clay, silt and sand, weathered and fractured basement complex, and highly weathered sandstone and limestone) and the hydraulic conductivity for this layer was estimated to be range from 10^{-3} m/d for weathered basement to 10^{-1} m/d for weathered limestone (fig. 11A).

The horizontal hydraulic conductivity of the layer-1 was applied to each active model cells by zoning the similar hydraulic conductivity areas depending on the surface spatial distribution of geologic materials (fig 11A).

The hydraulic conductivity of layer-2 of the model (main aquifer) was estimated from aquifer test data of 12 boreholes drilled in the study area at different times. Based on the pumping test analysis, the aquifer hydraulic conductivity ranges from 1.5 m/d for deep wells located near the hill sides to 10 m/d for wells for wells drilled in well sorted gravelly aquifers (fig. 11B).

Transmissivity for the layer-2 of the model was calculated from the pumping test result that is by multiplying the horizontal hydraulic conductivity by the total length of the screen. Since the assigned layer property of the simulated model was the layer type – 3 of MODFLOW Block-Centered-Flow (BCF) package, which is convertible between confined and unconfined, only horizontal hydraulic conductivity was assigned to the active cells of the entire model. The transmissivity values of both model layers were calculated entire the model by multiplying the horizontal hydraulic conductivity value by the saturated thickness of the layers.The horizontal hydraulic conductivity values obtained from aquifer test of 12 boreholes for layer-2 of the model was mapped using surfer-8 software and contoured for equal hydraulic conductivity areas. After grouping in to different zones, the conductivity for each zone was assigned to the active cells of layer-2 of the model (fig 11B).

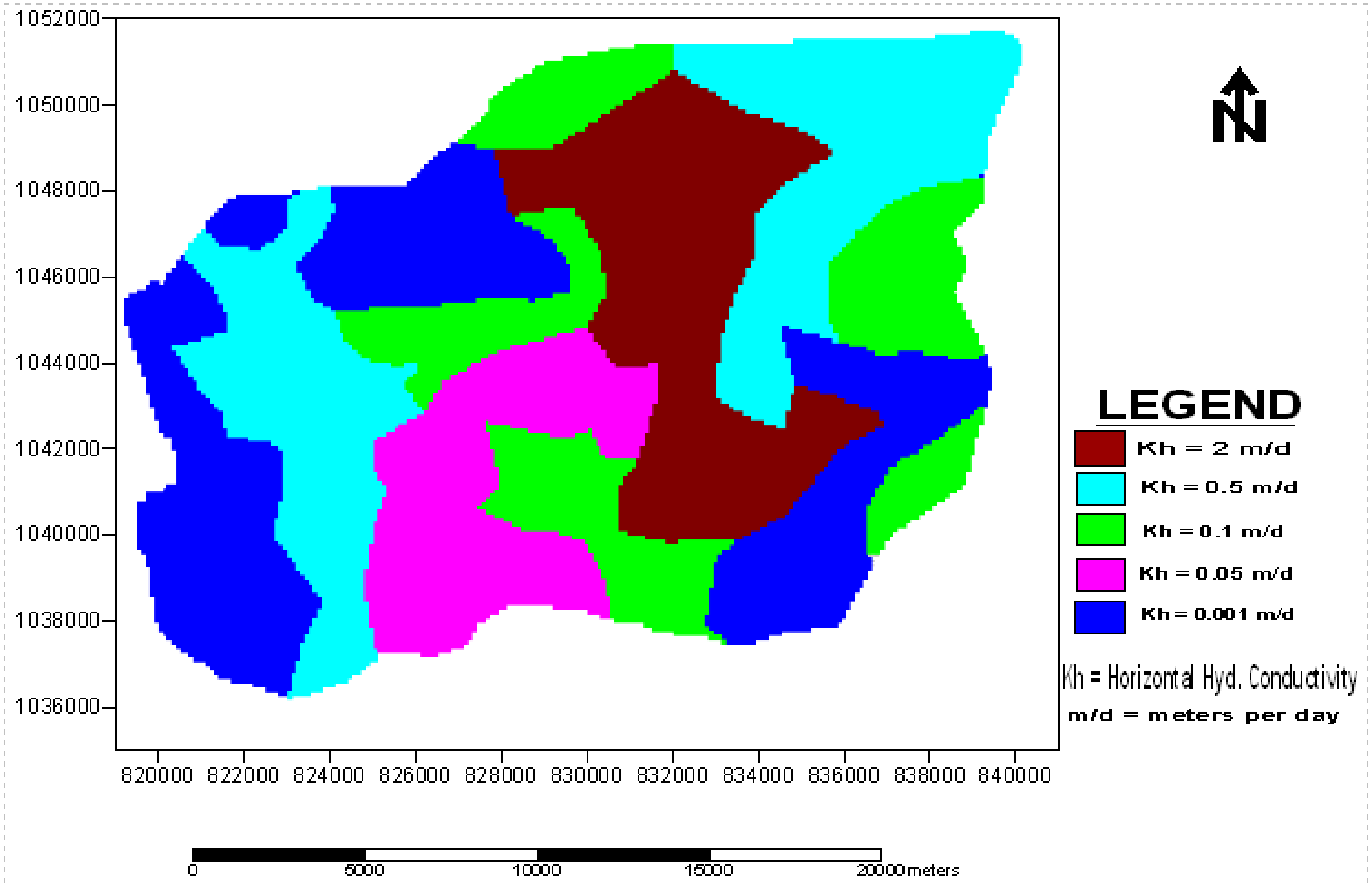


Fig. 11, A. Conceptual Model Horizontal Hydraulic Conductivity Map of the Study Area Layer 1

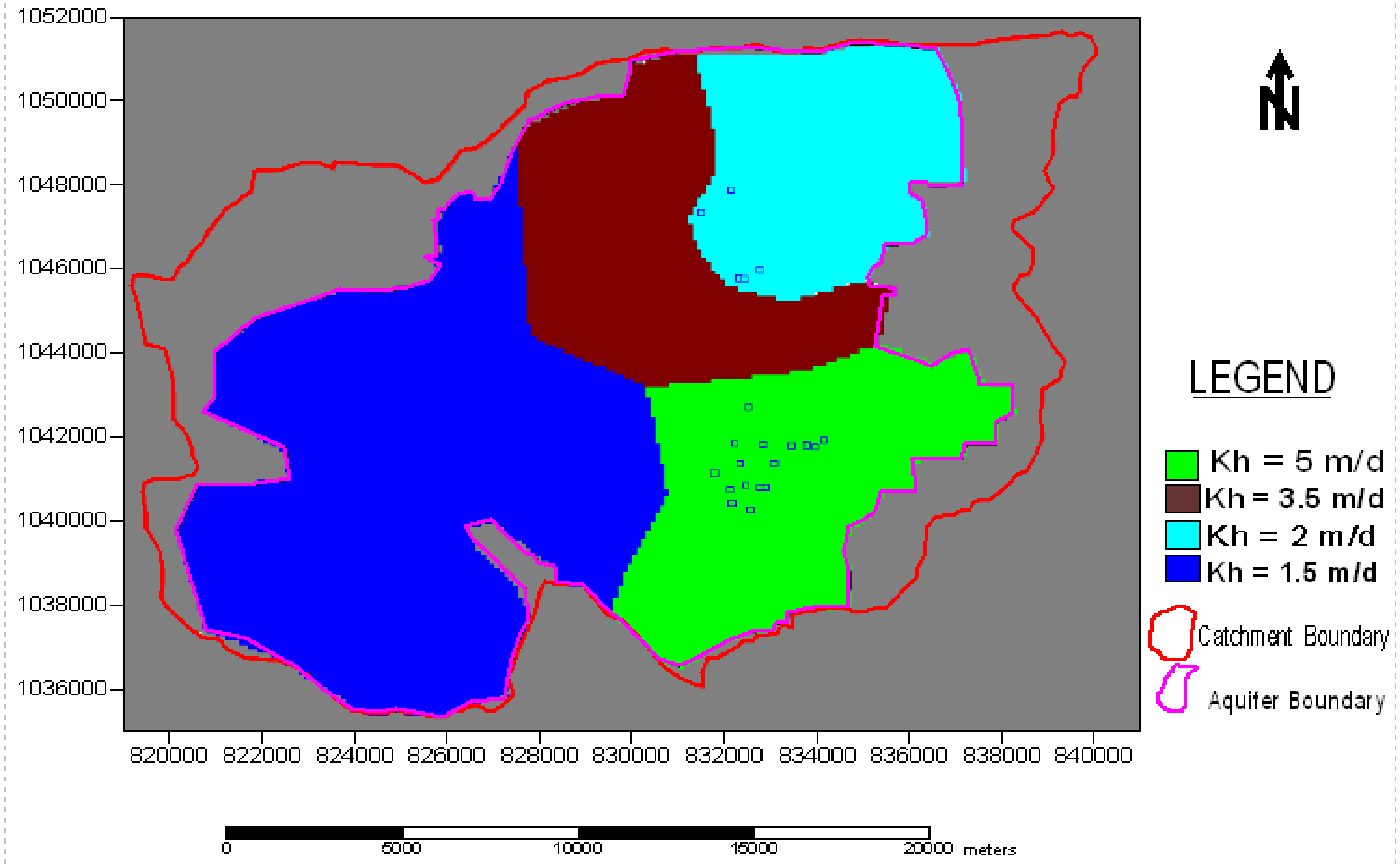


Fig. 11, B. Conceptual Horizontal Hydraulic Conductivity Map of the Study area Layer 2 Aquifer system

4.2.3 Vertical Leakance

Groundwater flow between model layers was assumed to be vertical and to occur when there is a difference in hydraulic head between layers. The vertical conductance between layers, which represent the ability of the aquifer to transmit water vertically, is calculated by the model using a specified vertical leakance value and the cell dimensions. The vertical leakance between model cells, which is the function of cell thickness and vertical hydraulic conductivity, was also calculated by the model. Vertical hydraulic conductivity was calculated by assuming ratios between horizontal and vertical hydraulic conductivities and adjusting the ratio to achieve model calibration. The ratio of vertical to horizontal hydraulic conductivities, as used by many hydrogeology literatures, is ranging from 0.01 to 0.1 (Freeze and Cherry, 1979; Anderson and Woessiner, 1992).

In the field, it not uncommon for layered heterogeneity to lead to regional anisotropy values on the order of 100:1 or even larger (Freeze and Cherry, 1979).

The vertical hydraulic conductivity of the aquifer units was assumed to be one-tenth of the horizontal hydraulic conductivity to account for bedding planes and laminations within the sediments (Anderson and Woessiner, 1992). For the study area, the initial vertical hydraulic conductivity was assumed to be 0.1 of the horizontal hydraulic conductivity. By multiplying the ratio to the horizontal hydraulic conductivity, the values are assigned to the active cells of the model accordingly.

4.4. Model Stresses

Hydraulic heads in the groundwater flow system respond to stresses on the system, which corresponds to recharge and discharge. As noted earlier, recharge to the groundwater system of the study area is from the infiltration of precipitation and discharge from the system is through groundwater pumpage, springs and minor groundwater evapo-transpiration where the water levels are near the surface.

4.4.1. Recharge

Recharge to the model is only from natural recharge which is from the infiltration of precipitation which left from evapo-transpiration and surface runoff. In general, precipitation recharge varies spatially with land surface permeability, which is a function of soil characteristics and land use. The spatial distribution of recharge rate in the study area was determined by averaging the different estimation systems, depending on the land use land cover data of the area by surface water balance calculated by different researchers and inflow outflow methods. By this estimation, the Haromaya sub-basin gets 42 mm/yr of groundwater recharge and the rest two sub-basins, Adelle and Finkile, get groundwater recharge around 20mm/yr, as estimated before. Recharge was applied to the top active cell of the model as a spatially varying, specified flux to the upper most active layer.

4.4.2. Withdrawals

Groundwater pumping is the major way by which the groundwater of the study area outflows from the system. Withdrawals from the aquifer system were simulated based on pumping for production wells used for town water supplies and industries, hand pumps used for rural water supply, hand-dug wells which were used for irrigation and springs. The data were collected from town water supplies record and other user community. The pumpage from each model layer was distributed such that much of pumpage is from layer-2 of the model. Groundwater pumpage for the model was simulated using well package of the MODFLOW depending on the geographic coordinates of the wells. Six assumed wells which pump cumulatively 2149m^3/d were applied to the three sub-catchments which compensate the hand-dug and shallow drilled wells in the areas.

4.5. Model Calibration

Model calibration is the process of making adjustments, within justifiable ranges, to initial estimation of selected model parameters and stresses to obtain reasonable agreement between simulated and measured values. It is the attempt to reduce the difference between model results and measured data by adjusting model input. Calibration is accomplished by finding a set of parameters, boundary conditions and stresses that produce simulated heads and fluxes that match field measured values with the pre-estimated range of errors.

The Adelle – Haromaya dry lakes catchment groundwater flow model was calibrated using trial-and-error method in adjusting initial estimates of aquifer properties (horizontal and vertical hydraulic conductivities), recharge and discharge to get the best match between simulated hydraulic heads and measured water levels and selected water budget items. The groundwater flow model of the area was calibrated using steady-state and transient simulation of groundwater flow.

4.5.1. Steady-State Simulation

Steady state flow conditions exist when inflow is equal to outflow and aquifer storage does not exist. The steady-state simulation of the study area based on the water level measurement of 58 wells in February, 2006 conditions, was made to provide initial conditions for the transient state simulation of the model. Prior to model calibration, criteria were established to evaluate the simulation result in relation to measured data. These criteria generally involve: (1) comparing simulated water level contours with observed water level contours; (2) Comparing measured water levels or drawdown in the well; (3) Comparing the simulated water budget and input data. The calibration criteria were set for the steady-state simulation depending on the existing data source, available time for the research work, and considering different limitations.

Based on the above conditions, the first calibration criterion for the steady state simulation was that the simulated potentiometeric surface and hydraulic gradients generally match those of the estimated average potentiometric surfaces (contours). The simulated steady state potentiometric surface (contour) generally are similar to the estimated average potentiometric surface (fig 12 A and B) for both layers in comparison to both hydraulic head and gradient, indicating satisfaction of this criterion.

A second calibration criterion for steady state simulation includes matching 90% of all wells to within ±10m of the observed hydraulic heads. This second criterion was considered adequate because 10m is less than 10% of the difference between the maximum and minimum hydraulic head of the estimated average of wells in the model area.

Simulated hydraulic heads matched observed values within ±10 m difference for 78.6% of the 58 observed wells and 99.5% of the observed wells is matched to the simulated heads within ±20m difference . A histogram shows the distribution of difference between observed and simulated hydraulic heads (residuals) (fig 13.).

Statistical comparison between the simulated and measured values of hydraulic heads (table 10) was done to quantitatively asses the calibration match. The mean error (ME), root mean square error (RMSE) and the mean absolute error (MAE) provide ways to determine the overall goodness-of-fit between the simulated and the measured hydraulic heads.

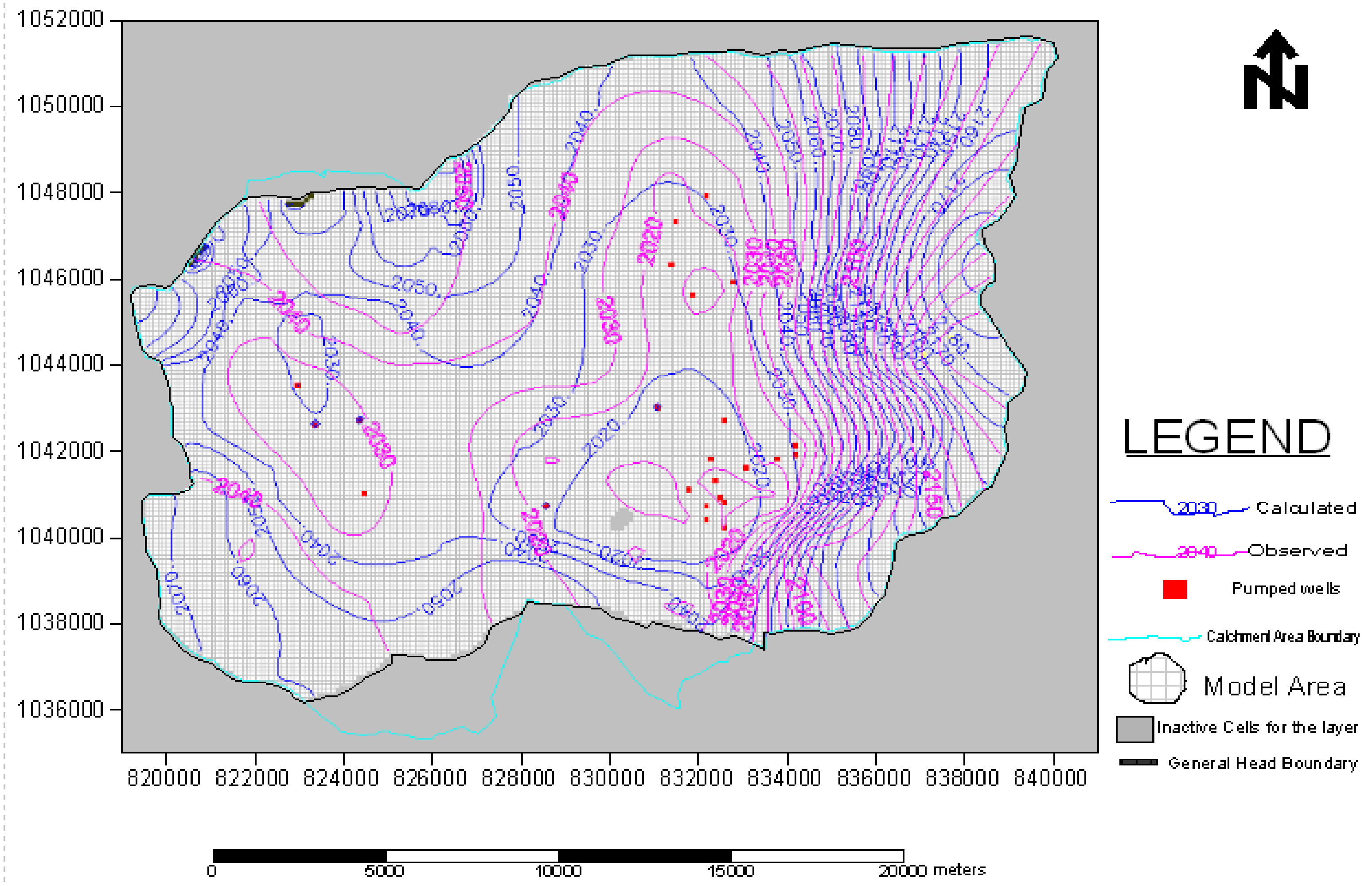


Fig.12, A. Comparison of Observed and Simulated Hydraulic Heads for Layer 1 of the Steady-state Simulation

