Groundwater Resource Assessment of the Aynalem Wellfield through Transient flow Modelling (Mekele, Ethiopia)

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by

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Dedicated to my mother

Abstract

The study focused on assessment of groundwater resources and its spatial and temporal variability of the Aynalem wellfield using transient state flow modelling. Most of the water for Mekele town is from the groundwater of the Aynalem wellfield that is facing rapid lowering due to increased abstraction for domestic and industrial water demand. Despite of this, the effect of abstraction with respect to recharge is not well assessed and the aquifer storativity and groundwater flow pattern was not known.

The groundwater recharge of the system was mainly from direct rainfall. WATBAL was employed to estimate the recharge. The WATBAL model was calibrated with river flow and groundwater level by minimizing the difference between the observed and simulated values. The groundwater recharge was estimated 32 mm/year (5% of the annual rainfall).

The finite difference schematization of the modelled area was discretized into a uniform squared grid size 250 by 250m, comprising 32 rows and 82 columns while 1705 numbers of active cells are used to represent the entire study area which is approximately 106 square kilometres in extent. Later the grid was refined into 125 by 125 cell size. The transient model was simulated with MODFLW 5.3 for a period of five years (2003 to 2007) for one layer aquifer of 50 meter thickness. The initial aquifer parameters (transmissivity and hydraulic conductivity) and initial hydraulic heads were used from the steady state model. The storage coefficient was obtained from the pumping test analysis.

The model was calibrated with trial and error in two steps. First the storage coefficient was adjusted then the groundwater recharge was adjusted by comparing the observed and simulated well hydrograph. In MODFLOW average groundwater recharge was simulated 30 mm/year (5% the annual rainfall). The water budget of the transient model shows that the aquifer storage declines some 17 mm/year and that the groundwater flow to the Aynalem River and outflow in the western outlet of the catchment decrease respectively some 68% and 14% for the simulation period. After four years of groundwater recharge without abstraction the wellfield recovers to the natural situation. On the other hand after abstraction of groundwater with 18000m^3/day for ten years, the groundwater declines with an average 53m.

Acknowledgements

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I gratefully acknowledge the Mekele water supply office, Ethiopian Meteorological Services of Mekele branch office allow me data for my study. I would like to extend my gratitude to Gebrerufael Hailu for his kind advice and the data he has provided me. I wish also to thank Tedros, Guesh, and Asay for providing data.

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1. Introduction

1.1. Background

In arid and semi-arid areas, assessment of groundwater recharge is one of the key challenges in determining the sustainable yield of aquifers as recharge rates are generally low in comparison with average annual rainfall or evapotranspiration (ET). The semi-arid areas of Ethiopia also have problems especially in the long dry season. The groundwater recharge and occurrence is mainly governed by geology, degree of fracturing, topography and also by amount and distribution of rainfall. While groundwater resources are limited, the population is increasing and towns are expanding leading to over abstraction of the groundwater.

Most of the water supply for Mekele town is from the groundwater of the Aynalem wellfield that faces rapid water table lowering due to increased abstraction for domestic and industrial water demand. Despite this, as noted by Gebrerufael (2008), the groundwater in the area is pumped with less consideration of groundwater recharge and effect of climatic variation on the recharge. "Quantifying the future evaluation of recharge over time requires not only the reliable forecasting of changes in key climatic variation but also modelling their impact on spatially varying recharge processes (Jyrkama and Sykes, 2007)"(Gebrerufael, 2008). It will be especially critical where large and concentrated demands for groundwater supplies exist as in the case of Aynalem wellfield. Thus, proper understanding of natural recharge and groundwater flow system through transient flow modelling is necessary for understanding of groundwater potential and the effect of abstraction in the area.

1.2. Problem statement

The Aynalem wellfield, located in Tigray region, northern Ethiopia is the most important wellfield for the groundwater supply of Mekele town. Previous studies conducted in the wellfield show existence of sufficient groundwater reserve in the wellfield. DEVECON (1993) has conducted a detailed study to evaluate the groundwater potential of the Aynalem wellfield for the Mekele town water supply and they conclude that the groundwater reserve was enough to provide supply for twenty years. Hussein (2000) has also arrived at similar conclusions in his MSc thesis work. Currently many production wells have been abandoned due to high drawdown or dryness. To meet the growing demands of water the Mekele town, Tigray water resource development mines and energy bureau has designed a short term and long term plan. As part of the short term (emergence recovery) new boreholes are under construction in the Aynalem wellfield, but the main problem is that some of the existing wells are getting abandoned due to the decline in the water level of the well field (Teklay, 2006). Despite the above, there has been no systematic study of the effect of abstraction the Aynalem wellfield on the sustainability of the aquifer. The potential of groundwater in the wellfield was not assessed, the hydrogeological system of the area is not well understood, the effect of abstraction with respect to recharge is not well known, and the aquifer storativity and the groundwater flow pattern are not well known. Because of the increasing population and expansion of Mekele town, resulting in high demand of water for domestic and industrial use, the pressure on the wellfield in the future will be more serious than at condition. To understand the sensitivity of the groundwater system with respect to well abstraction, recharge and aquifer storativity it is worthwhile to assess the hydrogeological properties of the groundwater flow system using a transient state model for present and future prediction and to generate greater public awareness of the issues.

1.3. Objective

1.3.1. General objective

The main objective of the study is to assess the groundwater resource and its spatial and temporal variability and improving the understanding of groundwater flow pattern of Aynalem wellfield using transient state groundwater flow modelling following from the steady-state model by Gebrerufael (2008).

1.3.2. Specific objective

- To develop a transient groundwater model of the Aynalem wellfield
- To understand and to evaluate the hydrogeological process and to quantify the groundwater resources of the Aynalem wellfield.
- To calibrate the transient model of the wellfield
- To make a prediction under various abstraction scenarios to illustrate the effect of future stresses on the groundwater resource.
- To give a recommendation on groundwater resources development and protection of the wellfield.

1.4. Research question and hypotheses

1.4.1. Research questions

- How to establish a transient model of the Aynalem wellfield?
- Which data are necessary to establish a transient model of the Aynalem wellfield?
- How to estimate the aquifer parameters especially aquifer storativty for the transient model?
- Can a transient state flow model improve our understanding of the effect of future abstractions with respect to recharge?
- How long does it take before the aquifer is affected by the groundwater abstractions?

1.4.2. Research hypothesis

- The spatial and temporal variation of the Aynalem wellfield water level of can be predicted through the transient flow model.

1.5. Literature review and previous work

1.5.1. Literature review

In the modern world of the science and technology, modelling has emerged as a major tool in all branches of science (Igboekwe et al., 2008). Groundwater models are simple representation of actual physical processes. According to Anderson and Woessner (1992) groundwater flow models can be either transient or steady state and can have one, two and three spatial dimension. Steady state simulation can not capture certain critical aspects of the groundwater system. The assessment of possible groundwater development scenarios is now possible through transient simulations (Bentley, 2007). Lubczynski (2006) advocate that transient models are more reliable in aquifer management than steady-state models because they are more constrained by temporal data and involve calibration of the storage coefficient, which is critical in groundwater storage prediction scenarios.

According to Lubczynski and Gurwin (2005), there are two types of transient models: partially transient and fully transient models. In partially transient model solutions the temporal head variability is only due to the change of aquifer storage driven by stresses, e.g. well abstraction, where as the fluxes R and ET_g are time invariant, similar to steady state solutions. Whereas fully transient models are temporally variable R and ETg but it is least explored due to demanding input data requirements. The use of time as a fourth dimension makes transient model calibration far more complicated than steady state model calibration, particularly when not only storage but also input fluxes are temporally variable. The time discretization into stress periods, which largely influences the transient model solution, is a critical modelling step. The advantage of dividing into stress periods and time steps is to allow the option of changing some parameters or stresses while the simulation progresses. More stress periods add more temporal variability in the calibration process, allow for a better fit between calculated and measured heads, but also make the calibration task more complicated and more time consuming because more stress periods and time steps need more input data and require therefore more processing time (Lubczynski and Gurwin, 2005).

Regarding to model validation and verifications different authors has different ideas. According to Rientjes (2007), due to a number of complex issues that come into play when the real world has to be representing by a model approach, the set of parameters, stresses and boundary conditions as used in the calibrated model may not accurately represent the real world system. In order to minimize the unreliability the model has to be tested against a second independent set of stress conditions. Unfortunately, it is often impossible to validate a model because usually only one set of observed data is available which already is explored for calibrations. A calibrated but unverified model can still be used to make predictions as long as careful sensitivity analysis of calibrated model is performed (Anderson and Woessner, 1992). According to Naomi et al. (1994), verification and validation of numerical models of natural systems is impossible. This is because natural systems are never closed and because model results are always non-unique. Models can be confirmed by the demonstration of agreement between observation and prediction, but confirmation is inherently partial. Complete confirmation is logically precluded by the fallacy of affirming the consequent and by incomplete access to natural phenomena. Models can only be evaluated in relative terms, and their predictive value is always open to question. The primary value of models is heuristic. Konikow (2003) also conclude that model calibration is a necessary modelling step, it is simply insufficient for model validation. It is described that by parameter uncertainty and solution non-uniqueness, declarations of validation (or verification) of a model are not meaningful.

The applications of MODFLOW to the description and prediction of the behaviour of groundwater systems have increased significantly over the last few years. MODFLOW can simulate for groundwater flow for confined, unconfined, or a combination of both aquifers, flows from external stresses such as flow to wells, aerial recharge, evapotranspiration, flow to drains, and flow through riverbeds. MODFLOW is a finite difference model code, developed by United States Geological Survey (McDonald and Harbaugh, 1988), to simulate transient groundwater flow in three-dimensions in a continuous porous medium under a variety of hydrogeological boundaries and stresses (Chiang and Kinzelbach, 1998). MODFLOW only simulates saturated flow in a porous medium with uniform temperature and density. MODFLOW cannot simulate multiphase flow, flow in the unsaturated zone and flow in fractured media, unless it can be considered to be an equivalent porous medium (Fetter, 2001). However, heterogeneity of fracture distribution and hydraulic discontinuity are the main difficulties in groundwater modelling. The equivalent porous medium (EPM) approach, however, which has been frequently applied to simulate flow in fractured media due to its ease of use, ignores this. Forming a conceptual model of fractured system requires either a gross simplification or detailed description of the aquifer properties controlling the groundwater flow (Anderson and Woessner, 1992). Fractured material is represented as an equivalent porous medium by replacing the primary and secondary porosity and hydraulic conductivity distributions with a continuous porous medium of equivalent or effective hydraulic properties. For describing groundwater flow in a fractured environment, porous media models or continuum approaches have been used by increasing the hydraulic conductivity value, cells where fracture flow occurs. In the work on the Aynalem wellfield it is always assumed that the fracture density is high enough to allow the use of the continuum approach.

Estimating the rate of aquifer replenishment is probably the most difficult problem in the evaluation of groundwater resources. There are many methods available for quantifying groundwater recharge (Gieske, 1992). Each of the methods has its own limitations in terms of applicability and reliability. Generally there is no accepted method or approach for proper assessment, and often simply using different models, assumptions and methods can lead to different conclusions regarding the impact of climate change on water resources (Yates, 1996). The objective of the recharge study should be known prior to selection of the appropriate method for quantifying groundwater recharge as this may dictate the required space and time scales of the recharge estimates. Water resource evaluations for instance would require information on recharge at large spatial and temporal scales whereas assessments of aquifer vulnerability to pollution would require more detailed information at local and shorter time scales. Estimation of recharge, by any method is normally subject to large uncertainties and errors.

In watersheds with gaining streams, groundwater recharge can be estimated from stream hydrograph separation. Use of base flow discharge to estimate recharge is based on a water-budget approach, in which recharge is equated to discharge. Determination of groundwater recharge in arid and semi-arid areas is neither straightforward nor easy. This is a consequence of the time variability of rainfall in arid and semi-arid climates, and spatial variability in soil characteristics, topography, vegetation and land use (Lerner et al., 1990). Moreover, recharge amounts are normally small in comparison with the resolution of the investigation methods.

WATBAL is an integrated water balance model developed for assessing the impact of climate change on river basin runoff. The conception of the model was originally developed by Yates (1996). WATBAL was designed to be a simple-to-use water balance model for assessing the impact of climate change on a river basin. The WATBAL model can be used on monthly based data and in areas of low data quality. The model determines the water balance based on continuous functional relations for runoff, interflow, base flow and actual evapotranspiration, contained in one differential equation. The model input parameter includes effective precipitations, evapotranspiration and runoff which is used for model calibrations. The output components are potential evapotranspiration, total modelled runoff, direct runoff, surface runoff, subsurface runoff; relative depth of water reserves in the basin and effective precipitation. The applicability of the model is tested in two case studies in humid and semi-arid climate. The two case studies show that the model behaves fairly well given its simplicity (Yates, 1996).

1.5.2. Previous work

The Mekele town water is mainly supplied by the groundwater of the Aynalem catchment. This part of the Mekele outlier has been subject to geological, hydrogeological and geophysical investigations for the last decades (Teklay, 2006). The groundwater table lowering of the well field creates a great concern in the region and shortage of drinking water is one of the critical issues in the town. As a result different geological and hydrogeological studies have been conducted by different consultancy and researchers.

DEVECON (1993) describes geology, structure and hydrogeology of Mekele area, aquifer properties of the major lithological units around Mekele areas and they pointed out that, the ground water is confined due to the alternative layer of shale, marl, limestone and dolerite; the main aquifers are found in the dolerite unit. The groundwater potential of the Aynalem wellfield was studied and it was concluded that the groundwater potential of the wellfield is sufficient enough to meet the demand of the Mekele town for twenty years.

WWDSE (2006), Water Works Design and Supervision Enterprise carried out a detailed study on geology and hydrogeology including other catchments. As part of the study, relevant meteorological and hydrogeological data is collected and different geophysical surveys have been conducted. According to the WWDSE (2006) the main units in area are shale and limestone, dolerites. The groundwater in the Aynalem is mainly confined to semi-confined. The main recharge is from rainfall and seasonal floods that generates from the ridges in the area. The groundwater recharge was estimated with two methods (WATBAL and water balance methods) and the estimated total recharge was 26% of the total rainfall. TAHAL (2007) (TAHAL Consulting Engineering LTD), made a summary report of previous studies and the present water supply sources. According TAHAL (2007) the present water supply is pumped from six water wells and five of these are located around Aynalem wellfield.

