GROUNDWATER FLOW MODELLING OF DIRE DAWA SUB-BASIN, ETHIOPIA

SOLOMON GEBRETSADIK

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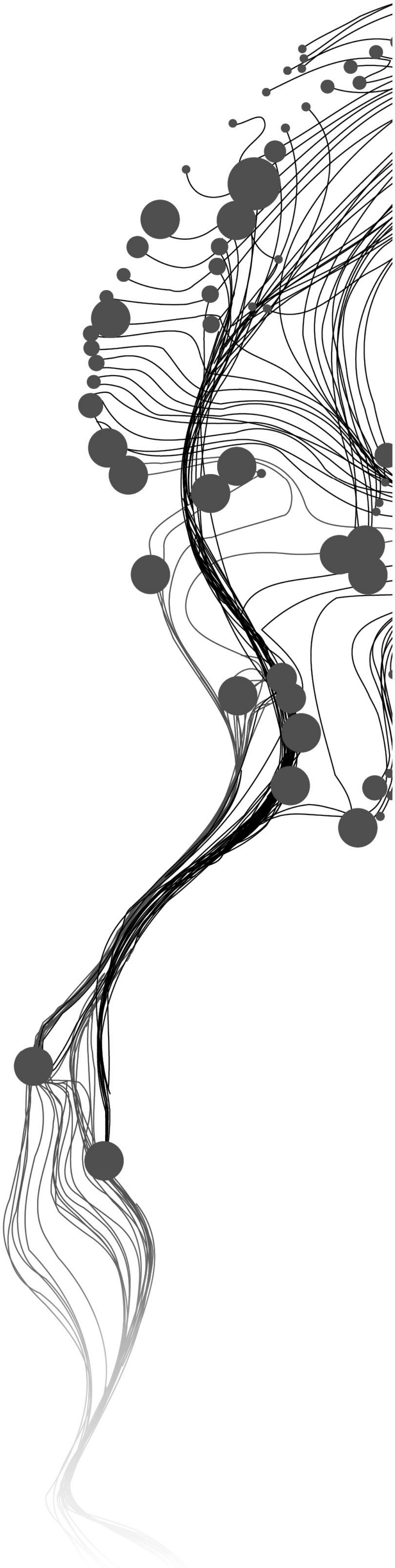

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SOLOMON GEBRETSADIK
Enschede, The Netherlands, March, 2011

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Water resources and environmental management

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Dedicated to

Our family with love and gratitude

ABSTRACT

The study focused on assessment of groundwater resource potential and prediction of the response to future abstractions through steady- state flow modelling in Dire Dawa groundwater sub-basin(eastern Ethiopia) , which is the only source of water for Dire Dawa and Harar areas. Boundary condition was assigned to the model to simulate inflow and outflow terms of the model domain. The model domain was delineated based on a DEM extracted from a SRTM image and a hydrogeological map. The aquifer system was modelled using PMWIN as pre and post processor for MODFLOW (Mc Donald and Harbaugh, 1998). The aquifer was simulated under unconfined condition and represented by a single layer of 74-300 m of variable thickness. Aquifer parameters were assigned by zoning based on analysis of pumping test data and a hydrogeological map. To represent the aquifer parameters in the model spatially grid cells of 200x200 m were taken for the entire area (256 km^2) later refined at the groundwater outlet area to 40x 40 m.

The recharge condition of the Dire Dawa groundwater sub-basin is characterized by two sources: direct rainfall and inflow water from the upstream areas through the southern boundary. Outflow condition is subsurface lateral outflow and well abstractions. The recharge of the groundwater sub-basin was estimated using chloride mass balance method (CMB) and from simulation of the model. The estimation was 47 $m^3 y^{-1}$ (183 mm) and 50 $m^3 y^{-1}$ (195 mm) respectively.

To calibrate the model using observed and simulated hydraulic head trial and error method was used by zoning based on hydrogeological map. The water budget of the Dire Dawa groundwater sub-basin simulated for 2025 reached equilibrium condition with recharge from both direct recharge from rainfall and inflow from the southern boundary of 50 m^3y^{-1}, well abstraction of 34.9 m^3y^{-1} (the average water demand up to 2025), and outflow through the general head boundary 15.1 $m^3 y^{-1}$. The calibration of the model was done with one year piezometric head data and needs calibration using more than one year data and verification to say the results obtained from the simulation fully represent the real condition the groundwater sub-basin. Based on the calibrated model results recommendation were made.

Key words: Dire Dawa groundwater sub-basin, groundwater modelling, recharge, abstraction

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1. INTRODUCTION

1.1. Background

Groundwater is the subsurface water that occurs beneath the water table in the soils and geologic formations that are fully saturated. It is the main source of fresh water in the world. It needs proper development to be sustainable. Development of groundwater resources can be viewed as sequential processes with three major phases. First, there is an exploration stage, in which surface and subsurface geological and geophysical techniques are brought to bear on the search for suitable aquifers. Second, there is an evaluation stage that encompasses the measurement of hydrogeological parameters, the design and analysis of wells, and the calculation of aquifer yields. Third, there is an exploitation or management phase, which must include consideration of optimal development strategies and an assessment of interactions between groundwater exploitation and the regional hydrologic system. Almost all developed countries are in a stage in which detailed evaluation of aquifers and careful management of known resources is done (Freeze & Cherry, 1979). In case of developing countries all these three phases are practising together since there is low coverage of access to clean water. Even all these three phases are practising together due to ambition to increase and distribute the coverage of access to clean water and limited capital resource, the evaluation and management phases are getting less emphasis. Due to this limited attention the sustainability of the groundwater resources is questioned. In many parts of Ethiopia specially in the towns like Harar, Gonder , Mekele and Shire the groundwater resources are depleted due to lack of proper management and less consideration to sustainability . These towns are now in problems of water supply. And Dire Dawa town may face similar problems since little is known about the groundwater resource. Hence assessment of the groundwater potential should be done and hydrologic responses to abstractions should be known to use the resource sustainably.

1.2. Resarch problem

Dire-Dawa is one of the bigger towns in the eastern part of Ethiopia. It is located in semi-arid climatic conditions with average rainfall of 610mmy^{-1}. It is fully dependent on groundwater sources. The groundwater is used for domestic water supply of the town, industrial and agricultural purposes. And more recently the groundwater is started to supply the town of Harar which is about 65 kms south of Dire-Dawa. Harar town is a relatively smaller town but with no other alternative sources for water supply. Previously their supply was coming from a small lake known as "Haromaya" and a few boreholes. However the lake became dry and the discharge from the existing wells is too low to satisfy the need of the population. As the town is growing the demand is also increasing. So far the proposed action is to use the groundwater sources from well fields in the Dire Dawa sub-basin.

The Dire dawa sub-basin in the southern part has three well fields. These well fields are Sabian, Dire-jara and Hasaliso. They have hydrogeological data. In The northern part there are shallow wells which do not have enough hydrogeological data.

Despite the high demands and abstractions, little is known about the groundwater resource in the Dire Dawa sub-basin. And the works done so far didn't consider the effect of the future developments for Dire-Dawa and Harar towns. For this reason we have to know the groundwater resource of the sub-basin, so that the resource will be treated in a sustainable way. Even though there is limitation in the hydrogeological data in the northern part of the sub-basin, To evaluate the sustainability of the resource reasonably a study should be conducted to assesses the groundwater resource potential and predict response of future abstractions.

Groundwater modelling is one of the main tools widely used in the hydrogeological sciences for assessment of the resource potential and prediction of future impact under different circumstances or stresses (Anderson & Woessner, 1992). Hence this tool is also used in the above mentioned assessment.

1.3. Research objective

1.3.1. General objective

The main objective of the study is to assess the groundwater resource potential and to predict the responses of the groundwater system to future abstractions using a steady-state groundwater flow model.

1.3.2. Specific objective

The following specific objectives are studied:

- To construct a conceptual model representing the hydrogeological condition of the sub-basin
- To develop a numerical model including calibration of the model and sensitivity analysis of hydraulic parameters recharge and boundary conditions
- To assess the physical and chemical condition of the water
- To estimate recharge

1.4. Research questions

To address the specified objectives; the questions to be answered are:-

- How can we integrate the geological, hydrological, remote sensing and geophysical data to construct the conceptual model?
- How can the conceptual model be transformed to a numerical model to allow simulation of the aquifer system?
- How accurate is the calibrated model?
- How sensitive are the aquifer parameters, stresses, and boundary condition
- Can the model assess the potential of the groundwater and predict the response of future abstractions?
- What are the physical and chemical behaviours of the groundwater?

1.5. Research Method

To achieve the objective mentioned above the methodology followed is as shown in figure 1.1 the methodology flow chart which are sectioned as pre-field work, field work and post field work.

In the pre-field work review of previous works, literature review, preliminary data processing and preparation of necessary field equipments was performed. The field work was collection of relevant secondary data, primary data and detailed observation of the study area. A field trip was arranged from September 9 to 30/ 2010. Pumping test, geological, hydrogeological, meteorological and well log data are among the collected data. The collected data and sources during the field trip are summarized in table 1.1 and table 1.2 (annexed).

The Post-fieldwork include description of the study area, data preparation and analysis, recharge estimation, modelling using MODFLOW, sensitivity analysis, discussions, conclusion and recommendation.

The study area's location, climate, topographic and geomorphic features, geology, hydrogeology, land use and soil types are explained.

Data needed as input to develop a model was prepared and analysed. Meteorological data, Hydro chemical, pumping test, water abstraction and demand are among the data prepared and analysed.

Recharge estimation of the groundwater area was done. Average recharge in basin scale can be estimated by Maxey-Eakin method (James et al 2004), isotope dating, chloride mass-balance, tracer mixing cell modelling, Darcian flow modelling, direct measurements of spring discharge or stream base-flow methods and recently by a combination of field measurements and remote sensing (Vries & Simmers, 2002).
Depending on the data available and arid to semi-arid condition of the region recharge was estimated using chloride mass balance method and inverse modelling.
Conceptual and numerical model was developed. During the development of the groundwater flow model, the so called model protocol was respected. The model protocol involves a number of steps that should be followed in order to produce meaningful values. Defining the purpose, developing conceptual and numerical model, sensitivity analysis, model calibration and prediction are among the steps.

1.6. Outline of the thesis

The thesis is outlined as follows
Chapter one: Describes the introduction of the research which includes background of the area, research problem, and research objective and research questions.
Chapter two: Discuses review of previous studies in the Dire Dawa groundwater sub-basin and literature reviews related to groundwater modelling and recharge estimations.
Chapter three: Describes the location, climate, topographic and geomorphic features, geology, land use and soil and hydrogeology
Chapter four: Data preparation and analysis including meteorological, hydro chemical, pumping test recharge estimation, water abstraction and demand.
Chapter five: focus on developing conceptual and numerical model, calibration sensitivity analysis
Chapter six: focus on results and discussions.
Chapter seven: focus on conclusion and recommendations

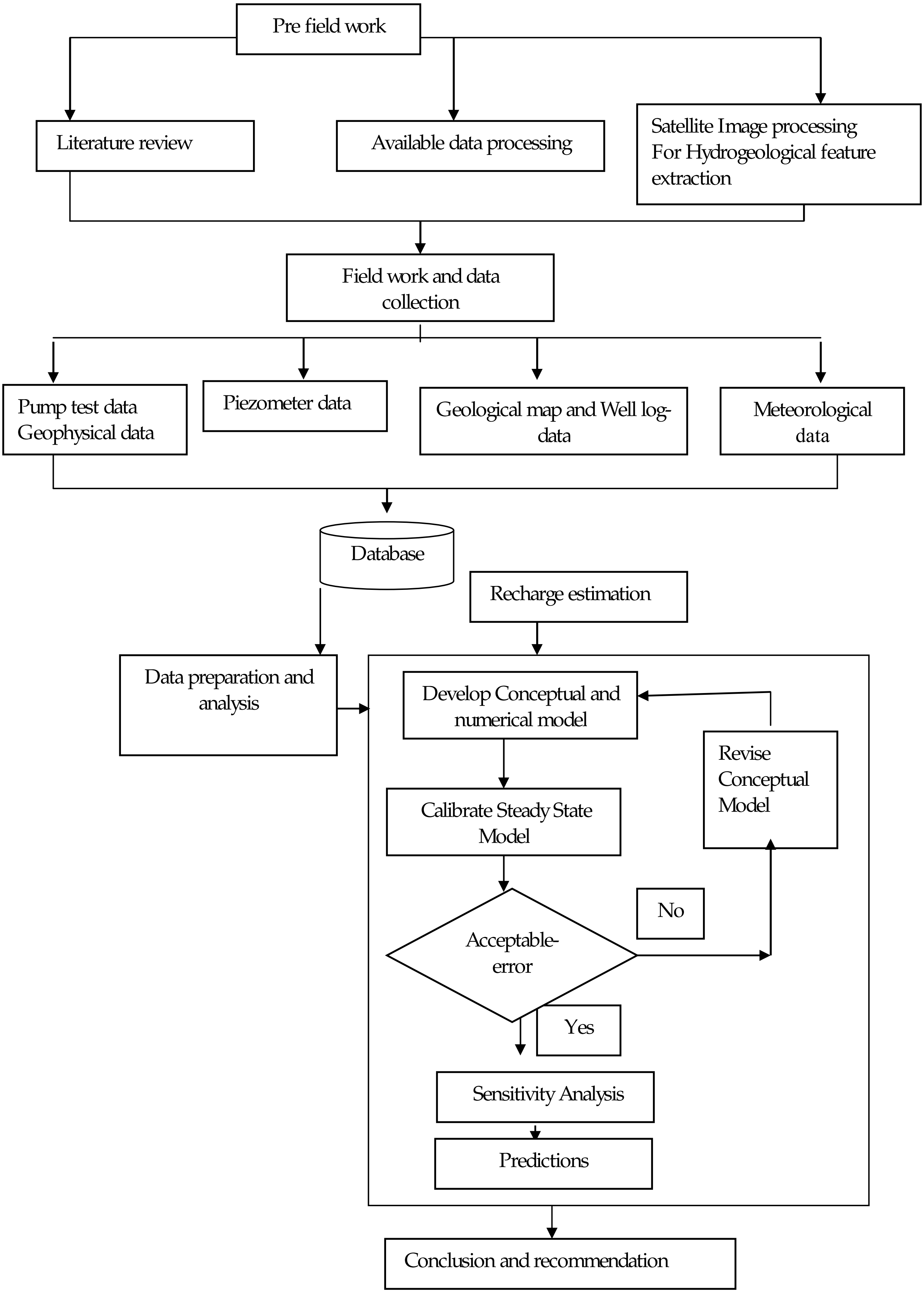

Figure 1-1: Flow chart of the methodology

2. LITERATURE REVIEW

2.1. Previos works in the study area

Previously geological, hydrological, hydrogeological, water quality studies and other related works have been performed for different purposes. Some of the previous works in the study area are listed in table 2.1 below.

Table 2-1 : List of previous works

no	Authors	Topic	organization	status
1	BECOM_WWDSE_CECE 2000	hydrological, hydrogeological geological and geophysical characterization of the sub-basin	Joint with water works Ethiopia	Unpublished regional developmental report
2	WWDSE 2004	hydrological, hydrogeological geological and geophysical characterization of the sub-basin	Water works Ethiopia	Unpublished regional developmental report
3	Tilahun & Merkel (2009)	Estimation of groundwater recharge using a GIS-based distributed water balance model in Dire Dawa, Ethiopia.	University of Oslo	*Hydrogeology Journal*, *17*(6), 1443-1457.
4	Eyilachew Yitayew (2010)	Anthropogenic Impacts on groundwater resources in the urban environment of Dire dawa	University of Oslo	(Abate, 2010) M.Sc. thesis
5	Meresa Kiros (2006)	GIS-based vulnerability and hazard mapping for the protection of Dire Dawa Groundwater basin	UNESCO-IHE Institute for water education Netherlands.	M.Sc. thesis

Initially BECOM_WWDSE_CECE studied Dire Dawa area focusing on hydrological, geological, hydrogeological and geophysical characterization of the basin in regional scale. Following BECOM_WWDSE_CECE, WWDSE in 2004 had studied by increasing the scale and making detail focus on the well fields. WWDSE has also estimated that groundwater recharge in the sub-basin is 37.56 mmy^{-1} using Darcian flow method. BECOM_WWDSE_CECE and WWDSE studies were financed by the government to develop the master plan of Dire Dawa town.

Additionally there are many studies in the study area for research case which are not financed by the government. Studies done by Tilahun & Merkel (2009), Eyilachew Yitayew (2010) and Meresa Kiros (2006) are among these studies.

Study of Tilahun & Merkel (2009) focussed on estimating the groundwater recharge in the basin using a GIS-based distributed water balance model. It was done for research purpose and is published in hydrogeological journal. They estimated a groundwater recharge 28mm y^{-1} and it was lower as compared to the result estimated by WWDSE 2004. Tilahun & Merkel also recommend the future groundwater development and management in the area should take the recharge into account and that the new result is useful for groundwater modelling and vulnerability studies in the area.

The studies of Eyilachew Yitayew (2010) and Meresa Kiros (2006) are done for their partial fulfilment of their master science in University of Oslo and UNESCO-IHE Institute for water education Netherlands respectively. They focused on Anthropogenic Impacts on groundwater resources in the urban environment of Dire Dawa and GIS-based vulnerability and hazard mapping for the protection of Dire Dawa Groundwater basin respectively.

2.2. Groundwater modelling

Groundwater modelling is one of the main tools widely used in the hydrogeological sciences for assessment of the resource potential and prediction of future impact under different circumstances or stresses(Anderson & Woessner, 1992). According to Rientjes, (2010) main applications of groundwater models are prediction and simulation of certain measures or activities, planning and evaluation of different scenarios and strategies and optimization in water resources management. It is a best way to make an informed analysis or prediction about the consequences of a proposed action. Applications of groundwater models require extensive field information for input data and for calibration (Anderson & Woessner, 1992).

2.3. Groundwater recharge

Recharge is defined in a general sense as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir (Vries & Simmers, 2002). Groundwater recharge is the most difficult component of the hydrologic cycle to measure (James et al 2004).

According to James et al. (2004) accurate representation of groundwater recharge rates and mechanisms in arid and semiarid regions is a significant challenge with in the hydrologic sciences for three reasons. First, there is the difficulty of measuring extremely small recharge fluxes that are highly variable in time and space. Secondly, recharge estimates often have legal and policy implications because they are tied to the ill-defined concept of safe yield. This constrains limiting groundwater pumping to the sum of natural and artificial recharge. Finally, an understanding of both recharge rates and mechanisms is critical for development of groundwater management strategies that go beyond the concept of safe yield and attempt to balance the demands for groundwater pumping while sustaining ecosystems. Recharge in desert basins is often considered to be the sum of several distinct processes occurring in different areas of the basin. It includes mountain recharge, diffuse recharge and ephemeral channel recharge. Mountainous regions are typically viewed as significant sources of recharge due to high precipitation input that results from orograghic effects.

3. STUDY AREA DESCRIPTION

3.1. Location of the study area

The study area is found at the margin of the eastern part of the Ethiopian rift valley covering an area of 727 km2. It lies between 09°28' to 09°49'N latitude and 41°38' to 42°19'E longitude. It is characterized by very diverse spatial variation of topographic features with an altitude range of 1018–2300 meters above sea level.

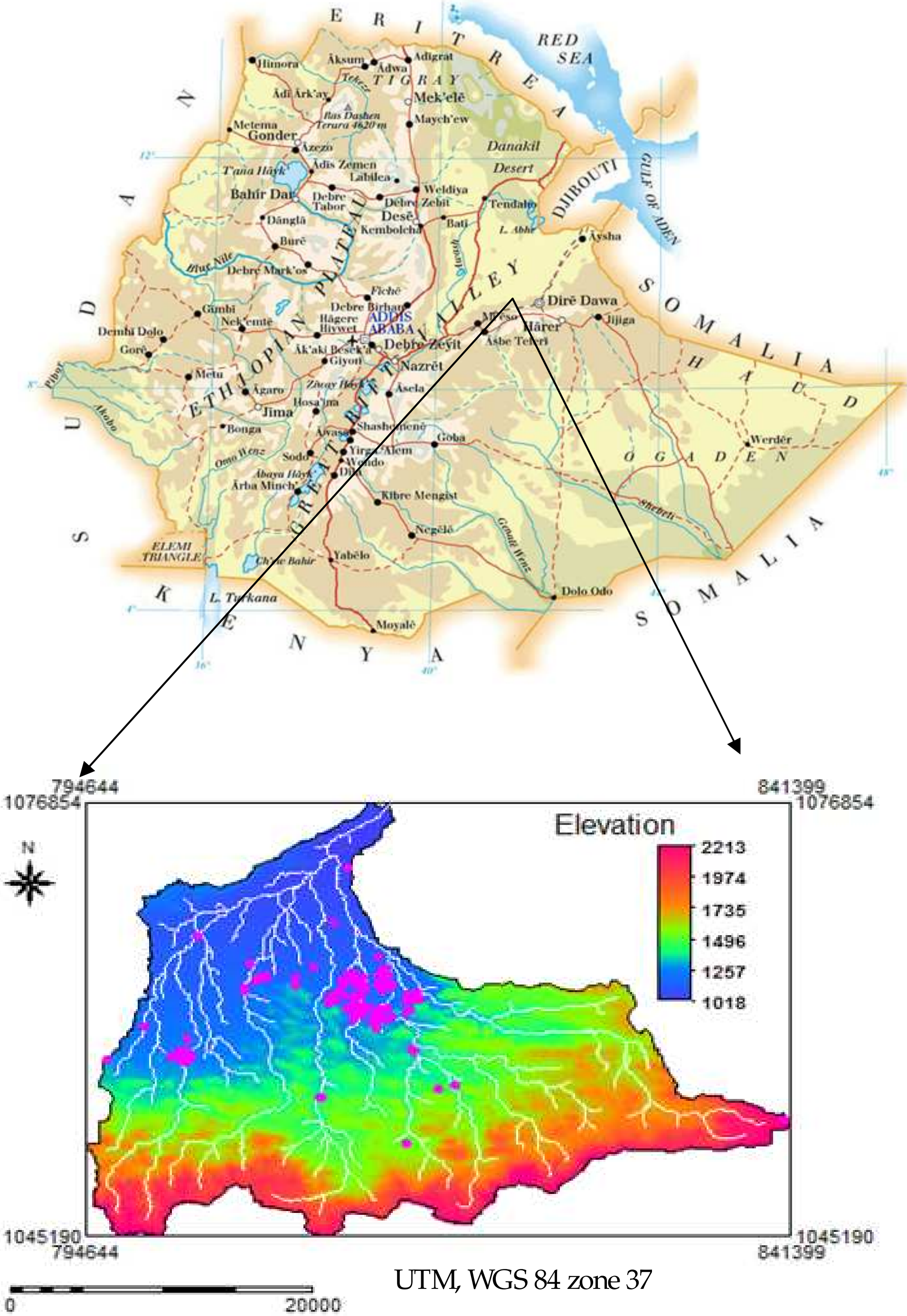

Figure 3-1 : Location and base map of study area (dot magenta colour =boreholes and white line segment)

3.2. Climate

The Dire Dawa area is characterized as Hot Semi-Arid Zone; whereas the Eastern and southern part of the region is classified as Warm Temperate Climate Zone. In the Hot Semi-Arid Climate Zone (the western, north-western and south-western part), the mean annual temperature lies between 17^0c and 27^0c; mean annual rainfall is between 509mm and 997 mm, potential evapotranspiration between 1286-2055mm and actual evapotranspiration of 468mm (75% of rainfall) (Ketema, 2009).