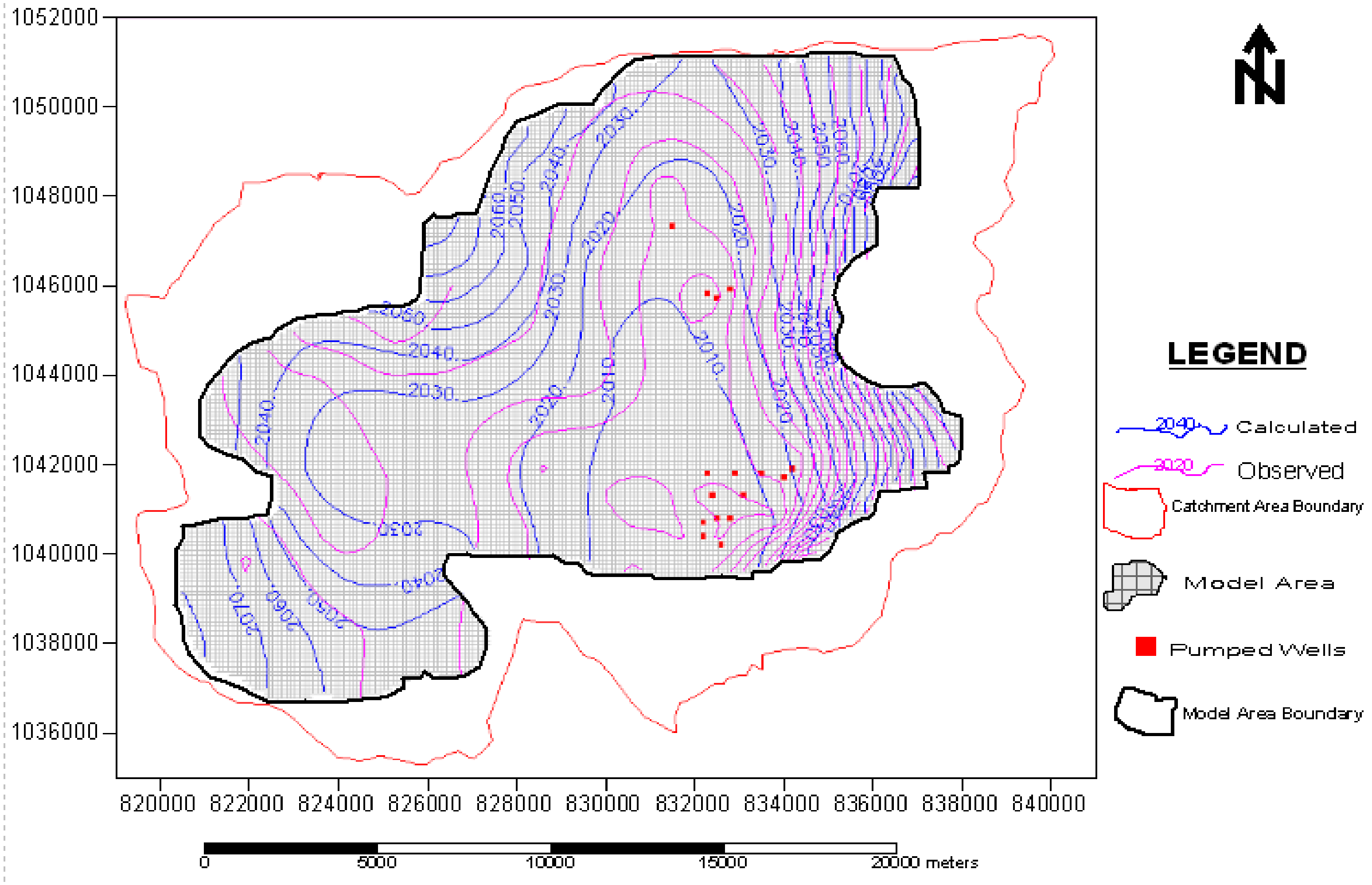


Fig. 12, B. Comparison of Observed and Simulated Hydraulic Heads Contour for Layer 2 of the Steady-state Simulation

1. The mean error (ME) is the mean difference between measured heads and simulated heads.

$$ME = 1/n\sum_{i=1}^{n}(h_m - h_s)_i \tag{2}$$

2. The mean absolute error (MAE) is the mean of the absolute value of the difference in measured and simulated heads.

$$MAE = 1/n\sum_{i=1}^{n}\left|(h_m - h_s)_i\right| \tag{3}$$

3. The root mean squared error (RMSE) or the standard deviation is the average of the squared differences in measured and simulated heads.

$$RMSE = [1/n\sum_{i=1}^{n}(h_m - h_s)^2_i]^{0.5} \tag{4}$$

Where:

n = the number of observation points
h_m = the measured heads
h_s = the simulated heads

(Anderson and Woessner, 1992).

The summary of statistics after steady state calibration for residual heads between simulated and observed values were calculated for 58 water levels measured during the study time and drilling water level reports. Based on this, the mean error (ME), the mean average error (MAE) and the root mean square error (RMSE) were computed for the number of wells (table 10). The mean error is -3.5m for all water level measurements for both aquifers and. This indicates that, the model is negatively skewed in which it favors to calculated water levels. The root mean square error for all wells is 9.08m for the 58 water levels. The mean average error for all wells is 7.08m. The statistical computation for residual errors is summarized in tables 10.

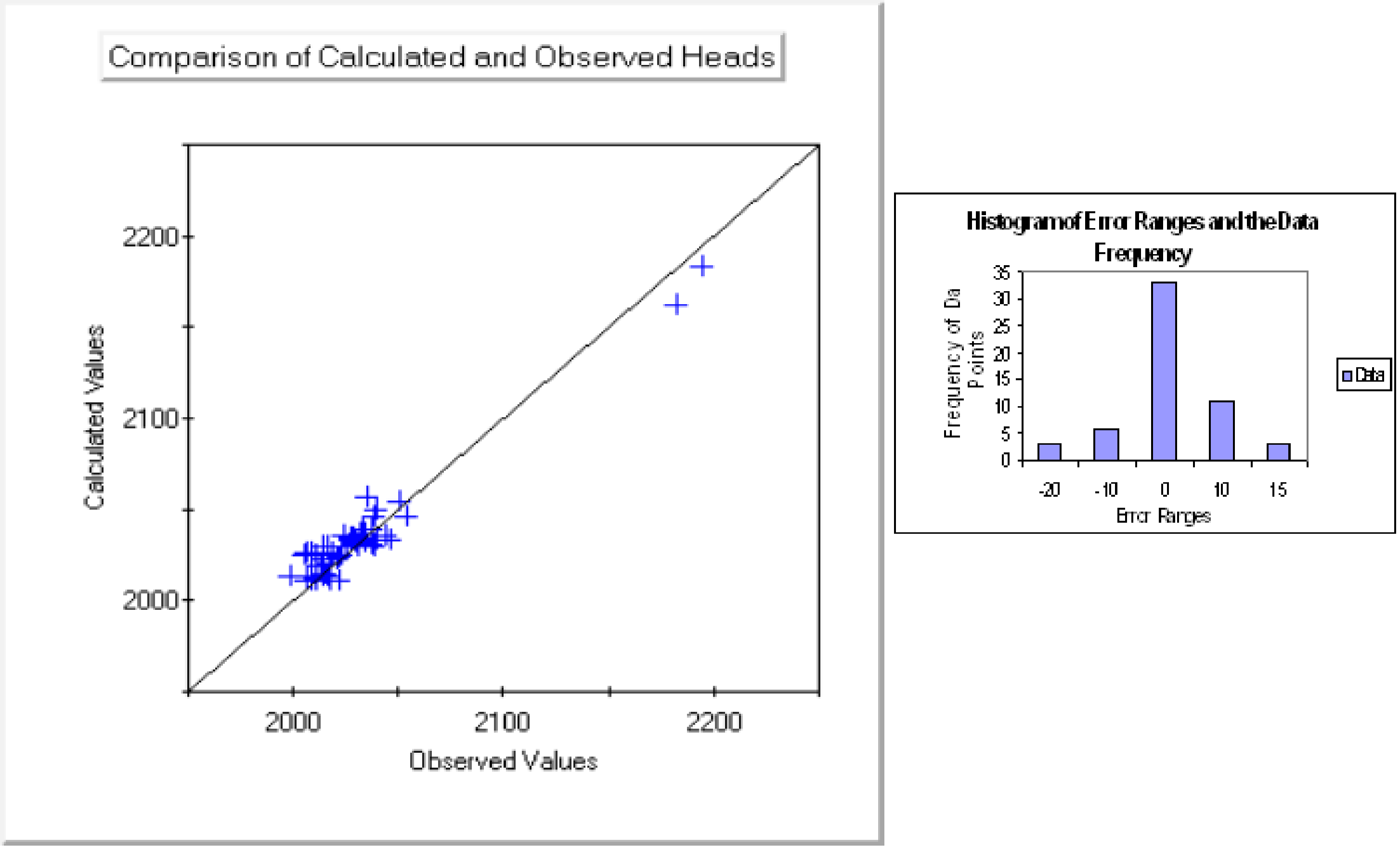


Fig 13. Comparison of Observed and Calculated Head Values of the Steady-state Simulation at 58 Observation points

4.5.1.1. Sensitivity Analysis

The purpose of sensitivity analysis is to quantify the uncertainties in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses and boundary conditions (Anderson and Woessner, 1992). Different methods are available to conduct such analysis, but there is no one method to conclusively determine model sensitivity. In this study, a traditional approach was used by adjusting the most important parameters by selected percentages and documenting the resulting change in simulated water levels and groundwater fluxes in different part of the model area.

The model is considered sensitive to parameter when a change of parameter value changes the distribution of the simulated hydraulic head. When the model is sensitive to an input parameter, the value of that parameter within the model is more accurately determined during model calibration because small changes to the parameter value cause large change in hydraulic head. If the change of parameter value does not change the simulated hydraulic head, the model is considered insensitive to that parameter.

The sensitivity of the model in steady-state mode was determined for the study area by systematical increasing or decreasing the model parameters and stresses from the calibrated values. The adjusted parameters and stresses include; horizontal hydraulic conductivity, vertical hydraulic conductivity, recharge and drain. The adjustment was done by increasing or decreasing the values by 20, 40 and 60 percents for the two layers of the aquifer system by the same factor. Effects of the adjustments on the simulated water level and groundwater flux were calculated (table 11 and fig.14). As observed from the values, the model was most sensitive to horizontal hydraulic conductivity and recharge.

Table 10. Comparison of Simulated and Observed Heads for steady-state Simulation.

S/N	Well ID	Simulated Head (S)	Measured Head (M)	M - S	$(M - S)^2$	|M - S|
1	HDWPV-6	2036.19	2029	-7.19	51.6961	7.19
2	HDWPV-7	2011.578	2009	-2.578	6.646084	2.578
3	SDWPU-1	2023.3	2014	-9.3	86.49	9.3
4	HDWPV-8	2038.029	2033	-5.029	25.290841	5.029
5	HDWPV-9	2025.918	2011	-14.918	222.546724	14.918
6	HDWPV-10	2037.893	2032	-5.893	34.727449	5.893
7	HDWPV-11	2037.194	2034	-3.194	10.201636	3.194
8	HDWPV-12	2031.481	2038	6.519	42.497361	6.519
9	SDWPU-3	2026.95	2009	-17.95	322.2025	17.95
10	HDWPV-13	2033.317	2040	6.683	44.662489	6.683
11	HDWPV-14	2023.189	2022.3	-0.889	0.790321	0.889
12	HDWPU-1	2022.026	2020.5	-1.526	2.328676	1.526
13	HDWPU-2	2020.496	2018	-2.496	6.230016	2.496
14	HDWPU-3	2019.526	2017	-2.526	6.380676	2.526
15	HDWPV-15	2019.06	2013	-6.06	36.7236	6.06
16	HDWPV-16	2013.163	2016.5	3.337	11.135569	3.337
17	HDWPV-17	2010.873	2022	11.127	123.810129	11.127
18	HDWPV-18	2024.467	2016.85	-7.617	58.018689	7.617
19	HDWPV-20	2029.819	2014.4	-15.419	237.745561	15.419
20	HDWPU-4	2032.082	2034.25	2.168	4.700224	2.168
21	HDWPV-21	2029.598	2030.65	1.052	1.106704	1.052
22	HDWPV-22	2029.056	2038.8	9.744	94.945536	9.744
23	HDWPV-23	2025.054	2009	-16.054	257.730916	16.054
24	HDWPV-24	2010.894	2007	-3.894	15.163236	3.894
25	HDWPV-25	2032.759	2027.2	-5.559	30.902481	5.559
26	HDWPV-26	2030.002	2023.5	-6.502	42.276004	6.502
27	HDWPV-27	2032.985	2030.21	-2.775	7.700625	2.775
28	HDWPV-28	2057.972	2035.3	-22.672	514.019584	22.672
29	HDWPV-30	2034.127	2046.2	12.073	145.757329	12.073
30	HDWPV-31	2036.35	2044.45	8.1	65.61	8.1
31	HDWPV-32	2037.818	2037.2	-0.618	0.381924	0.618
32	HDWPV-33	2049.937	2054.3	4.363	19.035769	4.363
33	HDWPV-34	2031.039	2030.9	-0.139	0.019321	0.139
34	HDWPV-35	2033.415	2034.1	0.685	0.469225	0.685
35	HDWPV-36	2054.113	2050.6	-3.513	12.341169	3.513
36	HDWPV-37	2038.521	2033	-5.521	30.481441	5.521
37	HDWPV-38	2035.443	2024	-11.443	130.942249	11.443
38	HDWPV-39	2034.293	2027.65	-6.643	44.129449	6.643
39	HDWPV-40	2048.701	2039.4	-9.301	86.508601	9.301
40	HDWPV-41	2045.533	2039.05	-6.483	42.029289	6.483
41	HDWPV-42	2015.417	2015	-0.417	0.173889	0.417
42	SDWPU-5	2013.83	2010.9	-2.93	8.5849	2.93
43	HTBH	2012.405	2018	5.595	31.304025	5.595

Table 10. Continued.

S/N	Well ID	Simulated Head (S)	Measured Head (M)	M - S	(M - S)2	│M - S│
44	HTBH	2014.459	1998.4	-16.059	257.891481	16.059
45	HTBH	2012.001	2011.22	-0.781	0.609961	0.781
46	HTBH	2013.879	2009.05	-4.829	23.319241	4.829
47	AUBH-5	2026.389	2023.3	-3.089	9.541921	3.089
48	HBBH-65	2026.356	2006	-20.356	414.366736	20.356
49	HBBH-59	2025.734	2005.4	-20.334	413.471556	20.334
50	HBBH-51	2030.412	2025	-5.412	29.289744	5.412
51	HBBH-85	2026.954	2018.55	-8.404	70.627216	8.404
52	SPRG1	2166.004	2183	16.996	288.864016	16.996
53	SPRG2	2185.828	2195	9.172	84.125584	9.172
54	HTBH	2012.688	2011.11	-1.578	2.490084	1.578
55	HTBH	2014.115	2006.14	-7.975	63.600625	7.975
56	HTBH	2014.665	2014.48	-0.185	0.034225	0.185
				-198.437	4574.6707	393.665
				ME=-3.5	81.6905482	**MAE= 7.0**
					RMS= 9.03	

Table11.Sensitivity Analysis of the Selected Parameters for steady-state simulation.

% Change in Parameters	RMS Values for the Selected Parameters		
	HHC	VHC	Recharge
−60	9.744	9.152	9.521
−40	9.537	9.114	9.411
−20	9.368	9.12	9.432
0	9.038	9.038	9.038
20	9.215	9.26	9.482
40	9.34	9.31	9.509
60	9.615	9.342	9.558

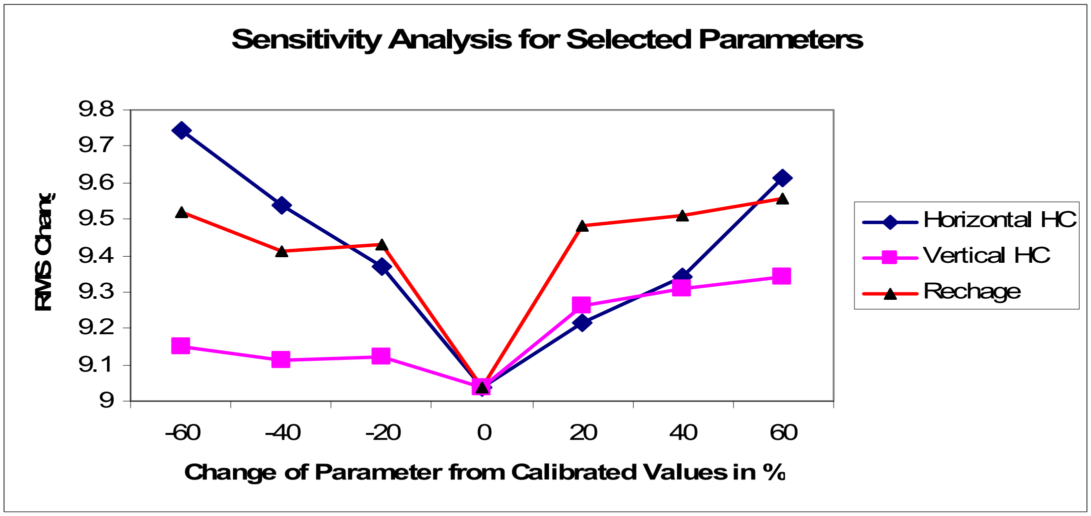


Fig.14. Sensitivity Analysis graph of the steady-state simulation.