A number of MSc students have also conducted their research with regard to the overall groundwater condition of the Aynalem wellfield and nearest catchments. Gebrerufael (2008) studied groundwater assessment through steady-state flow modelling of the Aynalem wellfield and concluded that the annual recharge in the Aynalem catchment is 30-40 mm (4.5-6 % of the average annual rainfall) based on the chloride mass balance method and the main recharge is direct recharge from rainfall. The same author, concluded from hydrochemical data analysis "that there exist at least two classes of water type in the Aynalem catchments. $Ca\text{-}CHO_3$ dominated water type at the upper catchment and $Ca\text{-}SO_4$ dominated water type in the lower extreme of the catchment". A steady state model was developed with and without pumping scenarios. The steady-state model resulting from the pumping scenario shows that groundwater abstraction of 7156 m^3day^{-1} has lead to groundwater table decline up to 37 meter in the wellfield area (Gebrerufael, 2008). Finally in his recommendation the author pointed out that, "after a better steady state model is done, transient state should be carried out for assessment groundwater pumping effect with respect to groundwater recharge".

Hussien (2000) after carrying out water balance and base flow separation of the Aynalem catchment, it was concluded that the annual recharge is 9% of the annual rainfall. In addition the groundwater of the catchment receives a total of about 0.3Mm^3/year from seepage of reservoirs constructed in the valley. In the thesis Samuel (2003), after conducting water balance of the Ilala-Aynalem catchments, the annual groundwater recharge is estimated to be 52mm/year which is in the same range with Hussien's (2000) result.

Teklay (2006) carried out a water balance study of the Aynalem catchment. From his analysis of the various hydrometeorological data, the mean annual precipitation of the catchment is 670mm and the corresponding actual and potential evapotranspiration are 607mm and 961mm respectively. The main sources of groundwater recharge are from rainfall in the catchment area and groundwater inflow from the surrounding aquifer. The open water evaporation from the micro-dams constructed with in the project area is also calculated to be 2.5mm/year. According to Teklay (2006), the monthly water balance of the Aynalem catchment was calculated based on Thornthwaite and Mather (1995) and there is a surplus of 62 mm and this is the main source of groundwater recharge from in situ rainfall. The surplus occurs in the month of August and 26 mm of the surplus leaves the catchment in the form of runoff, the remaining 36mm is used as groundwater recharge (Teklay, 2006).

Zeru (2008) has carried out groundwater modelling of the Aynalem wellfield with 20 layers and he concludes the groundwater receives recharge of 11% the total annual rainfall. The time of simulation in the transient was classified into two stress periods of wet and dry season based on the yearly rainfall distribution in the model area. The limited potential of recharge of the wellfield from direct precipitation is due to the presence of low permeable layer (shales and dolerite sills) intercalating the more permeable limestone unit, due to the confined nature of the aquifer and to some extent the presence of thick layer of low hydraulic conductivity soil such as clay. Finally from his model result it was concluded that the Aynalem wellfield will serve the public water supply safely for the coming 15 years depending on proper management.

1.6. Methodology

The methods followed to achieve the proposed objectives and to answer research questions, consist of three phases: pre-fieldwork, fieldwork and post-fieldwork period.

1.6.1. Pre-field work

- Review of previous works, literature review related to principle of groundwater modelling and others related to the study. The feasibility reports of the area will be reviewed to get insight about the problem and to define the work direction of the research.
- Acquisition of necessary equipment for fieldwork
- Acquisition of existing data and starting preliminary survey on the images and maps of the study area

1.6.2. Fieldwork

A one month field campaign starting from September first week to October first week 2008 was organized to collect data for the thesis work (secondary and primary data). Groundwater abstraction and water level monitoring data for five and four years respectively were collected from water supply office of Mekele town. Pumping test data (draw down test, constant rate test of single well test and for three wells with observation wells) were collected from the same office. Meteorological data (rainfall, wind speeds, minimum and maximum temperature, relative humidity, and sunshine hours) were collected from the Mekele airport station located in the study area. The data set from the National meteorological agency of Mekele branch offices was sixteen years (1992 to 2007). River discharge of Aynalem River were collected for ten years (1992 to 2001) which covers 69 km^2 of the study area and the river gauging is not working now due to increase of groundwater abstractions through pumping wells, leading to decline of river discharge. Other data and existing reports like well logging (lithological and geophysical logs), Geological maps and cross-sections, soil and land use maps were obtained from Mekele Water Resources Bureau. During the fieldwork groundwater level measuring at accessible wells, EC measurements (wells, rivers, ponds and springs), and ground truth observation were also made.

1.6.3. Post fieldwork (data processing and analysis)

In the post field work the data collected during pre-fieldwork and fieldwork are processed and analyzed. The main activities here are preparing of the collected data for the input of the modelling process (MODFLOW). For the data processing purpose Ilwis, Aquifer Test, Surfer and Excel are used. Pumping test data and geophysical data were analyzed to get aquifer parameters. Aquifer Test was used for pumping test data analysis. Finally, compiling and thesis writing based on the result of the analysis was made. The detailed methodological approach of the thesis is indicated in the flow chart of Figure 1.1.

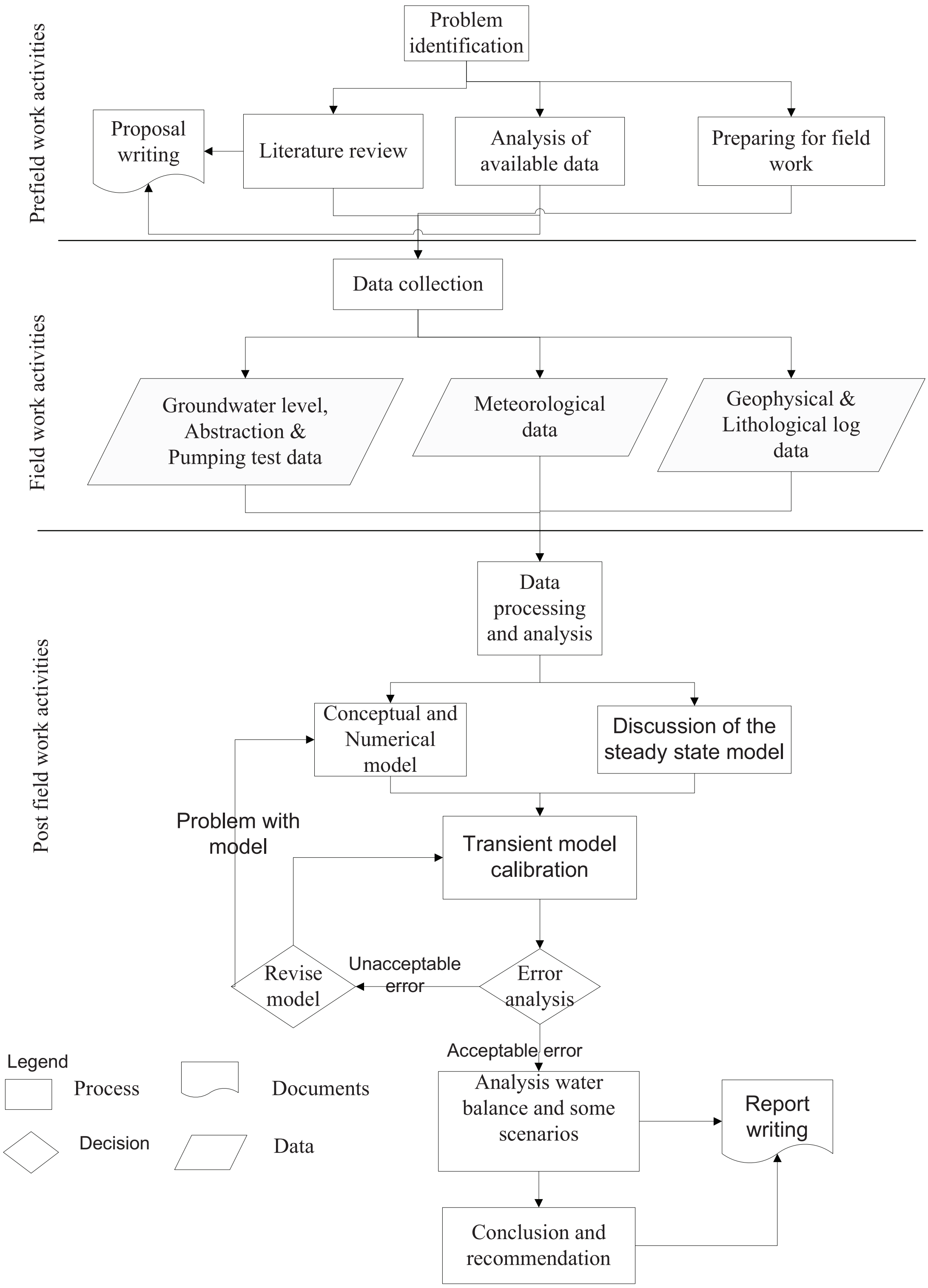


Figure 1-1: Flow chart of methodological approach

1.7. Outline of the Thesis

Chapter one gives an introduction to the background of the research, problem statement, objective and research questions and literature review related to groundwater modelling and recharge with discussion of previous work. In Chapter two a description of the study area is given in terms of location geomorphology and drainage, climate, geology and hydrogeology, land cover of the study area. The data processing is described in Chapter three. This chapter mainly focuses on pumping test analysis, recharge calculation and input data preparation to the modelling. The transient numerical model is developed in Chapter 4 and results are presented. Scenarios are dealt with in Chapter five while discussions are presented in Chapter six and finally conclusion and recommendation for future are presented.

2. Description of Study Area

2.1. Location

The Aynalem wellfield is located on the north eastern part of the central plateau, west of the rift valley of Ethiopia. It is particularly located about 5km south of Mekele town, capital city of the Tigray national regional state, northern Ethiopia (Figure.2.1). The geographic location of the area is between 1482790 to 1489455 East and 548838 to 569894 North. The study area covers about 106 km^2 with mean altitude of some 2200meter above sea level. As the area is near to the capital city of Tigray, Mekele, it is accessible by the main asphalted road joining Mekele-Addis Ababa and all weathered gravel roads give access to the wells in the area.

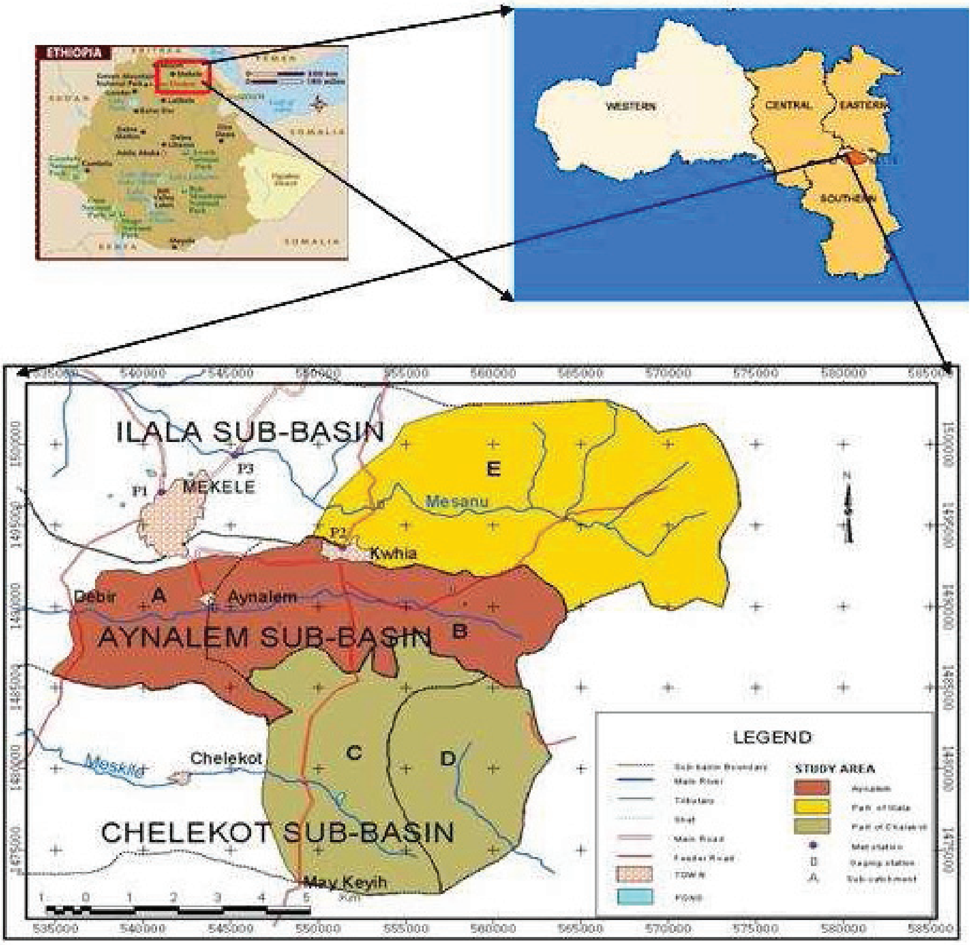


Figure 2-1: Location map of the study area (after WWDSE, 2006).

2.2. Geomorphology and drainage

The Aynalem sub-catchment is topographically bounded to North and South by dolerite ridges mainly oriented N-W and the valley is characterized by a gently rolling to flat topography (Figure 2.3). The elevation in the central part ranges from 2220m-2340 m above mean sea level. Generally the altitude of the catchment varies from 2108 m a.s.l at the mouth of the basin to 2450 m a.s.l at the extreme east of the catchments boundary (Figure 2.4). The dominant rock units which outcrop in large part of the study area are shale, limestone and igneous rocks, mainly Mekele dolerite, which has intruded into the sedimentary successions.

The Aynalem River is part of the Tekeze river basin. The Aynalem river (the main river in the area) that crosses the catchment divides the area almost in to two equal halves (Figure 2.2). The river drains from east to west direction almost parallel to the major regional structure. The river in the catchment is controlled by a fault system. Many seasonal tributaries feed the main stream both from the north and south with substantial amounts of water during the rainy season. The average maximum discharge of the Aynalem River is obtained during high rain season, in August which is about 2.47 Mm^3/month (Table3.7). During the field trip we observed springs flowing from the banks of the river. It is believed that the natural outflow to river has become much less due to increasing groundwater abstraction since the early 1990s.