The climate of the study region is dominated by various inter-related factors, but the main factors are the near equatorial location and the altitude. The year is divided in three seasons: a main rainy season (Kiremt) from July to mid - September, a dry season (Bega) from October to February, and finally a "small rainy" season (Belg) in March and April. The small rain, originated from the Indian Ocean are brought by south-east winds while the heavy rains in the wet season come from the Atlantic Ocean with south-west winds.
There is one meteorological station at Dire Dawa town. The station measures all meteorological elements including continuous rainfall measuring using an automatic rain gauge. There are no stations of any kind in the Dire-Dawa catchment. However, there are stations near Dire-Dawa catchment in the Southern and Western directions.

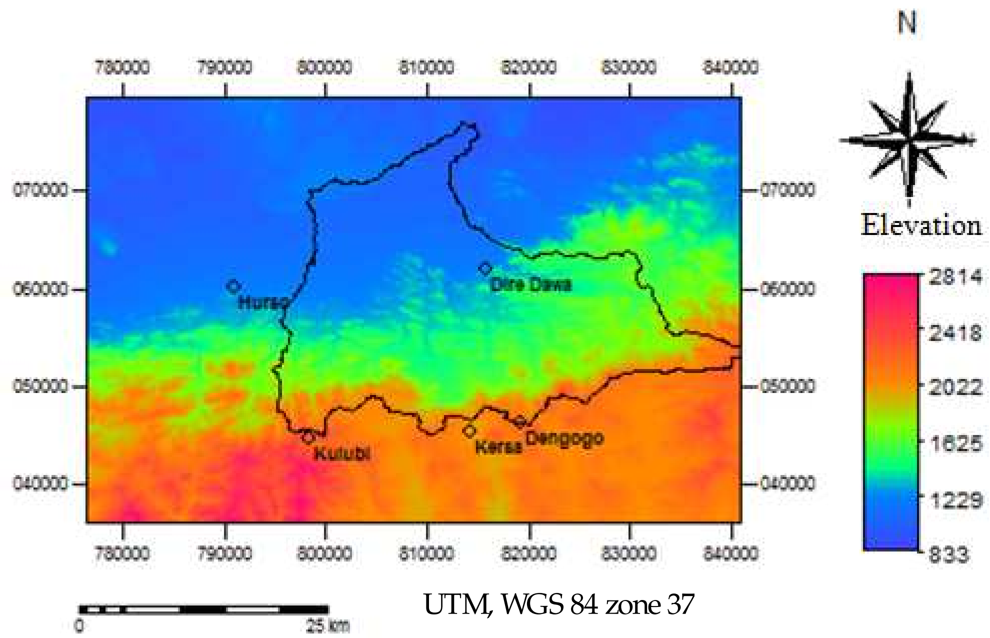

Figure 3-2: Distribution of the Meteorological stations in Dire-Dawa study area

Table 3-1 : Mean monthly values of Dire Dawa Meteorological variables (parameters) (after WWDSE)

Variables	Jan.	Feb.	Mar	Apr	May	June	July	Aug.	Sep	Oct	Nov	Dec	mean
Max. Temp.(0c)	28.2	29.9	30.2	31.7	33.6	34.8	33.3	32.6	31.4	32.0	30.2	28.6	31.5
Min. Temp. (0c)	15.3	16.6	19.2	20.5	21.6	22.6	21.1	20.6	20.9	18.9	15.9	15	19.0
Rel. Humidity (%)	39.3	42.5	44.4	47.5	35.2	30.0	41.4	40.8	34.6	27.6	29.6	29.9	41.4
Sun Shine (hr)	8,8	8	7,8	7,4	8,4	8,1	7,5	8	7,7	8,3	9,4	9,3	8,2
Evaporation(mm)	217	199	283	245	283	323	293	283	266	283	242	221	291
Wind Speed (m/s)	4.2	3.8	4.4	4.6	4.1	5.5	5.6	5.1	4.2	4.2	4.2	3.6	4.5
Rainfall (mm)	20.7	21.6	84.5	68.3	45.3	20.6	91.8	146	85.3	32	12.9	11.1	610

3.3. Topograghic and geomorphic features

The Dire Dawa region is located at the eastern margin of the main Rift Valley system and has three distinct Geomorphologies: plateau area, the escarpment and valley depression as can be seen from a three dimensional view of the study area fig 3.3.

The plateau marginal area, which demarcates the southern limit of the region, has elevations in the range of 2100-2400 m asl. The main rock units in the plateau area are consisting of Precambrian (gneiss), Hamaneli limestone and Sandstones of the Adigrat and Ambaradam formations.

The area of the escarpment, stepped margin of the valley depression, extending from the plateau to the southern limit of Dire Dawa town has elevations in the range of 1280-2100 masl. The main rock units in this part of the region consist of Precambrian (gneiss), limestone, sandstone and basalt.

The area of the valley depression, situated in the vicinity of the town of Dire Dawa extends to the north, west and eastern limits of the region. This valley depression lies at relatively low elevations of 1000-1280 masl. The area is covered by mainly Tertiary basalt, Quaternary sediment, travertine and alluvial deposit. Limestone and upper sandstone are occasionally encountered within the depression area.

Most of the settlements of the Dire-Dawa region are either nearby the foot of the escarpments or within the escarpment in valley depression areas, where water and fertile soil are available. The valley depression area has steep slope topography in which the possibility of rock falls and landslide occurrences are high.

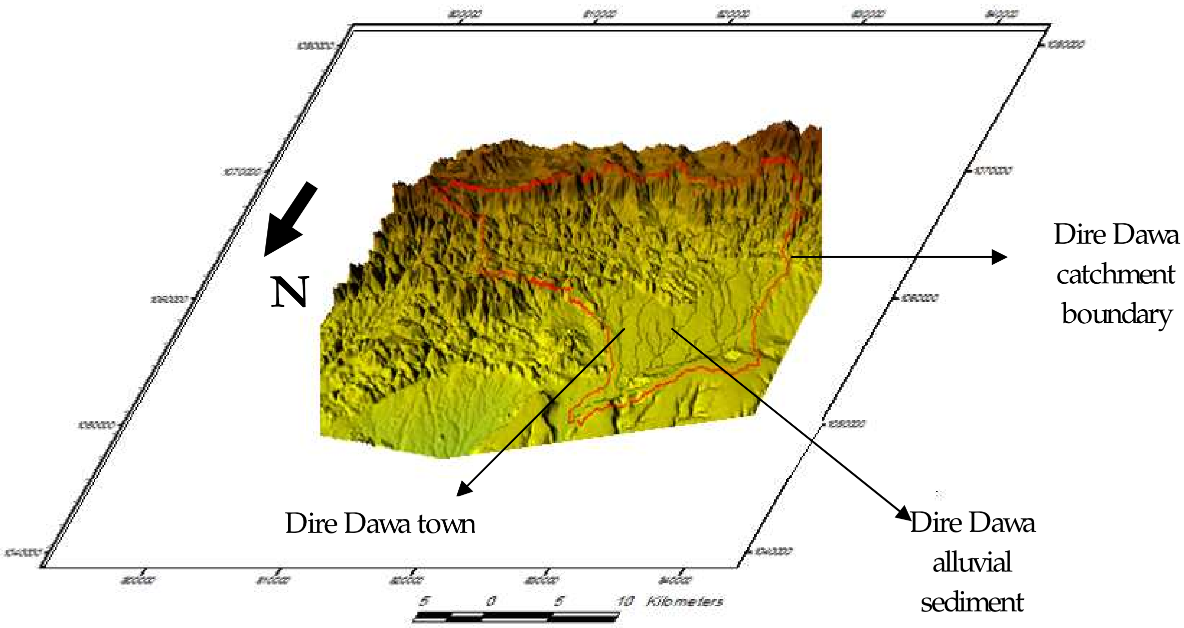

Figure 3-3: Three dimensional view of the study area

3.4. Geology of the study area

The geology of the area based on their regional stratigraphic position from the base upwards include Precambrian basement rocks, Mesozoic Sedimentary rocks, Tertiary to Quaternary volcanic rocks and Quaternary Sediments (WWDSE,2004 and Bosellini et al., (2001).

3.4.1. Precambrian basement rocks

The Precambrian metamorphic rocks of the area belong to the Archean complex of Alghe group and it is mainly composed of high-grade quartz-feldspar-bioitite gneiss, biotite-hornblende gneiss and pegmatites (Mengesha, T., etal, 1996).

This rock unit is exposed in the southern and south-eastern parts of the study area. It is unconformably overlain by the Adigrat sandstone and in the absence of this by Hamaneli limestone. Along the Dire Dawa-Dengego road and some other roadside outcrop, several basaltic dykes are observed cutting this basement rock. In most parts of the outcropped area, it is highly weathered and friable. Fresh rock outcrop is mainly encountered along the roadside and valley bottom.

3.4.2. Mesozoic sedimentary rocks

Mesozoic sedimentary rocks of the area, which are the result of the transgression and regression events, are grouped into three formations known as Adigrat Sandstone, Hamaneli Limestone and Amba Aradam (upper) Sandstone (WWDSE, 2004).

According to WWDSE, (2004) the Adigrat sandstone formation is a ferruginous origin unconformably overlying the basement complex and underlying the Hamaneli limestone. It is exposed mainly in the southern parts of the study area. This sandstone beds are dipping 16-26^{o} due south and southeast. In some parts of the area it is locally absent or unexposed. It is sandy calcareous formation, which are conglomeritic sandstone and grayish white in color at its base and calcareous sandstone and yellowish brown in color at the top. The conglomerates are composed of pink color rounded feldspar and quartz.

The thickness of the Adigrat sandstone in the Dire Dawa area is in the range of 0 to 50m (Bosellini, et al., 2001). The variation could be due to the rates of supply of the sandstone, distances of transportation from the source and paleo-morphology of the region during the transgression events.

Petrographic study of the Adigrat sandstone shows that it is composed of 30-39% quartz, up to 35% calcite cement, 15-62% potassium feldspar 4% plagioclase 2% muscovite, 2% zircon and 2% opaque minerals. The mineral grains are angular to sub angular in shape (WWDSE, 2004).

The Hamanlei limestone, which is marine origin conformably, overlies the Adigrat sandstone. In the absence of the Adigrat sandstone, it unconformably overlies the Precambrian basement rocks. It is exposed in the southern part of the area forming different step like ridges extended in the east-west direction and decreasing topographic elevation from south towards the north. The limestone beds are generally dipping towards south and southeast with varying dip angles ranging from 10° to 27°. The limestone has variable bedding thickness ranging from half a meter to two meters.

Due to the repetition of the limestone by the step like faults and the basal transition zone from the Adigrat sandstone top, it is difficult to determine the exact thickness of the Hamanlei formation.
This limestone in the DDAC area is very hard, massive, and gray in color. In hand specimen the dominant composition of the limestone is calcite and minor quartz. Calcite is highly reacting with 10% diluted Hydrochloric acid, while quartz is non-reactive (WWDSE, 2004).

Petrographic study of the gray color limestone which, is the dominant in the area, shows that it is composed of 80-98% calcite including the different fossils' shell microcrystalline compositions (micrite), 2-17% quartz, 1-3% plagioclase and 0-1% opaque minerals(WWDSE, 2004).

The Amba Aradom (upper) Sandstone is a ferruginous origin, is unconformably overlying the Hamanlei limestone. In the northeastern part of the area, the basalt is unconformably overlaying the sandstone. It is highly fractured and the fractures have similar trends with the main faults in the area (east-west and north-south).
The formation is conglomeratic, usually well cemented. In hand specimen, the rock is composed of sand to silt size fraction of mainly quartz grains cemented by silica. The conglomerates are sub-rounded quartz and pink color feldspar. Usually the rock is ferruginous giving colors ranging from yellowish to purple black, depending on the amount of iron oxides present; however, white color sandstone intercalations are common.
Petrographic study of the rock shows that it is composed of 40-90% quartz, up to 60% potassium feldspar, 5-15% plagioclase feldspar, 3-13% clay cement, 5% calcite cement and 1% opaque. The feldspar and quartz mineral grains are sub-rounded (WWDSE, 2004). The thickness of the formation is in the range of (200m-300m) (Bosellini, et al., 2001).

3.4.3. Tertiary volcanic

The Tertiary Volcanic rocks in the study area are Alaji Basalts and the Stratoid Basalts of the Afar series.The Alaji formation mainly consists of aphyric flood basalts associated with rhyolites (ignimbrites) and subordinate trachytes (Mengesha, T., etal, 1996).It is unconformably overlying the Amba Aradam sandstone and is exposed mainly in the north-western, central and north-eastern part of the area. The stratoid basalt exposed in the study area is the upper part of the Afar series and represented by the transitional type basalt (Mengesha, T., etal, 1996). It is exposed in the northwest and northeast of the Dire-Dawa region. It is most likely fissural eruptions and serves as a barrier in the Dire Dawa area.

3.4.4. Quaternary sediments

The Quaternary sediment deposit of the area is consisting of alluvial sediments and river sand deposit. The alluvial deposit, which is the weathering product of the existing rocks in the area, is mainly covering the lower most elevations of the Dire-Dawa region, which is part of the Afar depression. This deposit is consisting of boulders, gravels, sand, silt to clay sizes of the rock units described above (metamorphic rocks, sandstone limestone and basalt). The alluvial sediment has variable thickness. In the ground water test holes, TW-3 and TW-1 its thickness is 50m and 237m respectively. The river sand deposit is the most recent sediment in the area; it is deposited in the flood plains of the main stream in the area. Significant deposits are associated with the intermittent streams crossing the Dire Dawa town. The sand deposit is the weathering product of the rocks within the watersheds of the main stream and their tributaries. The deposit is composed of fragments of the metamorphic, sedimentary and volcanic rocks of the area.

3.5. Tectonic structures

The major structures in the area are faults associated with the formation of the Red Sea, East African Rift System and The Gulf of Aden. There are three major fault trends. The major fault trends are E-W, which is similar to that of the south coast of Gulf of Aden and forms the main escarpment with several normal step faults downthrown to the north. This faulting led to a system of tilted blocks completely attached to the Ethiopian graben systems, which originated the afar depression, on the border of which lies the Dire Dawa area. Due to this faulting, the sedimentary beddings are tilting towards south.

The second fault trend is NW-SE, which is similar to that of the Red Sea trend. This fault trends are mainly associated with the deeply incised streams flowing from the southeast to the northwest of the area.

The third fault trend is NE-SW, which is similar to that of the main Ethiopian Rift System trend.

3.6. Landuse and soil

The landuse in the study area is cultivated land, physiognomic vegetation, bare land and urban and built up area as shown in fig 3.4. The escarpment (southern part of the study area) is mainly cultivated land and bare land while the valley plain (the potential groundwater area) is physiognomic vegetation and cultivated land. The physiognomic vegetation includes dense shrub land, open shrub land and eucalyptus plantation. Most of the escarpment area is degraded bare land due to the steep topography, deforestation and intense rainfall.

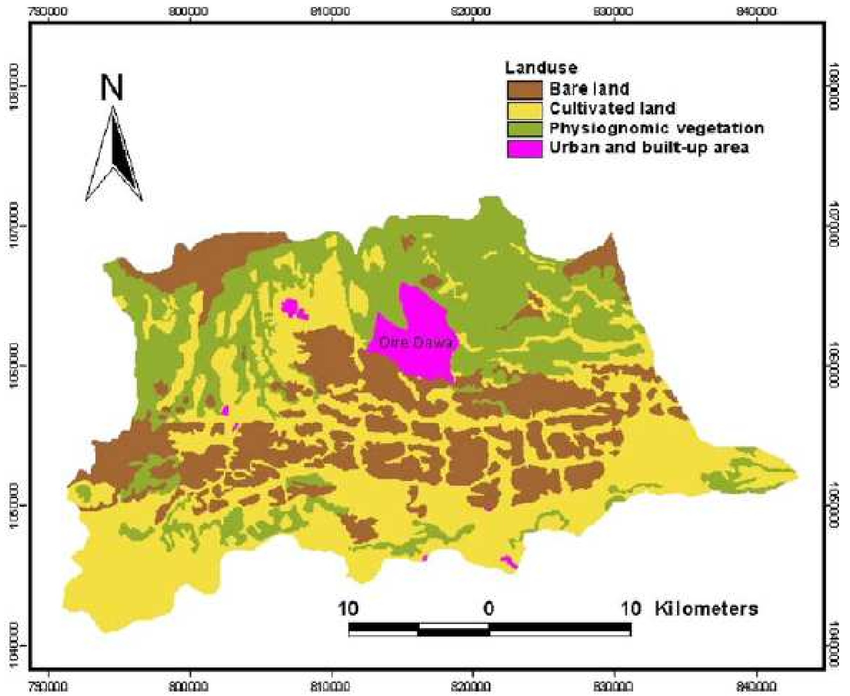

Figure 3-4: Land use map of Dire Dawa sub-basin (WWDSE, 2004)

The soil coverage of the study area based on their texture are loamy sand, sandy loam, loam, sandy clay loam, sandy clay and silt clay as shown in fig 3.5.

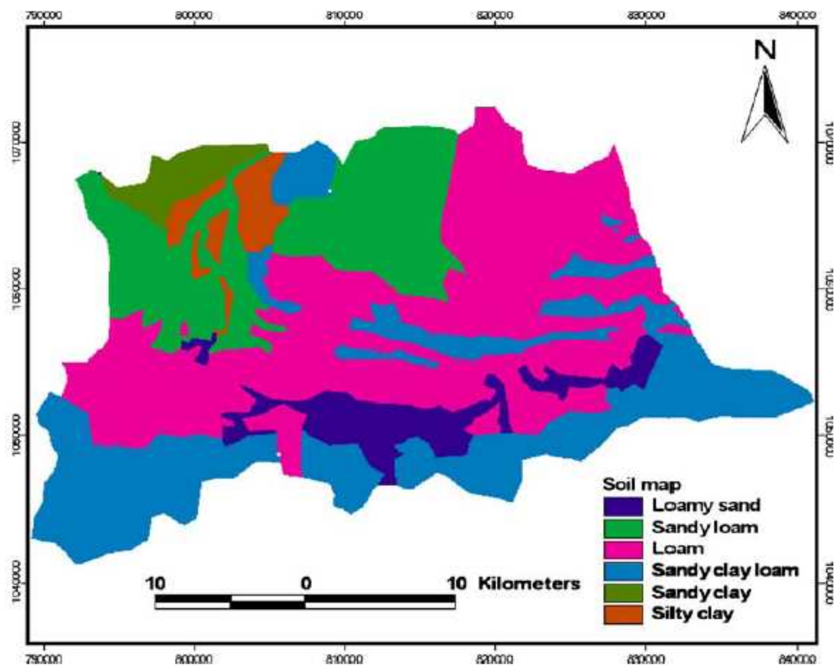

Figure 3-5: Soil map of Dire Dawa sub-basin (Ketema, 2009)

3.7. Hydrogeology

The groundwater occurrence and distribution in the sub-basin is mainly a function of the geological formations, geomorphology and tectonics. The geological formation which is a base for hydrogeological conditions of the area varies based on the geomorphology and tectonics. Depending on the geomorphology and tectonics pre-Cambrian rocks, Adigrat sandstone, Hamanalei limestone and basalts on the escarpment and alluvial deposits and upper sandstones on the down thrown plain (foot of the escarpment) are outcropped (fig 3.6). Hence based on topography, tectonics, geological formations, aerial and topological relationship of the geological formation, the Dire Dawa region can be categorized into two groundwater systems i.e. the escarpment and the foot of the escarpment (groundwater basin of Dire Dawa).

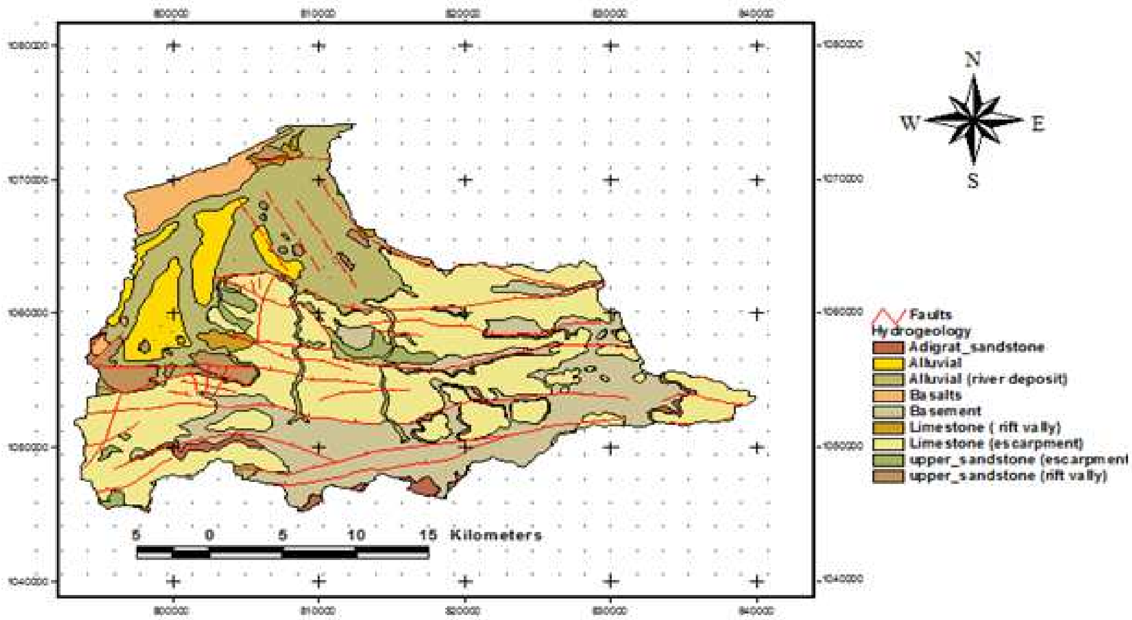

Figure 3-6: Hydrogeological map of the study area (adapted from WWDSE, 2004)

3.7.1. The escarpment groundwater

The escarpment occupies the southern, south-eastern and eastern parts of the Dire-Dawa region. It is highly rugged areas and intensively faulted by east-west trending faults. Geologically, the western part is dominated by sedimentary formations (limestone and sandstones), at the central part south of Dire Dawa town sedimentary and basement rocks dominates, and to the east volcanic and sedimentary rocks dominates. At the far north-eastern part of the escarpment the sedimentary formation, basement rocks outcrops and the topography highly enhances complete drainage of the groundwater out of the sedimentary formation.

3.7.2. The Dire Dawa groundwater basin (the foot of the escarpment)

The Dire Dawa Groundwater Basin (foot of the escarpment) occupies the western part (plains) of the region from Dire Dawa town along Melka Jebdu to Hurso and to the east. This area is considered to have high groundwater potential, where Dire Dawa town and Harare town water supply sources (Haseliso well field) are found. The groundwater occurrence and distribution in the basin is mainly a function of the geological formations, geomorphology and tectonics.