(HC = Hydraulic Conductivity)

4.5.1.2. Simulated Water Budget

The water budget for steady-state simulation is balanced (inflow minus outflow) within a percent discrepancy of -0.09 (table12). The recharge rate used for numerical model was within the range of the average value of recharge listed in conceptual model for the study area. It was estimated during model calibration and the simulated average over all area is 20mm/year. The comparison of steady-state water budget for the numerical simulation shows that, estimated groundwater balance for conceptual model with the minimum recharge 20mm/yr is more or less similar to simulated value with some variation which might be caused by boundary delineation for numerical model.

Table 12. Simulated Steady-state Groundwater Balance for the Model Area.

```
Volumetric Budget For Entire Model At End Of Time Step 1 In Stress Period 1

   Cumulative Volumes      L**3       Rates for This Time Step      L**3/T
        In:                                In:
     Constant Head =    0.0000        Constant Head =    0.0000
            Wells =          0.0000              Wells =          0.0000
           Drains =          0.0000             Drains =          0.0000
  H. Dep Bounds =      0.0000            H. Dep Bounds = 0.0000
    Recharge =           9491.7539                 Recharge = 9491.7539

         Total In =       9491.7539              Total In =9491.7539

       Out:                                        Out:
     Constant Head =  0.0000        Constant Head =      0.0000
            Wells =       8705.0400                Wells =       8705.0400
           Drains =        532.7971               Drains =        532.7971
  H. Dep Bounds =    262.7675         H. Dep Bounds =  262.7675
     Recharge =          0.0000            Recharge =       0.0000

        Total Out =        9500.6045       Total Out =       9500.6045
         In - Out =         -8.8506          In - Out =         -8.8506
     Percent Discrepancy =  -0.09     Percent Discrepancy = -0.09
```

4.5.2. Results of Steady-state simulation

Flow simulation of steady-state condition for Adelle – Haromaya dry lakes catchment aquifer system was used to obtain a robust model calibration. The overall model calibration using the groundwater level of Feb., 2006, and drilling report static water levels for steady-state simulation is summarized in this section.

The steady-state model was calibrated by varying model input parameters and stresses – horizontal and vertical hydraulic conductivity values, recharge and stream bed conductance – to obtain as close a match as possible between simulated and observed water levels. Calibration data consisted of 58 water level measurements taken at spatially distributed points of the study area, were used for observed values. Trial-and-error methods were used to calibrate the steady-state model. In trial-and-error methods, parameter values are adjusted manually until the match between simulated and observed values is considered reasonable.

The pre developed boundary condition of the conceptual model was used during the steady-state calibration. In this boundary condition, the major surface watershed boundary was used as no flow boundary. But, the watershed boundaries between the three sub-basins were taken as there is no boundary so that groundwater can move from one sub-basin to the other depending on the hydraulic properties and groundwater heads. The outer separate local depressions, which taken as catchment area, were not included in the model area (the area found south of Haromaya town).

Hydraulic properties of the aquifer system were adjusted manually to obtain close match between the observed and simulated groundwater levels. Horizontal and vertical hydraulic conductivity values were adjusted in zones from the conceptual model values (fig. 11, A and B) for the two layers. Initial zones were modified to better match observed heads by adding separate zones in different parts of the model area. The initial horizontal hydraulic conductivity, which ranges from 0.001 to 4 m/d for layer one and from 1.5 to 10 m/d for layer two of the model were modified to ranges from 0.001 to 6 m/d for layer one and from 0.1 to 10 m/d for layer two. The vertical hydraulic conductivity which was initially assumed as 10% of the horizontal hydraulic conductivity was modified to 1% of the horizontal hydraulic conductivity for both layers.

Calibrated recharge rate was also determined through trial-and-error method depending on the general groundwater outflow from the model area and previously estimated recharge amount. The rate of natural precipitation recharge calculated for Haromaya sub-basin (42mm/yr), the inflow-outflow balance of Finkile and Adelle sub-basins (11mm/yr and 18mm/yr respectively), were applied initially. But, through calibration process, the average 20mm/yr was a final steady-state calibrated value since there is sub-surface flow of the model to Haromaya sub-basin from the other two which compensate the groundwater discharge from Haromaya sub-basin.

Calculated groundwater level for the 58 data points of wells measured during study time (Feb., 2006) and drilling report for the steady-state model are shown in table 10 and figure 13. The mean Absolute difference between observed and model calculated water levels (MAE) was 7.02 for the whole data points and the root mean square of the error (RMS) was 9.038 for the data points. In some cases, large difference between observed and model calculated water levels may have resulted from the position of the observed wells near the model boundaries (for example, SDWPu-4).

The steady-state average annual hydrologic budget calculated with the calibrated model is shown in table 12. The total inflow of the model area was 9491.75m^3/d, which is only from recharge. The total outflow from the model area was 95000.605m^3/d, which is from wells, springs and groundwater outflows at the general head boundary.

The percent discrepancy between the inflow and outflow of the steady-state simulated water balance was -0.09. This is because the simulated groundwater outflow at the general head boundary condition may be greater than the actual condition. The balance was more or less similar with the conceptual model groundwater balance calculated using minimum inflow of the conceptualized groundwater recharge range.

A sensitivity analysis was performed to asses the response of the model simulation to changes in selected input parameters (fig. 14). As observed from the result after percentage decrease and increase of the parameters from calibrated values, the model is more sensitive to horizontal hydraulic conductivity and recharge.

The steady-state calibration result, generally, shows that the model is negatively skewed, which means that simulated value exceeds observed values of the water levels. This is most probably because of the groundwater flow from the two sub-basins to Haromaya sub-basin and increased the water level in Haromaya basin.

4.5.3. Transient Simulation

Transient simulations are needed to analyze time dependent problems. A transient simulation typically begins with steady state initial conditions and ends before or when a new steady state is reached (Anderson and Woessner, 1992).

Transient models were developed to simulate the variations in hydrologic conditions within an average annual cycle. Transient models are based on the steady-state models but incorporate time varying hydraulic stresses and boundary conditions. The spatial discretization of the model grids, boundary conditions other than specified flows, and spatial variation in stresses and hydraulic conductivities are the same in transient and steady-state models.

With the transient models, the low flow periods of the annual cycle can be simulated. Low flow periods, typically the critical dry seasons, often are particular concern in the evaluation of the effect of water management alternatives. During these periods, the effect of groundwater withdrawals and naturally low flows make the groundwater level low. Water demands also typically are higher during dry seasons. Thus, seasonally varying stresses and fluxes within the annual cycle often must be considered when the effect of water management alternatives are tested.

Upon achieving a satisfactory steady-state calibration, transient groundwater conditions of the study area were modeled for one year and one month period between February, 2005 and February, 2006. The transient state model consists of 13 monthly stress periods. Each stress period has 10 time-steps and the time units were days. Each month length is assumed to be 30 days. Generally, 390 stress periods were used in which the model simulates every three days.

Boundary conditions, in the transient model, were similar to that of steady-state model. As in the steady-state model, the lateral boundary for layer-1 and layer-2 of the aquifer system was no flow boundary except few localities which were simulated by general head boundaries. The bottom boundary of laye-2 is no flow boundary and the bottom boundary forlayer-1, in areas where layer-2 is absent is no flow boundary. The top boundary of layer-1 is a free head boundary which accepts specified fluxes, such as recharge. The top boundary of layer-2, in areas where it exposed to surface is also free surface boundary.

Water level elevations from the calibrated steady-state model were specified as the initial condition for the transient simulation. The calibrated steady-state water levels represent average annual condition. The transient simulation also began with stresses and boundary flow representing conditions in the month of February, 2005. Because, February, 2005 was the time at which the Harar Water Supply and Sewerage Authority started measuring water levels for the observation wells, it was used as the initial time for transient simulation. The Authority continued measuring the water levels every day since then but, the data available for this study was up to February, 2006. These data were used for the transient-state model calibration.

Average monthly recharge rates were based on the average annual recharge rate from the calibrated steady-state model. The temporal recharge pattern was based on the monthly distribution of precipitation and the time for recharge was the time at which precipitation exceeds soil moisture deficit and evapotranspiration. There are two months for the study area at which the precipitation exceeds these deficits, as observed from the water balance calculation of Wagari Furi, (2005); tables 5 and 6; August and September. But, as observed from the temporal pattern of groundwater level in the four observation wells (fig. 8), the level increases in the month of April even-though the abstraction continuous relatively in constant rate. So that, April is also considered as a month in which recharge takes place. Generally, the annual average groundwater recharge of the study area, 20mm/year, which is the annual average rate of the calibrated steady-state model, was averaged to the three months (April, August and September).

Monthly withdrawals for water supply and irrigation were set equal to average monthly volumes for the simulation time period. The annual average withdrawals from hand-dug wells were averaged for the six dry months of the year; November, December, January, February, May and June; these months, as information obtained from Haromaya Woreda irrigation Office, are the time at which irrigation is intensively undertaken. The withdrawals from hand pumps and deep wells were averaged by their monthly volume, which were used under steady-state condition, and applied to the transient model on daily basis. But, as observed from water meter reading of the Harar water supply boreholes, withdrawal was increased by almost 100% starting from November, 2005 to February, 2006 (table 8 and fig.8). The monthly average for this period was applied to the transient model.

A uniform value of 0.1 for specific yield and 0.005 for storage coefficient were used for both layers of the model area. These values are similar to the average values estimated in the conceptual model from different groundwater literatures.

Calibration of the transient state model involved trial-and-error adjustments of storage coefficient and specific yield and to some extent distribution of annual recharge in order to get reasonable agreement between simulated and measured values for water levels. The transient model was calibrated using available water level data from 4-wells for the period 2005 – 2006 at Harar water supply observation wells (table 13). The observation well data were used to compare measured and simulated water level over time. Calibration criteria for the transient simulation consisted of approximately reproducing the general temporal trends of the hydraulic heads of the 4-observation wells. There was no attempt to calibrate the transient simulation to match the hydraulic heads in the observation wells closer than the required for steady state simulation.

During model calibration, aquifer storage properties were varied to minimize the difference between simulated and measured water level fluctuation. Specific yield was varied between 0.1 and 0.15 and storage coefficient varied between 0.005 and 0.001.

Differences between simulated and observed water level fluctuations may have resulted from various causes, including model calibration error, discretizing effects, or inadequate simulation of aquifer geometry, storage properties, recharge or other hydrologic processes. The other thing which may create error in the study area is the interconnectivity of the aquifer system of the three groundwater sub-basins. Deviation between the monthly fluctuation of observed and simulated water level trends may by the time variation between the application of recharge and the actual condition (fig. 15).

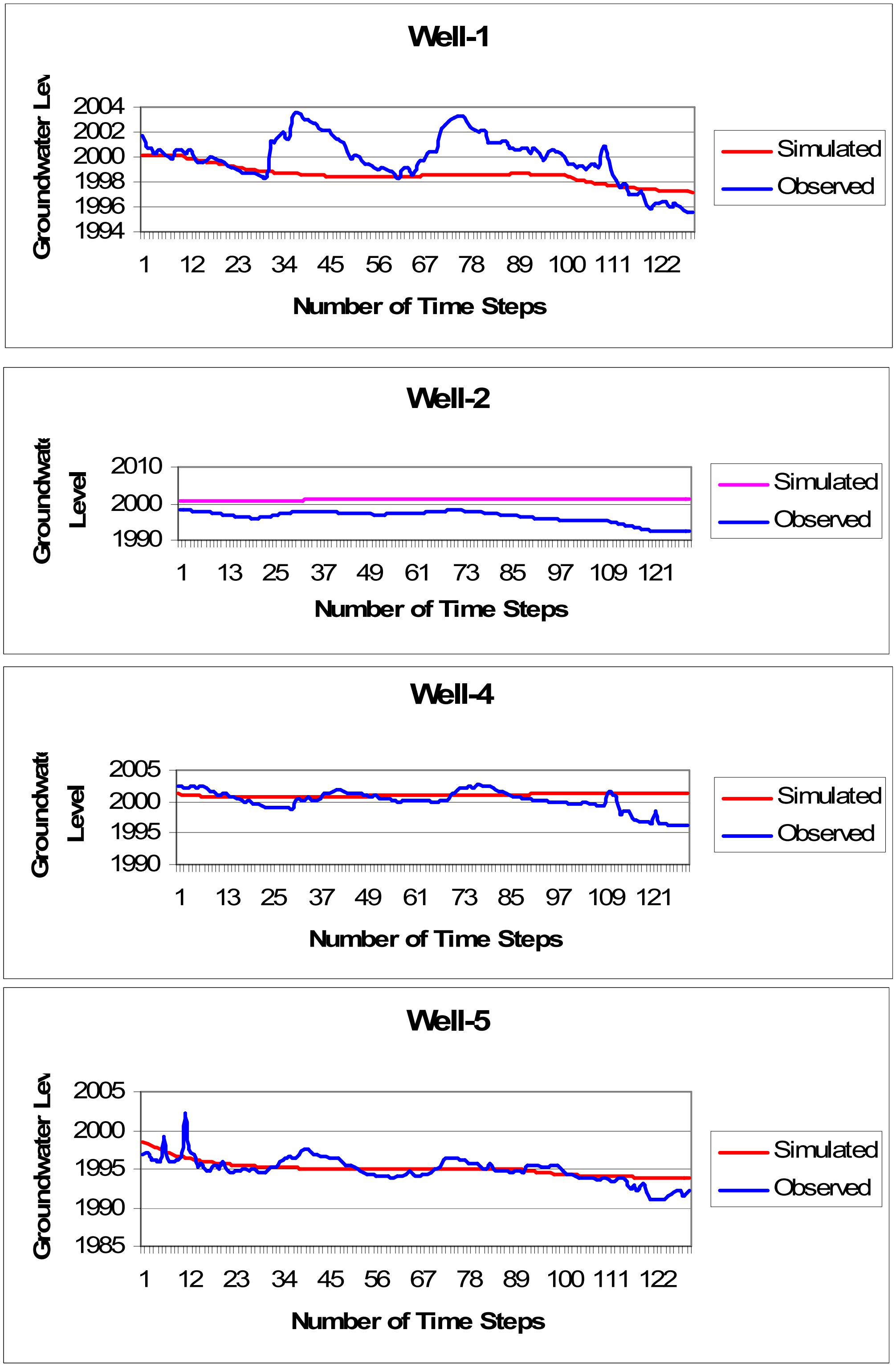


Fig. 15. Comparison of Simulated and Observed Water Levels, for Transient Simulation at the Harar Water Supply Observation Wells.

4.6. Model Limitations

The groundwater flow models are numerical simplification of real aquifer flow system. Model results are affected by numerical approximations used to solve the groundwater flow equation, discretization of the modeled area and the availability and accuracy of hydrogeologic data used to define boundary conditions, and model stresses.

The steady-state and transient flow models of the Adelle – Haromaya dry lakes catchment groundwater flow system was also subjected to many approximations starting from system conceptualization and grid design to model calibration. There are uncertainties in many model input parameters, most importantly, recharge, horizontal and vertical hydraulic conductivities and boundary conditions. Although these model input parameters had a major influence on model results, extensive data were not available. The combination of parameter values used in this model was based on many considerations. The parameter values were chosen within the general ranges of previously published values, and therefore models accuracy is dependent, in part, on the accuracy of those estimations.

The areal extent of the second aquifer layer (Layer-2) of the model was assumed from the surface lateral extent of alluvial materials found at the central parts of the three sub-basins. This surficial extension may not exactly fit with the extension of the lower aquifer. The difference between the assumption and the actual extent of the aquifer may affect the quality of the model results. The conceptualized lateral and vertical boundary conditions of the two layers of the model has also its own limitation especially in areas where surface water divide differs from groundwater divide which creates differences between simulated and observed water levels under steady-state and transient simulations.

Estimation of groundwater recharge for the entire basin of the study area was not quantified except for Haromaya sub-basin previously. Therefore, the conceptual groundwater recharge of the two sub-basins, Adelle and Finkille, was estimated from groundwater inflow-outflow balance by this study. Even-if it was adjusted during steady-state calibration by trial-and-error methods; the averaging of the value affected the quality of the model result, as it was observed from the steady-state calibrated values of the water levels in which the mean error between observed and simulated water levels biases to the simulated values. The seasonal groundwater discharge along streams to the seasonal lakes of the study area was not quantified previously and also by this study. This limitation also affected the quality of stresses applied to the model and affects the numerical groundwater balance of the steady-state simulation.