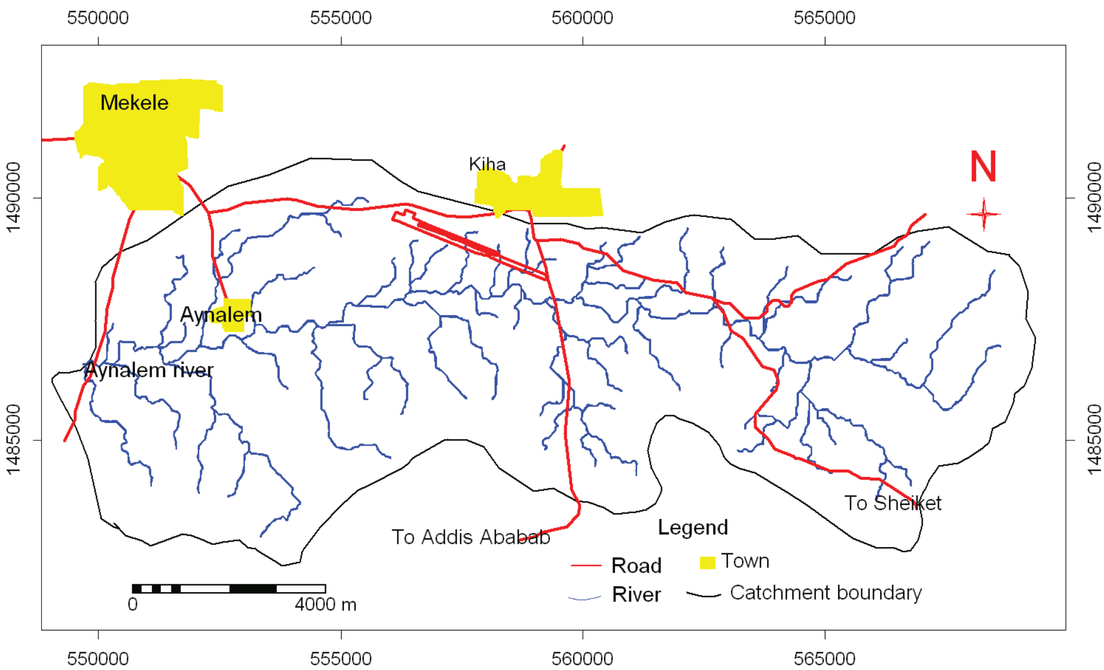


Figure 2-2: Drainage map of study area

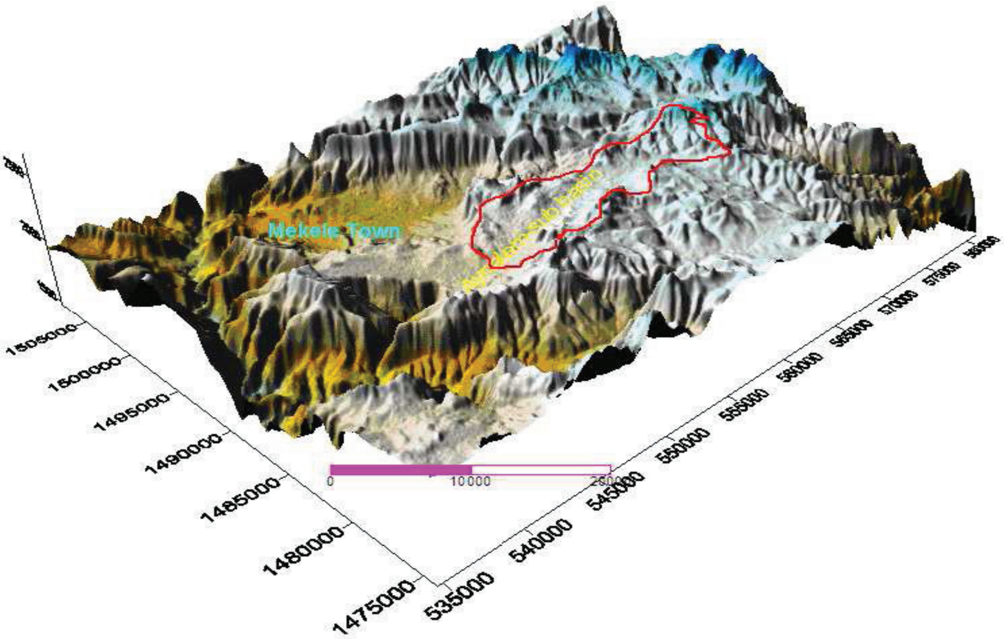


Figure 2-3: Three dimensional topographic map of study area (after WWDSE, 2006).

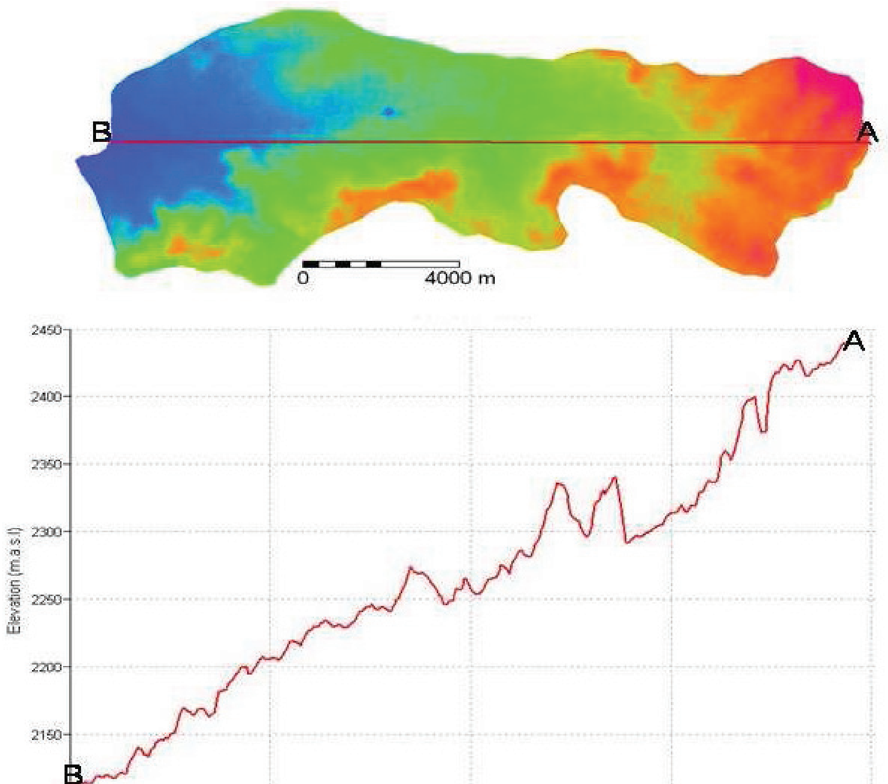


Figure 2-4: Elevation cross-section map of the study area extracted from ASTER DEM

2.3. Climate and hydrology

The climate of Ethiopia ranges from equatorial desert to hot and cool steppe, and from tropical savannah and rain forest to warm temperate, from hot lowland to cool high lands. In Ethiopia rainfall has uneven distribution both in time and space. The distribution of rainfall in Ethiopia is characterized by reference to the position of Inter-Tropical Convergence Zone (ITCZ), a low pressure area of convergence between tropical easterlies and equatorial westerlies (Gebrerufael, 2008). The big summer rains occur when the ITCZ is found north of Ethiopia. During this period the whole country is under the influence of equatorial westerlies from South Atlantic Ocean and southerly wind from the Indian Ocean. When the ITCZ moves to the south, the country will be under the influence of continental air currents from north and northeast. In spring (March, April, May) the ITCZ lies in the southern part and strong cyclonic cell (low pressure area) develops in over Sudan. Winds from the Gulf of Rift and the Indian Ocean (anticyclone) blow across central and southern Ethiopia and form the relatively smaller Belg rains (Tamiru, 2006). The rainfall varies between 250 mm in the low lands to 2800 mm on the southern plateau. Generally, the study area has a semi-arid climate. Average monthly maximum and minimum temperature is 24^{o}C and 12^{o}C respectively and the monthly average temperature is 18^{o}C. Maximum monthly temperature may go as high as 28^{o}C and minimum may go as low as 8^{o}C. Mean annual temperature ranges from 15^{o} to 16^{o}C over the central part. There are two rainy seasons, March to April and June to September. The mean annual rainfall is 602 mm based on data collected during the last 16 years. Most of the rainfall occurs during July and August (Figure 2.5).

2.4. Land cover

2.4.1. Soil characteristics

The soils in the study area are classified into four classes based on the grain size: Sandy loam, silty loam, clay loam and clay soils (Teklay, 2006). Sandy loam and silty loam are found on the hills whereas there is more clay in the valleys and flat areas. During the field observation the exposed soil thickness within the catchment ranges from 6m along the main stream of the Aynalem River to 0.5m on the flat area. The areal coverage of each soil type is indicated in Figure 2.6.

2.4.2. Vegetation

The density of vegetation in Tigray area is usually classified into three groups, as dense vegetation, scattered vegetation and little or no vegetation. In this classification the area around Mekele town generally belongs to the little or no vegetation class. Today it can be said that most part of the area is completely devoid of its forest cover.

2.4.3. Land cover and land use

The land cover in the Aynalem catchment mainly uses for rainfed agriculture, grazing land, settlement. The major land use of the study area is a highly cultivated agricultural land whereas the reforestation land covers only a small area as compared to other landuse pattern within the catchment. The land cover of the catchment indicated in Figure 2.7.

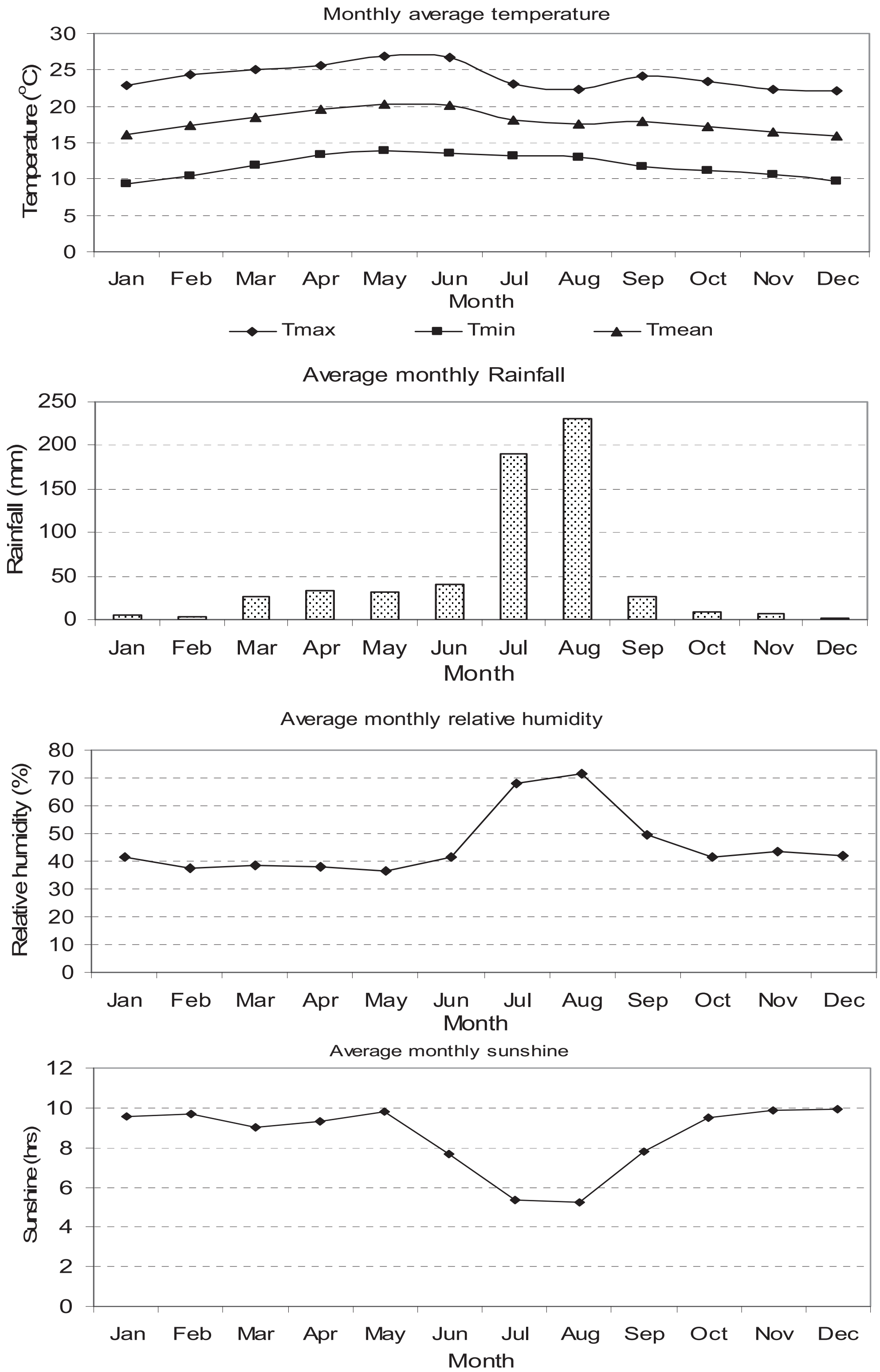


Figure 2-5: Mean monthly values of climatic variable**.**

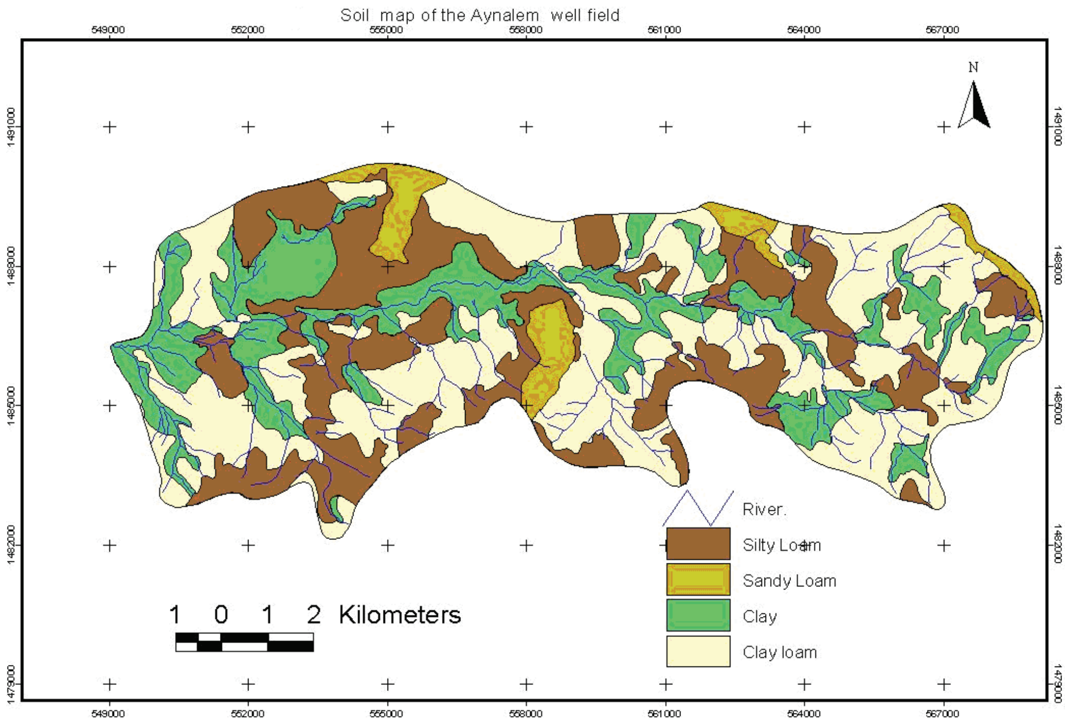


Figure 2-6: Soil map of Aynalem sub-catchment (after WWDSE, 2006)