Alluvial aquifers

The alluvial aquifer forms an extensive aquifer at Dire Dawa town and north of it, west of Dire Dawa town the occurrence of groundwater in this formation is limited along the alluvial fans and river channel deposits. The thickness of the alluvial sediment varies from 8.5 to 237 meters composed of clay, silt, sand, gravel and rock fragments. The ground water level varies in the alluvial sediments from 5 to 45 meters. The transimissivity of the alluvial formation varies from 8 to 700m^2d^{-1}, and the maximum transimissivity is registered at Shinile (WWDSE, 2004).

Tertiary volcanic rocks

Tertiary volcanic rocks in the DDAC are mainly stratiod basalts and Alaji basalts outcrops that occupy the elevated areas. Boreholes drilled on the basalts are practically dry except at Hurso area with a maximum specific well discharge of 0.01 $ls^{-1}m^{-1}$ (WWDSE, 2004).

Upper Sandstones

The upper sandstone outcrops at Haseliso, north of Dire Dawa at the airport and Northwest of Dire Dawa town. The static water level varies from 9.3 meters (Sabiyian) to 69.3 meters (Dire Jara) with the specific well discharge of 0.13 to 68.97 $ls^{-1}m^{-1}$. The transimissivity of the aquifer varies from 9 to 5512 m^2d^{-1} with a mean of 1810.9 and harmonic mean of 88m^2d^{-1} from pumping test analysis (WWDSE, 2004).

4. DATA PREPARATION AND ANALISIS

4.1. Meteorological data analisis

4.1.1. Rainfall

In order to analyze the rainfall data, the data that are available at stations that are located in the study area and the neighbouring stations have been considered. The available stations (section 3.2) whose data received from NMSA are at Dire Dawa (1st class), Dengogo (3rd class), Hurso (3rd class), Kersa (3rd class) and Kulubi (3rd class)).

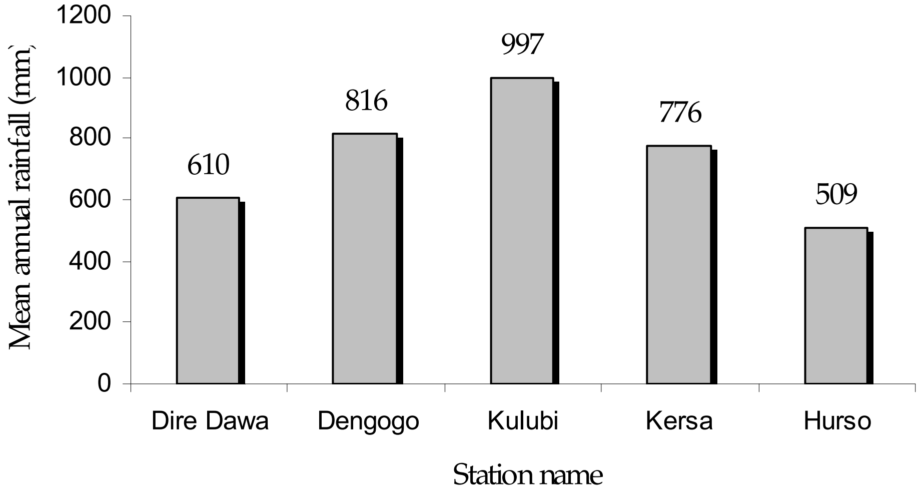

Figure 4-1: Mean annual rainfall the weather stations (1953-2007)

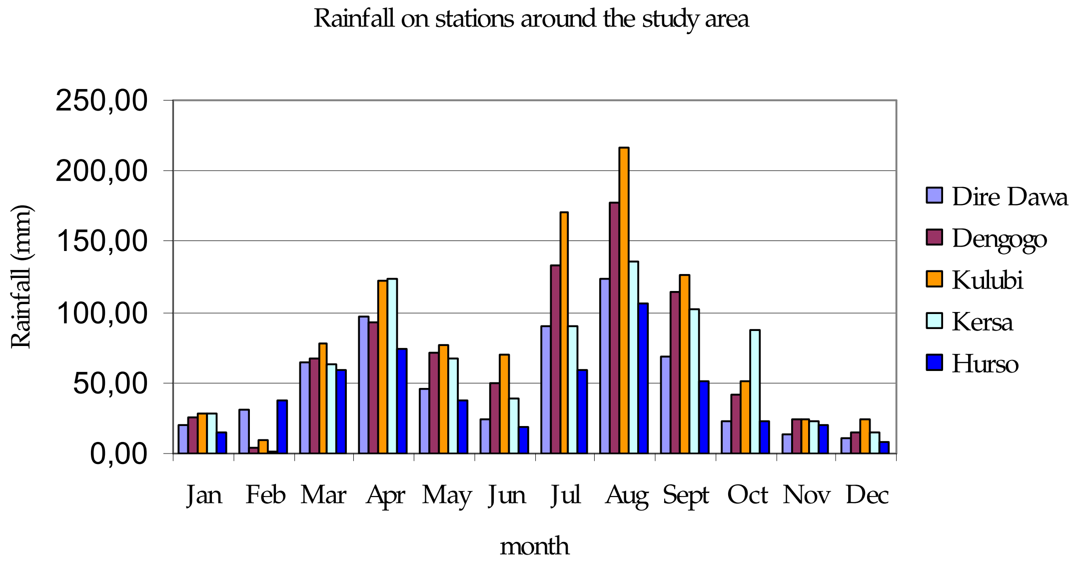

Figure 4-2: Mean monthly rainfall the weather stations

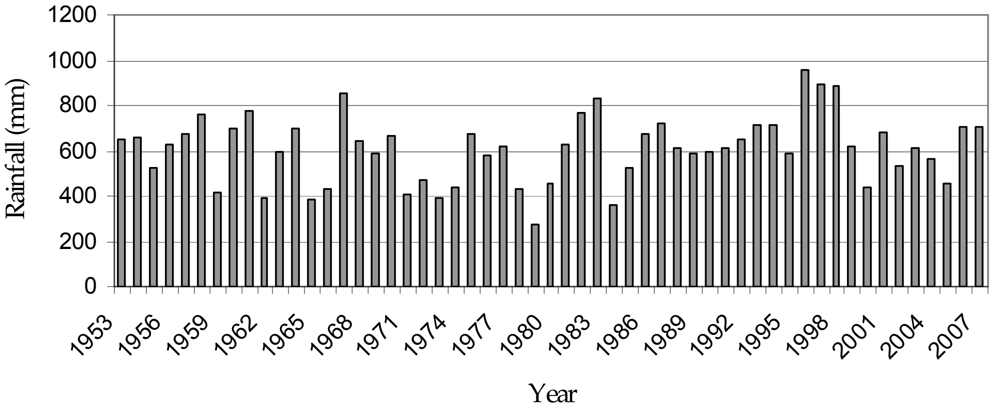

Figure 4-3: Mean annual rainfall the Dire Dawa station

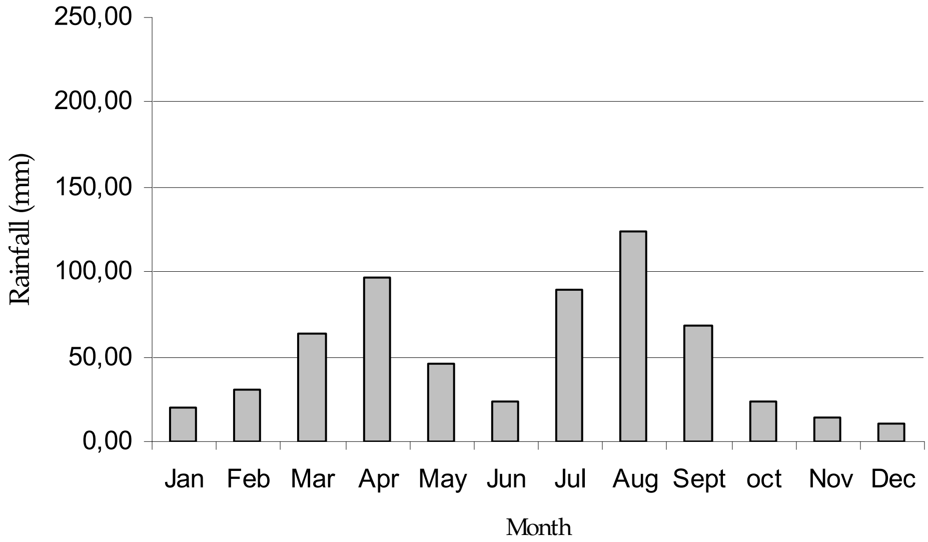

Figure 4-4: Mean monthly rainfall of the Dire Dawa station

4.1.2. Temperature

The mean annual temperature for Dire Dawa, Hurso and Dengogo areas are 25.3^{0}c, 27^{0}c and 16.2^{0}c respectively. The mean annual maximum temperatures are 31.5^{0}c, 32^{0}c and 21.6^{0}c with maximum monthly values of 34^{0}c, 35.8^{0}c and 24^{0}c respectively. Whereas the mean annual minimum temperature is 19^{0}c, 21.9^{0}c and 10.7^{0}c with mean minimum monthly values of 15^{0}c, 14^{0}c and 7.9^{0}c respectively. The hottest months are from the months of May to September, whereas the coldest months are from November to February.

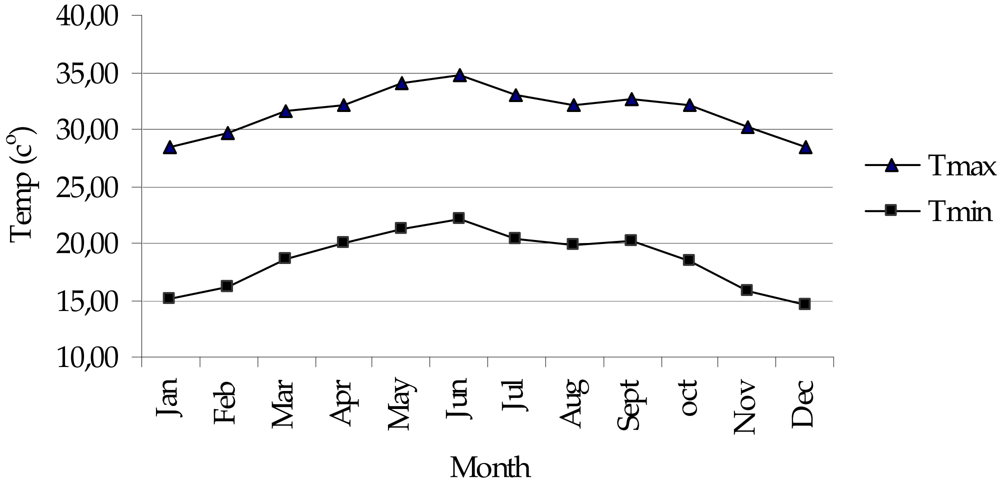

Figure 4-5: Mean monthly maximum and minimum temperature of Dire Dawa

4.1.3. Evapotranspiration

The annual potential evapotranspiration of the Dire Dawa catchment is 1833mm in average ranging from 1286 to 2055mm. The annual actual evapotranspiration is 468mm (75% of rainfall in the area) (Ketema et al. 2009). Monthly potential evaporation or open water portion evaporation of Dire Dawa town obtained from WWDSE is shown in figure 4.6.

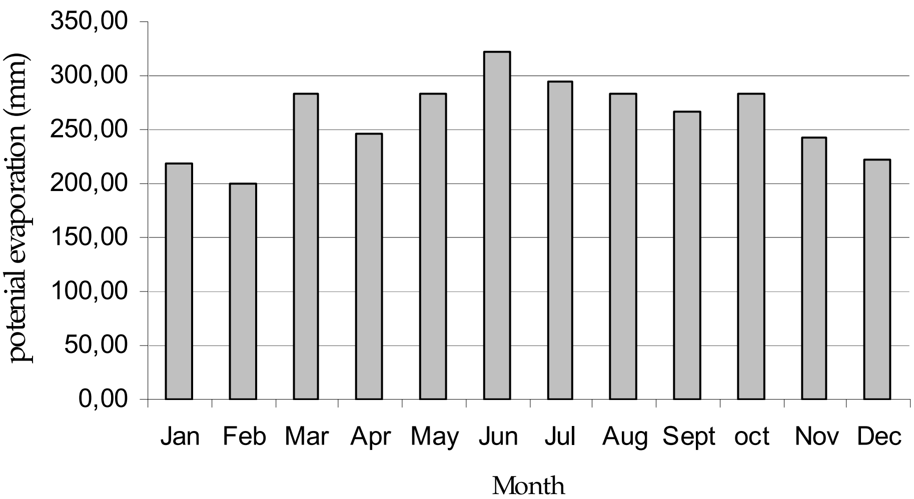

Figure 4-6: Mean monthly potential evaporation of Dire Dawa station (after WWDSE)

4.2. Hydrochemical analisis

4.2.1. Water quality

To study the water quality; laboratory data of 82 water samples were collected from WWDSE. The water quality parameters considered for analyses are:

- Physical characteristics: The main physical characteristics considered in the analysis are: Color, Turbidity, taste and odor Temperature

- Chemical Analysis: In the chemical analysis the following parameters were determined. The main cations (NH^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, total Iron and Manganese), The main anions (Cl-, NO^{2-}, NO_3^-, F^-, HCO_3^-, SO_4^{2-}, and PO_4^{3-}), Total alkalinity as mg/l of $CaCO_3$ and Total hardness as mg/l of $CaCO_3$, Conductivity, total dissolved solids and PH .

4.2.2. Reliability checking

As a check on chemical analysis, a cation-anion balance is usually performed (Fetter, 2004). The data were checked for correctness by checking the sum of the cations to be equal to the sum of the anions. The laboratory error for each analysis was checked by:

Laboratory Analysis error (%) = 100*/ (Sum of Cations – Sum of Anions)// (Sum of Cations +Sum of Anions)

All laboratory results were checked by the above relationship and it was found that more than 86% of the analyzed samples have less than 10% error and 14% of them 10% – 30 % error. All laboratory results with lab error of more than 10% were excluded from further analysis. And correlation of TDS and conductivity is also done (fig 4.6).

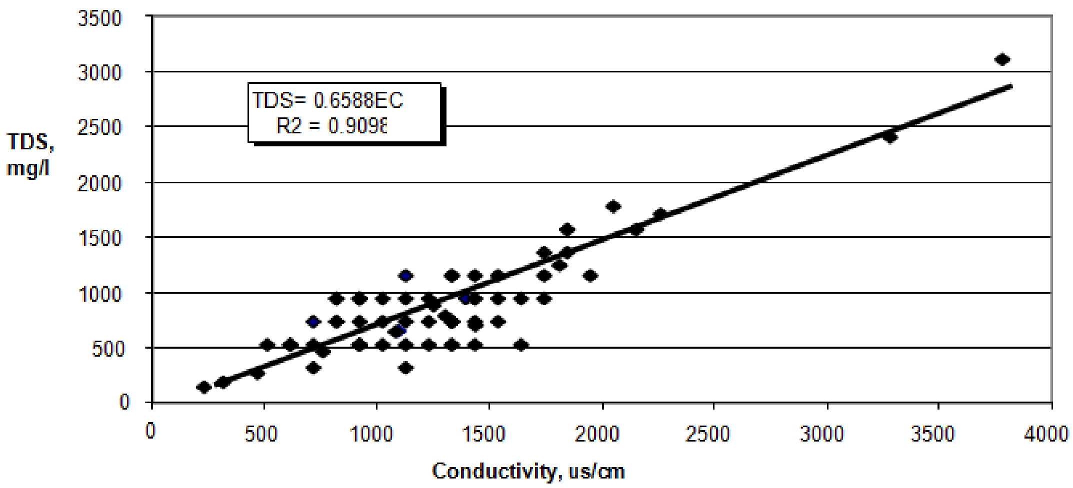

Figure 4-7: Correlation of conductivity with total dissolved solids (TDS) (after WWDSE)

4.2.3. Water quality indicators

As main water quality indicators are physical, chemical and bacteriological constituents of water. These constituents are affected by function of geological formation and human interferences. In this study it is focused on the physio-chemical characteristics of the water.

The water quality analysis showed that almost all of the water samples analyzed are colourless, odorless, non-turbid and tasteless. The total dissolved solutes and conductivity of the samples are 744 mgl^{-1} and 1017 mgl^{-1} ranging 146-1170 mgl^{-1} 230-1500 mgl^{-1} respectively. The water types are Ca-HCO_3 and Ca-Mg-HCO_3 for most of the spring and borehole samples and Ca-HCO_3-Cl, Ca-Na-HCO_3-Cl, Ca-Mg-HCO_3-Cl and Na-Ca-HCO_3-SO_4 for hand dug wells. The water type with chlorides, sulphides and sodium are modification due to humane interference. And most of these are from unprotected shallow wells. The summery of the physio-chemical analysis of the groundwater of the study area and the water type are shown in table 4.1. Most of the water samples show that they are the same type except some hand dug wells which are exposed to pollution. This can be seen in the piper diagram of the samples fig 4.8. On this figure we can see the clustering of the water samples in one area. This indicates the similarity in type of the samples. Hence we can say the groundwater system have nearly similar characteristics in geology and source of recharge.

Table 4-1 : Summary of Physio-chemical Composition of groundwater of the study area (after WWSDE)

Water quality indicator	pH	EC, μS/cm	Na+, mg/l	Ca++ mg/l	Mg++ mg/l	Mn4+ mg/l	Fe++ mg/l	Cl- mg/l	NO_3^- mg/l	F- mg/l	HCO3- mg/l	CO3- mg/l	SO4- mg/l	SAR
Min	6.7	178.0	2.0	32.0	3.0	0.0	0.0	8.0	0.0	0.1	107.4	7.2	2.4	0.4
Max	8.5	3780.0	600.0	472.0	109.4	0.2	0.8	694.1	244.0	2.4	700.3	16.8	1213.0	1.8
Average	7.5	1171.9	72.3	151.9	28.6	0.1	0.1	110.9	34.0	0.6	403.7	12.0	120.1	0.5
St. Dev.	0.3	588.2	89.4	63.7	22.2	0.0	0.2	122.0	50.7	0.3	100.6	6.8	208.6	0.4
Var%	21.0	95.0	100.0	93.0	97.0	95.0	99.0	99.0	100.0	94.0	85.0	57.0	100.0	0.9
Sample No	76.0	76.0	68.0	68.0	68.0	48.0	31.0	75.0	71.0	73.0	68.0	2.0	74.0	76.0

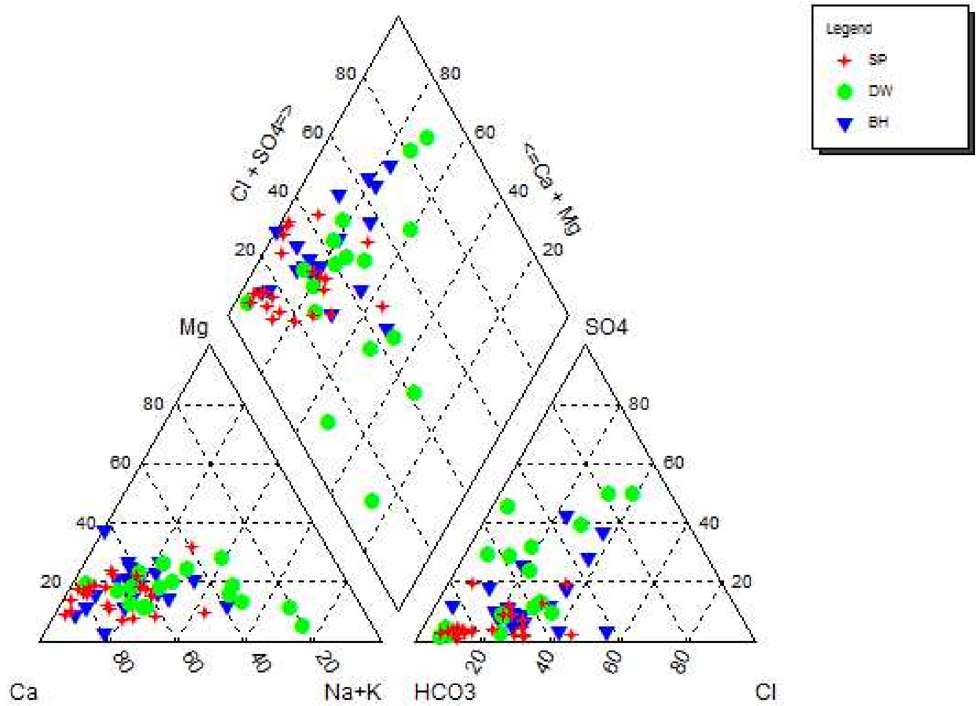

Figure 4-8: Piper diagram of water samples from boreholes (BH) springs (SP) and hand dug wells (DW)

4.3. Recharge

Recharge can be estimated by isotope dating, chloride mass-balance (CMB), tracer mixing cell modelling, Darcian flow modelling, direct measurements of spring discharge or stream base-flow methods and recently by a combination of field measurements and remote sensing(Vries & Simmers, 2002).
CMB method is used to estimate the recharge in this study area. The CMB approach has been most widely used for estimating low recharge rates, largely because of the lack of other suitable methods (Scanlon 2004). Chloride concentration in pore water can be used as quantitative indicator of areas high and low water flux (Scanlon, 2004).

According to Scanlon (2004) the mass flux of chloride into a system(precipitation and dry fallout, P) times the chloride concentration in precipitation(Cp) is balanced by mass flux of chloride moving out of the system (Drainage, D) times the chloride concentration in drainage water in the unsaturated zone(Cd), if surface runoff is assumed to be zero.

$$PCp = DCd \quad \rightarrow \quad D = PCp \;/\; Cd \qquad (4.1)$$

In case of Dire Dawa study area, the targeted area to be modelled receives recharge from direct precipitation and inflow water from upstream area. Hence the source for the flow flux and chloride became precipitation and groundwater inflow from upstream area. And the CMB can be reformulated as

$$R = \left(\frac{PCp}{Cg} + \frac{ICi}{Cg} \right) \qquad (4.2)$$

Where

R = recharge (Mm3 y^{-1})

P = Average precipitation for the modelled area (Mm3 y^{-1})

I = Average inflow to the modelled area (Mm3 y^{-1})

Cp = Chloride concentration of precipitation (mg l^{-1})

Ci = Chloride concentration of inflow (mgl^{-1})

Cg = Chloride concentration of groundwater (mg l^{-1})

The CMB method needs the area's average quantity of precipitation, average inflow to the modelled area chloride concentration of groundwater, chloride concentration of precipitation Chloride concentration of the inflow.

Rainwater

The average precipitation for the modelled area is taken from the Dire Dawa weather station. The Dire Dawa weather station is situated in the central part of the groundwater area. Hence the precipitation measured from this station represents the groundwater area. The precipitation measured is 610mm y-1. The Chloride concentration of precipitation of the study area is adapted from Akaki well field which is in the same basin (Awash basin). According to Tesfaye (2009) eight rainwater samples were analysed at ITC laboratory and the average result was 0.8mg l-1.