The groundwater flow model of the study area was calibrated in steady-state and transient modes using a process of trial-and-error parameter adjustments to minimize differences between simulated and measured values or estimated variances. Measurement of local hydraulic properties, however, may not be representative values of the adjacent areas. The fact that flow models do not have unique solutions which indicate that calibrated hydraulic parameters may not accurately reflect the actual hydraulic parameters of the simulated system. Calibrated solutions are considered plausible if simulated results match measurements or estimates reasonably well and calibrated parameters appear reasonable based on the hydrogeology of the study area.

The effects of temporal and spatial discretization also impose limitation on model use. The simulation time for transient model was very short due to lack of calibration data for the water level. The long-term temporal groundwater fluctuation was simulated based on the one year period calibration data.

CHAPTER FIVE

GROUNDWATER FLOW SYSTEM AND FUTURE MANAGEMENT CONDITIONS

Groundwater flow model was used to simulate possible effects on level caused by increased withdrawals from wells. The calibrated model can also be used to simulate potential groundwater management plans on hydraulic heads and groundwater movements in the basin depending on the general aquifer interconnectivity of the study area.

After calibrating the steady-state and transient simulations of the Adelle – Haromaya groundwater flow system, two scenarios were developed for future groundwater management of the area. These are; Groundwater flow system condition for the three sub-basins of the study area if there is flow from one sub-basin to the other and future groundwater pumping condition. The aquifer system properties determined as a result of the model calibration processes of the steady-state and (2005 – 2006) transient model were used for the scenario runs.

5.1. Groundwater Flow System Conditions

The Adelle – Haromaya dry lakes catchment, as discussed earlier, has three sub-basins (surface watersheds); Haromaya, Finkille and Adelle (fig. 2). The surface water flow for these sub-basins is separately to the seasonal lakes, but as information obtained from local people, previously there was a surface overflow from Finkille to Haromaya lake when the lakes were perennial. There is also one local depression area at Ararso locality, between lakes Finkille and Adelle, which has its own local surface catchment and ponds the surface water flow seasonally. The three major sub-basins were treated as a one big catchment, including the local depressions and groundwater flow model was simulated under steady-state and transient modes depending on the hydraulic properties of the local conditions.

The surface area coverage of the sub-basins includes Haromaya 27.5%, Finkille 32.5% and Adelle 40%. But, concerning the groundwater outflow by pump withdrawals and natural springs, Haromaya sub-catchment covers around 74.5% of the total daily discharge. Out of the 21 deep wells, which are installed with submersible pumps, found in the study area, 15 are found in Haromaya watershed (fig. 7). The two springs are also found in this sub-catchment.

The average annual groundwater recharge of the conceptual model was previously calculated by the other researchers' shows that, it is around 42mm/year for Haromaya sub-catchment. For the other two watersheds, there was no data calculated separately, but as estimated from the groundwater inflow-outflow balance, the annual net recharge is less than 15 mm/year. The average annual steady-state calibrated result of the groundwater recharge was 20mm/year for the whole study area. In this case, part of the groundwater discharge at Haromaya watershed comes from the other two watersheds depending on the groundwater level condition and aquifer properties of the areas.

The conceptual model groundwater level and its movement was developed from the water level measured at 53 selected wells during the study time (Feb.,2006) and the drilling report static water level for 12 boreholes. The 65 groundwater elevation data were fed to the software "surfer-8" and the level contour map was developed. When the groundwater flow direction was analyzed, it showed that the local flow is to the local surface depression of the lakes bottom. The general flow direction shows as flow is from Adelle to Finkille and then to Haromaya watersheds with some local divides (fig.9). Based on this analysis, the numerical groundwater flow model was developed for the entire study area assuming as there is flow interconnection among the sub-basins of the study area even if the hydraulic property differs. The hydraulic properties specified in the model for the localities of the watershed divides, among the sub-basins are lower than the other areas for the first layer of the model. But, there is a flow among the three sub-basins based on the water level conditions.

The scenario developed here was, what happens to the groundwater level; especially the Haromaya sub-basin, if there is minimum flow from one sub-catchment to the other? Does the result best fit with the groundwater level of the observation boreholes? The future groundwater pumping scenarios were developed depending on this result.

The approach taken to simulate the interconnectivity of the three sub-basin aquifer system was:

- Applying a horizontal flow barrier package of the MODFLOW which impede groundwater flow from one sub-basin to the other. The barrier was applied at the boundaries of the three sub-basins.
- The aquifer system properties determined as a result of model calibration process for the steady-state and transient simulation were used for this scenario.
- The average annual recharge developed by the conceptual model for the three sub-basins was applied to the scenario.
- Annual average discharge used in the steady-state calibration was used to the scenario.
- The model was run under steady-state condition.
- The water level simulated under this condition was compared with the steady-state calibrated water level and then compared with the observed water levels.

After applying the horizontal flow barrier of the MODFLOW to simulate the Haromaya sub-basin separately, the simulation result showed that slight water level change in the sub-basin which close to the actual measured values. From this result, it was assumed that the aquifer system in the sub-basin is probably not connected to the other two sub-basin aquifers. Based on this, the scenario developed for future groundwater pumping condition for Haromaya sub-basin performed by applying the horizontal flow barrier at the watershed boundaries.

5.2. Simulated Effect of Future Pumping Conditions

The calibrated groundwater flow model was used to simulate the potential effect of alternative water management plans on hydraulic heads and groundwater movement in the Haromaya sub-basin. Although water levels for a given scenario may not accurately represent the values in the real system, the relative differences in water levels overtime can be compared to provide managers with useful information for planning and decision making.

For this study, the model was used to simulate the aquifer system response to two potential pumping scenarios for Harar water supply wells for five years period starting from Feb, 2005. Five years period was designed because, after these years, as information obtained from Harar Water Supply and Sewerage Authority, the water supply system of the town and surrounding will be shifted to Dire Jarra groundwater (the area near Dire Dawa). The two scenarios are: 1) to simulate the effect of continuing the December 2005 pumping condition and 2) to simulate the effect of continuing the October 2005 pumping conditions (table 6). For both scenarios, the aquifer system properties determined as a results of model calibration process of Feb, 2005 – Feb, 2006 transient model were used for the scenario runs. But, horizontal flow barrier was applied to the watershed boundaries and recharge was changed from 20mm/yr. to 42mm/yr. for Haromaya sub-basin from the previously calculated value to avoid averaging, and for the other sub-basins, recharge was applied based on inflow-outflow balance. Head values calculated by the steady-state model were used as the starting heads for the scenario runs. As in the Feb, 2005 – Feb, 2006 transient model, a monthly time-step was used, each time-step has 30 days and 10 stress periods.

In the projection simulation, groundwater levels at Harar water supply observation wells decline from 2001.189m to 1999.434m for well number-1, from 2000.849m to 2000.527m for well number-2, from 2001.323m to 2000.963 for well number-4 and from 1999.67m to 1995.891m for well number-5, under the scenario-1 (fig.16). For scenario-2, the result shows, there is no or very minimum groundwater level changes for the above boreholes.

The result of scenario simulations show that, continuation of pumping under the December, 2005 rate for Harar water supply boreholes decrease the water level by around 5m for well number-5, for the others the depletion is minimum. For most of the boreholes, the above minimum elevations of the water levels are the top of the wells screen casings. Due to this condition continuation of the scenario-1 pumping condition may introduce vertical flow to the wells which may, in turn, decrease the yield of the wells.

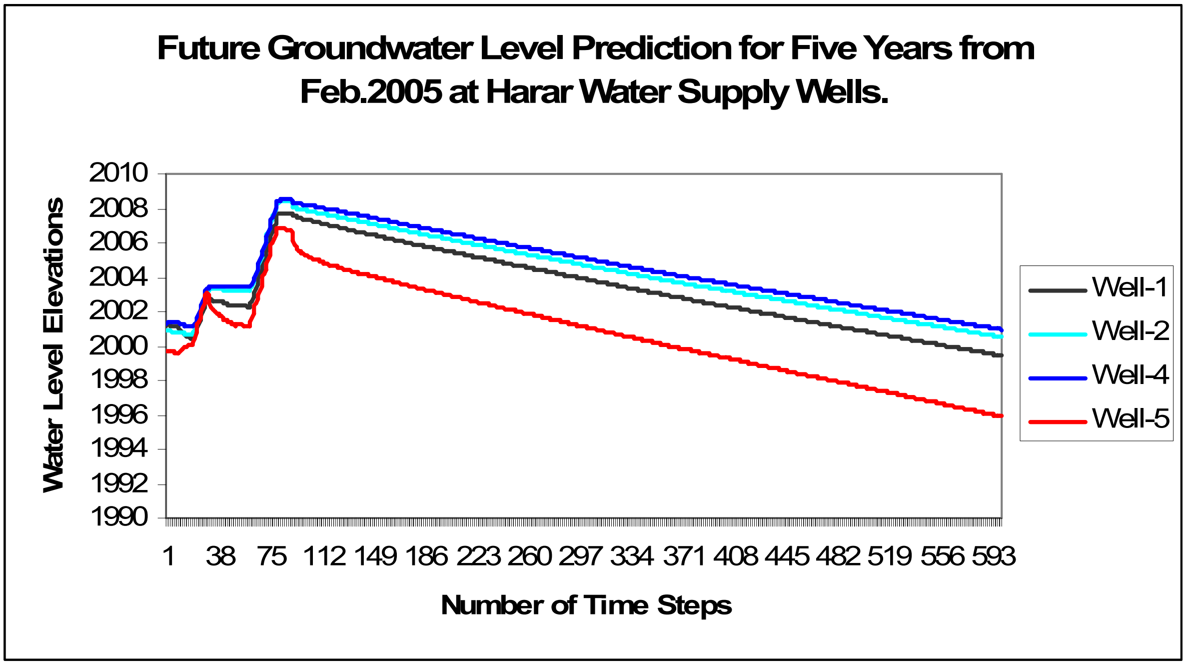


Fig ure 16. Future Groundwater Level Prediction of the Harar Boreholes for the next Five Years starting from February, 2005.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusion

The groundwater of the shallow aquifers of the Adelle – Haromaya dry lakes catchment became very important source for water supplies of Harar, Awaday and Haromaya towns, and Haromaya University main campus. The Harar Brewery and Hamaressa Edible Oil factory are also the beneficiaries of this groundwater source for industrial purposes. The rural community found in these basins including the big villages of Adelle, Finkile, Bate and Dengego are also using the groundwater of the area for their domestic consumption of human and animals. The groundwater of the area also is used for irrigation purpose from hand-dug wells by the rural community. The demand of the groundwater of this area is increasing from time to time since the pre-existing Haromaya and Adelle perennial lakes became seasonal before few years and increasing population. The reason why the lakes became seasonal, as stated by other researchers, was over pumping for irrigation, evapotranspiration from lake bodies and siltation, which resulted from the lakes area surrounding land use practice. The researchers also added, if groundwater pumping and well drilling continuous by the existing rate, the situation happened to the surface water bodies may be happened to the groundwater potential of the area.

A three dimensional numerical groundwater flow model was constructed for the Adelle – Haromaya dry lakes catchment as a tool to understand the aquifer system and how possible future groundwater pumping may affect the system. The result may help decision makers for future groundwater management system. Prior to develop the numerical groundwater flow model, the groundwater flow system was conceptualized based on the geo-hydrology of the study area.

The Adelle – Haromaya dry lakes basin consists of unconsolidated alluvial and lacustrine sediments which cover the wide low land central part of the lakes catchment and the thickness ranges from 10m to 80m at the northern part of the study area. The alluvium consists of poorly sorted clay, silt and sand at its upper part and well sorted sandy gravel and gravelly sand at its lower part. The hilly side outer part of the study area consists of weathered basement complex, which has thickness which ranges from few meters to 40m where it is highly weathered and fractured. The ridge forming Mesozoic sedimentary rocks of predominately sandstone and limestone, which overlay the basement complex, are highly weathered. The thickness of these formations reaches up to 250m at the outer most part of the study area in the northern part. Fractures are also observed in these rocks.

The study area was conceptually divided in to three sub-basins (Adelle, Finkile and Haromaya) based on the surface watersheds. There are also local depressions in between the major sub-basins and at their outer part which have their own watersheds. The three major sub-basins were conceptualized as one groundwater system based on the groundwater level and flow direction mapped during field study time, Feb. 2006, from the data collected at different measuring points. The local depression areas found at the boundaries of the major watersheds were not considered for numerical model even though they were considered as the catchment area.

The hydrostratigraphy of the study area was conceptually grouped vertically in to three aquifers and confining units; the upper low permeability aquifer, the lower high permeability aquifer and the confining bedrock. The grouping of the aquifers and confining units was based on the properties of the aquifer material and their hydraulic properties obtained from; borehole logs, geophysical surveys, field observations and well yields. Based on this, the upper low permeability aquifer unit (layer-1 of the model) consists – poorly sorted alluvial sediments, weathered and fractured basement complex and Mesozoic rocks of weathered sandstone and limestone. This aquifer unit covers almost all the surficial part of the model area except the area near the bottom of Haromaya dry lake where the lower aquifer unit outcrops to the surface. The lower high permeability aquifer (layer-2 of the model) consists – well sorted gravely sand and sandy gravel alluvial sediment found at the plain central part of the lakes sub-basins especially Haromaya and Finkile. Some part of Adelle sub-basin was also included in this aquifer unit. Parts of the areas between the three sub-basins were included to this aquifer system but, with minimum thickness for simulation purpose. The thickness of the lower aquifer unit ranges from 10m where the bedrock elevation is higher to 150m where the elevation of the bedrock is deeper. In actual condition, the maximum thickness of the unit reaches up to 80m but, to give the model enough thickness for better simulation, the thickness was extended to the above depth. The bedrock was conceptualized as the lower confining unit.

The lateral boundary of the upper aquifer unit was taken as the catchment area boundary except for the outer depression where the watershed of the major sub-basins was used as aquifer boundary. The top boundary of this aquifer unit was ground surface and the bottom boundary was assumed as the elevation 1980m above sea level. This elevation was taken because it is, in most cases, the elevation at which poorly sorted alluvial materials contact with well sorted alluvial materials as the well logs and geophysical survey results indicate. The lateral boundary of the lower high permeability aquifer unit was conceptually modeled as the areas where the well sorted alluvial sediments contacts with the bedrock laterally. From surface topography, the contact between alluvial sediments and basement rock was observed as it is the elevation of 2150m above sea level. Above this elevation, it was assumed as there is no alluvial sediment. For the layer-2 of the model, this elevation was taken as the lateral contact between the bedrock and the well sorted sediment.

The hydraulic conductivities, horizontal and vertical for the two layers of the aquifer system was conceptually evaluated from groundwater literatures and pumping test results for layers 1 and 2 respectively. Based on this, the horizontal hydraulic conductivity of the upper low permeability aquifer ranges from 0.001m/d to 4m/d and the horizontal hydraulic conductivity of the layer 2 of the aquifer system – the lower high permeability layer, ranges from 1.5m/d to 10m/d.

Areal recharge to the Adelle – Haromaya dry lakes catchment, the study area, aquifers occur from precipitation on the outcrop areas. Groundwater from areal recharge moves from areas of high altitude towards streams that gain flow from the upper low permeability and flows to the present day seasonal lakes temporarily. The amount of flow by these streams was not conceptually quantified since the flow is seasonal and, in most of the case, distributed over the study area. The amount of recharge quantified for the annual replenishment of the groundwater of the study area was estimated from previous works and inflow-outflow balance. As calculated from this, the annual average recharge for Haromaya sub-basin was 42mm/yr and 18mm/yr for Adelle sub-basin and 11mm/yr for Finkile sub-basin. Generally, inflow to the study area was conceptualized as only from groundwater recharge from precipitation surplus of soil moisture deficit and evapotranspiration.

Groundwater outflow from the study area includes; groundwater withdrawals for water supply, industries and irrigation purposes, temporal groundwater evapotranspiration where the water level is near surface, perennial springs and seasonal groundwater discharge to lakes along streams. The total amount outflow estimated conceptually for the study area was around 10,000m^3/d from withdrawals and springs. The conceptual inflow-outflow balance was estimated and found that the total inflow calculated by the minimum annual recharge range exceeds the estimated groundwater outflow for the study area. This is, most probably, due to two cases: 1) the seasonal groundwater discharge along the rills, gullies, streams and other local depressions to the lakes basin was not quantified by this study; and

2) the groundwater outflow from the study area along the topographically low boundaries (e.g. near Dangago and Balla Bakalcha) was not quantified. These two probable ways by which groundwater can outflow makes discrepancies for the conceptual model groundwater balance of the study area.

By the groundwater level data collected during field study of this project, Feb, 2006, and data obtained from boreholes drilling report static water level, groundwater level contour map was produced. The data were collected from 53 spatially selected shallow drilled and hand-dug wells during study time and 12 deep well drilling reports. The developed groundwater level map shows that, the local groundwater flow direction is to the three present day seasonal lakes. It also shows that the general groundwater flow direction is from parts of Adelle to Finkile and then to the Haromaya sub-basins. It was this general concept for the aquifer system of the study area to conceptualize as a one aquifer system and used for numerical model. As information obtained from local people around the study area (most of them are groundwater user for irrigation purpose), groundwater pumping caused water level decline especially at Haromaya sub-basin, by 6m since the development of groundwater in the area. The five meter water level decline observed at Harar water supply boreholes also supports this idea. The seasonal groundwater fluctuation reaches 4m for at the study area.

The conceptual model of the groundwater flow was simulated with the numerical model under steady-state and transient modes with two aquifer layers using MODFLOW-96+interface advective transport. The upper layer represents the upper low permeability aquifer unit and the lower layer represents the lower high permeability aquifer unit. The study area was divided in to grid blocks 100m by 100m on side, with 170 rows and 220 columns. Combination of general head and no-flow boundaries were used to best represent boundary conditions.