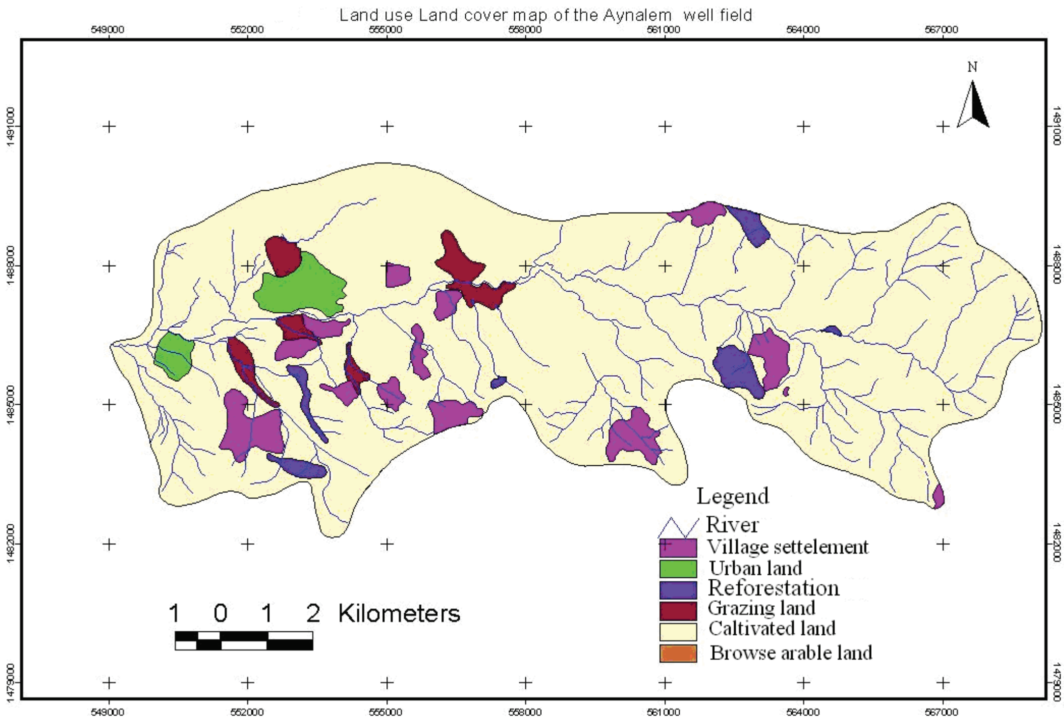


Figure 2-7: Land use map of Aynalem sub-catchment (after Teklay, 2007)

2.5. Geology

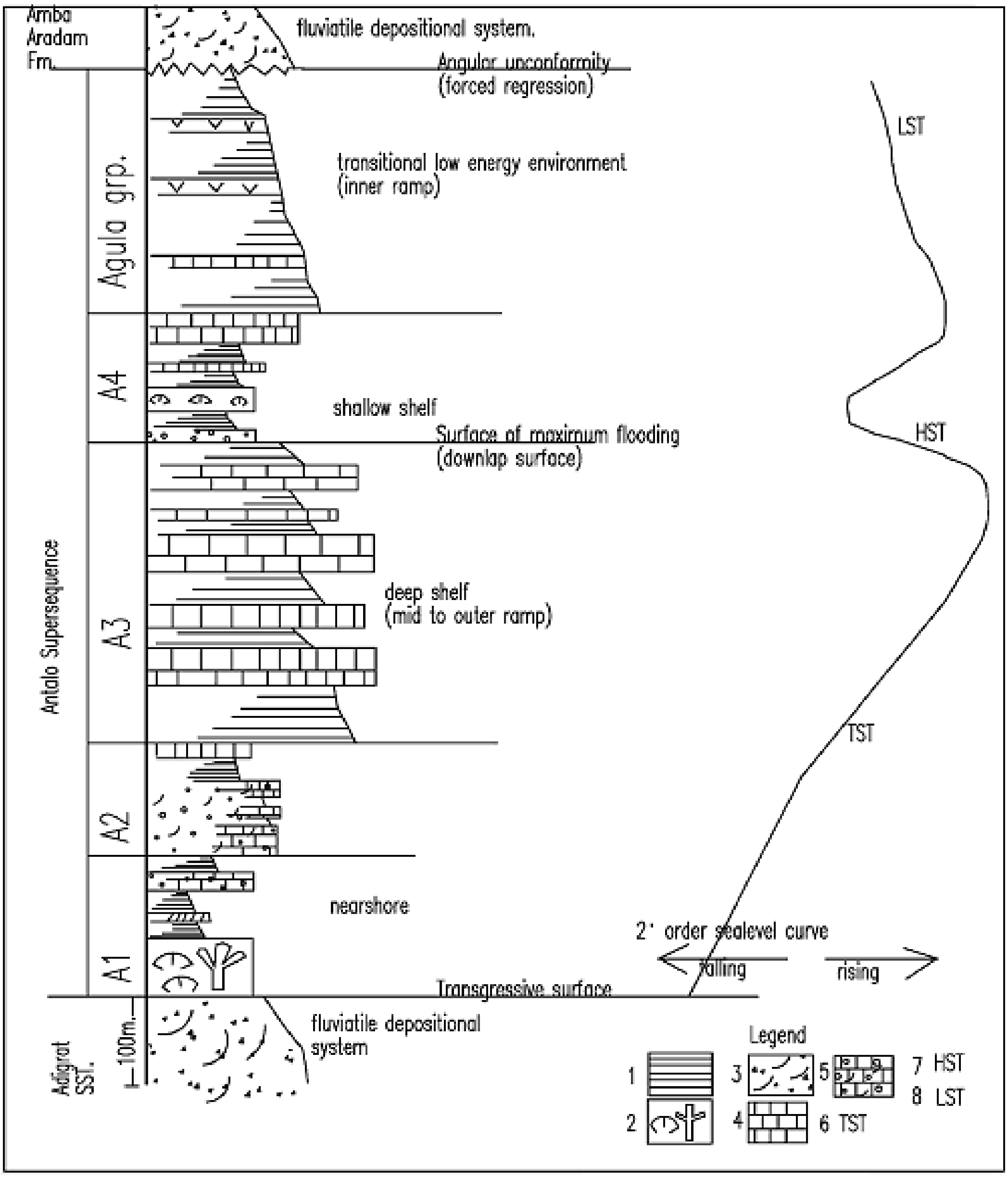
2.5.1. Regional geology

Ethiopia consists of a large variety of metamorphic, sedimentary and igneous rocks and there are three major geological units: Precambrian basement rocks, Palaeozoic rocks and Mesozoic sediments rocks. The Precambrian basement rock deposition contains the oldest rock in Tigray region. According to Kazmin (1975) the basement rocks have generally undergone only lowest degree of metamorphism reflecting the relatively low temperature since the time of deposition. The age of the basement is considered to be upper Proterozioc to lower Palaeozoic (Beyth, 1972). The Palaeozoic to early Mesozoic sedimentary rocks are formed during the peneplanation period at the end of Precambrian (Beyth, 1972). This period is particularly represented by the deposition of the Enticho sandstone and Edaga Arbi glacial which belong to the Palaeozoic age. The Mesozoic sedimentary succession of the region is the product of two major transgression-regression cycles that took place during Mesozoic (Beyth, 1972). Rocks representing a range of sedimentary environments are Adigrat sandstone, Antalo limestone, Agula Shale and Ambaradom sandstone.

The Mesozoic sedimentary succession of the Mekele outlier is the product of these cycles and rocks representing a range of sedimentary environments. The first cycle began during the early Jurassic or Late Triassic and resulted in the deposition of the Adigrat sandstone consisting mainly of sandstone and minor lenses of siltstone and the Antalo formation consisting mainly of fossiliferous limestone in Tigray Region (Mengesha et al., 1996). The regression the first phase caused the deposition of the Agula formation that is constitute of black shale, marl and claystone with some beds of black limestone in the Mekele area. Transgression of the second cycle took place in Aptian to Turonian but is not important for deposition in Mekele area. However, regression of the second phase during Late Cretaceous resulted in the deposition of Amba-Aradom formation that is constituted of siltstone, sandstone and conglomerates. The formation was named after the type locality south of Mekele. The stratigraphy of the Mekele outlier is shown in Figure 2.8.

2.5.2. Local geology

The Aynalem sub-catchment is surrounded by plateaus and ridges of dolerite which physically separate the valley from the adjacent catchments, Ilala and Chelekot. The dominant units outcropping in the study area are quaternary sediment deposits, dolerite, sandstone, limestone-marl-shale intercalation and well bedded limestone (Samuel, 2003). All the lithologies encountered in the area exposed in numerous cuttings are seen to be flat lying except the dolerite dykes which form ridges. Limestone unit dominate in the study area and outcrops in the low lying area of the Aynalem well field and in some places as blocks in high altitude above the dolerite sills. This could be the result of the dolerite intrusion which uplifted it. The dolerite unit outcrops in the form of sills, dykes and irregular bodies and usually the dykes form ridge like structures. Most of the ridges surrounding the boundary of the catchment area are formed from dolerite dykes and mainly oriented to the NW-SE and NE-SE direction. The sandstone unit is encountered in only a few places, as pockets of deposits over the limestone unit. Structurally the study area is affected by faults, fractures and joints. Two main sets of conjugate fault systems oriented in the NNW-SSE and N-S to NE-SW directions occur in the study area. The existence of these faults is recognized from the alignment of the dolerite ridges having the same trend to the Mekele fault belts and from the sharp contact of different lithologic units, older and younger units (Teklay, 2006).



(1) Marl, (2) Coral-stromatoporoid rich limestone, (3). Cross-bedded sandstone, (4). Limestone, (5) Cross-bedded oolitic limestone, (6) Transgressive system tract, (7). High stand system tract and (8). Low stand system tract.

Figure 2-8: Sratigraphy of sedimentary succession the Mekele outlier, (after Bosellini et al, 1995)

2.6. Hydrogeological setting

The groundwater in Aynalem wellfield mainly is in fracture rock and hence, fractures, faults and joints play an important role. With respect to the hydrogeology of the Aynalem area different studies were conducted. According to WWDSE (2006) the area is highly affected by fracturing and faulting which are aligned along NW-SE, and play an important role in the movement and occurrence in the groundwater in the study area. According to (Beyth, 1970), there are two major faults in the area: NW trending faults and N-E to NE-SW trending faults and they named as Wukro, Mekele and Fucea-mariam. With respect to groundwater recharge, aquifer type and boundaries and groundwater modelling different studies were conducted in the area.

2.6.1. Groundwater recharge

Groundwater recharge of Aynalem catchment was determined by different people using different methods. Some of the recharge results are summarized below. Hussein (2000), after carrying out water balance and base flow separation of the Aynalem valley, concluded that the annual recharge is 9% the average annual rainfall or 57 mm of the total rainfall. Samuel (2003) in his thesis after conducting water balance of the Ilala-Aynalem valleys, estimated the annual ground water recharge to be 52 mm/year. WWDSE (2006), also estimated groundwater recharge of Aynalem catchment with the WATBAL model and water balance methods. The result of recharge computation by water balance method was higher than the estimation by the WATBAL modelling method. The estimated total recharged groundwater in sub-basins was about 26% of the total rainfall, which is three times higher than the recharge estimated by Hussein and Samuel.

According WWDSE (2006) the main recharge is from rainwater and seasonal floods generated from the ridges in the area and additional the lower aquifer receives recharge from the surrounding catchments. WWDSE (2006) based on the drilling data, geophysics and well logging data, aquifer was classified into two layers with an aquiclude in between. In the Aynalem and surrounding basins they made cross section of the groundwater basin (Figure 2.10). As indicated in Figure 2.10 the groundwater flow direction to the lower aquifer is from surrounding catchment.

Gebrerufael (2008) and Teklay (2006), determine groundwater recharge of the catchment using different methods and found similar recharge values. Teklay (2006) concluded from his monthly water balance model and river discharge measurements analysis that, the main source of groundwater recharge to the wellfield is from direct rainfall in the catchment area and groundwater inflow from the surrounding aquifer. Recharge from in situ rainfall is estimated 36mm which accounts for about 5% of the mean annual rainfall. Similarly, Gebrerufael (2008) estimated groundwater recharge at 30-40 mm year^{-1} (4.5- 6% annual rainfall in the area) using the chloride mass balance method (CMB). The recharges determined by different authors are summarized in Table 2.1.

Table 2.1 Summary recharge detemined by different authors

	Author	Values	Methods
1	Hussien (2000)	9% annual rainfall	Water balance and base flow separation
2	Samuel (2003)	9% annual rainfall	Water balance
3	WWDSE (2006)	26% annual rainfall	WATBAL and Water balance
4	Teklay (2007)	5% annual rainfall	Water balance
5	Gebrerufael (2008)	4.5 - 6% annual rainfall	Chloride mass balance and MODFLOW
6	Zeru (2008)	11% annual rainfall	MODFLOW

2.6.2. Aquifer type and boundaries

For the investigation of groundwater potential and aquifer boundaries of Aynalem wellfield different geological, hydrogeological and geophysical studies were conducted. According to DEVECON (1993) based on the geophysics and test drilling, the groundwater in the study area is mostly confined because of the alternating layers of shale, marl, limestone and dolerite, while the main aquifers are found in the dolerite unit. They also studied the groundwater potential of the Aynalem wellfield and concluded that the ground water potential of the wellfield is sufficient to meet the demand of the Mekele town for twenty years. The dolerite aquifers have good water quality and high specific discharge and transmissivity. Thus DEVECON concluded that in the year 2005 (first stage demand) the maximum daily demand would be 132.4 l/s (11440m^3/day), and that the ground water potential around Mekele is adequate to meet the demand. MSc theses of Hussien (2000) and Samuel (2003) concluded that the main aquifer in the area is limestone. Based on geophysical investigations and well log data, transmissivities of different geologic units of Aynalem catchment are classified from high promising to low promising (Figure 2.9).