Groundwater

Chloride concentration of groundwater is taken by analysing 25 samples and the average concentration is 27mg l^{-1}.

Inflow water from upstream elevated area

The average inflow to the modelled area from upstream elevated area is the difference between precipitation and actual evaporation in that area. According to Ketema et al. (2009) the difference between rainfall and actual evaporation in the area is 153mm y^{-1} (25% of rainfall). Hence the total inflow is the difference between rainfall and actual evaporation over the upstream entire area which is 72.55Mm^3 y^{-1}. The inflow is expected to infiltrate near the southern boundary.

The chloride concentration of the inflow to the modelled area was also estimated from the water samples of four springs emerging from the upstream elevated area near the southern boundary. The average concentration is 16mg l^{-1}.

Hence the recharge is 47.8 Mm3 y^{-1} , 5.78 Mm3 y^{-1} (20mmy^{-1}) as direct recharge from precipitation and 42 Mm3 y^{-1} from inflow from upstream area as obtained from CMB method.

4.4. **Pumping test**

Hydraulic conductivity values represent a measure of the hydraulic capacity of the aquifer or its ability to transport groundwater. The conductivity data were mostly time-draw down measurements from single-well aquifer tests. 26 conductivity values are collected.

According to Halford K. J. et al (2006) single-well aquifer tests frequently are analysed with the Cooper-Jacob (1946) method because of its simplicity. And he adds that interpretation of single-well test with the Cooper-Jacob method remains more reasonable than most alternatives.

The pumping test data was processed using Aquitest computer software. Cooper and Jacob method was applied for the analysis of the pumping test data since the data collected is from single-wells. From Cooper and Jacob method the transmissivity can be estimated by fitting a straight line to draw downs on arithmetic axis versus time on a log-arithmetic axis in semi-log plot. Then the transmissivity was changed to conductivity by dividing to the aquifer thickness of the well. The results of conductivities show that the upper sandstone and hamanlei lime stones have high conductivity ranging from 1.4-80 md^{-1} followed by alluvial sediments 0.65-4.4 md^{-1}. The volcanic rocks (basalts) in the area have very low conductivity values less than 0.1md^{-1}. The summary of the conductivity on different geological formations is presented in table4.2.

Table 4-2 : Summary of conductivity of the different geological formation

Geological Formation	Conductivity in m d^{-1}			Aquifer productivity
	Min	Max	Mean	
Alluvial	0.65	4.4	2.0	Moderate
Basalts	0.04	0.07	0.05	Very low
Upper Sand Stone and Hamanlei Lime Stone	1.40	80.0	25.0	High

4.5. Hydraulic conductivity

The hydraulic conductivity values of the aquifers were assigned based on the pumping test obtained from WWDSE. To assign the representative hydraulic conductivity value of the aquifers initially zones were created. The zones created were based on the hydrogeological map of the study area. To represent the zones grouping of wells spatially in their respective zones were done. Then the zones were assigned average hydraulic conductivity values of the wells to represent the zone. They were assigned hydraulic conductivity values from 0.05m d^{-1} (basalt) to 25 m d^{-1} (sandstone). The assigned hydraulic conductivity values are in acceptable range as compared to hydraulic conductivity of formation given by Brassington, (1988). The zoning and values were as shown in fig 4.11.

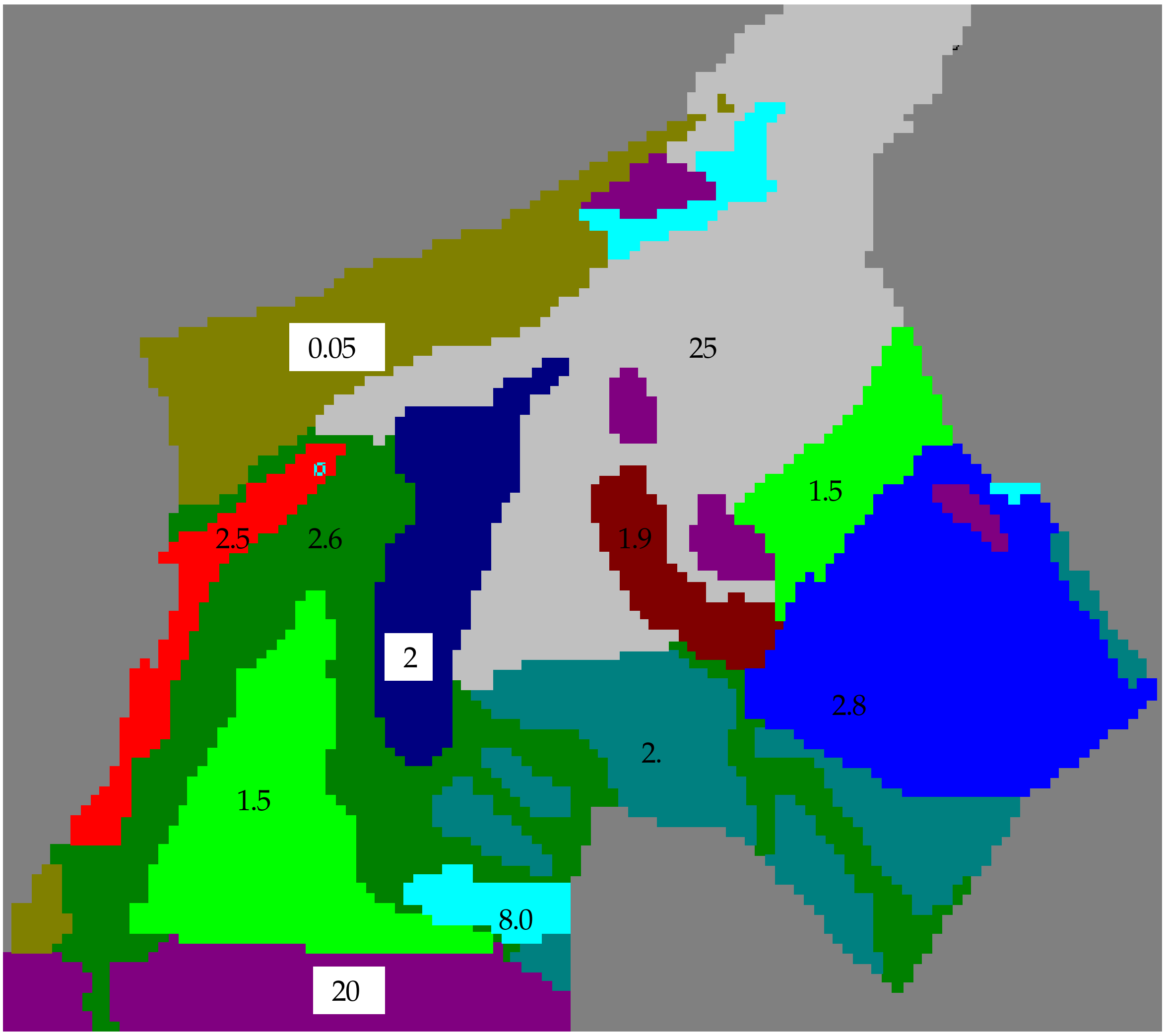

Figure 4-9: hydraulic conductivity zones and values of the Dire Dawa groundwater area (in m d^{-1})

4.6. Well abstaction and demand

4.6.1. Well abstraction

The total well abstraction is the sum of the average well abstraction from Sabian, Direjara, Hasaliso well fields and local villages. Sabian and Direjara well fields supply to Dire Dawa and Direjara towns 25920 m^3d^{-1} (300 ls^{-1}). Hasaliso well field supply to Harar town 20736 m^3d^{-1} (240 ls^{-1}). Shallow wells and hand dug wells in the local villages supply 8000 m^3d^{-1} to residence of local villages. Hence the total average water well abstraction is 54656 m^3 d^{-1} (19.95 Mm^3 y^{-1})

4.6.2. Water demand

In the design of any water work project it is necessary to estimate the amount of water that is required. The amount of water required is the sum of the domestic water demand, non-domestic water demand and system water loss within the design period of the project. It includes the quantity of water required for Domestic, Livestock, Gardening and Industrial uses. The average water demand is the sum of the Average Water Demand of Dire Dawa and Direjara towns 61632 m^3d^{-1} (714 l s^{-1}) as shown in table 4.3 and fig 4.12. The average water demand of Harar town is 25920 m^3d^{-1} (300 l s^{-1}) while the average water demand for the local village is 9000 m^3d^{-1}. Hence the total Average Water demand is 95552 m^3d^{-1} (34.876M m3 y^{-1})

Table 4-3 : Average Water Demand of Dire Dawa and Direjara towns (adapted from WWDSE, 2004)

Demand (m^3 d^{-1})	Year 2005	2010	2015	2020	2025	Average 2005-2025
Domestic	17801	25539	36661	52915	76618	41907
Public water (10% of domestic)	1780	2554	3666	5291	7662	41901
Livestock water	307	375	459	558	679	476
Gardening water	823	1006	1231	1497	1822	1276
Industrial water	71	71	71	71	71	71
Average day water demand	20782	29545	42088	60332	86852	47920
Loss in distribution system	28%	28%	28%	28%	28%	
	5819	8273	11785	17496	25187	13712
Total average day water demand (m^3 d^{-1})	26601	37818	53873	77828	112039	61632
Total average day water demand (l s^{-1})	308	438	624	901	1297	714

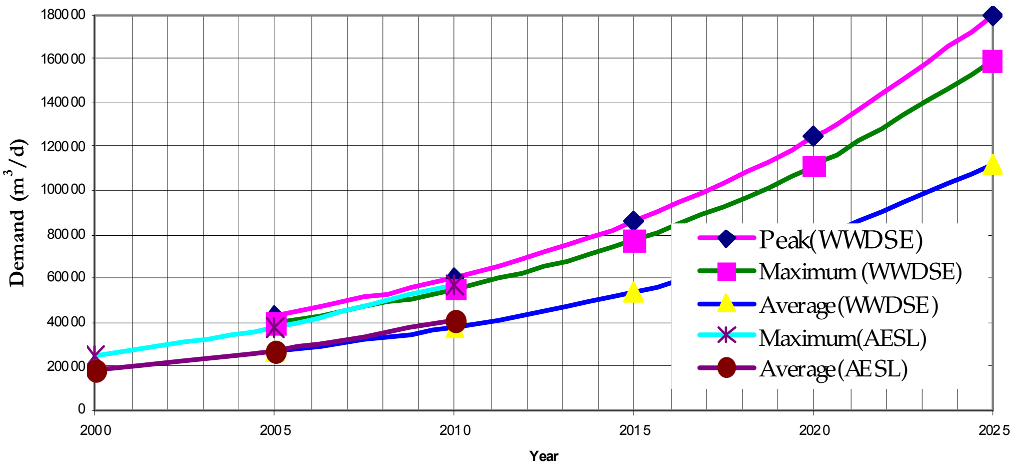

Figure 4-10: Average water demand of Dire Dawa and Direjara towns projected by WWDSE and AESL 2000-2025 (DWSA)

5. GROUNDWATER MODELLING

5.1. Introduction

Groundwater modelling is one of the main tools widely used in the hydrogeological sciences for assessment of the resource potential and prediction of future impact under different circumstances or stresses(Anderson & Woessner, 1992). According to Rientjes, (2010) main applications of groundwater models are prediction and simulation of certain measures or activities, planning and evaluation of different scenarios and strategies and optimization in water resources management.
Groundwater flow models can perform complex analyses and predictions. In groundwater flow modelling the governing equation is (Anderson & Woessner, 1992):

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)=Ss\frac{\partial h}{\partial t}-R \qquad 5.1$$

Where

h	=Hydraulic (piezometric) head	(L)
K	= components of the hydraulic conductivity	(LT^{-1})
S_S	=Specific storage	(L^{-1})
R	=Sink/Source function	(LT^{-1})
x, yz	= orthogonal Cartesian co-ordinates	(L)
t	= time	(T)

When developing a groundwater flow model, the so called model protocol should be respected that involves a number of steps that should be followed in order to produce meaningful values as summarized in fig 5.1. Defining the purpose, developing conceptual and numerical model, sensitivity analysis, model calibration and prediction are among the steps.

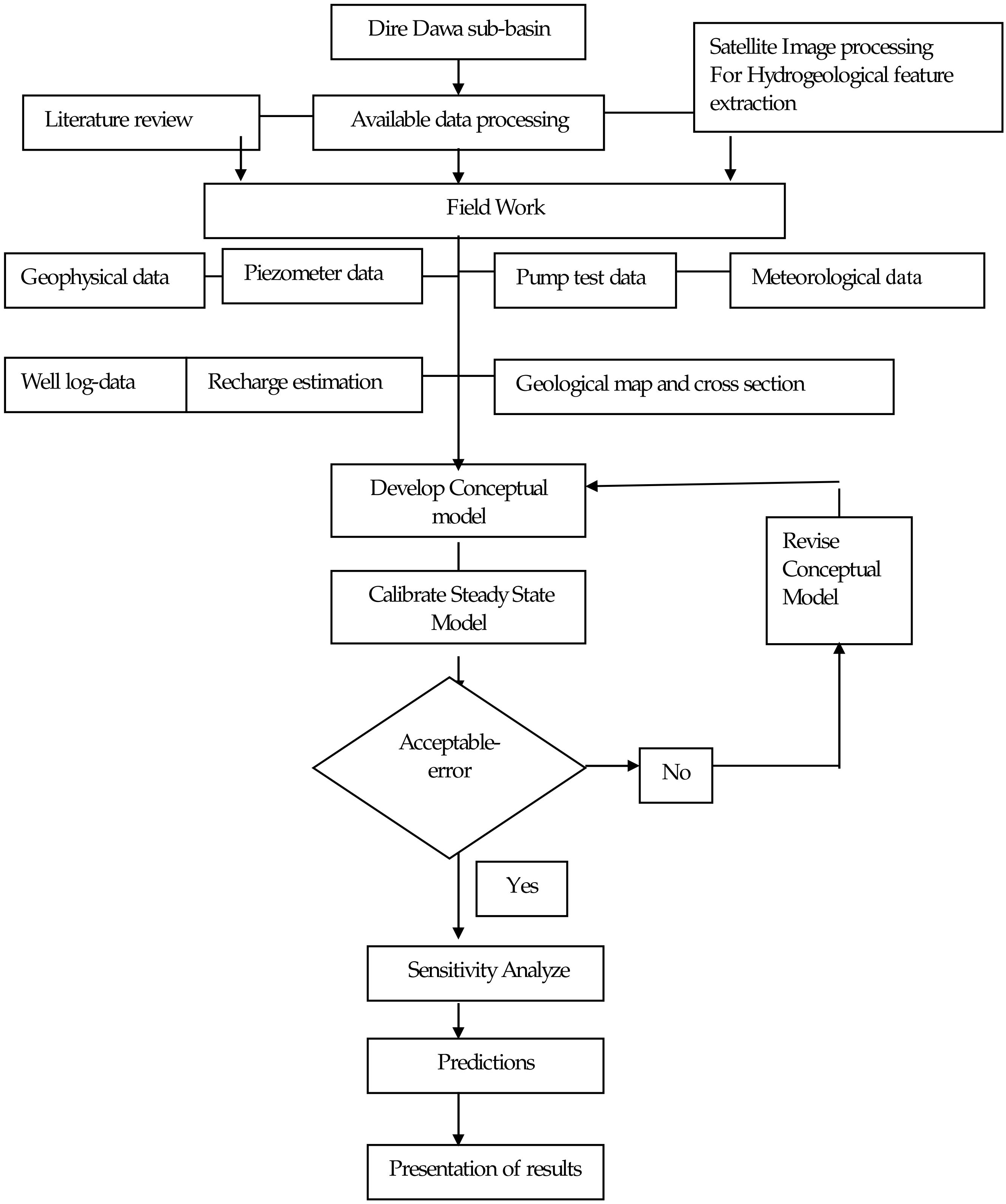

Figure 5-1: Steps in developing a groundwater model (adapted from Anderson and Woessner, 1992

5.2. Developing the conceptual model

According to Anderson and Woessner (1992) a conceptual model is a pictorial representation of the groundwater flow system and the first step in formulating the conceptual model is to define the area of interest or to identify the boundary of the model. Following the identification of the boundary of the area of interest, understanding sources and sinks, hydrostratigraghic units and the flow system are among the key tasks in the study area. Developing conceptualization model is to create a simplified model of the system to be simulated by simplifying a system to an extent that a logical model approach with appropriate model algorithms can be defined. The conceptual model of the study area is described pictorially in fig 5.2.

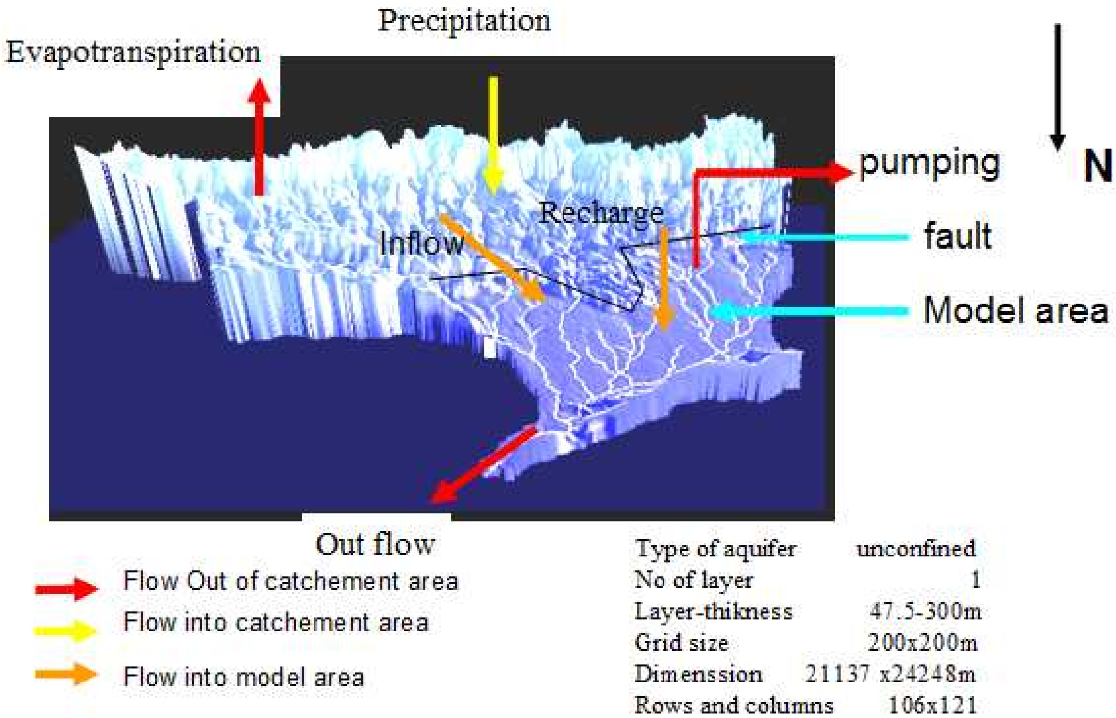

Figure 5-2: Pictorial description of the conceptual model of the study area

5.2.1. Boundary condition

World systems are continuous in space as well as in time. In modelling however we make selections with respect to specific areas of interest, but also with respect to the time period to be simulated. Therefore any system that is simulated is bounded in space as well as in time (Rientjes, 2010). Hence bounding conditions should be set. Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain which can be represented by the following three types (Anderson and Woessner, 1992).

I. Specified head a boundary (Dirichlet conditions) for which head is given.

$$h_{(xyz)} = h_o$$

Where $h_{(xyz)}$ is the head at point x, y, z, while h_o is the specified head value

II. Specified flow boundaries (Neumann conditions) for which the derivative of head (flux) across the boundary is given. A no-flow boundary condition is set by specifying flux to be zero

$$q_x = \frac{\partial h}{\partial x}$$

Where q_x is constant

III. Head dependent flow boundaries (Cauchy or mixed boundary conditions) for which flux across the boundary is calculated given a boundary head value. There are several types of head dependent flow boundaries. General Head Boundary (GHB) is one among them.

$$Q_x = C(h_s - h_c)$$

Where

Q_x = flow into the cell	($L^3 T^{-1}$)
C = a conductance term	($L^2 T^{-1}$)
hs = specified head of external source outside the boundary	(L)
hc = head inside the model boundary	(L)

The aquifer limits in the study area can be delineated by physical or hydrological boundaries as shown in fig 5.3. The northern outlet is assigned as general head boundary, since the groundwater subsurface outflow is expected through this area. To the east and west boundary of the model the no-flow boundaries is assigned assuming the groundwater divide coincides with the surface water divide. The south of the study area is also assigned as no-flow boundary as there are normal fault and impervious basement rock that limit the aquifer in the south, as can be seen from the north-south cross-section fig 5.4.

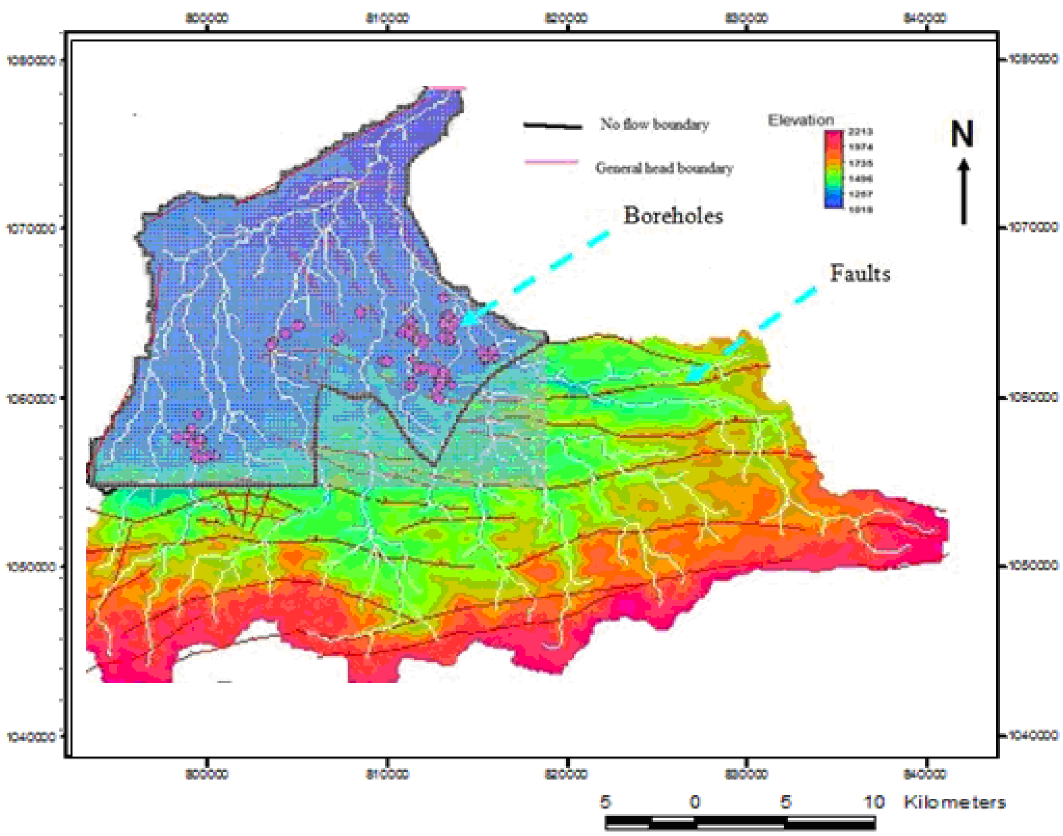

Figure 5-3: Boundary conditions of the study area

Hydrogeological map (fig 3.6) and three dimensional views (fig3.3) of the study area show that there are three major faults. These three faults are NNE_SSW, NNW_SSE and E-W trending faults. The NNE_SSW and NNW_SSE faults nearly coincide with the East and West surface catchment boundary of the study area.
The geological set up also strengthens that there are fault structures which have NNE_SSW, NNW_SSE and E-W directions which can be observed as transition from one unit to another unit. The E-W fault on the southern part of the study area has also downthrown the northern low laying areas which is evidenced by the basement (gneiss) exposure in the elevated area as can be seen from fig 5.4.