Estimated horizontal hydraulic conductivity for the two layers by the conceptual model was assigned to both layers by grouping similar conductivity area in to zones. Vertical hydraulic conductivity value was also assigned by multiplying the horizontal hydraulic conductivity by 0.1 factors.

The annual recharge rate for the steady-state simulation was assigned to the model as the model stress on daily bases in meter per day. Discharge rate of the study area was assigned to the model by well package of the MODFLOW on the daily basis in cubic meter per day.

The numerical model was calibrated for steady-state simulation to the water level measured during study time and the static water level of the drilling reports. The model was calibrated using trial-and-error method in adjusting initial estimates of aquifer properties, recharge, and general head boundary and drain conductance within plausible ranges to get a best match between simulated hydraulic heads and measured water levels and selected water budget items. Calibration criteria for the steady-state simulation included: 1) generally matching the simulated potentiometric surfaces and hydraulic gradients to those of the estimated potentiometric surfaces; 2) matching hydraulic heads at 80% of the wells to within ±10m of the observed hydraulic heads.

The summary statistics after steady-state calibration for residual heads between observed and simulated values were calculated for 58 measured water levels. The mean error (ME), the root squared mean error (RMS) and mean absolute error (MAE) were calculated for the residuals and found to be -3.05, 9.038 and 7.0 respectively. From the calculated values, it was observed that the model skews to the simulated value.

A sensitivity analysis was used to examine the response of the numerical model calibrated to the steady-state condition to change in model parameters including horizontal hydraulic conductivity, vertical hydraulic conductivity and recharge, which were increased and decreased from their calibrated values. The model was most sensitive to horizontal hydraulic conductivity and recharge.

The transient model, which was simulated for thirteen months period from Feb, 2005 to Feb, 2006, was calibrated to the water level recorded during this period at Harar water supply observation boreholes. The potentiometric surface calculated from steady-state simulation was used as an initial condition for the simulation. Parameters like specific yield and storage coefficient were adjusted by trial-and-error method to get the best match between observed and simulated temporal water level trends.

There may be three reasons why the steady-state models skews to simulated value and transient simulation water level trend somewhat different from the trends of the observed water levels. These are: 1) the aquifer system conceptually developed was assuming that the three sub-basins; Adelle, Finkile and Haromaya as a one aquifer system. Groundwater can flow from one sub-basin to the other depending on the head and hydraulic properties. This may compensate the water level in the topographical low areas and increase the water level. 2) In some cases, boundary condition may also affect the simulated water level. In areas where the wells are close to the model boundary, large differences between observed and simulated hydraulic heads are observed. 3) due to model calibration error, discretizing effect or inadequate simulation of the model and aquifer geometry the water level may be increased from the observed values.

To evaluate the aquifer interconnectivity of the three sub-basins of the study area and how the future groundwater pumping may affect the groundwater flow system, scenarios were developed. The aquifer system interconnectivity for the basins was simulated by applying the horizontal flow barrier of the MODFLOW between the three sub-basins at their watershed boundaries. In addition, conceptually estimated recharge was used for the basins separately. All the other parameters and stresses were similar with the steady-state calibration. After simulated in this condition under steady-state simulation, the simulated hydraulic head values for Haromaya sub-basin became closer to observed values than before. Depending on this, the two future groundwater pumping condition scenarios were developed under this condition since it was found that the aquifer systems of the three sub-basins are not interconnected, in most probable cases.

As the result of predictive simulation indicate under two pumping conditions, in the next five years period, if the pumping condition of December 2005 continues for Harar water supply boreholes, the groundwater level declines by around 6m which change the groundwater flow system of Haromaya sub-basin and decrease the yield of the wells by introducing vertical flow at least near the wells.

Generally, this study has limitations starting from aquifer system conceptualization which was developed from limited data source, assumptions and generalizations of field conditions, estimation of aquifer parameters, identification of aquifer system boundaries, and estimation of recharge. This conceptualization also affects the accuracy of the model results even if some parameters were adjusted during calibration. Grid design, boundary condition assignment, and the stress applied to the numerical model also affect the quality of the model results, in addition to the mathematical simplification of the numerical model to field conditions. By these all limitations, the groundwater flow system of the Adelle – Haromaya dry lakes catchment was simulated and future effect of groundwater pumping condition was predicted. Based on this, the following general conclusions were made.

- The groundwater flow system of the three sub-basins of the study area was simulated as one aquifer system with two layers. The result of the steady-state simulation showed that simulated water levels slightly higher than observed water levels which also have been seen during transient simulation. But, after the system was simulated by assigning horizontal flow barrier, the simulated and observed water levels are closer than before. From this it was concluded that the three aquifer systems have independent aquifer systems which are not interconnected.
- As the result of effect of future groundwater pumping condition scenario shows, continuing of pumping under the December 2005, for Harar water supply boreholes for the next five years affect the groundwater flow system of the Haromaya sub-basin. But, the continuation of pumping condition of October 2005 for the next five years is better for the flow system.

6.2. Recommendations

- Groundwater management system of the study area will be better if pumping condition before December 2005 will continue for Haromaya sub-basin aquifer system.
- It is strictly recommended to avoid construction of new deep wells in Haromaya sub-basin since the existing outflow condition is greater than inflow conditions.
- Continuous groundwater level monitoring mechanism for all deep wells of the study area should be developed to control the level fluctuation in water levels.
- Simulation of the effect of the dried lakes on the groundwater flow condition of the study area is recommended to manage the groundwater potential of the area.
- Advective transport model for the study area is recommended to follow the possible groundwater pollution since there are pollutant sources around the wells especially in Haromaya sub-basin where many boreholes are found.
- Post audit for this flow model should be done after some years to check the applicability of the model to the area.
- Estimation of groundwater recharge for the two sub-basins of the study area was only quantified by inflow-outflow system. It is recommended to estimate the recharge for these sub-basins by using different recharge estimation methods to get reliable value.
- Environmental protection activities which enhance groundwater recharge should be done to increase the natural recharge for the area.
- Strategies should be planned by the environmental protection institutions by which the pre-existing Haromaya and Adelle Lakes can be recovered in order to keep the natural balance of the area.

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Annex-1. Comparison of Transient Simulated heads and Observed heads for four wells of Harar water Supply for the simulation period from Feb. 2005 to Feb. 2006.

Simul. T Days	W -1 DD Meas.	Measured Head well-1	Smulated Head Well-1	W-2 DD Meas.	Measured Head Well-2	Simulated Head Well-2	W-4 DD Meas.	Measured head Well-4	Simulated Head Well-4	W-5 DD Meas.	Meas. head Well-5	Simul. Head Well-5
3	16.27	2001.73	2000.08	24.61	1998.39	2000.842	10.61	2002.39	2001.196	17.2	1996.8	1998.56
6	17.22	2000.78	2000.083	24.65	1998.35	2000.787	10.64	2002.36	2001.063	17	1997	1998.23
9	17.34	2000.66	2000.093	24.58	1998.42	2000.761	10.7	2002.3	2000.995	17.84	1996.16	1997.94
12	17.66	2000.34	2000.105	24.91	1998.09	2000.745	10.67	2002.33	2000.952	17.92	1996.08	1997.68
15	17.44	2000.56	2000.12	24.85	1998.15	2000.734	10.65	2002.35	2000.921	18.03	1995.97	1997.45
18	17.71	2000.29	2000.136	24.91	1998.09	2000.725	10.72	2002.28	2000.899	14.93	1999.07	1997.23
21	17.95	2000.05	2000.153	25.48	1997.52	2000.717	10.67	2002.33	2000.882	17.54	1996.46	1997.04
24	18.08	1999.92	2000.17	24.98	1998.02	2000.711	10.84	2002.16	2000.87	18.14	1995.86	1996.87
27	17.42	2000.58	2000.187	21.17	2001.83	2000.706	11.3	2001.7	2000.861	17.87	1996.13	1996.71
30	17.47	2000.53	2000.204	20.65	2002.35	2000.702	11.31	2001.69	2000.855	17.47	1996.53	1996.57
33	17.76	2000.24	2000.028	26.17	1996.83	2000.697	11.87	2001.13	2000.85	11.75	2002.25	1996.44
36	17.4	2000.6	1999.914	26.33	1996.67	2000.693	11.97	2001.03	2000.846	16.42	1997.58	1996.32
39	17.95	2000.05	1999.825	26.58	1996.42	2000.69	11.8	2001.2	2000.843	17.25	1996.75	1996.21
42	18.36	1999.64	1999.749	26.48	1996.52	2000.687	12.28	2000.72	2000.841	18.7	1995.3	1996.11
45	18.37	1999.63	1999.683	26.17	1996.83	2000.684	12.34	2000.66	2000.84	18.4	1995.6	1996.02
48	18.33	1999.67	1999.625	26.6	1996.4	2000.682	12.4	2000.6	2000.839	19.19	1994.81	1995.93
51	18.03	1999.97	1999.573	26.67	1996.33	2000.68	12.82	2000.18	2000.838	19.19	1994.81	1995.86
54	18.11	1999.89	1999.526	26.42	1996.58	2000.68	13.13	1999.87	2000.838	18.48	1995.52	1995.79
57	18.27	1999.73	1999.484	27.25	1995.75	2000.679	12.84	2000.16	2000.837	19.04	1994.96	1995.72
60	18.48	1999.52	1999.447	26.78	1996.22	2000.679	13.24	1999.76	2000.838	18.18	1995.82	1995.66
63	18.78	1999.22	1999.339	27.9	1995.1	2000.759	13.39	1999.61	2000.838	19.29	1994.71	1995.61
66	18.85	1999.15	1999.254	27.95	1995.05	2000.799	13.69	1999.31	2000.838	19.42	1994.58	1995.56
69	19.04	1998.96	1999.18	28.01	1994.99	2000.826	13.86	1999.14	2000.839	19.15	1994.85	1995.51
72	19.19	1998.81	1999.114	28.01	1994.99	2000.848	13.91	1999.09	2000.84	19.33	1994.67	1995.47
75	19.22	1998.78	1999.054	28.02	1994.98	2000.867	13.97	1999.03	2000.841	19.09	1994.91	1995.43
78	19.29	1998.71	1998.999	28.14	1994.86	2000.884	13.96	1999.04	2000.842	19.31	1994.69	1995.39
81	19.3	1998.7	1998.95	28.14	1994.86	2000.899	13.84	1999.16	2000.843	19.08	1994.92	1995.36

Annex-1. Continued.

Simul.	W -1	Measured	Smulated	W-2 DD	Measured	Simulated	W-4 DD	Measured	Simulated	W-5 DD	Meas.	Simul.
T	DD	Head	Head	Meas.	Head	Head	Meas.	head	Head	Meas.	head	Head
Days	Meas.	well-1	Well-1		Well-2	Well-2		Well-4	Well-4		Well-5	Well-5
84	19.45	1998.55	1998.904	28.15	1994.85	2000.913	13.97	1999.03	2000.844	19.26	1994.74	1995.32
87	19.5	1998.5	1998.863	28.04	1994.96	2000.926	14.08	1998.92	2000.846	19.4	1994.6	1995.29
90	19.56	1998.44	1998.824	28.08	1994.92	2000.938	14.12	1998.88	2000.847	19.55	1994.45	1995.27
93	16.65	2001.35	1998.795	27.5	1995.5	2000.952	12.45	2000.55	2000.849	18.92	1995.08	1995.24
96	16.92	2001.08	1998.767	27.32	1995.68	2000.965	12.86	2000.14	2000.851	18.67	1995.33	1995.22
99	16.34	2001.66	1998.74	27.13	1995.87	2000.976	12.83	2000.17	2000.852	18.49	1995.51	1995.19
102	16	2002	1998.716	27.1	1995.9	2000.988	12.38	2000.62	2000.854	17.84	1996.16	1995.17
105	16.61	2001.39	1998.694	26.9	1996.1	2000.998	12.8	2000.2	2000.856	17.68	1996.32	1995.15
108	14.8	2003.2	1998.673	26.6	1996.4	2001.008	12.68	2000.32	2000.859	17.38	1996.62	1995.14
111	14.48	2003.52	1998.654	26.3	1996.7	2001.018	12.53	2000.47	2000.861	17.65	1996.35	1995.12
114	14.53	2003.47	1998.637	26.25	1996.75	2001.027	11.67	2001.33	2000.863	17.06	1996.94	1995.1
117	14.93	2003.07	1998.62	26.5	1996.5	2001.036	11.63	2001.37	2000.866	16.48	1997.52	1995.09
120	15.07	2002.93	1998.605	25.55	1997.45	2001.045	11.49	2001.51	2000.868	16.44	1997.56	1995.07
123	15.31	2002.69	1998.569	25.23	1997.77	2001.021	11.15	2001.85	2000.871	16.82	1997.18	1995.06
126	15.43	2002.57	1998.54	25.45	1997.55	2001.013	11.23	2001.77	2000.873	17.1	1996.9	1995.05
129	15.8	2002.2	1998.515	25.5	1997.5	2001.008	11.33	2001.67	2000.876	17.37	1996.63	1995.04
132	15.82	2002.18	1998.492	25.7	1997.3	2001.005	11.75	2001.25	2000.879	17.41	1996.59	1995.03
135	15.9	2002.1	1998.472	25.8	1997.2	2001.004	11.65	2001.35	2000.882	17.49	1996.51	1995.02
138	16.42	2001.58	1998.452	25.83	1997.17	2001.004	11.75	2001.25	2000.885	17.64	1996.36	1995.01
141	16.64	2001.36	1998.435	25.93	1997.07	2001.004	11.67	2001.33	2000.889	17.7	1996.3	1995
144	16.85	2001.15	1998.419	26.1	1996.9	2001.005	12.05	2000.95	2000.892	18.16	1995.84	1994.99
147	17.6	2000.4	1998.404	26.43	1996.57	2001.005	12.06	2000.94	2000.895	18.44	1995.56	1994.99
150	18.1	1999.9	1998.39	26.27	1996.73	2001.007	12.28	2000.72	2000.899	18.52	1995.48	1994.98
153	17.86	2000.14	1998.406	26.52	1996.48	2001.046	12.08	2000.92	2000.903	18.74	1995.26	1994.97
156	18.04	1999.96	1998.414	26.75	1996.25	2001.066	12.46	2000.54	2000.906	19	1995	1994.97
159	18.53	1999.47	1998.421	26.8	1996.2	2001.08	12.51	2000.49	2000.91	19.35	1994.65	1994.96
162	18.6	1999.4	1998.427	26.88	1996.12	2001.092	12.64	2000.36	2000.914	19.68	1994.32	1994.96

Annex-1. Continued.

Simul.	***W -1***	**Measured**	**Smulated**	**W-2 DD**	**Measured**	**Simulated**	**W-4 DD**	**Measured**	**Simulated**	**W-5 DD**	**Meas.**	**Simul.**
T	***DD***	**Head**	**Head**	**Meas.**	**Head**	**Head**	**Meas.**	**head**	**Head**	**Meas.**	**head**	**Head**
Days	***Meas.***	**well-1**	**Well-1**		**Well-2**	**Well-2**		**Well-4**	**Well-4**		**Well-5**	**Well-5**
165	*18.68*	1999.32	1998.432	27.08	1995.92	2001.103	12.84	2000.16	2000.918	19.73	1994.27	1994.95
168	*19.06*	1998.94	1998.437	27.3	1995.7	2001.114	12.86	2000.14	2000.922	19.85	1994.15	1994.95
171	*18.9*	1999.1	1998.442	27.35	1995.65	2001.123	12.97	2000.03	2000.926	19.9	1994.1	1994.95
174	*19*	1999	1998.447	27.45	1995.55	2001.133	12.83	2000.17	2000.931	19.94	1994.06	1994.94
177	*19.18*	1998.82	1998.452	27.47	1995.53	2001.142	12.85	2000.15	2000.935	20.02	1993.98	1994.94
180	*19.32*	1998.68	1998.456	27.46	1995.54	2001.15	12.88	2000.12	2000.939	20.15	1993.85	1994.94
183	19.72	1998.28	1998.465	27.48	1995.52	2001.152	12.85	2000.15	2000.944	19.97	1994.03	1994.94
186	18.98	1999.02	1998.473	27.47	1995.53	2001.159	12.8	2000.2	2000.948	19.87	1994.13	1994.93
189	18.84	1999.16	1998.48	27.35	1995.65	2001.167	12.74	2000.26	2000.953	19.63	1994.37	1994.93
192	19.48	1998.52	1998.487	27.3	1995.7	2001.175	12.85	2000.15	2000.958	19.25	1994.75	1994.93
195	*19.15*	1998.85	1998.494	26.9	1996.1	2001.183	13.07	1999.93	2000.963	19.67	1994.33	1994.93
198	*18.3*	1999.7	1998.5	26.64	1996.36	2001.191	13.02	1999.98	2000.968	19.92	1994.08	1994.93
201	*18.25*	1999.75	1998.507	26.91	1996.09	2001.198	13.05	1999.95	2000.974	19.7	1994.3	1994.93
204	*17.72*	2000.28	1998.513	26.71	1996.29	2001.206	12.87	2000.13	2000.979	19.731	1994.269	1994.93
207	*17.6*	2000.4	1998.52	26.95	1996.05	2001.214	12.86	2000.14	2000.984	19.43	1994.57	1994.93
210	*17.56*	2000.44	1998.526	26.45	1996.55	2001.221	12.1	2000.9	2000.989	18.92	1995.08	1994.93
213	15.67	2002.33	1998.521	25.8	1997.2	2001.239	11.64	2001.36	2000.995	18.78	1995.22	1994.93
216	15.44	2002.56	1998.52	25.56	1997.44	2001.252	11.17	2001.83	2001	17.76	1996.24	1994.93
219	15.12	2002.88	1998.52	25.15	1997.85	2001.263	10.9	2002.1	2001.006	17.72	1996.28	1994.93
222	14.85	2003.15	1998.521	24.92	1998.08	2001.274	10.73	2002.27	2001.012	17.65	1996.35	1994.93
225	*14.74*	2003.26	1998.523	24.86	1998.14	2001.284	10.53	2002.47	2001.017	17.71	1996.29	1994.93
228	*14.67*	2003.33	1998.526	25	1998	2001.294	10.91	2002.09	2001.023	17.8	1996.2	1994.93
231	*15.2*	2002.8	1998.528	25.01	1997.99	2001.304	10.2	2002.8	2001.029	17.78	1996.22	1994.93
234	*15.5*	2002.5	1998.531	25.15	1997.85	2001.313	10.56	2002.44	2001.035	18.24	1995.76	1994.94
237	*15.87*	2002.13	1998.535	25.2	1997.8	2001.323	10.63	2002.37	2001.041	18.21	1995.79	1994.94
240	*15.96*	2002.04	1998.538	25.23	1997.77	2001.331	10.62	2002.38	2001.047	18.3	1995.7	1994.94
243	15.92	2002.08	1998.56	25.4	1997.6	2001.338	10.95	2002.05	2001.053	18.78	1995.22	1994.94

Annex-1. Continued.