WWDSE (2006) based on the drilling data, geophysics and well logging data, identify three lithological layers of shale with limestone intercalations, dolerite and limestone with shale intercalations. Based on these results the aquifer was classified into two layers with an aquiclude between them. The thickness of the lower aquifer is not yet penetrated by wells drilled in the Aynalem wellfield. The main aquifers in the area are the limestone unit and weathered and fractured dolerite. The groundwater occurrence, distribution and flow regime, in the Aynalem wellfield area is highly governed by dolerite sills which categorize the groundwater into two aquifer systems. In the area dolerites occur as sill and dykes intruding the limestone and shale. The dolerite is in the most case fresh and massive to be considered as an aquiclude. The transmissivity of the upper aquifer indicates that the upper part of Aynalem well field (around TW1-2005) has high transmissivity greater than 1000 m^2/day (WWDSE, 2006). The average transmissivity value of the sedimentary upper aquifer in the Aynalem ground water basin is about 820m^2/day, while the dolerite aquiclude has a transmissivity of 1.02 – 5.5 m^2/day and the higher value is fractured and weathered dolerite. In the Aynalem groundwater basin the lower aquifer (the main sedimentary aquifer) has a transmissivity varying from

100 to more than 3500 m^2/day with average transmissivity value of 730 m^2/day. According to Gebregziabher (2003) the area is highly faulted by NW-SE faults, the limestone unit is highly faulted than the dolerite and almost everywhere there are dolerite dykes or sills. The dolerite intrusions in the area caused a complex distribution of the hydrostratigraphic units forming an interbedded system of permeable and less permeable layers resulted in a confined to semi-confined aquifer system (Gebrerufael, 2008). According to WWDSE (2006), there are two aquifers: the upper and lower aquifer (Figure 2.10). But it is unclear if there hydraulic contact between the two aquifers. If so then the groundwater should move upward toward the Ilala and Chelekot valleys. Here it is assumed that there is no contact. Not much is known about the deep aquifer at present.

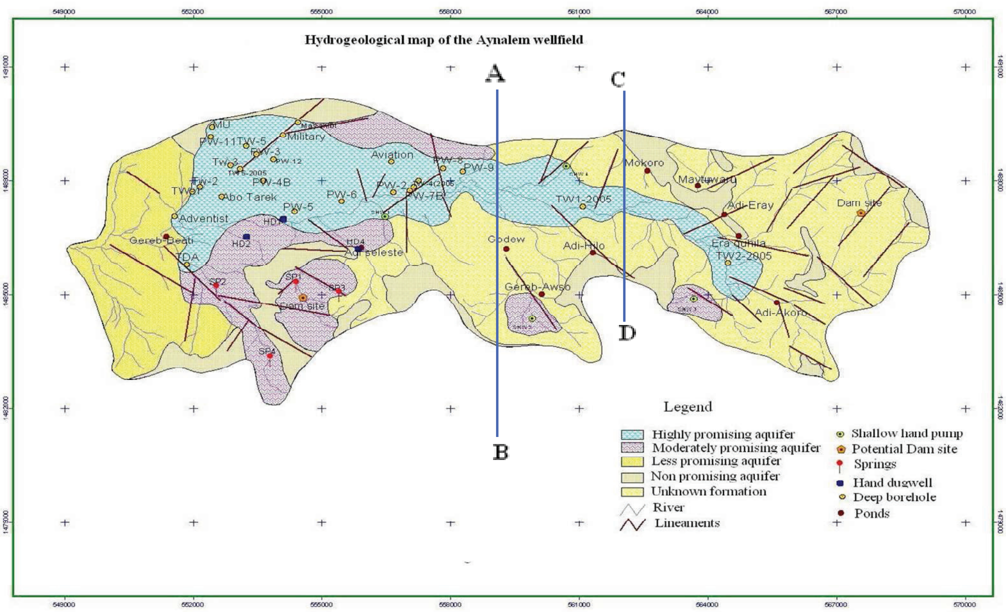


Figure 2-9: Hydrogeological map of Aynalem wellfield (after WWDSE, 2006).

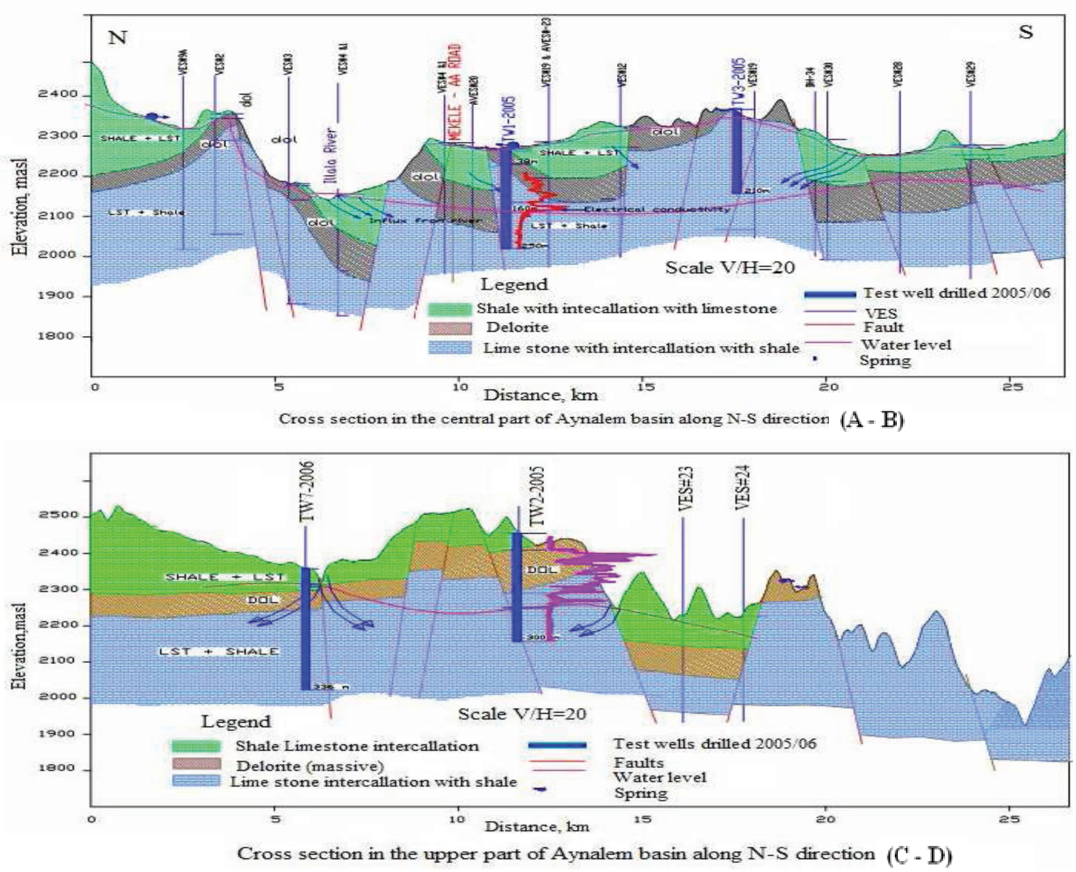


Figure 2-10: Hydrogeological cross sections in Aynalem basin (after WWDSE, 2006).

3. Data Processing

Data processing refers to data screening, analyzing and calculating of primary and secondary data for input into the transient model MODFLOW. The data to be analyzed includes pumping test data for determining aquifer storativity, meteorological data for groundwater recharge calculation using WATBAL and abstraction data for the input into the transient model.

3.1. Pumping test analysis

The principle of pumping test is that if we pump water from a well and measure the discharge of the well and the drawdown in the well and in piezometers at known distance from the well, we can substitute these measurements into an appropriate well flow equation and are these able to evaluate the hydraulic characteristics of the aquifer (Kruseman and de Ridder, 1991), such as transmissivity, storativity and well performance characteristics. In the analysis of these parameters such as transmissivity, storativity and hydraulic conductivity the acquisition of accurate hydrogeological field data with carefully monitored pumping test data is crucial.

During the field work pumping test data for Aynalem well field was collected for tests carried out during the drilling of wells (1998/99) and for some wells drilled recently. The pumping test data includes draw down test, constant rate test and recovery of single well pumping test. However, pumping test with observation wells for three wells was carried out only. The majority of the test was conducted under constant discharge rate for short time duration to determine the safe yield. A semi-log plots time vs. drawdown were constructed to identify the aquifer type and methods for the analysis of pumping test data. Some examples are indicated in Figure 3.1. As can be observed from the graph of time drawdown of each well, the trend is similar for all wells (Figure 3.1). In the initial stage the time drawdown graph is horizontal, the pumping rate has less influence and stability of the groundwater level was not reached when pumping was stopped. This may be because of existing of impermeable boundaries. The effect of a barrier to flow in some region of the aquifer is to accelerate the drawdown rate.

Commonly analytical interpretation of pumping test data is based on assumptions to represent actual aquifer configurations. However, in the real world aquifers are created by complex geologic process that leads to irregular stratigraphy, pinch outs trends of both aquifers and aquitards and aquifers are heterogeneous and anisotropic. These complex geology and heterogeneity may cause deviation of time drawdown graph from the theoretical one. This is clearly observed in most wells of Aynalem wellfield. Since the wells in the wellfield are clustered in one area, the intensive pumping of wells in the wellfield during the test causes local pressure drop which may also causes deviation from the theoretical curves. For example in pumping well number four (PW4) and pumping well number seven (PW7) Figure 3.1 are clearly observed such problems. In a pumping test, the type of aquifer and the inner and outer boundary conditions affect the drawdown behaviour of the system in their own individual ways. When the field data curves of drawdown versus time deviate from the theoretical curve of the main types of aquifer, the deviation is usually due to the specific boundary conditions (e.g. partial penetration of the well, well bore storage, recharge boundary or impermeable boundary

(Kruseman and de Ridder, 1991). When the cone of depression reaches the recharge boundary, the drawdown in the well stabilizes. An impermeable boundary causes an increase of the drawdown.

The drawdown curves were compared with the theoretical curves to visualize the aquifer type. The time drawdown plots of the wells are indicative of confined to semi-confined aquifers. The static water level data of the wells shows it is above the level at which the groundwater was struck during the drilling of the wells (Table 3.1). This can be evidence to consider the aquifer as confined or semi-confined aquifer system. Previous works of geophysical and test drilling indicates that the ground water in the study area is mostly confined because of the alternating layers of shale, marl, limestone and dolerite, and due to tectonic folds and fractures. The work of WWDSE (2006) confirms that, the groundwater in Aynalem is mainly confined to semi-confined aquifer.

Table 3.1 Summary of some wells during drilling

Well-Id	SWL (m)	Water strike (m)
PW1	11.20	21
PW2	31.30	109
PW4	20.55	80
PW7	8.01	20
PW8	19.31	38
PW9	16.26	58
PW11	9.80	62
PW12	14.97	28
Airport1	22.45	70
Airport2	8.65	15
TW3	19.51	56
TW4	16.05	81
TW5	17.56	72

In the Aynalem wellfield more than forty wells were drilled but pumping test data are obtained only for twelve wells from Mekele water supply office during the field trip; interpretations are made to calculate the transmissivity, specific capacity and aquifer storativity these twelve wells only.

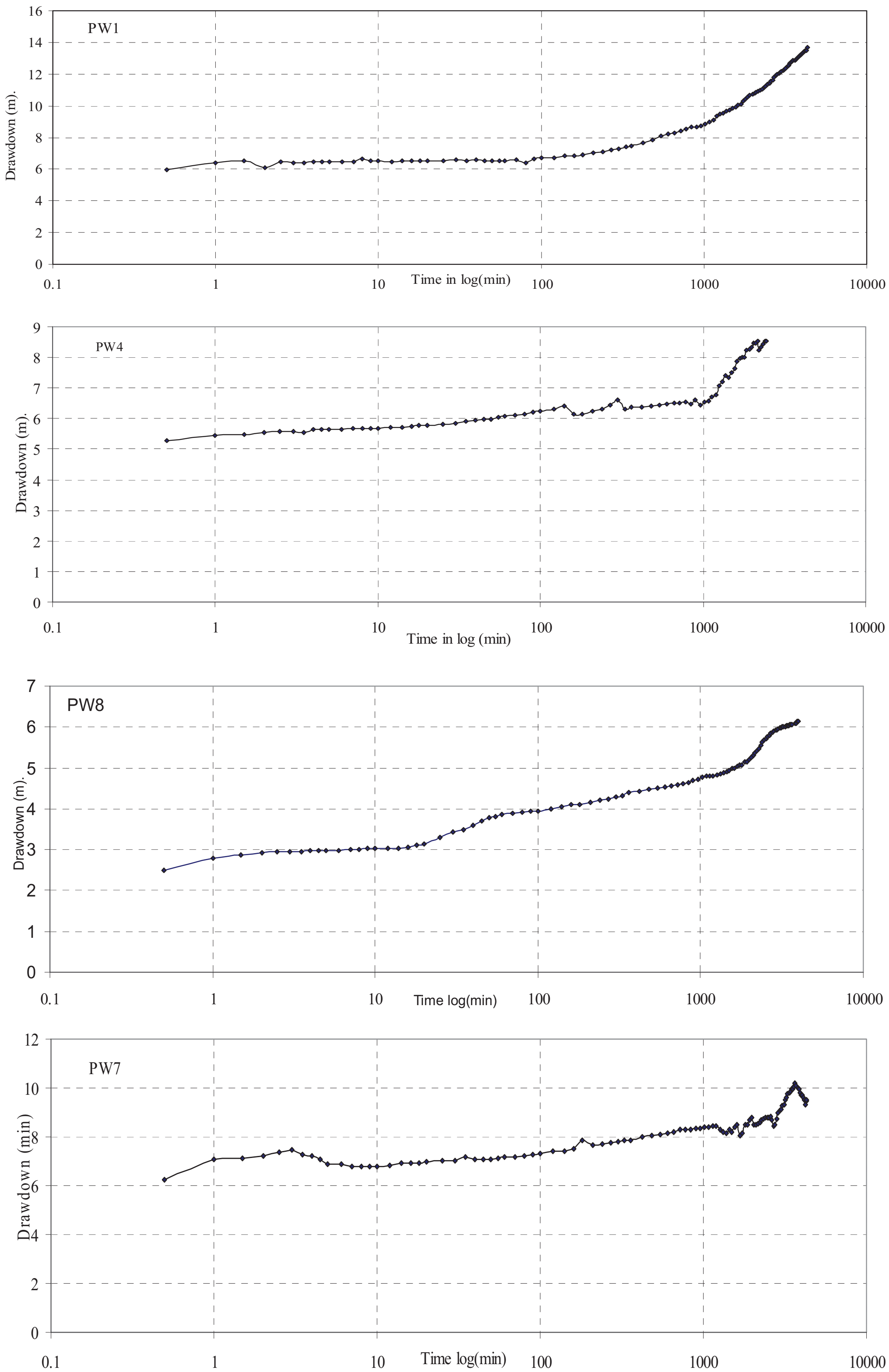


Figure 3-1: Time drawdown graph pumping test data

3.1.1. Pumping test

Pumping tests are conducted to evaluate an aquifer through constant pumping, while observing the aquifer's drawdown in observation wells. In this thesis all analysis on pumping test data are carried out using Aquifer Test 4.2 and Aquifer Test for windows (Waterloo hydrogeological) V.2.5. The pumping test results show that the common Theis assumptions are not met. The pumping test analysis results show that there is high range of transmissivity that varies from very low values (0.97 m^2day^{-1}) to high values (1541 m^2day^{-1}) Table 3.2. These values only represent the wells for which data was obtained during the fieldwork. The transmissivity values obtained from existing report was compiled in the Appendix 5.