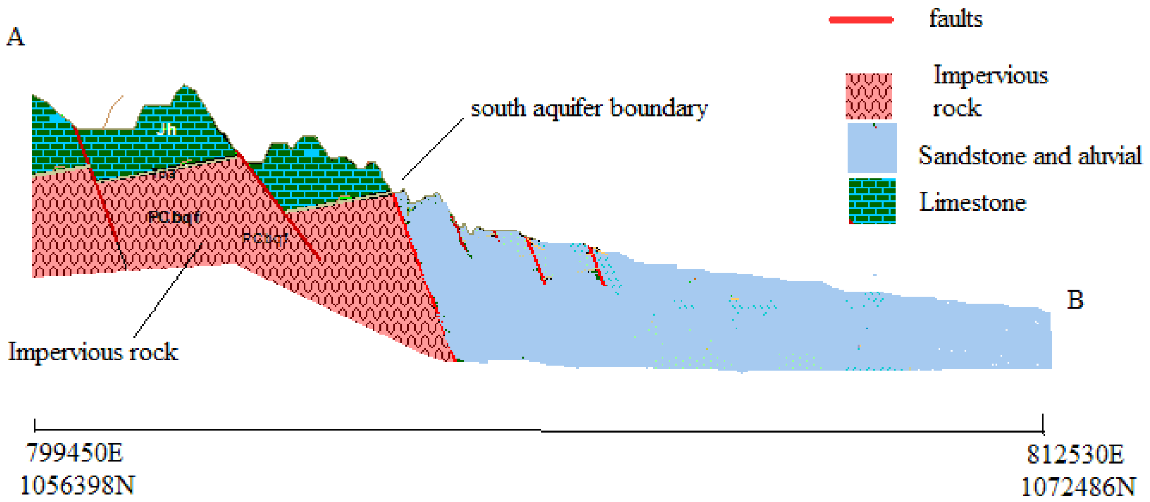

Figure 5-4: N_S geological cross section of the study area (adapted from WWSDE, 2004)

The elevation of the study area as can be seen from three dimentional view shows also that the low-lying well field area is surrounded by elevated formations. This matches also with the geological, structural set up of the area.

Hence the boundary condition can be assigned as no-flow boundary and general head boundary as shown in fig 5.3. The faults are normal faults which have downthrown the low-lying well field area. Additionally the low lying downthrown part is nearly in direct contact in south with the impermeable basement part of the up thrown.
The NNE_SSW and NNW_SSE faults in most parts are filled by later out coming impermeable fissure volcanic formations. They also coincide with the surface catchment boundary of the study area. By assuming that the groundwater divide coincides with surface catchment boundary, these surface catchment boundaries area assigned as no flow boundary.
The groundwater outlet area is also assigned as general head boundary (GHB) which flow out due GHB is directly proportional to the cross-sectional area, permeability and head difference associated with the flow media represented by the GHB, and inversely proportional to the length of the represented flow media. Hence the boundary of the area to be modelled (Dire Dawa groundwater sub-basin) in east and west coincides with the catchment water divide and in the south gets recharge from the upper streams draining towards it as shown in fig 5.2 (section 5.2).

5.2.2. Hydrostratigraghic unit

According to Anderson and Woessner (1992), hydrostratigraghic units comprise geologic units of similar hydrogeologic properties and several geologic formations may be combined into a single hydrostratigraghic unit or a geologic formation may be subdivided into aquifers and confining units. hydrostratigraghic unit of the study area is done by combining geological formations having similar hydrogeologic properties based on the regional and local Stratigraghy of the study area as given by Bosellini et al., (2001) fig 5.6 a, and b.

Hence three hydrostratigraghic unit are identified as Adigrat sandstone-Antalo limestone-Dire Dawa formation unit, Daghani shale unit and Ambaradom formation-mixed alluvial deposits unit. The Adigrat sandstone-Antalo limestone- Dire Dawa formation unit is a hydrostratigraghic unit confined by Danghani shale aqiuclude and the basement rocks. This unit has a thickness of around 190m and is not reached by drilling in the study area. The Daghani shale unit is an impermeable formation and acts as hydrogeological impermeable bed for the upper Ambaradom formation-mixed alluvial deposits unit. It has a thickness of 25m. Ambaradom formation-mixed alluvial deposits unit is a unit with relatively higher transmissivity 9-5512m^{2}day^{-1}, with a mean of 1810.9m^{2}day^{-1} and harmonic mean of 88m^{2}day^{-1} WWDSE (2004). It is course grained and stratified sandstone. It has thickness of 200-300m (Bosellini, et al., 2001) as shown in Fig 5.6, but from the drilling data the aquifer thickness is obtained to be from 47.5-252m thinning towards north.

To summarize, the study area is represented by the top unconfined aquifer layer (Ambaradom formation-mixed alluvial deposits unit) and the Daghani shale unit acting as hydraulically impermeable bed. The unconfined aquifer layer (Ambaradom formation-mixed alluvial deposits unit) has 47.5-300m thickness.

Table 5-1 : Hydrostratigraghic units

no	unit	transmissivity	type	Thickness(m)
1	Ambaradom formation-mixed alluvial deposits unit	Medium-high (1.4-80md^{-1})	Unconfined aquifer	47.5-300
2	Danghani shale unit	impermeable	Impermeable bed	25

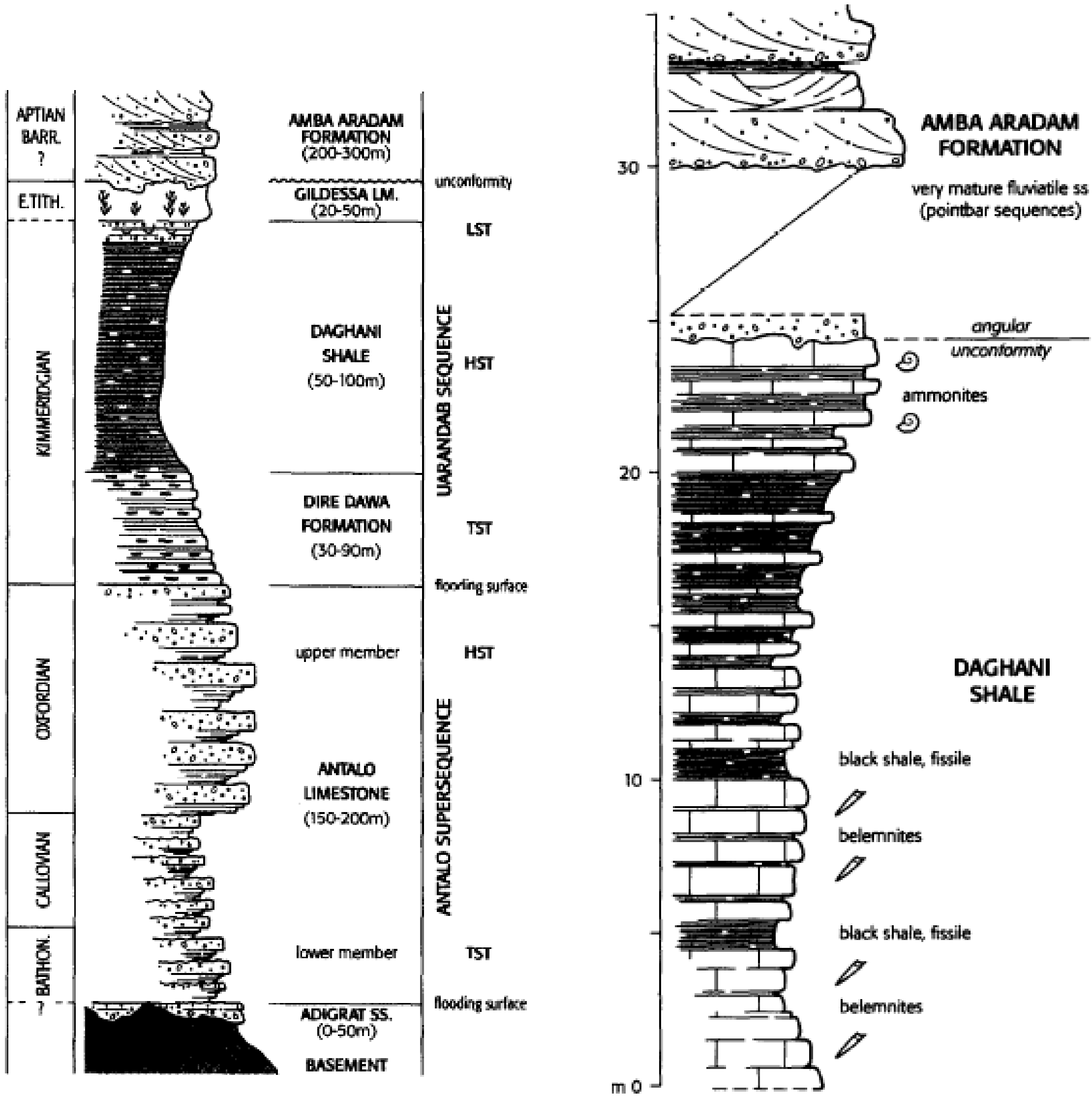

Figure 5-5: a) Regional Stratigraphy of Dire Dawa area (Bosellini, et al., 2001),b) Daghani shale of Dire Dawa ,unconformably overlain by the Ambaradom formation near the groundwater basin area (Bosellini, et al., 2001)

5.2.3. Sinks and sources

The Dire Dawa groundwater sub basin area has recharge from direct precipitation and inflow from the elevated upstream areas as groundwater sources and groundwater abstraction as sink.

5.3. Numerical model

A MODFLOW computer code is selected since MODFLOW is a modular- three dimensional finite difference ground water model that can describe and predict the behaviour of ground flow system (McDonald and Harbaugh, 1996). It uses Finite differences grids which are easy to understand and require less input data (Anderson & Woessner, 1992).

5.3.1. Designing the model

The boundary of the conceptual model stretches from 1056043mN-1076854mN and 795484mE to 819596mE. It has a length of 21km by 24 km. Most of the wells constructed in study area are 200m and above apart from one another spatially to minimize interference. Having this data and to use possible higher resolution the grid cell is set to be 200m x 200m. For the model area 106 raw and 121 column are defined for model grid discretisation. All grid elements that make up the model domain are equally sized rectangular grid elements with size of 200m X 200m. Later refining to 40m X 40m was also done on the outlet to assign the general head boundary with higher resolution and to observe the simulated heads easily for the sensitivity analysis.

5.3.2. Initial condition

Initial conditions refer to the head distribution everywhere in the system at the beginning of the simulation. According to Rientjes(2010) for steady models setting initial conditions is necessary and required by the numerical model to speed up convergence of the solution and do not have to be modelled with exactness since the time variable is set to infinite. Among the initial condition features the dynamic average steady-state condition was used. In the dynamic average steady-state condition the head varies spatially and flow into the system equals flow out of the system. The dynamic average steady-state condition is used most frequently (Anderson and Woessner, 1992). In transferring field data to the grid, the field data are processed to make them compatible with the scale of the model.

The recharge distribution is treated as input to the model systematically using recharge and well packages. As explained in section 4.3 the main sources of the recharge to the groundwater area are direct recharge from rainfall which covers the entire area and inflow from the elevated areas via the southern boundary. To represent these in the model recharge and well package are used respectively. The recharge package was used to feed the model representing the direct recharge from rainfall. The recharge was distributed in the entire model area with 20mm y^{-1} evenly. The well package was used to feed the model representing the inflow in the proper place. The wells (injection wells) were situated in the two last south rows of the model assuming that the inflow water will percolate with in 400m distance area from the southern boundary. The distribution and amount of the recharges used were as shown in fig 5.6. The larger area covered with blue colour represents the direct recharge with 20mm y^{-1}. The southern areas covered by red colour represent the inflow water from the southern boundary with 3178mm y^{-1}. It was applied in the well package by changing to the volume with in the grid cell. The well package quantifies the volume per the used unit time.

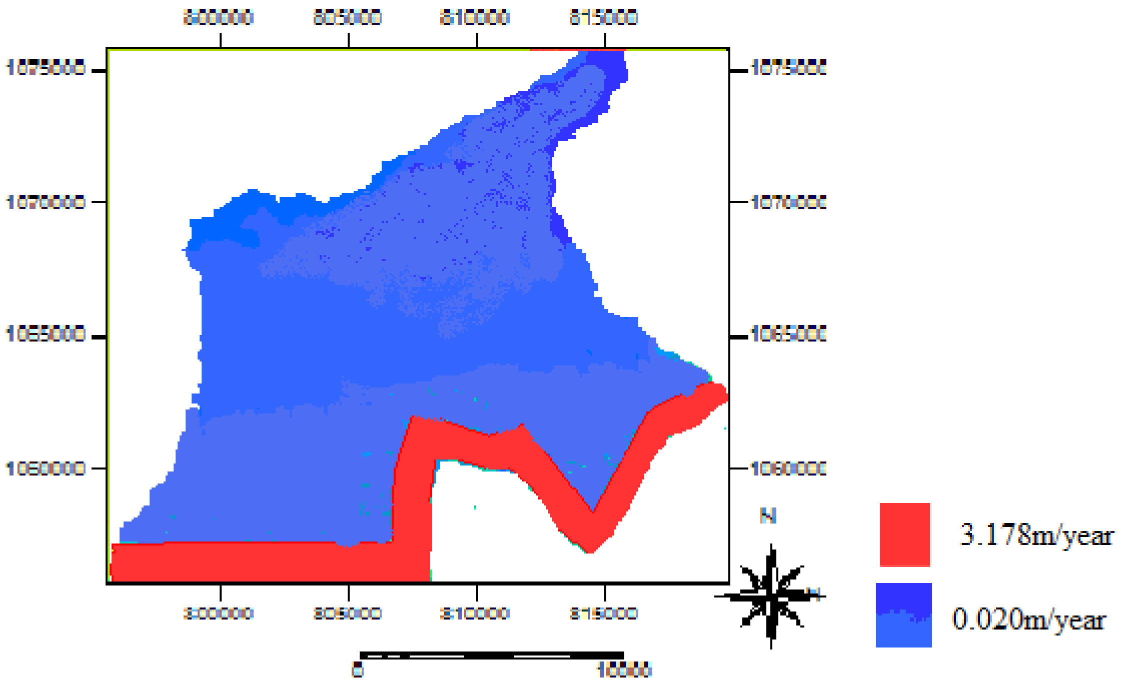

Figure 5-6: Recharge distribution in the modelled area

5.3.3. Model execution and checking

Execution of the model requires entry of input data into the computer files, running the model and interpreting (checking) of the results. After getting initial executions of the model, interpretation or checking of the result was done. The interpretation or checking of the result was done by changing the general head boundary, recharge and conductivity one at a time and comparing with real condition of the study area like water balance.

6. RESULTS AND DISCUSSIONS

In this chapter the results of the study area are explained and discussed. This part includes hydrochemistry, model results, recharge, hydraulic conductivity, groundwater budget, model limitations and discussion of the model.

6.1. Hydrochemistry

As main water quality indicators are physical, chemical and bacteriological constituents of water. These constituents are highly influenced as a function of geological formation and human interferences. In this study it is focused on the physio-chemical characteristics of the water. The water quality analysis has showed that almost all of the water samples analysed are colourless, odorless, non-turbid and tasteless. And the water type is mainly Ca-HCO3 and Ca-Mg-HCO3 but the water from hand dug wells are changed by human interference to Ca-HCO3-Cl, Ca-Na-HCO3-Cl, Ca-Mg-HCO3-Cl and Na-Ca-HCO3-SO4.

All laboratory results were checked for correctness by checking the sum of cations to be equal to the sum of anions and it was found that more than 86% of the analysed samples were found to have less than 10% error and 14% of them from 10 to 30% error. All laboratory results with lab error of more than 10% were excluded from further analysis.

6.2. Sensitivity analysis of the study area

To know how the study area behaves to different conditions, sensitivity analysis of the model area was done. To perform the sensitivity analysis the real world should be represented in conceptual model and transformed to numerical model. To transfer the conceptual model developed (section 5.2) to numerical model need the specific value of each inputs. In case of this study area the head dependent boundary (GHB) data was not measured. To estimate this head dependent boundary the data we have near the boundary area are the surface elevation (974 m), existence of shallow hand dug wells 5-45 m below the surface and no surface water that initiate from subsurface source. Having these data sensitivity analysis was done to get the piezometric head of the GHB and the length of the boundary cross section by comparing to the real condition of the area.

The sensitivity analysis was done by changing the general head boundary and the length of the boundary cross section one at a time (fig 6.1) and) (fig 6.2). The general head boundary was sensed starting from piezometric head of 910m by increasing 10m at a time. It was showing an increasing of 2-7m, 2m at the southern part and 7m on the northern part (near the outlet) of the model area. The length of the boundary cross section was also sensed by changing the number of grid cells on the boundary, starting 19 grid cells and decreasing 4 grid cells at a time. It was showing an increasing of 2.2-14.5m, 2.2m at the southern part and 14.7m on the northern part (near the outlet) of the model area. Eventually comparing to the historical condition of the area the piezometric head of GHB and length of the cross section was estimated. The piezometric head of GHB and length of the cross section estimated reasonably were (930-940) m and eleven grid cells (2.2km) respectively.

Similarly the sensitivity analysis of recharge and conductivity was done (fig 6.3) and (fig 6.4). The recharge is sensed starting from 20mm by increasing 20mm at a time. It was showing an increasing of 7m. Conductivity is sensed starting from 10 md^{-1} by increasing 10 md^{-1} at a time. It was showing a an increasing of 24-37 m, 37 m at southern part and the 24 m on the northern part (near the outlet) of the model area.

Lastly observing their sensitivities the best combination of general head boundary, recharge and conductivity by comparing with real condition of the study area was taken as initial guesses for a trail-and-error calibration. The best combination was general head boundary at 930 m with eleven model grid cells, recharge 20 mm and variable conductivity zoning based on the hydrogeological map explained in section 4.5 and pump test explained in section 4.4 (0.05-25) md^{-1}.

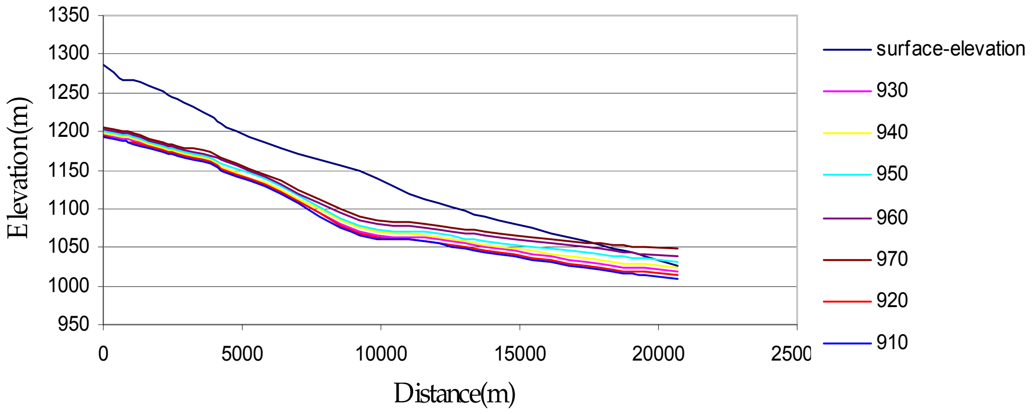

Figure 6-1: Sensitivity of simulated heads by changing general head boundary value from 910 to 970 m

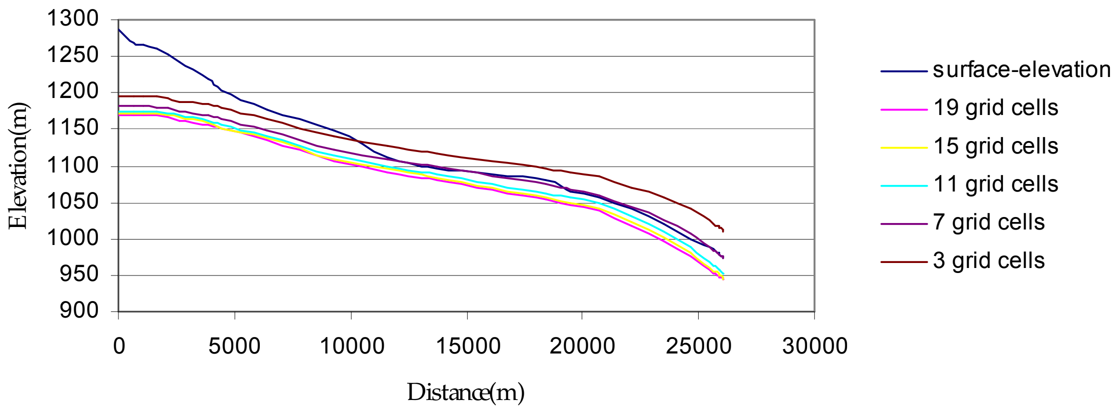

Figure 6-2: Sensitivity of simulated heads by changing number of general head boundary elements

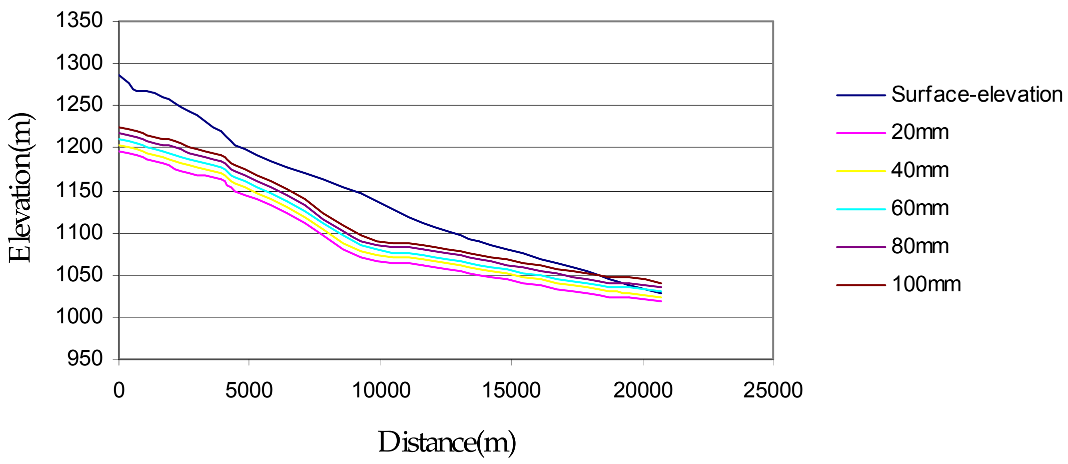

Figure 6-3: Sensitivity of simulated heads by changing recharge from 20 mm to 100 mm

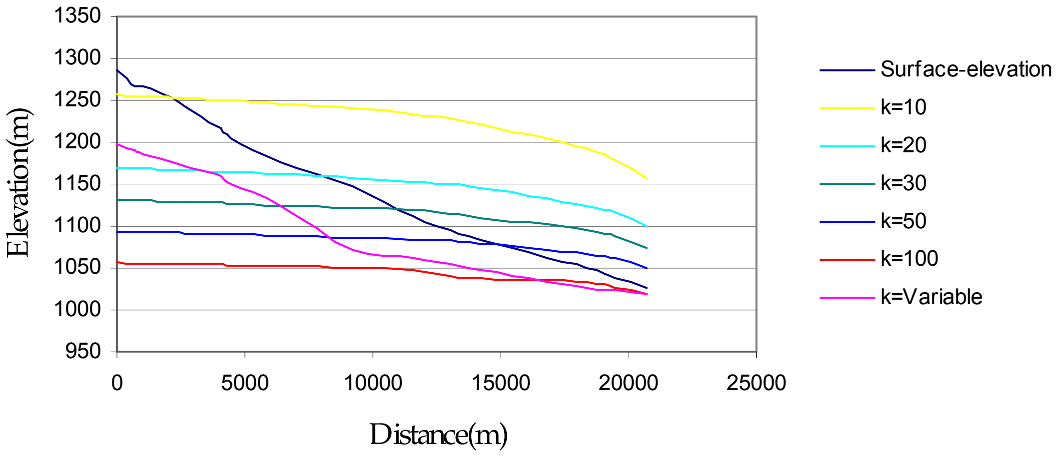

Figure 6-4: Sensitivity of simulated heads by changing conductivity

6.3. Calibration of the model

The model is calibrated by optimally adjusting set of parameters (conductivity, GHB and recharge) to get very close values between the simulated and measured water levels based on the hydrogeological map and sensitivity results. Manual trial-and–error adjustments of parameters were used until a reasonable match between the simulated and measured water levels is achieved. For evaluation the scatter plot and root means squared error (RMSE) were used. The scatter plot was used to visualize how they fit. The scatter plot was as shown in fig 6.5. RMSE was used that quantifies the average error in the calibration by using the average of the differences between measured and simulated heads. The final calibrated model's RMSE calculated was 3.7m.