Simul.	W -1	Measured	Smulated	W-2 DD	Measured	Simulated	W-4 DD	Measured	Simulated	W-5 DD	Meas.	Simul.
T	DD	Head	Head	Meas.	Head	Head	Meas.	head	Head	Meas.	head	Head
Days	Meas.	well-1	Well-1		Well-2	Well-2		Well-4	Well-4		Well-5	Well-5
246	16.82	2001.18	1998.576	25.57	1997.43	2001.345	11.33	2001.67	2001.059	19.02	1994.98	1994.94
249	16.87	2001.13	1998.59	25.62	1997.38	2001.352	11.5	2001.5	2001.066	18.33	1995.67	1994.94
252	16.89	2001.11	1998.602	25.85	1997.15	2001.359	11.7	2001.3	2001.072	19.09	1994.91	1994.95
255	16.88	2001.12	1998.615	25.95	1997.05	2001.367	11.84	2001.16	2001.078	19.29	1994.71	1994.95
258	16.76	2001.24	1998.626	26.22	1996.78	2001.374	12.16	2000.84	2001.084	19.23	1994.77	1994.95
261	17.25	2000.75	1998.637	26.35	1996.65	2001.381	12.24	2000.76	2001.091	19.15	1994.85	1994.95
264	17.34	2000.66	1998.648	26.57	1996.43	2001.389	12.47	2000.53	2001.097	19.54	1994.46	1994.95
267	17.45	2000.55	1998.659	26.6	1996.4	2001.396	12.58	2000.42	2001.103	19.3	1994.7	1994.96
270	17.35	2000.65	1998.669	26.8	1996.2	2001.403	12.65	2000.35	2001.109	19.16	1994.84	1994.96
273	17.3	2000.7	1998.649	26.83	1996.17	2001.288	12.75	2000.25	2001.302	19.37	1994.63	1994.87
276	17.7	2000.3	1998.637	26.94	1996.06	2001.233	12.8	2000.2	2001.344	18.65	1995.35	1994.78
279	17.35	2000.65	1998.629	26.95	1996.05	2001.195	12.85	2000.15	2001.348	18.64	1995.36	1994.7
282	17.65	2000.35	1998.621	27.05	1995.95	2001.166	12.87	2000.13	2001.341	18.6	1995.4	1994.63
285	18.22	1999.78	1998.614	27.15	1995.85	2001.142	12.96	2000.04	2001.331	18.74	1995.26	1994.57
288	17.86	2000.14	1998.609	27.13	1995.87	2001.122	13.02	1999.98	2001.319	18.78	1995.22	1994.51
291	17.45	2000.55	1998.604	27.19	1995.81	2001.105	13.13	1999.87	2001.308	18.81	1995.19	1994.46
294	17.59	2000.41	1998.6	27.21	1995.79	2001.09	13.1	1999.9	2001.297	18.63	1995.37	1994.41
297	17.7	2000.3	1998.596	27.27	1995.73	2001.078	13.12	1999.88	2001.287	18.45	1995.55	1994.36
300	18.05	1999.95	1998.593	27.5	1995.5	2001.067	13.29	1999.71	2001.278	19.2	1994.8	1994.32
303	18.51	1999.49	1998.404	27.65	1995.35	2001.057	13.33	1999.67	2001.27	19.59	1994.41	1994.28
306	18.56	1999.44	1998.287	27.9	1995.1	2001.048	13.31	1999.69	2001.262	19.8	1994.2	1994.25
309	18.81	1999.19	1998.195	27.7	1995.3	2001.04	13.42	1999.58	2001.255	19.9	1994.1	1994.21
312	18.67	1999.33	1998.114	27.65	1995.35	2001.033	13.22	1999.78	2001.249	20.06	1993.94	1994.18
315	19.03	1998.97	1998.042	27.8	1995.2	2001.026	13.4	1999.6	2001.243	20.08	1993.92	1994.16
318	18.66	1999.34	1997.977	27.82	1995.18	2001.02	13.45	1999.55	2001.239	20.18	1993.82	1994.13
321	18.56	1999.44	1997.916	27.54	1995.46	2001.015	13.73	1999.27	2001.234	20.2	1993.8	1994.11
324	18.9	1999.1	1997.859	27.92	1995.08	2001.01	13.53	1999.47	2001.23	20.4	1993.6	1994.08

Annex-1. Continued.

Simul.	*W -1*	**Measured**	Smulated	**W-2 DD**	**Measured**	Simulated	**W-4 DD**	**Measured**	Simulated	**W-5 DD**	Meas.	Simul.
T	***DD***	**Head**	Head	**Meas.**	**Head**	Head	**Meas.**	**head**	Head	**Meas.**	head	Head
Days	***Meas.***	**well-1**	Well-1		**Well-2**	Well-2		**Well-4**	Well-4		Well-5	Well-5
327	*17.1*	2000.9	1997.807	28.05	1994.95	2001.006	13.56	1999.44	2001.227	20.35	1993.65	1994.06
330	*17.67*	2000.33	1997.758	28.89	1994.11	2001.003	11.5	2001.5	2001.224	20.25	1993.75	1994.04
333	*11.45*	2006.55	1997.657	27.5	1995.5	2000.999	12.05	2000.95	2001.221	20.51	1993.49	1994.03
336	*10.94*	2007.06	1997.621	28.7	1994.3	2000.997	12.3	2000.7	2001.219	20.63	1993.37	1994.01
339	*11.1*	2006.9	1997.608	28.6	1994.4	2000.995	15.17	1997.83	2001.217	20.4	1993.6	1994
342	*10.63*	1997.8	1997.59	29.7	1993.3	2000.993	14.4	1998.6	2001.216	20.25	1993.75	1993.98
345	*18*	1997.07	1997.554	28.5	1994.5	2000.991	14.57	1998.43	2001.215	20.35	1993.65	1993.97
348	*18.95*	1999.05	1997.52	29.46	1993.54	2000.99	15.57	1997.43	2001.214	21.65	1992.35	1993.96
351	*11.4*	2006.6	1997.488	30.3	1992.7	2000.989	16.05	1996.95	2001.213	21.1	1992.9	1993.94
354	*11.3*	2006.7	1997.458	30.1	1992.9	2000.989	16.16	1996.84	2001.213	21.87	1992.13	1993.93
270	*17.35*	2000.65	1998.669	26.8	1996.2	2001.403	12.65	2000.35	2001.109	19.16	1994.84	1994.96
273	17.3	2000.7	1998.649	26.83	1996.17	2001.288	12.75	2000.25	2001.302	19.37	1994.63	1994.87
276	17.7	2000.3	1998.637	26.94	1996.06	2001.233	12.8	2000.2	2001.344	18.65	1995.35	1994.78
279	17.35	2000.65	1998.629	26.95	1996.05	2001.195	12.85	2000.15	2001.348	18.64	1995.36	1994.7
282	17.65	2000.35	1998.621	27.05	1995.95	2001.166	12.87	2000.13	2001.341	18.6	1995.4	1994.63
285	18.22	1999.78	1998.614	27.15	1995.85	2001.142	12.96	2000.04	2001.331	18.74	1995.26	1994.57
288	17.86	2000.14	1998.609	27.13	1995.87	2001.122	13.02	1999.98	2001.319	18.78	1995.22	1994.51
291	17.45	2000.55	1998.604	27.19	1995.81	2001.105	13.13	1999.87	2001.308	18.81	1995.19	1994.46
294	*17.59*	2000.41	1998.6	27.21	1995.79	2001.09	13.1	1999.9	2001.297	18.63	1995.37	1994.41
297	*17.7*	2000.3	1998.596	27.27	1995.73	2001.078	13.12	1999.88	2001.287	18.45	1995.55	1994.36
300	*18.05*	1999.95	1998.593	27.5	1995.5	2001.067	13.29	1999.71	2001.278	19.2	1994.8	1994.32
303	18.51	1999.49	1998.404	27.65	1995.35	2001.057	13.33	1999.67	2001.27	19.59	1994.41	1994.28
306	18.56	1999.44	1998.287	27.9	1995.1	2001.048	13.31	1999.69	2001.262	19.8	1994.2	1994.25
309	18.81	1999.19	1998.195	27.7	1995.3	2001.04	13.42	1999.58	2001.255	19.9	1994.1	1994.21
312	18.67	1999.33	1998.114	27.65	1995.35	2001.033	13.22	1999.78	2001.249	20.06	1993.94	1994.18
315	19.03	1998.97	1998.042	27.8	1995.2	2001.026	13.4	1999.6	2001.243	20.08	1993.92	1994.16
318	18.66	1999.34	1997.977	27.82	1995.18	2001.02	13.45	1999.55	2001.239	20.18	1993.82	1994.13

Annex-1. Continued.

Simul.	W -1	Measured	Smulated	W-2 DD	Measured	Simulated	W-4 DD	Measured	Simulated	W-5 DD	Meas.	Simul.
T	DD	Head	Head	Meas.	Head	Head	Meas.	head	Head	Meas.	head	Head
Days	Meas.	well-1	Well-1		Well-2	Well-2		Well-4	Well-4		Well-5	Well-5
321	18.56	1999.44	1997.916	27.54	1995.46	2001.015	13.73	1999.27	2001.234	20.2	1993.8	1994.11
324	18.9	1999.1	1997.859	27.92	1995.08	2001.01	13.53	1999.47	2001.23	20.4	1993.6	1994.08
327	17.1	2000.9	1997.807	28.05	1994.95	2001.006	13.56	1999.44	2001.227	20.35	1993.65	1994.06
330	17.67	2000.33	1997.758	28.89	1994.11	2001.003	11.5	2001.5	2001.224	20.25	1993.75	1994.04
333	11.45	2006.55	1997.657	27.5	1995.5	2000.999	12.05	2000.95	2001.221	20.51	1993.49	1994.03
336	10.94	2007.06	1997.621	28.7	1994.3	2000.997	12.3	2000.7	2001.219	20.63	1993.37	1994.01
339	11.1	2006.9	1997.608	28.6	1994.4	2000.995	15.17	1997.83	2001.217	20.4	1993.6	1994
342	10.63	1997.8	1997.59	29.7	1993.3	2000.993	14.4	1998.6	2001.216	20.25	1993.75	1993.98
345	18	1997.07	1997.554	28.5	1994.5	2000.991	14.57	1998.43	2001.215	20.35	1993.65	1993.97
348	18.95	1999.05	1997.52	29.46	1993.54	2000.99	15.57	1997.43	2001.214	21.65	1992.35	1993.96
351	11.4	2006.6	1997.488	30.3	1992.7	2000.989	16.05	1996.95	2001.213	21.1	1992.9	1993.94
354	11.3	2006.7	1997.458	30.1	1992.9	2000.989	16.16	1996.84	2001.213	21.87	1992.13	1993.93
357	11.1	2006.9	1997.43	30.13	1992.87	2000.988	16.22	1996.78	2001.213	20.86	1993.14	1993.92
360	19.82	1998.18	1997.403	30.23	1992.77	2000.988	16.23	1996.77	2001.214	22.08	1991.92	1993.91
363	18.14	1999.86	1997.377	30.02	1992.98	2000.989	16.42	1996.58	2001.214	22.9	1991.1	1993.91
366	20.93	1997.07	1997.353	30.18	1992.82	2000.989	14.53	1998.47	2001.214	23.06	1990.94	1993.9
369	19.07	1998.93	1997.33	30.52	1992.48	2000.989	16.55	1996.45	2001.215	23	1991	1993.89
372	18.85	1999.15	1997.308	30.5	1992.5	2000.99	16.6	1996.4	2001.216	22.89	1991.11	1993.88
375	18.53	1999.47	1997.288	30.67	1992.33	2000.991	16.64	1996.36	2001.218	22.44	1991.56	1993.88
378	19.1	1998.9	1997.268	30.92	1992.08	2000.992	16.69	1996.31	2001.219	22.17	1991.83	1993.87
381	22.05	1995.95	1997.25	30.52	1992.48	2000.993	16.7	1996.3	2001.221	21.88	1992.12	1993.87
384	22.35	1995.65	1997.232	30.42	1992.58	2000.994	16.74	1996.26	2001.222	21.76	1992.24	1993.86
387	22.39	1995.61	1997.216	30.36	1992.64	2000.995	16.82	1996.18	2001.224	22.57	1991.43	1993.86
390	22.43	1995.57	1997.2	30.39	1992.61	2000.997	16.86	1996.14	2001.226	21.75	1992.25	1993.85

Annex-2. Measured Groundwater Level and Geographic Location of Wells which was taken during study time, Feb. 2006.

S/N	Borehole ID.Number	Coordinate (UTM,Adindan Z-37)		Ground Surface Elevation (m)	Depth to Water Level (m)	Elevation of Water Table (m)	Borehole total Depth (bgl)
		Easting	Northing				
1	HDWPv-1	832844	1037611	2064	15.3	2048.7	18
2	HDWPv-2	832137	1038222	2021	6.2	2014.8	8
3	HDWPv-3	831168	1038733	2012	2.2	2009.8	4
4	HDWPv-4	831414	1037739	2010	3	2007	4
5	HDWPv-5	831668	1037322	2008	4.5	2003.5	7
6	HDWPv-6	834441	1042135	2037	8	2029	10
7	HDWPv-7	831675	1040513	2015	6	2009	7
8	SDWPu-1	832449	1044323	2026	12	2014	
9	HDWPv-8	833486	1046880	2039	6	2033	7
10	HDWPv-9	832183	1046351	2015	4	2011	6
11	HDWPv-10	833169	1048338	2038	6	2032	8
12	HDWPv-11	833226	1047979	2043	9	2034	10.5
13	HDWPv-12	833255	1045294	2048	10	2038	
14	SDWPu-2	834373	1039838	2115	9	2106	15
15	SDWPu-3	833867	1040797	2025	16	2009	32
16	HDWPv-13	826158	1040879	2072	32	2040	34
17	HDWPv-14	827956	1040551	2043	20.7	2022.3	25
18	HDWPu-1	828174	1040464	2039	18.5	2020.5	
19	HDWPu-2	828430	1040269	2048	30	2018	32
20	HDWPu-3	828658	1040537	2025	8	2017	10
21	HDWPv-15	828717	1040429	2026	13	2013	14
22	HDWPv-16	829776	1040269	2019	2.5	2016.5	4
23	HDWPv-17	830651	1039655	2026	4	2022	7
24	HDWPv-18	831447	1038873	2026	9.15	2016.85	18
25	HDWPv-19	831757	1038360	2018	10.5	2007.5	11.5
26	HDWPv-20	831291	1048132	2017	2.6	2014.4	
27	HDWPu-4	830154	1048253	2040	5.75	2034.25	12

Annex-2. Continued.

S/N	Borehole ID.Number	Coordinate (UTM,Adindan Z-37)		Ground Surface	Depth to	Elevation of	Borehole total
		Easting	Northing	Elevation (m)	Water Level (m)	Water Table (m)	Depth (bgl)
28	HDWPv-21	830186	1047416	2036	5.35	2030.65	6.5
29	HDWPv-22	829544	1044150	2046	7.2	2038.8	8
30	HDWPv-23	828532	1041893	2017	8	2009	9.5
31	HDWPv-24	830672	1040852	2010	3	2007	4.5
32	HDWPv-25	824744	1041458	2033	5.8	2027.2	
33	HDWPv-26	823268	1042870	2027	3.5	2023.5	
34	HDWPv-27	822435	1044681	2033	2.8	2030.2	
35	HDWPv-28	822030	1045591	2039	3.7	2035.3	
36	SDWPu-4	821208	1046485	2056	15	2041	
37	HDWPv-29	823256	1046715	2060	3.8	2056.2	
38	HDWPv-30	823306	1045039	2053	6.8	2046.2	
39	HDWPv-31	824284	1044797	2050	5.55	2044.45	
40	HDWPv-32	825664	1043797	2043	5.8	2037.2	
41	HDWPv-33	825256	1045033	2061	6.7	2054.3	
42	HDWPv-34	823576	1044053	2033	2.1	2030.9	
43	HDWPv-35	825255	1042672	2036	1.9	2034.1	
44	HDWPv-36	822035	1039950	2055	4.4	2050.6	5.5
45	HDWPv-37	823975	1039792	2036	3	2033	4
46	HDWPv-38	824068	1040583	2028	4	2024	5
47	HDWPv-39	824679	1040809	2030	2.35	2027.65	4.35
48	HDWPv-40	824779	1038257	2041	1.6	2039.4	
49	HDWPv-41	824719	1038718	2041	1.95	2039.05	
50	HDWPv-42	832061	1042297	2025	10	2015	
51	SDWPu-5	832418	1040667	2025	14.1	2010.9	37
52	SPRG1	837033	1044216		_	2183	
53	SPRG2	837645	1044644		_	2195	
54	HTBH No.1	832105	1040754	2018	24.00	2015.8	
55	HTBH No.2	832551	1040269	2023	27.00	2009.01	

Annex-2. Continued.