Table 3.2 Constant pumping test analysis result

Well-id	Depth (m)	SWL (m)	Q (m^3d^{-1})	Drawdown (m)	Sc (m^2d^{-1})	Duration (min)	T (m^2d^{-1})
PW1	120	11.2	1728	13.7	126.1	4320	86.7
PW2	118	31.1	2684	36.9	72.8	4320	20.5
PW3	120	20.6	1776	3.1	569.4	4320	1540.8
PW4	120	15.2	1309	8.9	147.8	2460	133.1
PW5	104	13.3	1134	74.1	15.3	1800	1.0
PW6	75	19.7	1877	1.4	1390.7	4320	839.5
PW7	65	8.0	6912	9.5	728.4	3960	436.3
PW8	90	16.2	3629	22.0	164.7	2940	181.4
PW9	72	16.3	467	29.4	15.9	4320	9.3
PW11	75	9.8	1877	10.6	177.5	4320	105.7
PW12	80	15.0	8208	7.5	1091.5	4320	731.5
TW6-2008	120	44.5	2748	3.4	798.7	4320	308.2

There are only three wells where pumping test with observation well was carried out. For these wells the storage coefficients were found ranging from $6.56x10^{-3}$ to $2.57x10^{-7}$. The values obtained for transmissivity and storage coefficient in this interpretation, are comparable with the previously reported values. They can be used as initial values in the transient state modelling and can be optimized in model calibration. The pumping test analysis here can not represent the entire well field especially the upper eastern part of the catchment, because the test wells are clustered in the north-western part of the well field. The curve matching used for the mathematical solution to obtain the transmissivity and storage coefficient is given in Appendix 6.

3.1.2. Well performance analysis

A step drawdown test is a single well test in which the well pumped is at a low constant discharge rate until the drawdown in the well stabilizes. The pumping rate is then increased to a higher constant discharge rate and the well is pumped until the drawdown stabilizes once again. This process is repeated through at least three steps which should be of equal duration (Kruseman and de Ridder, 1991). Step-drawdown tests are a valuable tool for assessment of pumping well and aquifer characteristics because it allow to assess the efficiency of a well to be used as a production or water supply well (Amarasingha, 2007). The total drawdown in a pumped well consists of aquifer losses and well losses. Well performance analysis is conducted to determine these losses. Aquifer losses are the head losses that occur in an aquifer where the flow is laminar. Well losses are linear or non-linear and caused by aquifer damage during drilling and completion of the well. All these losses cause that the drawdown inside the well is much larger than one would expect on theoretical grounds. The step drawdown test data for Aynalem was collected for some wells and analysed based on Hanthush-Bierschenk well loss techniques. The analysis results and responses of each well under varying pumping rates are summarised in Table 3.3. To obtain the information on the condition or efficiencies of the well, the relation between calculated aquifer loss (BQ) and well loss (CQ^2) have been applied (Equation 3.1). The results are given in Table 3.3. Graphs for a single well are indicated below. The data for the other wells are compiled in Appendix 6.

$$Well\ efficiency = \frac{BQ}{BQ + CQ^2} \tag{3.1}$$

Where: *BQ* represents the drawdown due to formation loss, and CQ^2 represents the drawdown due to well loss. The efficiency of a well is governed largely by the magnitude of the well loss and thus falls off rapidly as discharge is increased. The efficiency of a well in an aquifer having a high transmissivity is affected by well loss to a greater degree than the efficiency of a well in an aquifer having a low transmissivity, and it is least affected by partial penetration of aquifers having a large transmissivity.

Table 3.3 Summary of step test analysis

Well-id	No. Steps	Q (m^3d^{-1})	DD (m)	SC (sm^{-1})	10^{-4}BQ (sm^{-2})	$10^{-7}CQ^2$ (s^2m^{-5})
	1	864	11.4	75.9		
	2	1123	17.9	62.8		
	3	1296	23.9	54.2		
PW2	4	1512	33.1	45.7	13.0	100.0
	1	4320	1.7	2526.3		
	2	5616	1.9	2894.9		
	3	6653	2.1	3168.0		
PW3	4	7344	2.2	3368.8	5.0	0.3
	1	1037	2.4	426.7		
	2	1296	3.8	344.7		
PW4	3	1555	5.0	309.2	6.0	20.0
	1	1123	0.5	2496.0		
	2	1382	0.5	2608.3		
PW6	3	1555	0.7	2356.4	3.0	0.5
	1	3456	2.5	1376.9		
	2	4320	3.9	1113.4		
	3	6048	6.2	973.9		
PW7	4	6912	10.4	667.8	0.3	2.0
	1	2592	5.8	447.7		
	2	2938	12.3	238.8		
PW8	3	3283	15.9	206.6	-73.0	40.0
	1	864	1.5	595.9		
	2	1123	2.9	394.1		
PW11	3	1382	4.3	320.0	-7.0	30.0
	1	5184	2.3	2293.8		
	2	6048	3.7	1648.0		
PW12	3	6912	4.8	1455.2	3.0	1.0
	1	691	0.1	6283.6		
	2	1296	0.3	3927.3		
	3	1953	0.7	2914.4		
TW6-2008	4	2592	1.1	2468.6	0.8	1.0

Where

Q = discharge

DD = drawdown

SC = Specific capacity

BQ and CQ^2 indicated in Equation 3.1

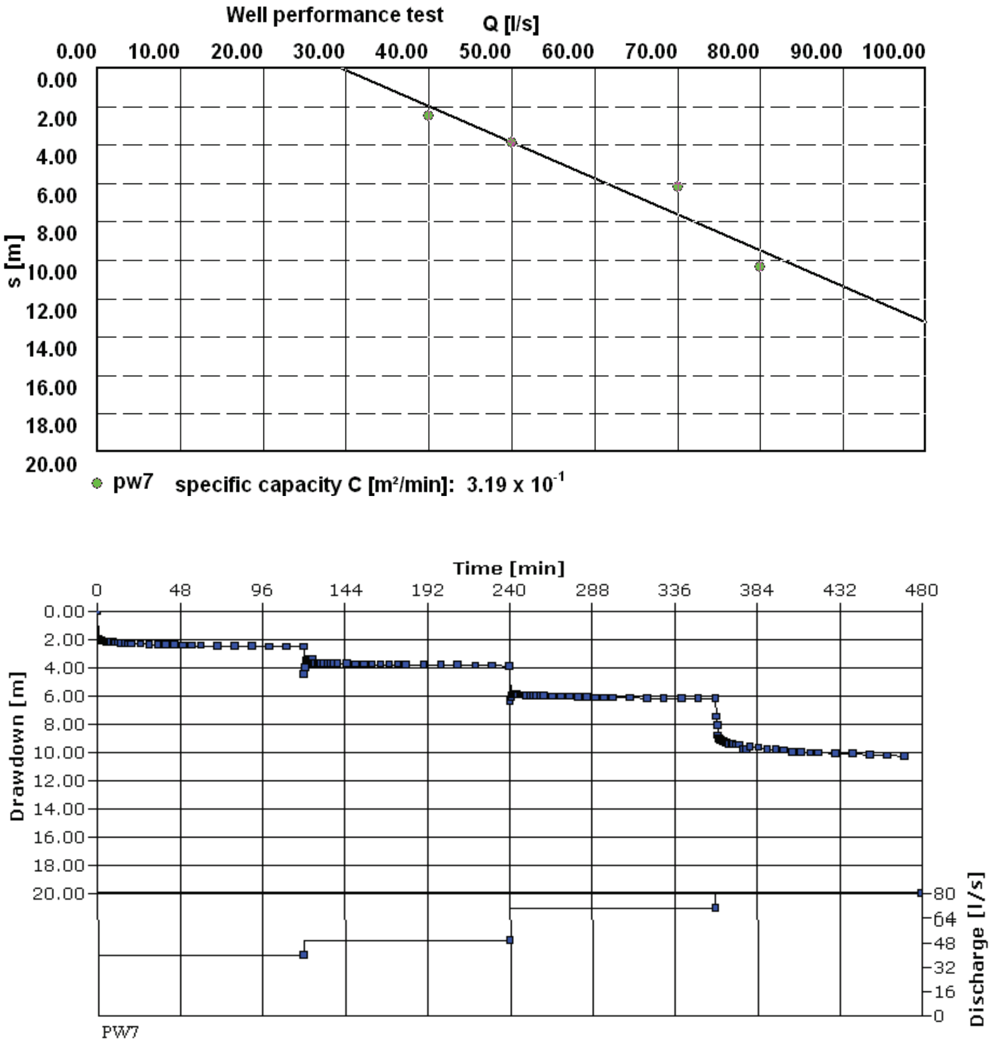


Figure 3-2: Step drawdown and well performance test (example PW7)

3.2. Groundwater level records

The groundwater levels in the Aynalem wells are not well monitored. Most of the wells in the wellfield are not well accessible to measure the water level and a lot of the wells are constructed without observation pipe. Also for wells constructed with observation pipe the measuring ceased after some time. Out of more than fifteen functional boreholes only for seven wells monitoring data were collected for four years. Even for the monitoring wells the recorded data are not continuous and contain a lot of errors.

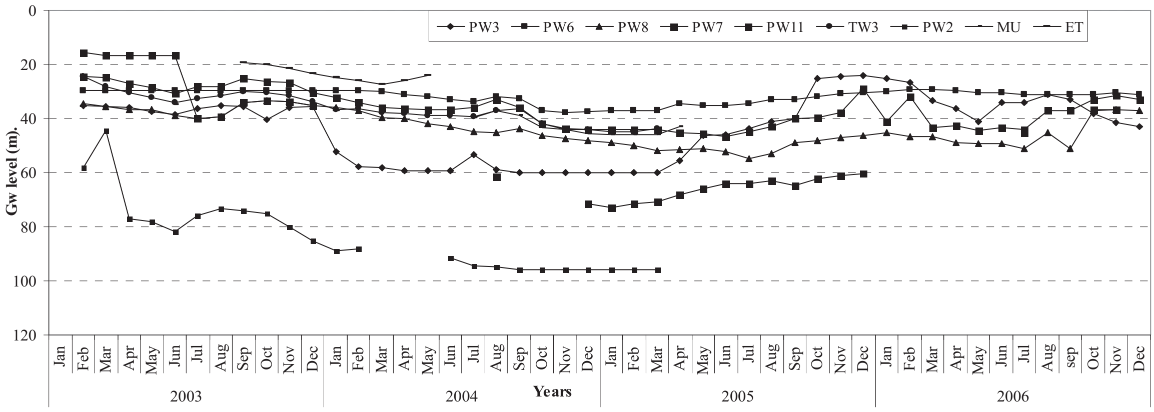


Figure 3-3: Monthly groundwater levels for monitoring wells

When most of the wells were drilled, were designed for a period of twenty years. However, after two years pumping, several wells have dried up and the groundwater level of the wellfield has declined an average of 27.5 m. The groundwater levels show a direct response to rainfall. As can be observed from Figure 3.4 below in months of low rainfall, the groundwater level also declined.

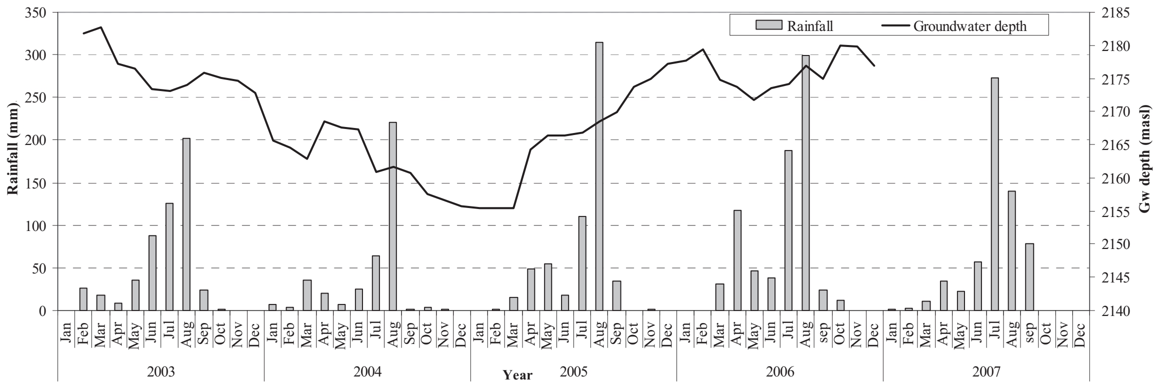


Figure 3-4: Average depth to groundwater and monthly rainfall the Aynalem wellfield

3.3. Well abstraction analysis

More groundwater has been abstracted from the Aynalem wellfield since 1998/99 for the water supply of Mekele town. According to WWDSE (2006), since 1981 the daily production of Aynalem was only 882 m^3 day^{-1}, mainly from spring and one well. Since 1998/99 more than 40 wells were drilled for public and private use but more wells are abandoned. At this time not more than 20 wells are functional. The abstraction data of the boreholes indicates that even the functional wells are not continuously operational. Five years abstraction (2003 to 2007) data were collected and average daily abstraction is calculated 7346 m^3d^{-1} depending on the continuous functional wells. All the functional wells no operate in the same time window. Previously wells have been clustered in the northwest of the catchment. Additional wells are drilled with increasing depth and the wellfield is expanding to the eastern of the catchment. The abstraction rate for the functional wells are summarized in Table 3.4 and total monthly abstraction rates are indicated the Figure 3.5.