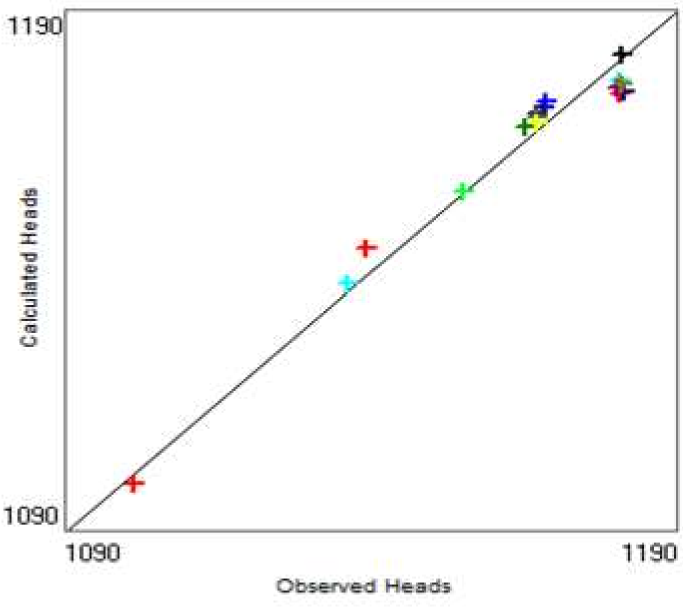

Figure 6-5: Plot of calculated and observed heads in September, 2002

6.4. **Sensitivity analysis of the calibrated model**

The purpose of a Sensitivity analysis is to quantify the uncertainty caused by uncertainty in the estimate of aquifer parameters, stresses, and boundary condition(Anderson & Woessner, 1992). The sensitivity analysis was done by changing the calibrated values for hydraulic conductivity and recharge systematically (20 %) The magnitude of change in heads from the calibrated solution is a measure of the sensitivity of the solution to that particular parameter. Both hydraulic conductivity and recharge are sensitive to the change from the calibrated model. Hydraulic conductivity is more sensitive than recharge. The result of the sensitivity analysis is displayed in graph as shown in figure fig 5.8.

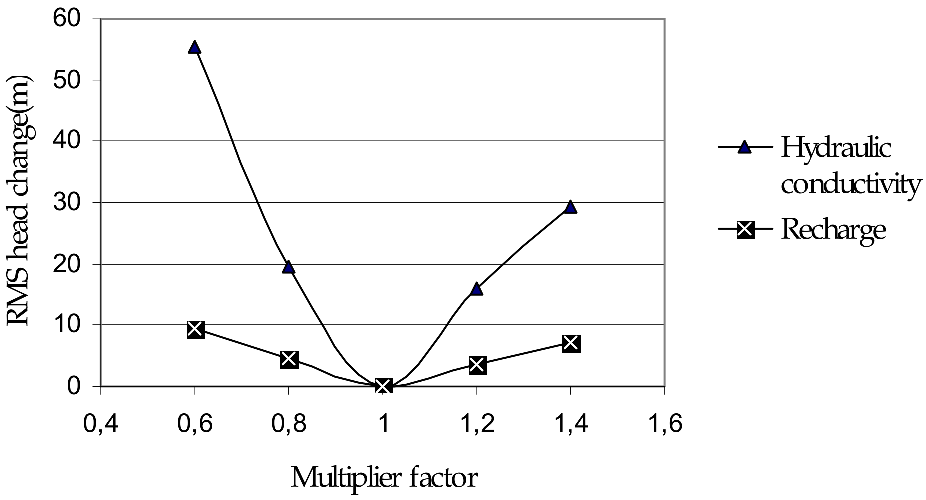

Figure 6-6: Sensitivity analysis of hydraulic conductivity and recharge

6.5. **Recharge**

The recharge sources for the study area are direct precipitation and inflow water from the upstream area. Depending on the available data CMB method was used as starting recharge model input. The CMB method need the area's average quantity of precipitation, area's average quantity of Inflow water, groundwater chloride concentration, precipitation chloride concentration and inflow water chloride concentration.

The average precipitation for the modelled area is taken from the Dire Dawa weather station which is 610mmy^{-1}. The Chloride concentration of precipitation of the study area is also adapted from Akaki well field (0.8mgl^{-1}) which is in the same basin (Awash basin). The average inflow to the modelled area from upstream elevated area is also the difference between precipitation and evaporation in that area. According to Ketema et al. (2009) the difference between precipitation and evaporation in the area is 153mmy^{-1} (25% of precipitation). Hence the total inflow is 72.55 Mm3y^{-1} and most of the inflow is expected to infiltrate near the southern boundary.

The total recharge obtained is 47.8Mm^{3}y^{-1} (183 mm) using CMB method and 50.2Mm3y^{-1} (195mm) from the model simulation. The recharge estimated by the CMB method is 5.78 Mm3y^{-1} (20 mm) as direct recharge from precipitation and 42 Mm^{3}y^{-1} (163 mm) from inflow from upstream area. There is a variation in the total amount of recharge estimated by both methods. This variation is probably from the uncertainty associated in the CMB method. In the CMB method some of the uncertainties associated are due to the uncertainty in measured chloride content, amount of rainfall and inflow water.

6.6. Simulated hydraulic heads and pumping responses

Contour map of the hydraulic heads simulated without abstraction (fig 6.7) shows that the general flow direction of the Dire Dawa groundwater system follows the general trend of the surface topography. It is from south-west to north-east. It shows also agreement with the flow system defined on the conceptual model (section 5.2) of the study area.

To observe the response of the Dire Dawa groundwater system to pumping, abstraction wells were applied to the model. The abstraction wells applied were in the existing well fields having 19.95 Mm^3y^{-1} and 34.87 Mm^3y^{-1} , which is the recent(2010) abstraction and 2025 demand explained in section 4.6. It can be seen from the contour maps of the simulated hydraulic heads that there is a groundwater level decline(fig 6.8). To observe the decline a cross-section was constructed from the contour maps that pass through the existing Dire-Jara well field. The Cross section constructed(fig 6.9) was from south-west to north-east of the study area. Comparing the simulated hydraulic heads for the pumping and without pumping cases, the ground water level of Dire-Jara well field shows a decline of 40metres for recent abstraction case and 62metres for the future abstraction case(2025).

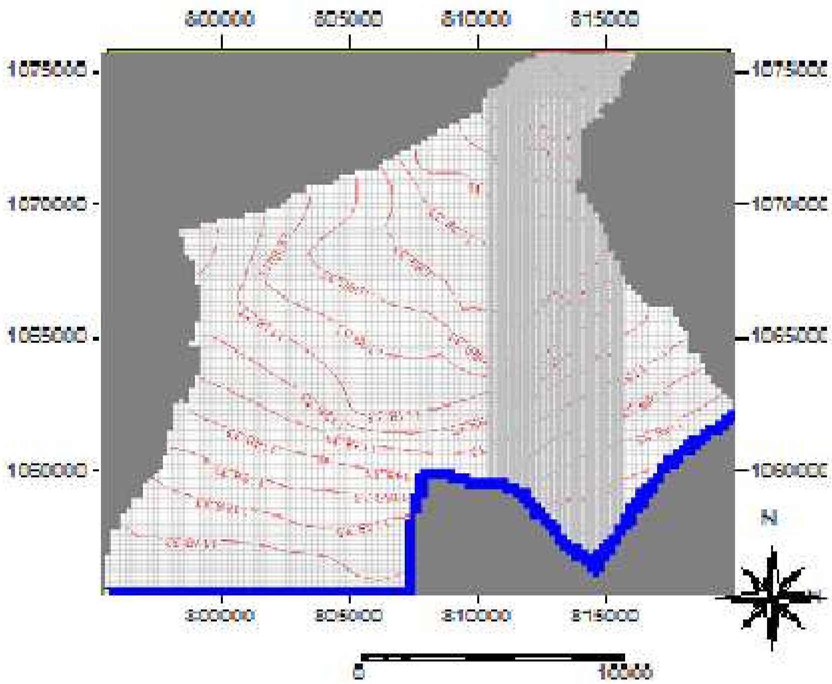

Figure 6-7: contour map of hydraulic head simulations without pumping

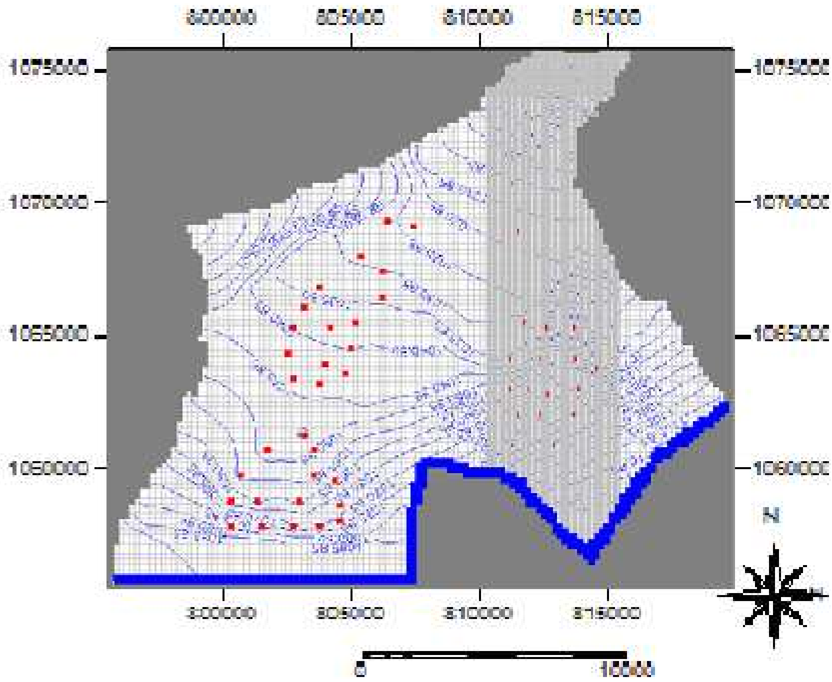

Figure 6-8: contour map of hydraulic head simulations with pumping (with the demand of 2025)

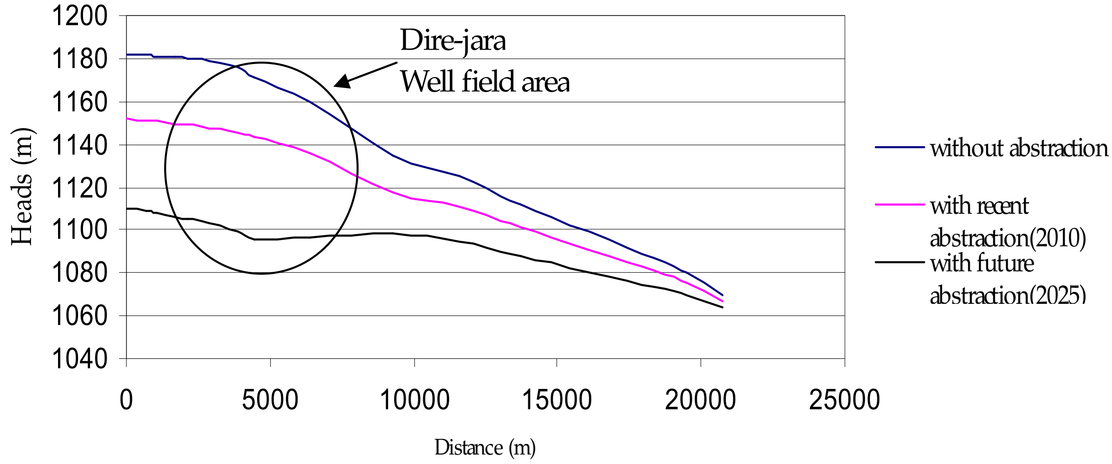

Figure 6-9: Cross section of hydraulic head simulations without pumping and with pumping

6.7. **Groundwater budget**

The ground water budget components of the modelled area are direct recharge from rainfall, groundwater inflow, well abstractions and head dependent groundwater flow. The direct recharge from rainfall and the groundwater inflow are input to the system and the well abstractions and head dependent groundwater flow are outflow from the system.

The model simulated groundwater budget in this study shows the groundwater inflow as wells. This is due to the MODFLOW model set up that the groundwater inflow was treated as injection wells. The total inflow to the system is 139923m^3d^{-1}, which is 15843m^3d^{-1} direct recharge from rainfall and 124080m^3d^{-1} groundwater inflow. The outflow from the system can be seen in two cases when there is no abstraction and with abstraction. When there is no abstraction the outflow from the system became totally head dependent out-flow 139923m^3d^{-1}. When there is abstraction the outflow from the system became head dependent out-flow and abstraction. The abstraction is 98384m^3d^{-1} which is 70% of the total recharge. The head dependent out-flow is 41539m^3d^{-1} which is 30% the recharge. Hence the recharge is in excesses by 30% to the future abstraction (2025) as shown tables 6.1 and 6.2.

Table 6-1: Groundwater budget with average future pumping (situation in 2025)

Water budget of the whole model area	m^3d^{-1}	m^3d^{-1}
Flow term	In	Out
Wells	124080	98384
Recharge	15843	
Head dependent boundary		41539
Sum	139923	139923

Table 6-2: Groundwater budget without pumping

Water budget of the whole model area	m^3d^{-1}	m^3d^{-1}
Flow term	In	Out
Wells	124000	
Recharge	15843	
Head dependent boundary		139923
Sum	139923	139923

7. CONCLUSION AND RECOMMENDATIONS

7.1. Conclusions

Groundwater is the only source of water for Dire Dawa and Harar areas. It is the primary need in the study area since it is an arid region. Not only the arid condition makes the groundwater a primary need but also they are using it for industry, irrigation and other uses. Additionally with the increasing of population the water demand is rising. Therefore, the potential of this precious resource should be properly managed. The intensive unmanaged utilization of groundwater can lead to depletion of the resource and to negative environmental impacts. Thus, it is found vital to manage the resource properly in a sustainable way. To keep the sustainability of the groundwater resource the recharge and abstraction should have to balance and the quality of the water should be controlled.

The calibrated groundwater modelling of the study area show that the general hydraulic gradient follows the surface topography and flow is towards northeast. It also showed that the main sources of recharge to aquifers of the groundwater sub-basin are mainly from rainfall in the southern elevated areas and direct recharge from precipitation. Both flow direction and source of the recharge simulated from the calibrated model are in good agreement with the flow system and sources of recharge defined in the conceptual model of the area.

The estimation of recharge using groundwater modelling (inverse modelling) and CMB method of the study area are 50 Mm3y^{-1} (195mm), and 47 Mm3y^{-1} (183mm) respectively. Previously recharge was also estimated by WWDSE using Darcian method 38.8 Mm3y^{-1} (175mm). They are nearly in good agreement and they are showing the recharge to the Dire Dawa groundwater sub-basin is higher than the yearly demands projected up to 2025 (34.9 Mm3y^{-1}). Appling abstraction on the calibrated model with the average yearly demand shows average drawdown of 62 meters on the well fields.

The results of the hydro-chemical analysis also show that most of the shallow water sources (hand dug wells) are affected and changed by humane interference.

The model simulated heads were found sensitive to hydraulic conductivity, recharge and hydraulic head and width of the general head boundary. As if one parameter is more sensitive than others, the degree of uncertainty of that parameter will have a greater effect on the model results than the other parameters. So, care has been taken during the calibration of such parameter to which the model was most sensitive.

The study concludes that the groundwater resource will be sustainable up to the project period (2025) accepting the 62m drawdown. And groundwater flow modelling is useful for developing an understanding of the system and can predict responses future abstraction.

7.2. Recommendations

The study is developed under some assumption, simplifications and not evenly distributed data. However given the limitations in data availability, the study can be a good start for the groundwater assessments in the sub-basin. With additional detailed entire area covering hydrologic and geologic knowledge of the area the assessment can be refined and improved.

Continuous measurements of the water level in wells provide the historical and recent status of groundwater resource. They are basic to real representation of the study area and to meaningful evaluations of the groundwater resource. Therefore; the operational wells should have to be equipped with observation pipe and evenly distributed and representative observation wells should be placed in the study area. This will help also to carry out transient groundwater flow modelling so that the system responses to induced stresses can be predicated with greater confidence.

The sensitivity analysis has shown that the area is sensitive to recharge and hydraulic conductivity. And it is indicating environmental protection activities and recharge enhancing works should have to be done in order to keep and upgrade the natural characteristics of the aquifer and the sustainability of the resource.

The hydro chemical laboratory data showed that the water quality of most of the shallow wells is deteriorating. This is also indicating action of protecting the existing water source and recharge area from probable causes of pollution should be carried out.

The simulated heads obtained from the calibrated model by inserting abstraction wells with equivalent amount of the future average demand (up to 2025) show 62 meter decline of water on the existing well fields. This amount of decline in water level can disturb the natural condition of the water bearing aquifer that may lead decreasing the conductivity of the water media. To be safe fairly distribution of abstraction wells should be used.

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APPENDICES

Appendix 1 summaries of the collected data and sources

no	data	sources	Title of the sources	contents
1	Hydraulic (piezometric) heads	WWDSE, MWR & DDWSSA	Evaluation of well drilling and testing program, Dire Dawa, 1987 Dire Dawa administrative council integrated resource development master plan study project (2003) water wells drilling and construction completion report (Harar water supply and sanitation project) march, 2008	>104 boreholes Data collected on August and September,2002
2	Hydro metrological data	NMSA and WWDSE	Dire Dawa administrative council integrated resource development master plan study project (WWDSE, 2003)	Temp Rainfall Relative-Humidity Wind- speed Sunshine- hours Evaporation(open water portion)
2	Geological, hydrogeological data	EGS+ WWDSE	DDAC integrated resource development master plan study project (WWDSE, 2003)	Geological, hydrogeological reports
3	Pumping test	WWDSE, MWR DDWSSA	Evaluation of well drilling and testing program, Dire Dawa, 1987 DDAC integrated resource development master plan study project (WWDSE, 2003)) Harar water supply and sanitation project (WWDC, 2008)	Group pump test and single well pump tests
4	Well completion and log	WWDSE	Evaluation of well drilling and testing program, Dire Dawa, 1987 DDAC integrated resource development master plan study project (WWDSE, 2003)) - Harar water supply and sanitation project) march, 2008	Well completion and log representing the study area
5	Geophysical data	WWDSE + EGS	- DDAC integrated resource development master plan study project (WWDSE, 2003)	-Resistivity Geophysical data taken by portable integrated resistivity meter, OYO MC OHM, mark-2, model-2115A
6	Topographic maps1:50,000	WWDSE+MWR	Ministry of water resources GIS & RS data base and WWDSE	20,50m contour interval

Appendix2 Meteorological data

Site no	Meteorological stations	UTMN	UTME	Data type	Data available (years)	Frequency
1	Dire Dawa	812857	1062643	TEMP	1953-2005	Monthly
					2005-2009	Daily
				Rainfall		
					1953-2005	Monthly
					2005-2009	Daily
				Relative-Humidity		
					2005-2009	Monthly
				Wind- speed		Daily
				Sunshine- hours	2005-2009	Monthly
						Daily
				Evaporation(open water portion)	2005-2009	Monthly
						Daily
					2005-2009	Mean monthly
2	Hurso	798803	1077868	TEMP	1981-1990	Monthly
					2005-2009	daily
				Rainfall	1962-2005	Monthly
					2005-2009	
3	Kulibi	798248	1044848	TEMP	1980-2005	Monthly
					2005-2009	daily
				Rainfall	1980-2005	Monthly
					2005-2009	daily
4	Kersa	814000	1045530	Rainfall	1972-2005	Monthly
					2005-2009	daily
5	Dengogo	819248	1046264	TEMP	1981-2005	Monthly
					2005-2009	daily
				Rainfall	1981-2005	Monthly
					2005-2009	daily
				Relative-Humidity	----------	Mean monthly
				Wind- speed		Mean monthly

Appendix 3 Borehole data (WWDSE)