S/N	Borehole ID.Number	Coordinate (UTM,Adindan Z-37)		Ground Surface	Depth to	Elevation of	Borehole total
		Easting	Northing	Elevation (m)	Water Level (m)	Water Table (m)	Depth (bgl)
56	HTBH No.3	831774	1041150	2015	18.00	2011.22	
57	HTBH No.4	832446	1040863	2013	18.00	2009.05	
58	HTBH No.5	832149	1040439	2014	24.00	2011.11	
59	HTBH No.6	832329	1041370	2011	33.00	2006.14	
60	HTBH No.7	832217	1041860	2020	26.00	2014.48	
61	HBBH-65	832432	1045791	2008	34.00	2006	
62	HBBH-59	832300	1045792	2008	12.00	2005.4	
63	HBBH-51	832140	1047901	2026	18.00	2025	
64	HBBH-85	831498	1047365	2020	24.00	2018.55	
65	AUBH4	833430	1041804	2034	21.61	2021.75	

Annex-3. Future Groundwater Level Elevation Prediction Table at Harar Water Supply Wells for the next Five years from Feb. 2005 under the December, 2005 Pumping Scenario.

Step	Well-1	Well-2	Well-4	well-5	Step	Well-1	Well-2	Well-4	well-5
3	2001.189	2000.849	2001.323	1999.671	933	2003.73	2004.546	2004.944	2000.934
6	2001.224	2000.893	2001.432	1999.663	936	2003.714	2004.531	2004.93	2000.915
9	2001.208	2000.88	2001.417	1999.655	939	2003.698	2004.515	2004.914	2000.897
12	2001.189	2000.861	2001.4	1999.647	942	2003.682	2004.5	2004.9	2000.879
15	2001.174	2000.845	2001.39	1999.639	945	2003.666	2004.485	2004.885	2000.86
18	2001.163	2000.832	2001.384	1999.631	948	2003.65	2004.47	2004.87	2000.842
21	2001.153	2000.82	2001.38	1999.623	951	2003.634	2004.455	2004.855	2000.823
24	2001.144	2000.81	2001.377	1999.615	954	2003.617	2004.44	2004.84	2000.805
27	2001.136	2000.801	2001.375	1999.607	957	2003.601	2004.425	2004.825	2000.787
30	2001.129	2000.793	2001.374	1999.599	960	2003.585	2004.41	2004.81	2000.768
33	2000.868	2000.753	2001.261	1999.752	963	2003.569	2004.394	2004.795	2000.75
36	2000.759	2000.737	2001.233	1999.852	966	2003.553	2004.379	2004.78	2000.731
39	2000.683	2000.729	2001.217	1999.918	969	2003.537	2004.364	2004.765	2000.713
42	2000.624	2000.722	2001.202	1999.962	972	2003.521	2004.349	2004.75	2000.695
45	2000.575	2000.715	2001.188	1999.992	975	2003.505	2004.334	2004.735	2000.676
48	2000.535	2000.708	2001.175	2000.013	978	2003.488	2004.319	2004.72	2000.658
51	2000.5	2000.702	2001.162	2000.027	981	2003.472	2004.304	2004.705	2000.64
54	2000.469	2000.695	2001.15	2000.035	984	2003.456	2004.289	2004.69	2000.621
57	2000.442	2000.689	2001.138	2000.041	987	2003.44	2004.273	2004.675	2000.603
60	2000.417	2000.682	2001.127	2000.043	990	2003.424	2004.258	2004.66	2000.585
63	2000.596	2000.938	2001.278	2000.407	993	2003.408	2004.243	2004.645	2000.566
66	2000.798	2001.162	2001.437	2000.742	996	2003.392	2004.228	2004.63	2000.548
69	2001.024	2001.402	2001.634	2001.059	999	2003.376	2004.213	2004.615	2000.529
72	2001.264	2001.654	2001.855	2001.364	1002	2003.36	2004.198	2004.6	2000.511
75	2001.513	2001.913	2002.09	2001.662	1005	2003.344	2004.183	2004.586	2000.493
78	2001.768	2002.176	2002.335	2001.953	1008	2003.328	2004.168	2004.571	2000.474
81	2002.027	2002.442	2002.586	2002.241	1011	2003.312	2004.153	2004.556	2000.456
84	2002.288	2002.709	2002.84	2002.527	1014	2003.296	2004.138	2004.541	2000.437
87	2002.551	2002.978	2003.098	2002.809	1017	2003.28	2004.123	2004.526	2000.419
90	2002.816	2003.247	2003.357	2003.091	1020	2003.263	2004.108	2004.511	2000.401
93	2002.724	2003.262	2003.371	2002.704	1023	2003.247	2004.093	2004.496	2000.382
96	2002.696	2003.278	2003.4	2002.449	1026	2003.231	2004.078	2004.481	2000.364
99	2002.673	2003.289	2003.419	2002.272	1029	2003.215	2004.063	2004.466	2000.346
102	2002.652	2003.296	2003.432	2002.14	1032	2003.199	2004.047	2004.451	2000.327
105	2002.631	2003.299	2003.439	2002.038	1035	2003.183	2004.032	2004.436	2000.309
108	2002.612	2003.301	2003.445	2001.956	1038	2003.167	2004.017	2004.421	2000.291
111	2002.594	2003.301	2003.448	2001.886	1041	2003.151	2004.002	2004.406	2000.272
114	2002.577	2003.301	2003.452	2001.825	1044	2003.135	2003.987	2004.392	2000.254
117	2002.561	2003.3	2003.454	2001.771	1047	2003.119	2003.972	2004.377	2000.236
120	2002.546	2003.298	2003.455	2001.723	1050	2003.103	2003.957	2004.362	2000.217
123	2002.499	2003.253	2003.442	2001.626	1053	2003.087	2003.942	2004.347	2000.199
126	2002.471	2003.237	2003.436	2001.551	1056	2003.072	2003.927	2004.333	2000.181
129	2002.446	2003.225	2003.431	2001.488	1059	2003.056	2003.912	2004.318	2000.162
132	2002.423	2003.214	2003.425	2001.434	1062	2003.039	2003.897	2004.303	2000.144

Annex-3. Continued.

Step	Well-1	Well-2	Well-4	well-5	Step	Well-1	Well-2	Well-4	well-5
135	2002.403	2003.204	2003.42	2001.386	1065	2003.024	2003.882	2004.288	2000.125
138	2002.384	2003.195	2003.415	2001.342	1068	2003.007	2003.867	2004.273	2000.107
141	2002.365	2003.187	2003.41	2001.301	1071	2002.991	2003.852	2004.258	2000.089
144	2002.348	2003.178	2003.405	2001.264	1074	2002.975	2003.837	2004.243	2000.07
147	2002.331	2003.169	2003.399	2001.228	1077	2002.959	2003.822	2004.228	2000.052
150	2002.315	2003.161	2003.394	2001.194	1080	2002.943	2003.807	2004.213	2000.034
153	2002.339	2003.202	2003.415	2001.226	1083	2002.928	2003.793	2004.199	2000.016
156	2002.341	2003.206	2003.419	2001.237	1086	2002.913	2003.779	2004.186	1999.999
159	2002.34	2003.207	2003.421	2001.238	1089	2002.898	2003.765	2004.172	1999.982
162	2002.336	2003.206	2003.421	2001.231	1092	2002.883	2003.751	2004.158	1999.965
165	2002.331	2003.203	2003.421	2001.221	1095	2002.868	2003.737	2004.144	1999.947
168	2002.325	2003.2	2003.419	2001.208	1098	2002.854	2003.723	2004.13	1999.93
171	2002.318	2003.195	2003.417	2001.194	1101	2002.839	2003.709	2004.116	1999.913
174	2002.31	2003.19	2003.414	2001.179	1104	2002.824	2003.695	2004.102	1999.896
177	2002.303	2003.185	2003.411	2001.163	1107	2002.809	2003.681	2004.089	1999.878
180	2002.294	2003.179	2003.407	2001.147	1110	2002.794	2003.667	2004.075	1999.861
183	2002.445	2003.295	2003.452	2001.391	1113	2002.779	2003.653	2004.061	1999.844
186	2002.641	2003.473	2003.584	2001.646	1116	2002.764	2003.639	2004.047	1999.827
189	2002.869	2003.688	2003.772	2001.909	1119	2002.749	2003.625	2004.033	1999.81
192	2003.114	2003.923	2003.992	2002.175	1122	2002.734	2003.611	2004.019	1999.793
195	2003.369	2004.169	2004.229	2002.445	1125	2002.719	2003.597	2004.005	1999.775
198	2003.63	2004.422	2004.476	2002.717	1128	2002.704	2003.583	2003.992	1999.758
201	2003.895	2004.679	2004.73	2002.991	1131	2002.689	2003.569	2003.978	1999.741
204	2004.162	2004.939	2004.988	2003.265	1134	2002.675	2003.555	2003.964	1999.724
207	2004.432	2005.202	2005.249	2003.541	1137	2002.66	2003.541	2003.95	1999.707
210	2004.702	2005.465	2005.512	2003.817	1140	2002.645	2003.527	2003.936	1999.69
213	2004.971	2005.755	2005.786	2004.163	1143	2002.63	2003.514	2003.922	1999.672
216	2005.242	2006.028	2006.058	2004.484	1146	2002.615	2003.5	2003.909	1999.655
219	2005.515	2006.299	2006.328	2004.79	1149	2002.6	2003.486	2003.895	1999.638
222	2005.79	2006.57	2006.6	2005.089	1152	2002.586	2003.472	2003.882	1999.621
225	2006.067	2006.842	2006.875	2005.382	1155	2002.571	2003.458	2003.868	1999.604
228	2006.346	2007.115	2007.151	2005.672	1158	2002.556	2003.444	2003.854	1999.587
231	2006.63	2007.391	2007.431	2005.966	1161	2002.541	2003.43	2003.84	1999.569
234	2006.922	2007.671	2007.721	2006.265	1164	2002.526	2003.417	2003.826	1999.552
237	2007.237	2007.958	2008.023	2006.566	1167	2002.511	2003.402	2003.813	1999.535
240	2007.665	2008.262	2008.365	2006.87	1170	2002.496	2003.389	2003.799	1999.518
243	2007.697	2008.33	2008.433	2006.852	1173	2002.482	2003.375	2003.786	1999.501
246	2007.722	2008.364	2008.484	2006.838	1176	2002.467	2003.361	2003.772	1999.483
249	2007.735	2008.382	2008.514	2006.826	1179	2002.452	2003.347	2003.758	1999.466
252	2007.74	2008.391	2008.533	2006.815	1182	2002.437	2003.333	2003.744	1999.449
255	2007.742	2008.396	2008.544	2006.805	1185	2002.422	2003.319	2003.73	1999.432
258	2007.742	2008.399	2008.552	2006.795	1188	2002.408	2003.306	2003.716	1999.415
261	2007.74	2008.4	2008.557	2006.785	1191	2002.393	2003.292	2003.704	1999.398
264	2007.738	2008.399	2008.561	2006.776	1194	2002.378	2003.278	2003.69	1999.381
267	2007.736	2008.399	2008.565	2006.766	1197	2002.363	2003.264	2003.676	1999.364
270	2007.733	2008.398	2008.567	2006.756	1200	2002.349	2003.25	2003.662	1999.346
273	2007.603	2008.152	2008.402	2006.338	1203	2002.334	2003.236	2003.648	1999.329

Annex-3. Continued

Step	Well-1	Well-2	Well-4	well-5	Step	Well-1	Well-2	Well-4	well-5
276	2007.553	2008.081	2008.35	2006.071	1206	2002.319	2003.223	2003.635	1999.312
279	2007.522	2008.043	2008.323	2005.887	1209	2002.304	2003.209	2003.621	1999.295
282	2007.497	2008.015	2008.305	2005.753	1212	2002.29	2003.195	2003.607	1999.278
285	2007.475	2007.994	2008.29	2005.648	1215	2002.275	2003.181	2003.594	1999.261
288	2007.454	2007.975	2008.277	2005.563	1218	2002.26	2003.167	2003.58	1999.244
291	2007.433	2007.956	2008.263	2005.491	1221	2002.245	2003.154	2003.567	1999.226
294	2007.413	2007.939	2008.249	2005.427	1224	2002.231	2003.14	2003.553	1999.209
297	2007.392	2007.922	2008.236	2005.371	1227	2002.216	2003.126	2003.539	1999.192
300	2007.373	2007.905	2008.222	2005.319	1230	2002.201	2003.112	2003.525	1999.175
303	2007.353	2007.889	2008.209	2005.272	1233	2002.187	2003.099	2003.512	1999.158
306	2007.333	2007.872	2008.194	2005.228	1236	2002.172	2003.085	2003.498	1999.141
309	2007.313	2007.855	2008.18	2005.186	1239	2002.157	2003.071	2003.484	1999.124
312	2007.294	2007.839	2008.165	2005.147	1242	2002.142	2003.057	2003.47	1999.107
315	2007.274	2007.822	2008.15	2005.109	1245	2002.128	2003.043	2003.457	1999.089
318	2007.255	2007.805	2008.134	2005.073	1248	2002.113	2003.029	2003.443	1999.072
321	2007.235	2007.788	2008.118	2005.039	1251	2002.098	2003.015	2003.429	1999.055
324	2007.216	2007.771	2008.103	2005.006	1254	2002.083	2003.002	2003.416	1999.038
327	2007.197	2007.755	2008.087	2004.973	1257	2002.069	2002.988	2003.403	1999.021
330	2007.177	2007.738	2008.071	2004.942	1260	2002.054	2002.974	2003.389	1999.004
333	2007.158	2007.721	2008.055	2004.912	1263	2002.039	2002.96	2003.375	1998.987
336	2007.139	2007.704	2008.039	2004.882	1266	2002.025	2002.947	2003.362	1998.97
339	2007.12	2007.687	2008.023	2004.854	1269	2002.01	2002.933	2003.348	1998.953
342	2007.1	2007.67	2008.008	2004.826	1272	2001.995	2002.919	2003.334	1998.935
345	2007.081	2007.654	2007.992	2004.798	1275	2001.98	2002.905	2003.32	1998.918
348	2007.062	2007.637	2007.976	2004.771	1278	2001.966	2002.892	2003.307	1998.901
351	2007.043	2007.62	2007.96	2004.744	1281	2001.951	2002.878	2003.293	1998.884
354	2007.024	2007.603	2007.944	2004.718	1284	2001.936	2002.864	2003.279	1998.867
357	2007.005	2007.587	2007.929	2004.693	1287	2001.922	2002.85	2003.266	1998.849
360	2006.986	2007.57	2007.913	2004.667	1290	2001.907	2002.837	2003.252	1998.832
363	2006.967	2007.553	2007.897	2004.642	1293	2001.892	2002.823	2003.239	1998.815
366	2006.948	2007.536	2007.881	2004.618	1296	2001.878	2002.809	2003.225	1998.798
369	2006.929	2007.52	2007.866	2004.594	1299	2001.863	2002.795	2003.212	1998.781
372	2006.91	2007.503	2007.85	2004.57	1302	2001.848	2002.781	2003.198	1998.764
375	2006.891	2007.487	2007.834	2004.547	1305	2001.834	2002.768	2003.185	1998.747
378	2006.873	2007.47	2007.818	2004.523	1308	2001.819	2002.754	2003.171	1998.73
381	2006.853	2007.453	2007.801	2004.501	1311	2001.804	2002.74	2003.157	1998.713
384	2006.835	2007.436	2007.785	2004.478	1314	2001.79	2002.727	2003.144	1998.696
387	2006.816	2007.419	2007.768	2004.455	1317	2001.775	2002.713	2003.13	1998.678
390	2006.797	2007.402	2007.752	2004.432	1320	2001.76	2002.699	2003.116	1998.661
393	2006.779	2007.386	2007.736	2004.41	1323	2001.746	2002.686	2003.103	1998.644
396	2006.76	2007.369	2007.72	2004.388	1326	2001.731	2002.672	2003.089	1998.627
399	2006.741	2007.352	2007.703	2004.366	1329	2001.716	2002.658	2003.075	1998.61
402	2006.722	2007.335	2007.686	2004.345	1332	2001.702	2002.644	2003.062	1998.593
405	2006.704	2007.318	2007.67	2004.323	1335	2001.687	2002.63	2003.048	1998.576
408	2006.685	2007.301	2007.654	2004.302	1338	2001.672	2002.617	2003.034	1998.559
411	2006.666	2007.284	2007.637	2004.28	1341	2001.658	2002.603	2003.021	1998.541
414	2006.648	2007.268	2007.621	2004.259	1344	2001.643	2002.589	2003.007	1998.524