Table 3.4 Daily average abstraction for the operational wells

Well-id	East (UTM)	North (UTM)	Altitude (m)	Q (m^3d^{-1})
MU	552511	1489648	2209	448
PW2	556722	1487915	2223	1082
PW3	553941	1488821	2206	511
PW8	557809	1488359	2242	1529
TW2	556722	1487915	2223	972
PW11	552490	1489376	2197	165
ET	552315	1488492	2175	506
PW-7B	557108	1488028	2224	1173
PW-4B	553706	1488251	2200	589
TW12005	561057	1487352	2274	1567
TW42005	557234	1488028	2232	1307
TW3	552945	1488663	2195	355
Ms	552590	1488475	2194	205
TW5	553207	1488955	2205	198

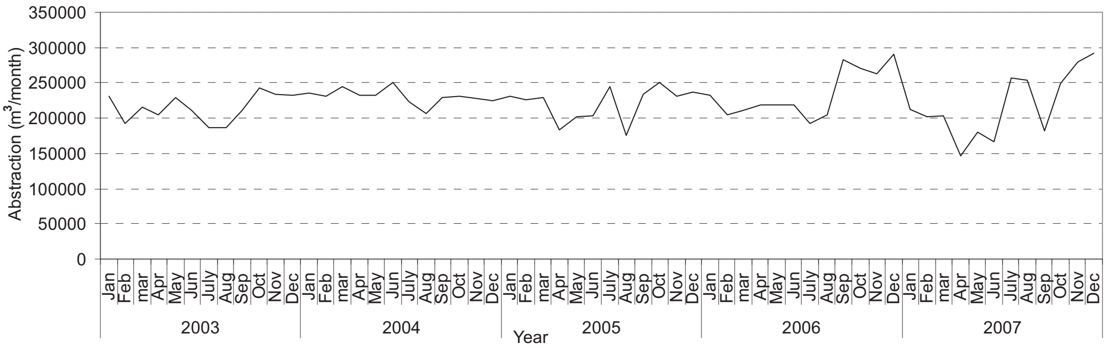


Figure 3-5: Monthly well abstractions for monitoring wells

3.4. Climatic data

Monthly meteorological data was collected from National Meteorological Agency Mekele Branch Office for Airport station which located in the study area. The climatic data rainfall, temperature, humidity, sunshine duration and wind speed for 1992 to 2007 were collected and processed (Figure 2.5). The main influences on weather circulation in Ethiopia are Inter Tropical Convergence Zone (ITCZ), the north-eastern trade winds and the south-western monsoons (WWDSE, 2006). The catchments under study (Aynalem) also have characteristics of receiving rain from the movement of ITCZ towards northern part of the country, during wet season. Additionally the influence of warm moist air mass and continental dry mass contributes for the formation of rain in this area.

3.4.1. Precipitation

The rainfall pattern of the study area is mono-modal type with most of the rainfall occurring in wet season (July and August). 70% rainfall occurs in these two months and the rest 30% occurs the dry season. Depending on the available recorded data, the average annual rainfall is 602 mm. In the 16 years period the highest rainfall is occurred in 2006 and lowest in 2004, with rainfall amounts of 755 mm and 390 mm per year respectively (Figure 3.6).

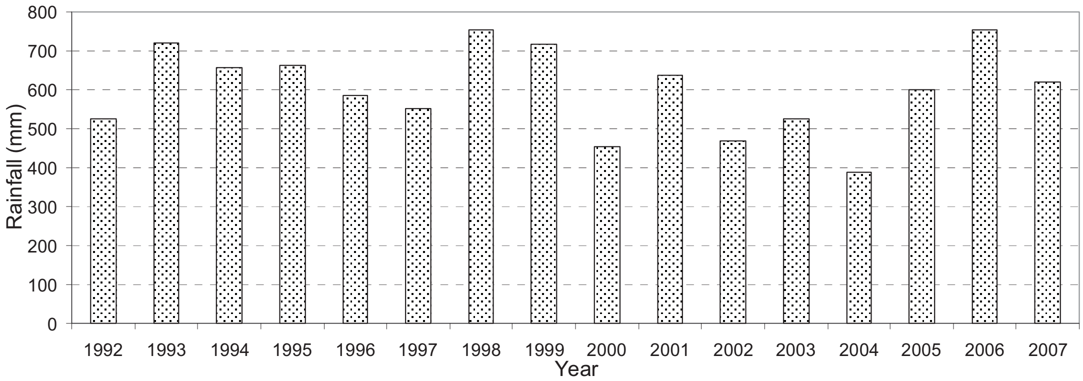


Figure 3-6: Annual rainfalls for Mekele Airport station.

3.4.2. Temperature

The variability of mean monthly temperature recorded from the stations is 16 - 20^{0}C. The maximum temperature is in the range of 22 to 27^{0}C, while the minimum is 9 to14^{0}C. The monthly variation of temperature is high in May and low in December.

3.4.3. Sunshine duration

The length of sunshine hours greatly affects the rate of evapotranspiration. Mean monthly sunshine duration varies from 9.9 hrs day^{-1} (December) to 5.3 hrs day^{-1} (August).

3.4.4. Relative humidity

The rate of actual and potential evapotranspiration is greatly influenced by the relative humidity and the temperature at which the vapour pressure is measured. According to the record made on these stations the mean monthly relative humidity varies from 75 % (August) to 39 % (May).

3.4.5. Wind speed

Mean monthly wind speed measured at 2m height is used for the analysis. The mean monthly wind speed is varying from 1.7 ms^{-1} to 4.1 ms^{-1}.

Table 3.5 Mean monthly values of climatic data

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean T_{max} (^{0}C)	22.9	24.3	25.1	25.6	26.8	26.8	23.1	22.2	24.2	23.4	22.4	22.2
Mean T_{min}(^{0}C)	9.4	10.5	12.0	13.3	13.9	13.5	13.2	13.0	11.7	11.1	10.7	9.7
T_{mean} (^{0}C)	16.1	17.4	18.5	19.5	20.4	20.1	18.1	17.6	17.9	17.3	16.5	15.9
Sunshine (hrs d^{-1})	9.6	9.7	9.0	9.3	9.8	7.6	5.3	5.2	7.8	9.5	9.8	9.9
Rel. humid. (%)	46.0	41.0	41.0	42.0	39.0	43.0	71.0	75.0	52.0	44.0	47.0	44.0
U_2 (ms^{-1})	3.6	4.1	4.1	3.9	3.2	2.4	2.0	1.7	1.7	2.9	3.5	3.7

3.4.6. Evapotranspiration

The potential evaporatranspiration for the study area was calculated using the Hargreaves method and Penman-Monteith method (Equation 3.2 and 3.3 respectively).
(Note: the name potential evapotranspiration is referring to the reference evapotranspiration).

$$ET_o = 0.0023(T_{\max} - T_{\min})^{0.5}(T_{mean} + 17.8)R_a \tag{3.2}$$

Where:

ET_0	=	potential evapotranspiration [mm day^{-1}]
T_{max}	=	maximum temperature [^{0}C]
T_{min}	=	minimum temperature [^{0}C]
T_{mean}	=	mean temperature [^{0}C]
R_a	=	extraterrestrial short wave radiation [mm day^{-1}].

The Penman-Monteith method equation is given as:

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3.3}$$

Where:

ET_0	=	Potential evapotranspiration [mm day^{-1}]
R_n	=	Net radiation [MJ m^{-2} day^{-1}]
G	=	Soil heat flux density [MJ m^{-2} day^{-1}]
T	=	Air temperature at 2 m height [^{0}C]
u_2	=	Wind speed at 2 m height [m s^{-1}]
Δ	=	Slope vapor pressure curve [kPa ^{0}C^{-1}]
γ	=	Psychometric constant [kPa ^{0}C^{-1}]
e_s and e_a	=	Saturation and actual vapor pressure respectively [kpa]

The results of the two methods were compared and low correlations are found (Figure 3.7). Since wind speed in the study area is very high, especially in the dry season the Hargreaves method gives lower evapotranspiration estimates than the Penman-Monteith method. The Hargreaves method requires only maximum and minimum air temperature (Equation 3.2). The Penman-Monteith method is considers all the meteorological data for the computation of potential evapotranspiration, ET_0 (Allen et al., 1998).

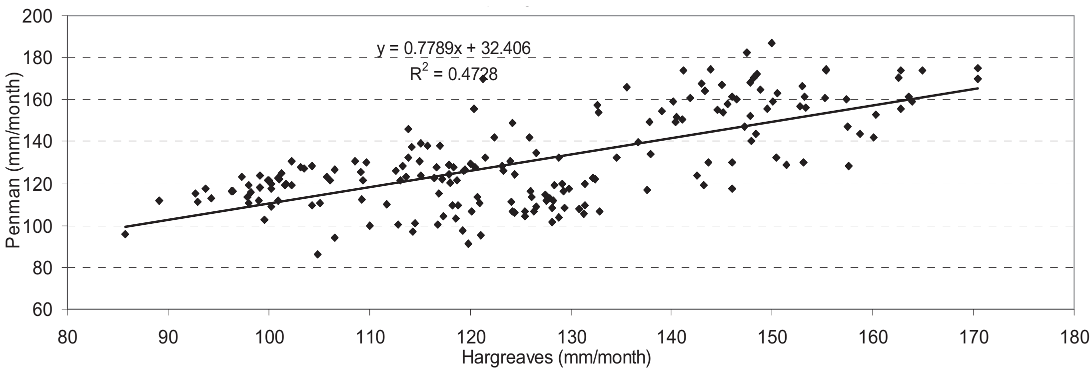


Figure 3-7: Potential Evapotranspiration of Penman and Hargreaves methods

The potential evapotranspiration ET_0 calculated by Penman-Monteith was used for the estimation of actual evapotranspiration and the mean monthly potential evapotranspiration is summarized in Table 3.6 below.

Table 3.6 Mean monthly ET_o

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_0 (mm month^{-1})	123.8	136	157.4	159.3	163.6	139.5	112.1	101.7	114.4	126.4	115.9	118.5

3.5. River discharge

Aynalem River is the only river in Aynalem catchment. Discharge data recorded is available from 1992 to 2001 and was collected at Metere gauging station which is located at some distance upstream from the outlet (553925E, 1486922N) and covers 69 km^2. There is no gauging station in the outlet of the catchment. As shown on Figure 3.8 below more than 90% of the annual flow is generated in July, August and September. Due to the fact that there are intense rainfall showers and scarce vegetation, during the rainy season frequent floods are occurring. As can be seen from the hydrograph (Figure 3.8) the peak discharge is observed in high rainfall months showing direct response to the rainfall.

Table 3.7 Mean monthly flow Aynalem river (1992 to 2001)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Runoff (Mm^3)	0.02	0.00	0.00	0.02	0.03	0.08	1.10	2.47	0.82	0.12	0.08	0.04

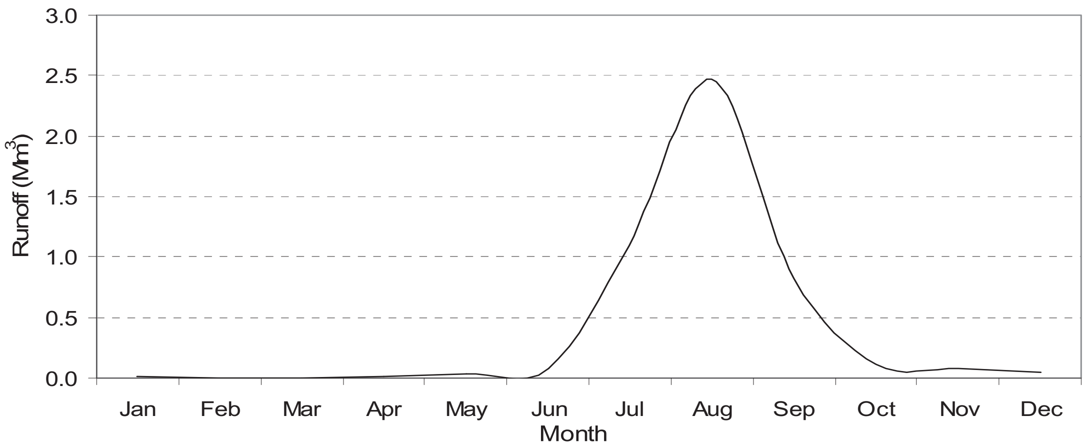


Figure 3-8: Average hydrograph of Aynalem River (1992 to 2001)

3.6. Groundwater recharge estimation

3.6.1. Concept of WATBAL_GW

The methodology selected for the estimation of groundwater recharge using WATBAL: an integrated water balance model. The WATBAL model was used to calculate the groundwater recharge input for the transient state model and at the same time to have an idea the water balance of the Aynalem sub-catchment. WATBAL model is developed for assessing the impact of climate change on river basin runoff. The conception of the model was originally developed by David Yates in USA (Yates, 1996). Yates realized the entire system of the model through the Microsoft Excel 5.0 electronic software worksheet (Kestutis Kilkus, 2006). The model has been modified by combining it with a linear reservoir of 1D EARTH (LINRES) model and incorporating of groundwater abstraction for estimation of groundwater recharge of the study area. The linear reservoir is a useful and accurate optimization part of the model in order to fit the calculated and measured groundwater levels (Hiwot, 2008). The combined model is called WATBAL_GW and implemented in DELPHI 6 (Gieske and Gebrehaweria, 2008).

WATBAL accounts for changes in the soil moisture by taking into account precipitation, runoff and actual evapotranspiration (AET), while using potential evapotranspiration (PET) to drive the extraction of water from the soil moisture. The uniqueness of this lumped conceptual model to represent water balance is the use of continuous functions of relative-storage to represent surface outflow, sub-surface outflow, and evapotranspiration and storage is lumped as a single, conceptualized bucket (Figure 3.9). The water balance component of the model comprises six parameters related to a) direct runoff (β), b) surface runoff (ε), c) sub-surface runoff (α and γ), d) maximum catchment water-holding capacity (S_{max}) and e) base flow (R_b). The monthly soil moisture balance is written as:

$$S_{\max} \frac{dz}{dt} = P_{eff}(t)(1-\beta) - R_s(z,t) - R_{ss}(z,t) - AET(PET, z, t) - R_b \qquad (3.4)$$

Where:

P_{eff}	=	Effective precipitation (LT^{-1})
R_s	=	Surface runoff (LT^{-1})
R_{ss}	=	Sub-surface runoff (LT^{-1})
AET	=	Actual evapotranspiration (LT^{-1})
PET	=	Potential evapotranspiration (LT^{-1})
R_b	=	Base flow (length/time)
S_{max}	=	Maximum storage capacity (L)
z	=	Relative storage (-) ($0 \leq z \geq 1$)

S_{max}, the maximum water holding capacity of a catchment reflects the relative importance of water storage on the hydrological regime of a catchment. It is dependent primarily on the nature of catchment geology and soils. The storage variable, z, is given as the relative storage state and is a value between 0 and 1. Consequently, when S_{max} is multiplied by z, it gives the volume of water stored in the catchment at any given time (WWDSE, 2006). Effective precipitation, potential evapotranspiration, runoff and average groundwater level for calibration, are time series inputs for the model.