Well Index	Local Name	UTM norrth	UTM east	Elev. Masl	Well depth, m	SWL, m	Well Type	Geological Formation	Well Discharge, l/s	Dynamic water level, m	Specific discharge, l/s/m	Aquifer Type	Transmissivity, m2/day	Permeability, m/day
BH-01	Armakule	1086779	844564	932			Cased	Basalts						
BH-02	Hurso	1062924	789718				Cased	Basalts						
BH-04	Cheremiti-#2	1079607	864535	1152	101	21,42	Cased	Basalts	0,4					
BH-09	Melka Jebdu-3	1063299	805167	1131	106	23	Cased	Hamaneil Limestone	3	30				
BH-52	Rail way statio	1061662	813936	1180	62	29,77	Cased	Upper Sandstones	6					
BH-54	Textile-1(old)	1062643	816702	1192	45,7	25,1	Cased	Upper Sandstones	2		0,102	conifined		
BH-07	D/Dawa food com	1063426	814520	1177	115	30	Cased	Upper Sandstones						
BH-15	Hafcat #2	1063539	814941	1167	56		Cased	Upper Sandstones						
BH-16	East Afri Bot#1	1061196	814096		105	37	Cased	Upper Sandstones						
BH-08	Melka Jebdu #2	1063341	805241	1141	95,6	29,5	Cased	Alluvial						
BH-12	Palace	1061499	814172	1202	48,8	34,1	Cased	Upper Sandstones	3,8	34,86	5			
BH-14	Hafcat #1	1063384	814865	1168	86		Cased	Upper Sandstones						
BH-26	Dire Jara W-1	1058803	801010	1230	163,5	49,6	Cased	Upper Sandstones	10	86,5	0,27	Confined	60,08	2,5
BH-27	Dire Jara W-2	1059555	801394	1210	161,5	88,22	Cased	Basalts	1	157,6	0,014		5,72	0,24
BH-28	Dire Jara W-3	1058786	801437	1229	172		Open	Basalts						
BH-29	Dire Jara W-4	1058414	800965	1238	123,4	56,6	Cased	Hamaneil Limestone	20,3	60,11	6,4	Confined	2296,65	93,4
BH-30	Dire Jara W-5	1058126	801225	1245	156,5	64,5	Cased	Upper Sandstones	20,01	75,39	1,84	confind	675,9	28,2
BH-31	Dire Jara W-6	1058414	800965	1240	105,5	59,6	Open	Upper Sandstones	22,8	59,94	67,29	Confined	3014	167,5
BH-05	Cement Factory	1061804	812378			16	Cased	Alluvial						
BH-06	Ras Hotel # 2	1061350	813870	1197		45	Cased	Upper Sandstones						
BH-32	Dire Jara W-7	1057966	801409	1247	172	67,45	Cased	Upper Sandstones	18,7	73,86	2,92		3815,68	159,02
BH-33	Dire Jara W-8	1057939	801047	1251	187,6	69,8	Open	Upper Sandstones	10,74	120,19	0,18	Confined	29	0,96
BH-34	Dire Jara W-9	1058620	801238		176	52,08	Cased	Upper Sandstones	3,41	76,4	0,14			
BH-35	Dire Jara w-10	1058257	801606	1239	150,45	58,45	Cased	Upper Sandstones	19,8	58,49	19,22		1802,5	59,1
BH-36	Dire Jara W-11	1058418	800722	1239	126	57,71	Cased	Upper Sandstones	20,3	59,53	11,15		5512	180,13
BH-37	Dire Jara W-12	1058122	800800	1234			Open	Alluvial						
BH-38	Dire Jara W-13	1058627	800859	1245			Open	Alluvial						
BH-39	Dire Jara W-14	1058356	801484		154	50,12	Cased	Hamaneil Limestone	20,3	60,96	1,87	Confined	160,95	5,3
BH-56	Textile Old W-3	1062864	816481	1191	61	25,9	Cased	Upper Sandstones	4,3					
BH-57	Textile No. 4	1062510	816792	1189	62,5	27,4	Cased	Upper Sandstones	1,9	62,2	0,055			

Borehole data (WWDSE)

Well Index	Local Name	UTM norrth	UTM east	Elev. Masl	Well depth, m	SWL, m	Well Type	Geological Formation	Well Discharge, l/s	Dynamic water level, m	Specific discharge, l/s/m	Aquifer Type	Transmissivity, m2/day	Permeability, m/day
BH-17	Amdael #2	1064632	8E+05	1136	124	24	Cased	Upper Sandstones	3					
BH-18	Cheremiti-1	1079210	9E+05	1163	70		Cased	Basalts						
BH-19	Haseliso	1058803	8E+05	1264	119,4	28,21	Cased	Alluvial		96,68				
BH-24	WMERO	1063811	8E+05	1169		35,57	Cased	NA						
BH-25	Jeldesa	1076753	8E+05	1073	90	23,7	Cased	Basalts	0,4			Unconfined		
BH-10	East Afri Bot#2	1061049	8E+05	1205	120	36,5	Cased	Upper Sandstones	3,3					
BH-11	East Afri Bot#3	1061049	8E+05	1205	125	36,5	Cased	Upper Sandstones	4,5	1060	738			
BH-71	Sabian TW-6(89)	1064343	8E+05	1145	122,3		Open	Hamaneil Limestone						
BH-72	Sabian TW-7(89)	1063652	8E+05				Open	Basalts						
BH-73	Sabian TW-8(89)	1062764	8E+05	1155	100		Open	Basalts						
BH-74	Sabian TW-9(89)	1064371	8E+05	1130	129,2	17	Open	Hamaneil Limestone						
BH-75	Sabian TW-10(89	1063444	8E+05	1160	76	21	Cased	Basalts						
BH-76	Sabian TW-11(89	1063785	8E+05	1150	78	11	Open	Basalts						
BH-80	Genderige BH-3	1063115	8E+05	1150	80	11,55	Cased	Alluvial	5		0,21		44,31	1,76
BH-91	Hurso mil.camp	1057037	8E+05	1293	115	23,84	Cased	Upper Sandstones	20	0,29	68,97			
BH-92	Bisrate Gebriel	1063340	8E+05	38,5		38,5		Alluvial						
BH-93	MIN.of Mines	1063530	8E+05	1192		30,2		NA						
BH-94	Min.of Mines	1061970	8E+05	1172		25,42		NA						
BH-20	Ras Hotel #1	1061280	8E+05	1199		45	Cased	Upper Sandstones						
BH-21	High school	1060388	8E+05	1212	79,2	48	Cased	Hamaneil Limestone						
BH-22	Dil Chora Hospi	1061139	8E+05	1210	47	39,1	Cased	Upper Sandstones						
BH-23	Dire dawa food	1063426	8E+05	1170	112	33	Cased	Upper Sandstones						
BH-40	Dire Jara W-15	1058252	8E+05	1241	175	60,56	Cased	Hamaneil Limestone	19	64,51	4,81		2799	
BH-41	Dire Jara W-16	1058325	8E+05	1236	198,5	54,64	Cased	Upper Sandstones	19,8	74,41	1,001		375,26	
BH-42	Dire Jara W-17	1058408	8E+05		141,7	54,63	Cased	Hamaneil Limestone	19	57,85	5,9		868,4	
BH-43	Sabian Pw-1	1063930	8E+05	1147	72,4	13,5	Cased	Upper Sandstones	45,4		8,2		2012	
BH-44	Sabian Pw-2	1063961	8E+05	1144	98,8	9,3	Cased	Upper Sandstones	42		1,47		126	
BH-45	Sabian Pw-3	1063930	8E+05	1147	55		Cased	Upper Sandstones						
BH-46	Sabian Pw-4	1063543	8E+05	1163	104,6	19,7	Cased	Upper Sandstones	40,8		2,88		765	
BH-47	Sabian Pw-5	1063793	8E+05	1157	101,8	15,9	Cased	Upper Sandstones	14		1,48		273	

Borehole data (WWDSE)

Well Index	Local Name	UTM norrth	UTM east	Elev. Masl	Well depth, m	SWL, m	Well Type	Geological Formation	Well Discharge, l/s	Dynamic water level, m	Specific discharge, l/s/m	Aquifer Type	Transmissivity, m2/day	Permeability, m/day
BH-48	Sabian Pw-6	1063462	8E+05	1174	86,2	22,8	Cased	Upper Sandstones	13,3		0,79		688	
BH-49	Sabian Pw-7	1063268	8E+05	1169	82,7	23,7	Cased	Upper Sandstones	13		0,56		230	
BH-50	Sabian Pw-8	1062411	8E+05	1190	87,7	15	Cased	Upper Sandstones	13,3		0,94		262	
BH-51	Sabian Pw-9	1063263	8E+05	1169	71	21,25	Cased	Upper Sandstones						
BH-55	Textile-2(old)	1062781	8E+05	1195	61	18,8	Cased	Basalts	4,1	23,6	0,854			
BH-53	Elfora	1062360	8E+05	1210	82	22,32	Cased	NA						
BH-77	Bore TW4(2002)	1058100	8E+05		160	31,06	Cased	Upper Sandstones	21,3					
BH-78	GoladegTW3(2003	1066500	8E+05		300		Open	Basalts						
BH-79	TW1(2003)	1062200	8E+05		236,53		Open	Alluvial						
BH-95	Prison	1063530	8E+05	1160	47,8	21,7	Cased	Upper Sandstones	3,3	31,15				
BH-96	Cement factory	1062330	8E+05	1195		19,05		Alluvial						
BH-97	Airport	1063420	8E+05				Cased	Upper Sandstones						
BH-98	Airport(erer pr	1064100	8E+05	120		16		Upper Sandstones	5	17				
BH-99	Municipality#1	1061310	8E+05	1192	33,5	25,3		Upper Sandstones	4,5					
BH-100	Municipality#2	1060990	8E+05	1197	35	21,9		Upper Sandstones	6,7	26,65	1,41			
BH-101	Municipality#3	1060990	8E+05	1195	32,5	10,3		Upper Sandstones	6,7	28,6	0,367			
BH-13	Amdael well #1	1064666	8E+05	1136	135	24	Cased	Upper Sandstones						
BH-2	Dechatu	1058832	8E+05	112			Cased	NA						
BH-81	MelkaJebdu bh-1	1064055	8E+05	1140	100			Basalts						
BH-82	Commnd post	1062310	8E+05	1200		26		NA						
BH-107	Former Railway	1061390	8E+05	1212	54,9	38		Upper Sandstones						
BH-108	Gebremedihn	1060750	8E+05	1218		41		NA						
BH-109	Coca Cola(old)	1060990	8E+05	1217		30		Upper Sandstones						
BH-83	Genderige BH-5	1063462	8E+05	1145	80	18,68	Cased	Alluvial	6,5	23,8	1,14		270,07	11,74
BH-84	Genderige BH-6	1063792	8E+05	1100	50	18	Cased	Alluvial	3	38,9	0,12		23,6	1,37
BH-102	Shinile milit.	1065654	8E+05	1112	119	11	Cased	Alluvial						
BH-103	Russian camp	1061868	8E+05	1190		25,8		NA						
BH-104	Ejaneni	1058772	8E+05	104		93,5		NA						
BH-105	Police training	1061950	8E+05	1189	65,6	22		Hamaneil Limestone	0,6					
BH-106	Well drilling c	1061880	8E+05			41,1		Alluvial	2,2	45,67	0,48			

Borehole data (WWDSE)

Well Index	Local Name	UTM norrth	UTM east	Elev. Masl	Well depth, m	SWL, m	Well Type	Geological Formation	Well Discharge, l/s	Dynamic water level, m	Specific discharge, l/s/m	Aquifer Type	Transmissivity, m2/day	Permeability, m/day
BH-112	D/D CFE	1061785	8E+05	1200	54,9	39		Alluvial						
BH-58	Textile Old W-5	1062140	8E+05		70,1	35	Cased	Alluvial	1					
BH-59	Textile Old W-6	1062485	8E+05	1133	45,7	35	Cased	Alluvial						
BH-60	Textile Old W-7	1062567	8E+05	1188	45,7	36	Cased	Alluvial						
BH-61	Textile Old W-8	1062460	8E+05		52,6	45	Cased	Alluvial						
Bh-62	Textile Old W-9	1062886	8E+05	1174	50	39	Cased	Alluvial	5,42					
BH-63	Textile Old W10	1062825	8E+05	1185	50	41	Cased	Alluvial	1,5					
BH-64	Textil Old W-11	1062984	8E+05	1175	59	17	Cased	Upper Sandstones	1					
BH-65	Textile O.W-14	1067017	8E+05	1177	78	42,2	Cased	Alluvial	5,17		3,19			
BH-66	Textile A.W-1	1064427	8E+05	1133	116	37,3	Cased	Upper Sandstones	7,7		0,224		9,03	
BH-67	Textile A.W-2	1064390	8E+05	1135	82,3	32,13	Cased	Upper Sandstones	8,2	40,5	0,98		446,07	
BH-68	Textile A.W 3	1064064	8E+05	1134	91	26,42	Cased	Upper Sandstones	5,2	39,6	0,395		96,65	
BH-69	Textile A.W. 4	1064772	8E+05			35,71	Cased	Upper Sandstones	3,3	44,26	0,133		27,41	
BH-70	Textile N.W 3	1062892	8E+05			14,86	Cased	Upper Sandstones	6					
BH-85	Cement old BH-2	1062350	8E+05	1192	25	12,8	Cased	Alluvial	4,4					
BH-86	High way author	1062031	8E+05	1190	47,2	30,5	Cased	Upper Sandstones	0,78					
BH-87	D/D R.R.C.	1064275	8E+05	1187	63	27,5	Cased	Upper Sandstones	2,58	31,5	0,632		10,03	
BH-88	Locust control	1062708	8E+05		48,7	21	Cased	Alluvial	4	36,8				
BH-110	Melka old well	1064100	8E+05	83				Basalts						
BH-111	TW5(2002)	1064843	8E+05	1129	124	33,4		Hamaneil Limestone						
BH-113	Melkajebdu(old)	1064183	8E+05	1100	125,9	43,4		Basalts	0,4					
BH-89	Pig farm	1062681	8E+05	1187		20,74	Cased	Basalts	1,87					
BH-90	D/D Staium	1060452	8E+05				Cased	Basalts						

Appendix 4 water quality data (WWDSE)

N/N	Index	LOCAL NAME	UTM_E	UTM_N	Cond (microS/cm)	TDS, mg/l	Temp oC	PH	NH4, mg/l	Na, mg/l	K, mg/l	Ca, mg/l	Mg, mg/l	FE_TOTAL, mg/l	Mn, mg/l	Cl, mg/l	NO2, mg/l	NO, mg/l	F, mg/l	HCO3, mg/l	CO3, mg/l	SO4, mg/l	PO4, mg/l	HARDNESS, mg/l	DATE_ANALY
1	BH-01	Armakule	844564	1086779	1093	653	35	8,04		120	1,1	84	15,08	0,01	0,1	78,1	0,0023	9,24	0,89	400,16		145,1	0,03	272	16-9-2002
2	BH-02	Hurso	789718	1062924	1829	1296	23	7,45		100	1	208	65,66		0,1	188,1	0,03	25,52	0,51	466,04		448,4		790	16-9-2002
3	BH-04	Cheremiti-#2	864535	1079607	758	466	22,7	7,88		55	2,8	88	14,11		0,1	39,6	0,05	9,68	0,47	363,56		73,8	0,11	278	16-9-2002
4	BH-09	Melka Jebdu-3	805167	1063299							1,3	104	37,9		0,1	67,1			0,48	392,84		31,6	0,09		16-9-2002
5	BH-52	Rail way statio	813936	1061662	1582	1092		8,08		60	2,2	214	29,5			165,9		129,4	0,71	322	16,8	56,7	0,05	656	16-9-2002
6	BH-07	D/Dawa food com	814520	1063426	1996	1060	28,6	7,59		40	1,3	188,8	36,5			144,1	0,02	155,32	0,67	319,64		92,3	0,01	620	
7	BH-15	Hafcat #2	814941	1063539	2250	1583	26	7,29		125	1,8	264	68,1		0,1	331,1	0,023	58,96	0,69	412,36		448,5	0,33	940	4-1-2003
8	BH-16	East Afri Bot#1	814096	1061196																					
9	BH-08	Melka Jebdu #2	805241	1063341	957	598	24,2	7,27		30	2,5	128	34,1	0,01	0,1	67,1	0,02	9,68	0,51	441,64		47,5	0,07	460	2-9-2016
10	BH-12	Palace	814172	1061499	2140	1570	18,7	7,46		125	3,2	240	41,34			314,6	0,023	220	0,49	414,8		23,7	0,38	770	16-6-2003
11	BH-14	Hafcat #1	814865	1063384	1810	1245	26,3	7,69		80	1,1	240	44,75		0,1	215,6	0,02	184,8	0,55	353,8		221,5	0,19	784	16-9-2002
12	BH-29	Dire Jara W-4	800965	1058414	967	469		7,6								18		0,2	0,4			114	0,84	440	17-10-1999
13	BH-05	Cement Factory	812378	1061804	994	532	24,6	7,43		30	1,7	116	28,7		0,1	83,6	0,03		0,65	373,32		18,46	0,09	408	16-9-2002
14	BH-06	Ras Hotel # 2	813870	1061350	1393	946	19	7,6		60	1,5	200	20,92	0,03	0,2	149,6	0,023	115,28		378,2		50	0,07	586	16-9-2002
15	BH-34	Dire Jara W-9	801238	1058620	986	477		8,49						0,11	0,06	35		0,2	0,4			131	0,45	398	18-12-1999
16	BH-35	Dire Jara w-10	801606	1058257	955	461		7,93								15			0,39			145	0,73	436	
17	BH-36	Dire Jara W-11	800722	1058418	928	449		7,73						0,14	0,16	13	0,02	0,6	0,54			119	0,53	430	19-12-1999
18	BH-39	Dire Jara W-14	801484	1058356	893	433		8,18						0,11	0,05	13		0,3	0,44			77	0,44	370	19-12-1999
19	BH-25	Jeldesa	842515	1076753	1436	703		7,71	0,2					0,61	0,2		3,3	0,03	0,97			284	0,19	548	16-9-2002
20	BH-10	East Afri Bot#2	814020	1061049	1137	834	24,8	7,27		40	1,2	152	30,16		0,1	80,6	0,023	92,84	0,39	373,32		39,56	0,09	504	16-9-2003
21	BH-11	East Afri Bot#3	814520	1061049			25,3	7,22		20	2,7	160	19,46		0,1	72,6	0,02	98,56	0,51	334,28		26,37	0,1	480	16-9-2003
22	SP-7	Belewa	842176	1057346	786	458	22,3	7,47		13		144	17,02			28,6	0,003	14,52	0,51	446,52		15,82	0,14	430	16-9-2003
23	SP-8	Medekedjima	804366	1052194	1081	644	19,4	7,56		50	1,3	148	31,62			94,6	0,003	12,76	0,46	461,16		47,5	0,13	500	16-8-2002
24	SP-9	Gende Boru	803501	1050527	746	426	18	7,57		20	1,3	128	19,46			34,1	0,007	12,32	0,32	419,68		2,64	0,22	400	16-9-2002
25	DW-14	D/DEdible oil f	812941	1061925	1084	650	29,5	7,73		60	1,1	140	24,32		0,1	100		34,76	0,42	397,72		31,65	0,22	450	16-9-2002
26	DW-20	Jelobelina	815939	1052060	1844	560	22	7,6		200	4	188	21,89		0,1	298,1	0,003	24,64	0,99	610		15,8	0,38	560	16-9-2002

27	DW- 30	Tony farm #1	8117 69	1063 611				7, 14		5	1, 1	18 3	18			91, 2		25,5	0, 94	475,8		65,9	0,62	535	

Water quality data (WWDSE)

N/N	Index	LOCAL NAME	UTM_E	UTM_N	Cond (microS/cm)	TDS, mg/l	Temp oC	PH	NH4, mg/l	Na, mg/l	K, mg/l	Ca, mg/l	Mg, mg/l	FE_TOTAL, mg/l	Mn, mg/l	Cl, mg/l	NO2, mg/l	NO3, mg/l	F, mg/l	HCO3, mg/l	CO3,mg/l	SO4,mg/l	PO4,mg/l	HARDNESS, mg/l	DATE_ANALY
28	SP- 10	HARAWA TU	80352 2	10503 33	774	462	18,9	7,7 4		20	1,3	12 0	24,3 2	0,01	0,1	39, 6		12, 76	0,1 6	419,68		10,6	0,31	400	16-4-2003
29	SP1 1	Borte	80039 1	10495 34	749	432	19,7	7,2 5		9	1,3	14 0	17,0 2	0,01	0,2	17, 6	0,00 3	14, 08	0,4 5	427		7,9	0,08	420	16-9-2002
30	SP- 13	Fechase	83194 5	10555 46	1056	686	20,9	7,4 1		6	0,9	16 0	9,73		0,1	94, 6	0,97	25, 96	0,6 5	402,6		7,9	0,27	440	16-9-2002
31	SP- 14	Cement Factory	81225 5	10612 80	908	526	24,8	7,6		4	1,9	13 2	17,0 2		0,1	94, 6	0,4	18, 92	0,5 7	356,24		7,9	0,1	400	16-9-2002
32	SP- 15	Eftua	84318 5	10545 57	719	408	17,3	7,3 7		8	1,4	14 4	9,73			23, 1		12, 32	0,3 9	405,04		10,6	0,01	400	16-9-2002
33	SP- 30	Legahrtu(ho tsp)	84798 8	10857 80	3330	241 4	60	8,0 3		60 0	31, 5	82, 3	8,5		0,2	412 ,3		0,4 4	2,3 5	161	7,2	1000,5	0,39	240	19-11-2002
34	SP-1	Legemeda	80762 1	10535 59	1890	126 8	21,5	7,4		14	2,9	18 4	60,8		0,1	281 ,6	0,00 3	18, 92	0,1 4	427		290,2	0,31	710	16-9-2002
35	SP-2	Halobusa(L egego	81008 4	10536 90	1797	127 0	20	7,6		14 0	7,3	17 2	82,6 7		0,1	226 ,6		44	0,8 1	524,6		168,8	0,22	770	16-9-2002
36	SP-3	Keche	82044 9	10468 54	546	408	20,3	7,1		35	3,1	20 0	4,86	0,01		34, 1	0,02 6	17, 6	0,5 6	231,8		5,27	0,23	220	16-9-2002
37	SP-4	Adada	81911 2	10562 68	810	480	16,7	7,4		40	3,5	12 8	7,29			83, 6	0,00 7	7,9 2	0,3 7	324,52		15,8	0,2	350	16-9-2002
38	SP- 16	Serkama	84512 9	10573 87	800	468	18,1	7,6 5		30	3,9	14 0	12,1 6	0,01		34, 1		11, 88	0,2 9	392,84		13,2	0,12	400	16-9-2002