Annex-3. Continued

Step	**Well-1**	**Well-2**	**Well-4**	**well-5**	**Step**	**Well-1**	**Well-2**	**Well-4**	**well-5**
417	2006.63	2007.251	2007.605	2004.238	1347	2001.628	2002.576	2002.994	1998.507
420	2006.611	2007.234	2007.588	2004.217	1350	2001.614	2002.562	2002.98	1998.49
423	2006.593	2007.218	2007.572	2004.196	1353	2001.599	2002.548	2002.967	1998.473
426	2006.575	2007.201	2007.556	2004.175	1356	2001.584	2002.535	2002.953	1998.456
429	2006.557	2007.184	2007.539	2004.155	1359	2001.57	2002.521	2002.939	1998.439
432	2006.539	2007.168	2007.523	2004.134	1362	2001.555	2002.507	2002.926	1998.421
435	2006.521	2007.151	2007.507	2004.113	1365	2001.541	2002.494	2002.913	1998.404
438	2006.503	2007.135	2007.491	2004.092	1368	2001.526	2002.479	2002.899	1998.387
441	2006.485	2007.118	2007.475	2004.072	1371	2001.511	2002.466	2002.886	1998.37
444	2006.467	2007.102	2007.459	2004.051	1374	2001.497	2002.452	2002.872	1998.353
447	2006.449	2007.085	2007.443	2004.03	1377	2001.482	2002.438	2002.858	1998.336
450	2006.431	2007.069	2007.427	2004.01	1380	2001.467	2002.425	2002.845	1998.319
453	2006.413	2007.052	2007.41	2003.989	1383	2001.452	2002.411	2002.831	1998.302
456	2006.396	2007.036	2007.394	2003.969	1386	2001.438	2002.398	2002.818	1998.285
459	2006.378	2007.02	2007.378	2003.948	1389	2001.424	2002.384	2002.804	1998.267
462	2006.36	2007.003	2007.362	2003.928	1392	2001.409	2002.37	2002.791	1998.25
465	2006.342	2006.987	2007.346	2003.908	1395	2001.394	2002.356	2002.777	1998.233
468	2006.324	2006.97	2007.33	2003.887	1398	2001.379	2002.343	2002.763	1998.216
471	2006.307	2006.954	2007.313	2003.867	1401	2001.365	2002.329	2002.75	1998.199
474	2006.289	2006.937	2007.298	2003.847	1404	2001.35	2002.315	2002.736	1998.182
477	2006.271	2006.921	2007.282	2003.827	1407	2001.336	2002.302	2002.723	1998.164
480	2006.254	2006.905	2007.266	2003.806	1410	2001.321	2002.288	2002.709	1998.147
483	2006.236	2006.888	2007.249	2003.786	1413	2001.307	2002.275	2002.696	1998.13
486	2006.218	2006.872	2007.233	2003.766	1416	2001.292	2002.261	2002.682	1998.113
489	2006.201	2006.856	2007.218	2003.746	1419	2001.278	2002.247	2002.669	1998.096
492	2006.183	2006.839	2007.202	2003.726	1422	2001.263	2002.234	2002.655	1998.079
495	2006.166	2006.823	2007.186	2003.706	1425	2001.248	2002.22	2002.641	1998.062
498	2006.148	2006.807	2007.169	2003.686	1428	2001.234	2002.206	2002.628	1998.044
501	2006.13	2006.79	2007.153	2003.666	1431	2001.219	2002.192	2002.614	1998.027
504	2006.113	2006.774	2007.137	2003.646	1434	2001.205	2002.179	2002.601	1998.01
507	2006.096	2006.758	2007.122	2003.626	1437	2001.19	2002.165	2002.587	1997.993
510	2006.078	2006.742	2007.106	2003.606	1440	2001.175	2002.152	2002.574	1997.976
513	2006.061	2006.725	2007.089	2003.587	1443	2001.161	2002.138	2002.56	1997.958
516	2006.043	2006.709	2007.074	2003.567	1446	2001.146	2002.125	2002.547	1997.941
519	2006.026	2006.693	2007.058	2003.547	1449	2001.131	2002.111	2002.533	1997.924
522	2006.009	2006.677	2007.042	2003.527	1452	2001.117	2002.097	2002.52	1997.907
525	2005.992	2006.661	2007.026	2003.507	1455	2001.102	2002.083	2002.506	1997.89
528	2005.974	2006.645	2007.011	2003.488	1458	2001.088	2002.07	2002.493	1997.873
531	2005.957	2006.628	2006.994	2003.468	1461	2001.073	2002.056	2002.479	1997.855
534	2005.939	2006.612	2006.979	2003.448	1464	2001.059	2002.043	2002.466	1997.838
537	2005.922	2006.596	2006.963	2003.428	1467	2001.044	2002.029	2002.452	1997.821
540	2005.905	2006.58	2006.947	2003.409	1470	2001.03	2002.016	2002.439	1997.804
543	2005.888	2006.564	2006.932	2003.389	1473	2001.015	2002.002	2002.425	1997.787
546	2005.871	2006.548	2006.916	2003.37	1476	2001	2001.988	2002.412	1997.769
549	2005.854	2006.532	2006.9	2003.35	1479	2000.986	2001.974	2002.398	1997.752
552	2005.836	2006.516	2006.884	2003.33	1482	2000.971	2001.961	2002.385	1997.735
555	2005.819	2006.5	2006.868	2003.311	1485	2000.957	2001.947	2002.371	1997.718

Annex-3. Continued

Step	Well-1	Well-2	Well-4	well-5	Step	Well-1	Well-2	Well-4	well-5
561	2005.785	2006.468	2006.837	2003.272	1491	2000.927	2001.92	2002.344	1997.684
564	2005.768	2006.452	2006.822	2003.252	1494	2000.913	2001.907	2002.331	1997.666
567	2005.75	2006.436	2006.806	2003.233	1497	2000.898	2001.893	2002.317	1997.649
570	2005.733	2006.42	2006.79	2003.213	1500	2000.884	2001.879	2002.304	1997.632
573	2005.716	2006.404	2006.775	2003.194	1503	2000.869	2001.865	2002.29	1997.615
576	2005.699	2006.388	2006.759	2003.175	1506	2000.855	2001.852	2002.277	1997.598
579	2005.682	2006.372	2006.743	2003.155	1509	2000.84	2001.838	2002.263	1997.58
582	2005.665	2006.357	2006.728	2003.136	1512	2000.826	2001.825	2002.25	1997.563
585	2005.648	2006.341	2006.712	2003.116	1515	2000.811	2001.811	2002.236	1997.546
588	2005.631	2006.325	2006.696	2003.097	1518	2000.797	2001.798	2002.223	1997.529
591	2005.614	2006.309	2006.681	2003.078	1521	2000.782	2001.784	2002.209	1997.511
594	2005.597	2006.293	2006.665	2003.058	1524	2000.768	2001.771	2002.196	1997.494
597	2005.58	2006.277	2006.649	2003.039	1527	2000.753	2001.756	2002.182	1997.477
600	2005.563	2006.261	2006.634	2003.019	1530	2000.738	2001.743	2002.169	1997.459
603	2005.546	2006.245	2006.618	2003	1533	2000.724	2001.73	2002.156	1997.442
606	2005.529	2006.229	2006.602	2002.981	1536	2000.709	2001.716	2002.142	1997.425
609	2005.512	2006.214	2006.587	2002.962	1539	2000.695	2001.703	2002.129	1997.408
612	2005.495	2006.198	2006.571	2002.943	1542	2000.68	2001.689	2002.115	1997.391
615	2005.478	2006.182	2006.556	2002.923	1545	2000.666	2001.675	2002.102	1997.374
618	2005.461	2006.166	2006.54	2002.904	1548	2000.651	2001.661	2002.088	1997.356
621	2005.444	2006.15	2006.525	2002.885	1551	2000.637	2001.648	2002.075	1997.339
624	2005.427	2006.134	2006.509	2002.866	1554	2000.622	2001.634	2002.061	1997.322
627	2005.41	2006.118	2006.493	2002.846	1557	2000.608	2001.621	2002.048	1997.304
630	2005.393	2006.102	2006.478	2002.827	1560	2000.593	2001.608	2002.035	1997.287
633	2005.376	2006.087	2006.462	2002.808	1563	2000.578	2001.594	2002.021	1997.27
636	2005.359	2006.071	2006.447	2002.789	1566	2000.564	2001.58	2002.007	1997.253
639	2005.342	2006.055	2006.431	2002.769	1569	2000.549	2001.567	2001.994	1997.235
642	2005.326	2006.04	2006.416	2002.75	1572	2000.535	2001.553	2001.981	1997.218
645	2005.309	2006.024	2006.401	2002.731	1575	2000.521	2001.54	2001.967	1997.201
648	2005.292	2006.008	2006.385	2002.712	1578	2000.506	2001.526	2001.953	1997.184
651	2005.275	2005.992	2006.37	2002.693	1581	2000.491	2001.513	2001.94	1997.167
654	2005.258	2005.977	2006.354	2002.674	1584	2000.477	2001.499	2001.926	1997.149
657	2005.242	2005.961	2006.339	2002.655	1587	2000.463	2001.485	2001.913	1997.132
660	2005.225	2005.945	2006.324	2002.636	1590	2000.448	2001.472	2001.899	1997.114
663	2005.208	2005.93	2006.308	2002.616	1593	2000.433	2001.458	2001.886	1997.097
666	2005.192	2005.914	2006.293	2002.597	1596	2000.419	2001.445	2001.873	1997.08
669	2005.175	2005.899	2006.278	2002.578	1599	2000.404	2001.431	2001.859	1997.062
672	2005.158	2005.883	2006.262	2002.559	1602	2000.39	2001.418	2001.846	1997.045
675	2005.141	2005.867	2006.247	2002.54	1605	2000.375	2001.404	2001.832	1997.028
678	2005.125	2005.852	2006.232	2002.521	1608	2000.361	2001.391	2001.819	1997.011
681	2005.108	2005.836	2006.216	2002.502	1611	2000.346	2001.377	2001.806	1996.993
684	2005.091	2005.82	2006.201	2002.483	1614	2000.332	2001.363	2001.792	1996.976
687	2005.074	2005.805	2006.186	2002.464	1617	2000.317	2001.35	2001.779	1996.959
690	2005.058	2005.789	2006.17	2002.445	1620	2000.303	2001.337	2001.766	1996.942
693	2005.041	2005.773	2006.154	2002.426	1623	2000.288	2001.323	2001.752	1996.924
696	2005.024	2005.758	2006.139	2002.407	1626	2000.274	2001.309	2001.739	1996.907
699	2005.008	2005.742	2006.124	2002.388	1629	2000.259	2001.296	2001.725	1996.889

Annex-3. Continued

Step	**Well-1**	**Well-2**	**Well-4**	**well-5**	**Step**	**Well-1**	**Well-2**	**Well-4**	**well-5**
702	2004.991	2005.727	2006.109	2002.369	1632	2000.245	2001.282	2001.712	1996.872
705	2004.974	2005.711	2006.093	2002.35	1635	2000.23	2001.269	2001.698	1996.855
708	2004.958	2005.696	2006.078	2002.331	1638	2000.216	2001.255	2001.684	1996.837
711	2004.941	2005.68	2006.063	2002.312	1641	2000.201	2001.242	2001.672	1996.82
714	2004.924	2005.664	2006.047	2002.294	1644	2000.187	2001.228	2001.659	1996.803
717	2004.908	2005.649	2006.032	2002.275	1647	2000.172	2001.214	2001.644	1996.785
720	2004.891	2005.633	2006.016	2002.256	1650	2000.158	2001.201	2001.631	1996.768
723	2004.875	2005.618	2006.002	2002.237	1653	2000.144	2001.188	2001.618	1996.751
726	2004.858	2005.602	2005.986	2002.218	1656	2000.129	2001.174	2001.604	1996.733
729	2004.841	2005.587	2005.971	2002.199	1659	2000.115	2001.161	2001.591	1996.716
732	2004.825	2005.571	2005.956	2002.18	1662	2000.1	2001.147	2001.578	1996.699
735	2004.808	2005.555	2005.94	2002.161	1665	2000.085	2001.133	2001.564	1996.681
738	2004.792	2005.54	2005.925	2002.142	1668	2000.071	2001.12	2001.551	1996.664
741	2004.775	2005.524	2005.91	2002.123	1671	2000.057	2001.107	2001.538	1996.646
744	2004.759	2005.509	2005.895	2002.105	1674	2000.042	2001.093	2001.524	1996.629
747	2004.742	2005.494	2005.879	2002.086	1677	2000.028	2001.08	2001.511	1996.612
750	2004.725	2005.478	2005.864	2002.067	1680	2000.013	2001.066	2001.498	1996.594
753	2004.709	2005.463	2005.849	2002.048	1683	1999.998	2001.052	2001.484	1996.577
756	2004.692	2005.447	2005.834	2002.029	1686	1999.984	2001.039	2001.47	1996.56
759	2004.676	2005.432	2005.818	2002.01	1689	1999.97	2001.026	2001.457	1996.542
762	2004.659	2005.417	2005.803	2001.992	1692	1999.955	2001.012	2001.443	1996.525
765	2004.643	2005.401	2005.788	2001.973	1695	1999.941	2000.999	2001.43	1996.507
768	2004.626	2005.386	2005.773	2001.954	1698	1999.926	2000.985	2001.417	1996.49
771	2004.61	2005.37	2005.757	2001.935	1701	1999.911	2000.971	2001.403	1996.473
774	2004.593	2005.355	2005.743	2001.916	1704	1999.897	2000.958	2001.39	1996.455
777	2004.577	2005.339	2005.727	2001.898	1707	1999.883	2000.945	2001.377	1996.438
780	2004.56	2005.324	2005.712	2001.879	1710	1999.868	2000.931	2001.363	1996.42
783	2004.544	2005.308	2005.696	2001.86	1713	1999.854	2000.918	2001.35	1996.403
786	2004.527	2005.293	2005.681	2001.842	1716	1999.839	2000.904	2001.337	1996.386
789	2004.511	2005.278	2005.667	2001.823	1719	1999.824	2000.89	2001.323	1996.368
792	2004.494	2005.262	2005.651	2001.804	1722	1999.81	2000.877	2001.31	1996.35
795	2004.478	2005.247	2005.636	2001.785	1725	1999.796	2000.864	2001.297	1996.333
798	2004.462	2005.232	2005.621	2001.767	1728	1999.781	2000.85	2001.282	1996.316
801	2004.446	2005.216	2005.606	2001.748	1731	1999.767	2000.837	2001.27	1996.298
804	2004.429	2005.201	2005.591	2001.729	1734	1999.753	2000.823	2001.257	1996.281
807	2004.413	2005.185	2005.576	2001.711	1737	1999.738	2000.81	2001.243	1996.263
810	2004.396	2005.17	2005.561	2001.692	1740	1999.723	2000.796	2001.229	1996.246
813	2004.38	2005.155	2005.545	2001.674	1743	1999.709	2000.783	2001.216	1996.228
816	2004.364	2005.139	2005.53	2001.655	1746	1999.695	2000.77	2001.203	1996.211
819	2004.347	2005.124	2005.516	2001.636	1749	1999.68	2000.756	2001.189	1996.193
822	2004.331	2005.109	2005.501	2001.618	1752	1999.666	2000.742	2001.176	1996.176
825	2004.314	2005.093	2005.485	2001.599	1755	1999.651	2000.729	2001.163	1996.158
828	2004.298	2005.078	2005.47	2001.58	1758	1999.637	2000.716	2001.15	1996.141
831	2004.282	2005.063	2005.455	2001.562	1761	1999.622	2000.702	2001.136	1996.123
834	2004.266	2005.048	2005.44	2001.543	1764	1999.608	2000.689	2001.123	1996.106
837	2004.25	2005.033	2005.425	2001.525	1767	1999.594	2000.675	2001.109	1996.088
840	2004.233	2005.017	2005.41	2001.506	1770	1999.579	2000.661	2001.096	1996.071

Annex-3. Continued

Step	Well-1	Well-2	Well-4	well-5	Step	Well-1	Well-2	Well-4	well-5
843	2004.217	2005.002	2005.395	2001.488	1773	1999.564	2000.648	2001.082	1996.053
846	2004.2	2004.987	2005.38	2001.469	1776	1999.55	2000.635	2001.069	1996.036
849	2004.184	2004.972	2005.365	2001.451	1779	1999.536	2000.621	2001.056	1996.018
852	2004.168	2004.956	2005.35	2001.432	1782	1999.521	2000.608	2001.042	1996.001
855	2004.151	2004.941	2005.334	2001.414	1785	1999.507	2000.594	2001.029	1995.983
858	2004.135	2004.925	2005.319	2001.395	1788	1999.492	2000.581	2001.016	1995.966
861	2004.119	2004.91	2005.304	2001.377	1791	1999.478	2000.568	2001.003	1995.948
864	2004.103	2004.895	2005.29	2001.358	1794	1999.463	2000.554	2000.989	1995.93
867	2004.087	2004.88	2005.275	2001.34	1797	1999.449	2000.541	2000.976	1995.913
870	2004.07	2004.865	2005.26	2001.321	1800	1999.434	2000.527	2000.963	1995.895
873	2004.054	2004.849	2005.244	2001.303					
876	2004.038	2004.834	2005.229	2001.284					
879	2004.021	2004.819	2005.214	2001.266					
882	2004.005	2004.804	2005.199	2001.247					
885	2003.989	2004.788	2005.184	2001.229					
888	2003.973	2004.773	2005.169	2001.21					
891	2003.957	2004.758	2005.155	2001.192					
894	2003.941	2004.743	2005.139	2001.173					
897	2003.925	2004.728	2005.124	2001.155					
900	2003.908	2004.712	2005.109	2001.136					
903	2003.892	2004.697	2005.094	2001.118					
906	2003.876	2004.682	2005.079	2001.1					
909	2003.859	2004.667	2005.064	2001.081					
912	2003.843	2004.652	2005.049	2001.063					
915	2003.827	2004.636	2005.034	2001.044					
918	2003.811	2004.621	2005.019	2001.026					
921	2003.795	2004.606	2005.004	2001.008					
924	2003.779	2004.591	2004.989	2000.989					
927	2003.763	2004.576	2004.974	2000.971					
930	2003.746	2004.561	2004.959	2000.952					