	SP-	Awale	83677	10521				7,4			12	19,4			28,	0,00	10,	0,2					
39	18	Roresa	5	44	730	408	18	3	12	1,7	8	6	0,01	0,2	6	7	56	3	412,36	15,8	0,07	400	16-9-2002
	SP-		83059	10588				7,4			15				105	0,00	35,	0,5					
40	19	Bishambaye	5	62	1062	680	20,7	4	60	1,2	2	9,73	0,01	0,1	,6	3	64	1	390,4	5,27	0,17	420	16-9-2002
			82979	10520											34,		15,	0,3					
41	SP-5	Biyoawale	4	57	466	270	17,3	7,3	35	1,2	64	4,86		0,1	1		4	9	187,88	18,2	0,38	180	16-9-2002
		Gende	83759	10572				7,6			17	24,3			78,		46,	0,7					
42	SP-6	kurto	5	43	1108	752	21	1	50	4,5	6	2			1	0,01	2	6	429,44	31,6	0,14	540	16-9-2002
	SP-		81821	10616				7,3			14	24,3			56,		4,8	0,2					
43	21	Legehare	9	25	966	570	24,8	8	50	6,1	0	2		0,2	1		4	2	507,52	15,8	0,23	450	16-9-2002
	SP-	Mudi	82099	10632				7,6			20	109,			39,	0,00	2,6	0,3					
44	22	Anano	5	52	890	559	20,6	8	20	0,9	0	44			6	3	4	7	480,68	2,6	0,21	950	16-9-2002
	SP-	Jarso-	85282	10498											12,			0,1					
45	24	Gendelege	3	30	314	190	14,3	7,9	9	3,7	52	4,86		0,1	1		8,8	5	165,92	2,4	0,44	150	
	SP-	Legedomirg	81343	10485				7,3			14	24,3			56,		4,8	0,2					
46	25	a	8	87	966	570	21,5	8	50	6,1	0	2		0,2	1		4	2	507,52	15,8	0,23	450	16-9-2002
	BH-	Dire Jara	80142	10582												0,00							
47	40	W-15	5	52	978	472		7,6					0,116		18	49		0,5		122	1650	496	17-10-1999
	BH-	Dire Jara	80027	10583				7,9						0,0				0,5					
48	41	W-16	6	25	859	418		6					0,78	77	8	0,04	0,2	1		125	0,43	368	
	BH-	Dire Jara	80173	10584				7,9						0,0				0,4					
49	42	W-17	8	08	965	467		8					0,09	7	18		0,2	1		142	0,84	450	19-12-1999
	BH-		81249	10639				7,1			13	30,1			105	0,02	34,	0,6					
50	43	Sabian Pw-1	1	30	1057	622		9	50	1,3	6	6		0,1	,6	3	32	5	424,56	44,8	0,22	464	16-9-2002
	BH-		81252	10635				7,0			16	15,5			105	0,01	35,	0,7					
51	46	Sabian Pw-4	7	43	1060	670	20	1	50	1,4	0	7	0,01		,6	3	2	6	407,48	29	0,03	464	16-9-2002
	BH-		81236	10637				7,0			15				75,		23,	0,9					
52	47	Sabian Pw-5	2	93	1017	618		2	40	1,3	9	3			7		76	6	407,5	47,5	0,04	410	16-9-2002
	BH-		81276	10634				7,0			17	22,8			138		69,	0,4					
53	48	Sabian Pw-6	7	62	1232			3	60	1,4	6	7		0,1	,6	0,01	52	1	383,08	63,3	0,06	532	16-8-2002
	BH-		81308	10632						16,	17				130		99,						
54	49	Sabian Pw-7	1	68				7,2	34	5	6	64,2			,5	0,1	7		320			704	25-11-1989

Water quality data (WWDSE)

N/N	Index	LOCAL NAME	UTM_E	UTM_N	Cond (microS/cm)	TDS, mg/l	Temp oC	PH	NH4, mg/l	Na, mg/l	K, mg/l	Ca, mg/l	Mg, mg/l	FE_TOTAL, mg/l	Mn, mg/l	Cl, mg/l	NO2, mg/l	NO, mg/l	F, mg/l	HCO3, mg/l	CO3, mg/l	SO4, mg/l	PO4, mg/l	HARDNESS, mg/l	DATE_ANALY
55	BH-50	Sabian Pw-8	812573	1062411				7,4		56,1	2	156	20,4			81	0,01	9	0,4	360				472	
56	BH-51	Sabian Pw-9	813111	1063263				7,2						0,3				13	1,4						25-11-1989
57	SP-26	Jelobelina	817946	1051086	882	544	20,3	7,62		20	1,4	128	26,75		0,1	94,6	0,003	22		295,24		50,1	0,17	430	16-9-2003
58	SP-27	Jarso Sebelo	858960	1050555	230	146	12,6	7,03		11	7,7	32	4,86	0,39	0,1	17,6		7,92	0,39	107,36		3,96	0,45	100	16-9-2002
59	SP-28	Koriso	799366	1051072	835	554	20,5	7,23		12	1,8	152	21,89		0,1	23,1	0,003	12,32	0,55	400,16		81,6	0,2	470	16-8-2002
60	BH-53	Elfora	810907	1062360	1080	650		7,16		50	1,6	151,2	21,5			83,4		23,8	0,37	446		56,7	0,06	466	11-12-2002
61	BH-77	Bore TW4(2002)	796050	1058100	704	415		7,49		15	1,5	134	11,5			14,6			0,64	392,8		43,5	0,24	382	11-12-2002
62	BH-13	Amdael well #1	814356	1064666	1302	790	24	7,09		100	2	112	31,13	0,01	0,1	160,6	0,03	21,12	0,54	383,08		14,5	0,19	508	16-9-2002
63	BH-2	Dechatu	816294	1058832	784	470	25,7	7,33		10	3	140	8,27	0,01	0,2	28,6	0,023	27,72	0,27	400,16		12,1	0,06	384	16-9-2002
64	DW-01	Jeldesa	841574	1075928	890	526	23,4	7,61		40	3	120	27,86	0,01		61,6	0,007	244	0,51	297,68		147,7	0,08	390	16-9-2002
65	DW-02	Garba Anano	857203	1072551	3780	3110	24	7,48		300	1,5	472	109,44	0,04		694,1	0,007	2,64	1,19	363,56		1213	0,22	1630	16-9-2002
66	DW-03	Kalicha	833527	1059032	1250	882	21,5	7,74		80	1	180	24,32		0,1	533,1		45,76	0,77	441,6		55,4	0,15	550	16-9-2002
67	DW-04	Tsehay Hotel	813009	1061596	1380	878	22,2	6,97		80	4,3	180	19,46			133,1	27,89	92,4	0,56	700,28		15,8	0,82	530	16-9-2002
68	DW-05	Mudi Anano	819238	1066909	704	446	27,7	8,09		130	2,1	32	4,86	0,01	0,1	23,1		11	1,4	378		5,3	0,2	100	2-9-2016
69	DW-06	Kenchera #1	810272	1055328	964	610	23,1	7,67		50	2,2	150	17,02		0,1	78,1		14,08	0,65	439,2		42,2	0,45	460	16-9-2002
70	DW-07	Ejaneni	819113	1056268	1245	884	23,1	6,68		80	1,9	184	19,46	0,01	0,1	160,6		30,8	0,45	431,88		55,4	0,29	540	16-9-2002
71	DW-08	Belewa#1	840894	1058278	890	508	21,2	7,35		9	1	160	24,32	0,02	0,1	23,1		2,64		531,92		5,3	0,31	500	3-9-2016
72	DW-09	Gende Sur	799308	1062084	872	532		7,87		100	1,1	68	17,02	0,01		23,1			0,67	524,6		21,1	0,33	240	16-9-2003
73	DW-10	Bore	798554	1060531	1218	804	25,2	7,92		140	1,4	88	29,18		0,1	34,1		3,08	1,07	563,64		200,4	0,31	340	16-9-2002
74	DW-12	Grba Anano	857182	1072675	2260	1710	25	7,64		150	4,7	288	55,94		0,1	325,6		0,44	0,83	327		685	0,19	950	16-9-2002
75	DW-11	Koran Goga	800714	1063496	1373	872	25,3	7,79		220	0,9	60	19,46	0,04	0,2	72,6		8,8	1,12	549		208,4	0,32	230	16-9-2002
76	DW-13	Melka Jebdu	805579	1065086	1457	974	27,3	7,2		240	1	136	31,62	0,08	0,1	127,6		10,12	0,76	549		184,6	0,3	470	16-9-2002
77	DW-15	Goladeg	802030	1067013	1257	862	25,5	7,41		100	0,8	128	41,34	0,01		23,1		6,16	0,87	470,92		329,7	0,21	490	16-9-2002

78	DW- 16	Arsho Adele	8060 00	1067 040	2090	14 16	26, 5	7, 42	20 0	0, 9	144	75,3 9	0,01		248 ,6	0,0 03	13, 2	1, 21	463,6	448,4	0,3	670	16-9- 2002
79	SP- 29	Melka(Fua d Haji	8051 06	1062 727	720	41 2	22, 5	6, 67	40	2, 5	80	24,3 2		0, 1	78, 1	0,0 86	3,0 8	0, 27	275,72	39,56	0,19	300	
80	DW- 18	Gende Alo	8059 43	1064 012	1223	80 8	26, 7	7, 3	60	1, 9	188	31,6 2	0,01		138 ,6	0,0 03	26, 84	0, 5	446,52	81,8	0,29	580	16-9- 2002
81	DW- 19	Gende Rige	8063 16	1064 129	1068	67 0	26, 4	7, 31	40	1, 7	168	24,3 2	0,09	0, 01	83, 6		11	0, 5	461,16	42,24	0,24	520	16-9- 2002

Appendix 5 dug wells data (WWDSE)

Well Index	Local Name	UTM norrth	UTM east	Elev. Masl	Well depth, m	SWL, m	Well Type	Geological Formation
DW-14	D/DEdible oil f	1061925	812941	1181	25	23	Cased	Alluvial
DW-20	Jelobelina	1052060	815939	1490			Cased	Alluvial
DW-30	Tony farm # 1	1063611	811769	1190	17	15,5	Open	Alluvial
DW-31	Christos school	1061283	814820	1236	42	38	Open	Alluvial
DW-32	Ras hotel	1061030	813690	1210		45		Alluvial
DW-17	Pigtry	1062750	812380	1175		26,2		Alluvial
DW-33	Lime factory	1062590	810820	1173		19		Alluvial
DW-34	Old Italian wel	1061720	811710	17		17		Alluvial
DW-35	Lime fact.Kemal	1061620	811350			9		Alluvial
DW-36	Malaria Control	1061560	814800			44		Alluvial
DW-37	Abdela Ahmed	1061825	8142630	1208		36		Alluvial
DW-38	Asefa Adefres	1062740	812520			27,1		Alluvial
DW-39	Abdurahman hus	1061625	815980	1177		5,4		Alluvial
DW-40	She Ismael mosq	1061450	815930	1205		24,4		Alluvial
DW-41	Belewa # 2	1053804	840942	22		22		Alluvial
DW-42	Kanchara # 2	1055427	810324	1334		8		Alluvial
DW-43	Kenchera # 3	1055386	810150	1336				Alluvial
DW-01	Jeldesa	1075928	841574			25	Cased	Alluvial
DW-02	Garba Anano	1072551	857203	1201		5	Cased	Alluvial
DW-25	St.Gebriel scho	1061800	813338				Open	Alluvial
DW-26	Goro(sheh Moham	1062220	810773	1211	16		Open	Alluvial
DW-27	Goro(Mohamed)	1062334	810738	1200	18	17	Open	Alluvial
DW-03	Kalicha	1059032	833527	1590	18	12	Cased	Alluvial
DW-22	Catholic ch.	1061685	816161	1193			Cased	Alluvial
DW-23	ELFORA	1062365	811200	1210		26	Open	Alluvial
DW-04	Tsehay Hotel	1061596	813009	1179	15	14	Open	Alluvial
DW-05	Mudi Anano	1066909	819238	1146			Cased	Alluvial
DW-06	Kenchera # 1	1055328	810272	8		8	Cased	Alluvial
DW-07	Ejaneni	1056268	819113	1388	13	10	Cased	Alluvial
DW-08	Belewa# 1	1058278	840894	1729		12	Cased	Alluvial
DW-09	Gende Sur	1062084	799308			24	Cased	Alluvial
DW-10	Bore	1060531	798554	1161		25	Cased	Alluvial
DW-12	Grba Anano	1072675	857182	1197		5	Cased	Alluvial
DW-11	Koran Goga	1063496	800714		21	15,25	Cased	Alluvial
DW-13	Melka Jebdu	1065086	805579	1114	27		Cased	Alluvial
DW-15	Goladeg	1067013	802030	1091	27	24,9	Cased	Alluvial
DW-16	Arsho Adele	1067040	806000		26	21	Cased	Alluvial
DW-18	Gende Alo	1064012	805943	1132			Cased	Alluvial
DW-19	Gende Rige	1064129	806316	1130			Cased	Alluvial
DW-21	Cement Factory	1061937	812282	1180		5,7	Open	Alluvial
DW-24	WFP(ABIKIAN)	1063061	814317	1189		26	Open	Alluvial
DW-28	Tony Farm # 3	1063118	811366	1181	23	19	Open	Alluvial
DW-29	Tony farm # 2	1063807	811633	1173	18	17	Open	Alluvial

Appendix 6 pump test data of boreholes (WWDSE)

PW5		PW6		PW7		PW8		PW9	
Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m
1	6,68	1	10,06	1	10,26	1	9,05	1	13,9
2	8,58	2	14,65	2	15,96	2	11,70	2	18,75
3	10,64	3	17,45	3	19,36	3	14,82	3	20,36
4	11,49	4	19,2	4	21,52	4	15,50	4	21,11
5	11,9	5	20,3	5	22,88	5	16,04	5	21,6
6	12,19	6	20,92	6	23,7	6	16,33	6	21,93
7	12,39	7	21,37	7	24,27	7	16,44	7	22,02
8	12,5	8	21,73	8	24,63	8	16,50	8	22,17
9	12,61	9	21,84	9	24,9	9	16,60	9	22,25
10	12,69	10	21,97	10	25,03	10	16,66	10	22,33
12	12,84	12	22,1	12	25,23	12	16,75	12	22,48
14	12,95	14	22,17	14	25,32	14	16,79	14	22,55
16	13,08	16	22,2	16	25,34	16	16,88	16	22,59
18	13,17	18	22,24	18	25,35	18	16,93	18	22,64
20	13,24	20	22,27	20	25,37	20	16,97	20	22,67
25	13,41	25	22,27	25	25,41	25	17,07	25	22,73
30	13,57	30	22,28	30	25,42	30	17,10	30	22,8
35	13,67	35	22,25	35	25,43	35	17,15	35	22,86
40	13,73	40	22,25	40	25,48	40	17,20	40	22,83
45	13,79	45	22,24	45	25,52	45	17,25	45	22,88
50	13,87	50	22,26	50	25,53	50	17,29	50	22,88
55	13,9	55	22,23	60	25,56	55	17,34	60	22,85
60	13,94	60	22,22	70	25,59	60	17,35	70	22,79
70	14,04	70	22,2	80	25,58	70	17,37	80	22,76
80	14,11	80	22,24	90	25,59	80	17,38	90	22,76
90	14,14	90	22,26	100	25,59	90	17,40	100	22,77

Pump test data

PW5		PW6		PW7		PW8		PW9	
Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m
100	14,19	100	22,27	100	25,6	100	17,43	120	22,79
120	14,29	120	22,26	120	25,59	120	17,49	160	23,02
140	14,32	140	22,27	140	25,56	140	17,50	180	23,09
160	14,35	160	22,27	160	25,55	160	17,52	210	23,22
180	14,38	180	22,29	180	25,57	180	17,53	240	23,26
210	14,44	210	22,27	210	25,58	210	17,56	270	23,33
240	14,49	240	22,24	240	25,56	240	17,59	300	23,39
270	14,5	270	22,22	270	25,68	270	17,60	330	23,48
300	14,54	300	22,24	300	25,8	300	17,63	360	23,57
330	14,57	330	22,18	330	25,78	330	17,66	420	23,68
360	14,6	360	22,18	360	25,84	360	17,68	480	23,77
420	14,64	420	22,19	420	25,95	420	17,75	540	23,9
480	14,68	480	22,19	480	25,99	480	17,77	600	23,98
540	14,74	540	22,26	540	26,2	540	17,80	660	24,06
600	14,84	600	22,16	600	26,33	600	17,84	720	24,24
660	14,94	660	22,62	660	26,49	660	17,88	780	24,37
720	13,85	720	22,62	720	26,56	720	17,89	840	24,42
780	13,79	780	22,62	780	26,61	780	17,91	900	24,38
840	13,73	840	22,65	840	26,65	840	17,92	960	24,41
900	13,7	900	22,69	900	26,65	900	17,95	1020	24,42
960	13,67	960	22,73	960	26,65	960	17,98	1080	24,43
1020	13,66	1020	22,73	1020	26,64	1020	17,99	1140	24,45
1080	13,65	1080	22,74	1080	26,71	1080	18,01	1200	24,47
1140	13,62	1140	22,79	1140	26,73	1140	18,03	1260	24,49
1200	13,62	1200	22,84	1200	26,74	1200	18,06	1320	24,55
1260	13,63	1260	22,86	1260	26,74	1260	18,06	1350	24,63
1320	13,58	1320	22,84	1320	26,76	1320	18,04		
1380	13,62	1380	22,85	1380	26,88	1380	17,99		
1440	13,62	1440	22,85	1440	26,92	1440	17,96		

Pump test data(WWDSE)

NPW1		NPW2		NPW3		NPW4	
Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m
1	0,64	1	0,76	1	0,69	1	5,16
2	0,64	2	0,86	2	0,71	2	5,13
3	0,65	3	0,82	3	0,69	3	5,13
4	0,65	4	0,82	4	0,67	4	5,09
5	0,65	5	0,83	5	0,66	5	5,09
6	0,64	6	0,83	6	0,66	6	5,1
7	0,64	7	0,83	7	0,66	7	5,1
8	0,64	8	0,83	8	0,66	8	5,07
9	0,64	9	0,84	9	0,65	9	5,08
10	0,64	10	0,84	10	0,65	10	5,08
12	0,64	12	0,84	12	0,66	12	5,09
14	0,64	14	0,85	14	0,66	14	5,1
16	0,64	16	0,84	16	0,66	16	5,11
18	0,64	18	0,84	18	0,66	18	5,13
20	0,64	20	0,85	20	0,66	20	5,09
25	0,64	25	0,85	25	0,67	25	5,07
30	0,64	30	0,86	30	0,67	30	5,07
35	0,64	35	0,86	35	0,67	35	5,09
40	0,64	40	0,87	40	0,69	40	5,09
45	0,64	45	0,86	45	0,69	45	5,1
50	0,65	50	0,86	50	0,71	50	5,1
55	0,65	55	0,86	55	0,76	55	5,1
60	0,66	60	0,86	60	0,77	60	5,1
70	0,66	70	0,87	70	0,77	70	5,11
80	0,66	80	0,88	80	0,78	80	5,12
90	0,66	90	0,88	90	0,78	90	5,12
100	0,66	100	0,88	100	0,79	100	5,11
120	0,66	120	0,89	120	0,79	120	5,11
140	0,66	140	0,9	140	0,8	140	5,12
160	0,65	160	0,9	160	0,8	160	5,12
180	0,65	180	0,9	180	0,81	180	5,12
210	0,65	210	0,91	210	0,82	210	5,12
240	0,66	240	0,92	240	0,82	240	5,12
270	0,67	270	0,92	270	0,82	270	5,13
300	0,68	300	0,92	300	0,83	300	5,13
360	0,68	360	0,93	360	0,83	360	5,08
420	0,68	420	0,94	420	0,84	420	4,35
480	0,68	480	0,95	480	0,84	480	4,38

Pump test data

NPW1		NPW2		NPW3		NPW4	
Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m
540	0,69	540	0,96	540	0,85	540	4,4
600	0,7	600	0,98	600	0,86	600	4,42
660	0,7	660	0,99	660	0,87	660	4,43
720	0,7	720	1,01	720	0,88	720	4,45
780	0,71	780	1,02	780	0,89	780	4,46
840	0,72	840	1,02	840	0,9	840	4,47
900	0,73	900	1,03	900	0,91	900	4,48
960	0,73	960	1,03	960	0,92	960	4,5
1020	0,73	1020	1,04	1020	0,92	1020	4,52
1080	0,73	1080	1,04	1080	0,93	1080	4,53
1140	0,74	1140	1,05	1140	0,93	1140	4,53
1200	0,74	1200	1,06	1200	0,93	1200	4,53
1260	0,74	1260	1,08	1260	0,94	1260	4,53
1320	0,75	1320	1,08	1320	0,95	1320	4,53
1380	0,76	1380	1,09	1380	0,96	1380	4,53
1440	0,77	1440	1,09	1440	0,97	1440	4,53
1500	0,78	1500	1,1	1500	0,98	1500	4,53
1560	0,78	1560	1,1	1560	0,99	1560	4,53
1620	0,79	1620	1,12	1620	0,99	1620	4,54
1680	0,79	1680	1,13	1680	1	1680	4,54
1740	0,8	1740	1,14	1740	1	1740	4,55
1800	0,81	1800	1,14	1800	1,01	1800	4,55
1860	0,81	1860	1,14	1860	1,01	1860	4,55
1920	0,81	1920	1,16	1920	1,02	1920	4,57
1980	0,82	1980	1,18	1980	1,03	1980	4,57
2040	0,82	2040	1,2	2040	1,03	2040	4,58
2100	0,82	2100	1,2	2100	1,03	2100	4,58
2160	0,83	2160	1,2	2160	1,04	2160	4,58
2220	0,83	2220	1,2	2220	1,04	2220	4,6
2280	0,84	2280	1,21	2280	1,05	2280	4,6
2340	0,84	2340	1,21	2340	1,05	2340	4,61
2400	0,85	2400	1,22	2400	1,06	2400	4,62
2460	0,85	2460	1,22	2460	1,06	2460	4,62
2520	0,86	2520	1,22	2520	1,06	2520	4,65
2580	0,86	2580	1,24	2580	1,07	2580	4,66
2640	0,86	2640	1,26	2640	1,07	2640	4,68

Pump test data

NPW1		NPW2		NPW3		NPW4	
Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m	Time, min	Draw Down, m
2700	0,86	2700	1,27	2700	1,07	2700	4,68
2760	0,86	2760	1,28	2760	1,09	2760	4,68
2820	0,86	2820	1,28	2820	1,11	2820	4,69
2880	0,87	2880	1,28	2880	1,12	2880	4,69
2940	0,87	2940	1,28	2940	1,13	2940	4,69
3000	0,88	3000	1,29	3000	1,15	3000	4,69
3060	0,89	3060	1,29	3060	1,15	3060	4,69
3120	0,89	3120	1,3	3120	1,15	3120	4,7
3180	0,89	3180	1,3	3180	1,15	3180	4,7
3240	0,89	3240	1,31	3240	1,16	3240	4,71
3300	0,9	3300	1,32	3300	1,16	3300	4,71
3360	0,9	3360	1,32	3360	1,17	3360	4,72
3420	0,9	3420	1,33	3420	1,17	3420	4,73
3480	0,9	3480	1,33	3480	1,17	3480	4,73
3540	0,91	3540	1,34	3540	1,18	3540	4,74
3600	0,91	3600	1,35	3600	1,18	3600	4,74
3660	0,91	3660	1,35	3660	1,18	3660	4,74
3720	0,92	3720	1,36	3720	1,2	3720	4,75
3780	0,93	3780	1,36	3780	1,22	3780	4,75
3840	0,93	3840	1,36	3840	1,25	3840	4,75
3900	0,93	3900	1,37	3900	1,25	3900	4,76
3960	0,93	3960	1,38	3960	1,25	3960	4,76
4020	0,93	4020	1,38	4020	1,26	4020	4,76
4080	0,93	4080	1,39	4080	1,26	4080	4,77
4140	0,93	4140	1,4	4140	1,28	4140	4,77
4200	0,93	4200	1,41	4200	1,29	4200	4,77
4260	0,94	4260	1,41	4260	1,29	4260	4,77
4320	0,94	4320	1,41	4320	1,3	4320	4,77