Effective precipitation (P_{eff}) must be corrected for orographic effects, gauging errors and seasonal fluctuations. The effective precipitation for input of the model was corrected as:

$P_{eff} = 0.95P$, Where P is precipitation (3.5)

Actual evapotranspiration (AET) is a function of potential evapotranspiration (ET_0) and the relative current storage state (z). Potential evapotranspiration (ET_0) was calculated using the Penman-Monteith equation (Equation 3.3). A non-linear relation is used to compute the actual evapotranspiration (AET) from potential evapotranspiration (ET_0).

$$AET(z, ET_o, t) = ET_o\left(\frac{5z - 2z^2}{3}\right) \tag{3.6}$$

Surface runoff (R_s) is described in terms of the storage state, z, the effective precipitation, P_{eff} and base flow. ε, is a calibration parameter that allows for surface runoff to vary both linearly and non-linearly with storage.

$$R_s(z, P_{eff}, t) = \begin{cases} z^{\varepsilon}(P_{eff} - R_b) & \text{for } P_{eff} > R_b \\ 0 & \text{for } P_{eff} \leq R_b \end{cases} \tag{3.7}$$

Direct runoff (R_d) is a function of the effective precipitation P_{eff}. β is the proportion of effective precipitation that becomes direct runoff.

$$R_d = \beta P_{eff} \tag{3.8}$$

Sub-Surface runoff (R_{ss}) is a function of the relative storage state and a multiplied by a coefficient α. In most cases the value of γ is 2.

$$R_{ss} = \alpha \ z^{\gamma} \tag{3.9}$$

It assumed that in the early 1990s groundwater abstraction was small and base flow and subsurface runoff was high. As groundwater abstraction increased base flow plus subsurface runoff decreased. The base flow (R_b) must be entered into the model as a constant value, determined by the user. Well abstraction (W) depends on water abstracted from the groundwater pumped by the functional wells. The groundwater recharge for each time step is the sum of sub-surface flow and base flow.

$$R = R_{ss} + R_b \tag{3.10}$$

Where:

R	=	Recharge (L T^{-1})
R_{ss}	=	Sub-surface flow (L T^{-1})
R_b	=	Base flow (L T^{-1})

The linear reservoir equation is as follows

$$S\frac{dh}{dt} = -\frac{h}{D} + R \tag{3.11}$$

Where:

S	=	Storage coefficient (-)
R	=	Recharge (L T^{-1})
H	=	Water level (L)
D	=	Time (T), DS = 12 month

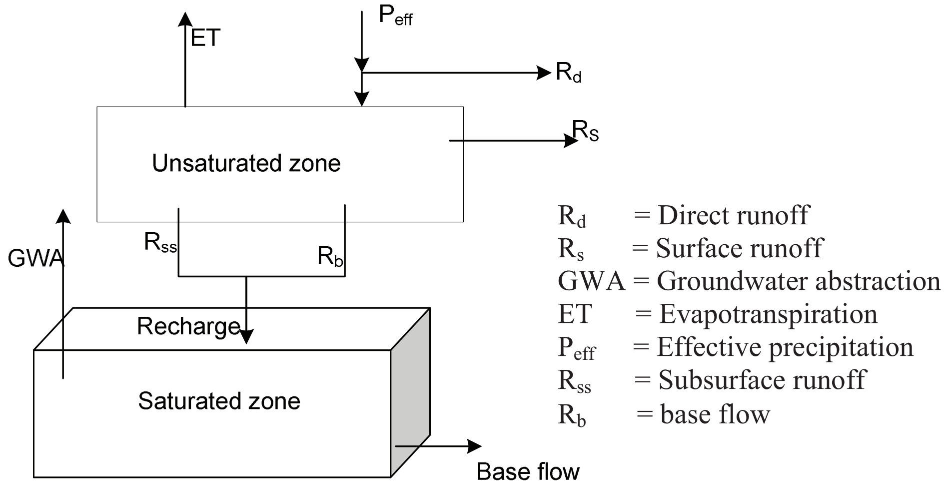


Figure 3-9: Concept of the WATBAL_GW model

The base flow from the saturated zone includes the groundwater outflow in the general head boundary, seepage to rivers from river banks, Aynalem springs and swamps (ceased to flow now) and groundwater evapotranspiration.

3.6.2. Calibration and output simulation

3.6.2.1. Calibration

The monthly meteorological data record used for the Aynalem catchment spans the years 1992 to 2007 except runoff data which is from 1992 to 2001. The data for groundwater abstraction and groundwater level monitoring were only available form 2003 to 2007 and 2003 to 2006 respectively. Groundwater abstraction before 2003 was not recorded and estimation was considered. Based on conceptual approximation described above and time series data input, WATBAL_GW simulations are performed. Consequently it is necessary to adjust or optimize parameters until the model output is an acceptable estimate of the observed runoff and groundwater level. In order to do this it is necessary to use observed runoff data and groundwater level against which to calibrate parameter values. Therefore the observed runoff Aynalem River from 1992 to 2001 and the groundwater level monitoring from 2003 to 2006 were used for the calibration of the model. The calibration surface flow parameters used in the WATBAL_GW model sub-surface runoff exponent, γ, sub-surface runoff coefficient, α, surface runoff exponent, ε, maximum storage, S_{max}, and direct runoff coefficient, β and linear groundwater parameters storage coefficient, S, D, h_o and h_{base}. Optimal model parameters is rarely found on the first model run, consequently fine-tuning of parameters are needed, which is done manually.

3.6.2.2. Output simulation

For the estimation of potential evapotranspiration in the sub-catchment the Penman method was selected (Section 3.4.6). Other climatic parameters such as temperature, relative humidity, sunshine duration, wind speed and rainfall were taken from the observations of the Airport station. The groundwater level data collected during the field campaign from Mekele water supply office was used. The model is then applied for sub-catchment using the climatic parameters, runoff generated in the Aynalem sub-catchment and groundwater level from the wellfield. For simulation purposes the model is calibrated against ten years (1992 to 2001) monthly runoff data and monthly groundwater level for four years (2003 to 2006) by minimizing the differences between the observed and simulated values. The reliability of the calibration model was ensured by fitting a graph between observed and model simulated runoff and groundwater level data (Figure 3.11) and with RMSE (Equation 3.11) and Nash-Sutcliffe coefficient of efficiency of the runoff modelling (Equation 3.9). Nash–Sutcliffe coefficient measures the efficiency by relating goodness of fit to the variance of the observed data (Abeyou, 2008). Nash –Sutcliffe efficiency can range from -∞ to 1. An efficiency of 1 corresponds to perfect match of modelled data to observed data. An efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data. Where as an efficiency less than zero ($-\infty < NS^2 < 0$) occurs when the observed mean is a better predictor than the model.

$$NS = \frac{\sum_{i=1}^{n}(q_{obs,i} - q_{calc,i})^2}{\sum_{i=1}^{n}(q_{obs,i} - \bar{q}_{obs})^2} \qquad (3.11)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(q_{obs,i} - q_{calc,i})^2}{n}} \tag{3.12}$$

According to the simulation result the maximum soil moisture depth of the sub-catchments is 1300 mm. The time series of the maximum soil moisture is a function of the relative depth (z). The groundwater recharge was estimated based on WATBAL_GW model result as 32 mm per year (5% of the annual rainfall) and the actual evapotranspiration is 490 mm/year. The average observed ($Q_{obs.avg}$) and calculated ($Q_{cal.avg}$) discharge of the Aynalem River is 53 mm/year and 55 mm/year respectively. Based on Equation 3.11 and Equation 3.12 the Nash-Sutcliffe coefficient (NS^2) and RMSE for the discharge are 0.71 and 5.87 Mm^3/month respectively. Optimised parameter values after calibration of the WABAL_GW are shown in Table 3.8 and Table 3.9. The water balance of the catchment is also calculated and is shown in Table 3.10. Figure 3.10 compares graphically the observed and simulated monthly flow volumes at Aynalem sub-basin, groundwater level, groundwater abstraction and base flow. As can be observed from Figure3.10 the observed and simulated match reasonably well for the calibration period.

Table 3.8 Surface flow parameters Watbal_GW after manual calibration

α	50	Mm^3/month
β	0.02	(-)
γ	1.8	(-)
ε	2	(-)
S_{max}	1300	mm
R_b	0.1	Mm^3/month
z_0	0.2	

Table 3.9 Linear groundwater reservoir Watbal_GW

S	0.001	
D	12000	
h_0	40	m
h_{base}	20	m

Table 3.10 Average annual water balance for 16 years (1992-2007), mm/year

R_d	11.4	**total runoff**	50.1
R_s	38.7		
R_{ss}	30.6	**total recharge**	31.8
R_b	1.2		
		base outflow (spring) (bank seepage) (dam) (gw outflow)	13.9
		gw abstraction	20.2
		depletion	-2.3

Table 3.11 Average annual water balance for 16 years (1992-2007) m^3/day

R_d	3311	total runoff	14550
R_s	11239		
R_{ss}	8887	total recharge	9235
R_b	348		
		base outflow (spring) (bank seepage) (dam) (gw outflow, gw ET)	4037
		gw abstraction	5866
		depletion	-668

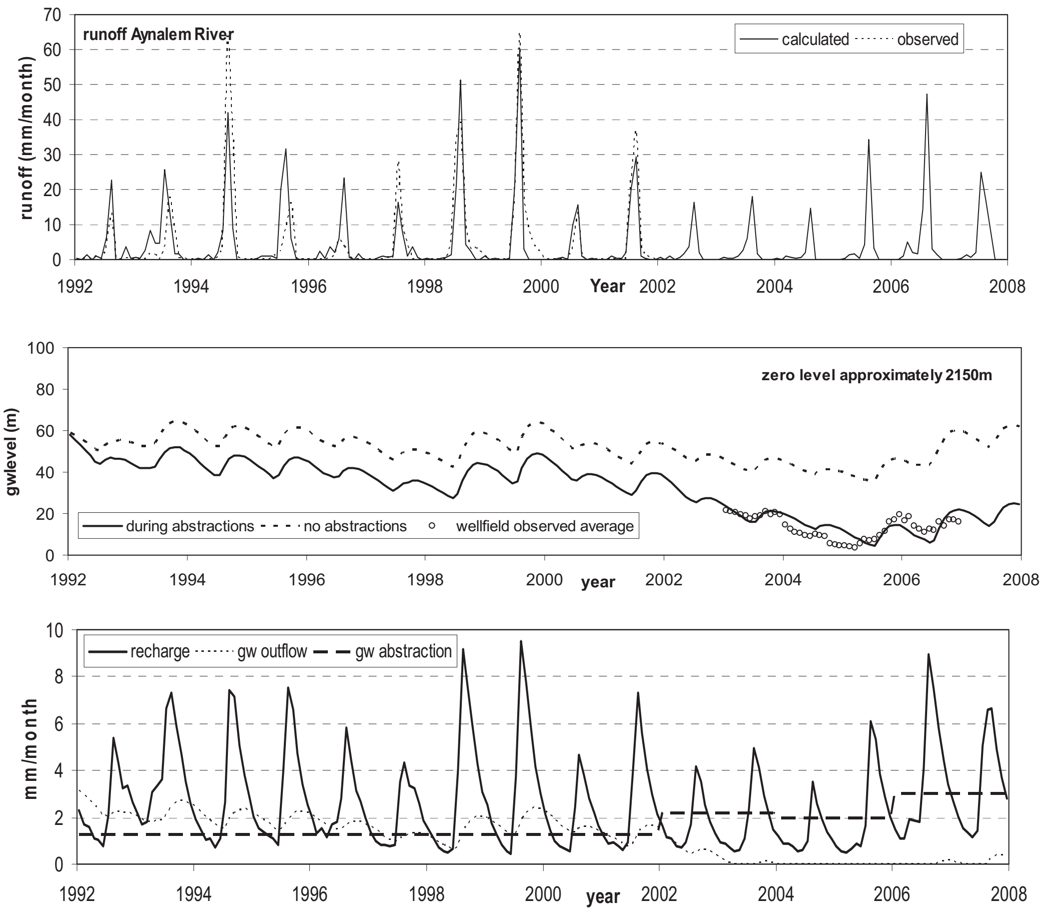


Figure 3-10: Calibration of result of WATBAL_GW for the Aynalem catchment

4. Conceptual and Numerical Groundwater Model

4.1. Conceptual model boundaries

4.1.1. Introduction

A conceptual model is a pictorial representation of the groundwater flow system, frequently in the form of a block diagram or a cross section. It is a simplified but valid representation of field situation. Developing a conceptual model is the most important part of the modelling process. Its significance is to simplify the field situation and to organize associated field data for easy analysis of the system and also determine the dimensions of the numerical model and the design of the grid (Shaki and Adeloye, 2007).

To build a conceptual model the concept of hydrographic unit will be apply. This concept implies that units having similar hydro-geological properties may be combined into a single hydrostratigraphic unit or a geological formation may be subdivided in to aquifers and confining units depending on their hydrogeological characteristics (Anderson and Woessner, 1992). In general more valid data is needed for construction of a model. The extent of the aquifer location and boundaries, the flow of water into and out of the aquifer (recharge and discharge zones), hydrostratigraphic unit, area of interconnection for surface water and groundwater are the most important data for the conceptual model. The conceptual model of Aynalem (study area) is developed by making use of existing well and geophysical log data, hydrostratigraphic, geological map and geological cross section and topo sheet and DEM extracted from ASTER images of previous reports.

4.1.2. Hydrostratigraphic units and well log results

Hydrostratigraphic units are defined as geological units of similar hydrogeologic properties. In modelling regional flow systems, aquifers and confining beds are defined using the concept of hydrostratigraphic units that comprise geological units of similar hydrogeological properties. Several geological formations may be combined into a single hydrostratigraphic unit or a geological formation may be subdivided into aquifers of confining units (Anderson and Woessner, 1992). Geological formation including geological maps and cross sections, well logs and borings are combined with formation on hydrogeological properties to define hydrostratigraphic units of the conceptual model. The main hydrostratigraphic units of the study area are comprised Limestone, shale and dolerites. The main water bearing formation in the area is a limestone unit and the weathered and fractured part of dolerite. The geophysical and test drilling has shown that the groundwater in the study area is mostly confined to semi-confined because of the alternating layers of shale, marl, limestone and dolerite, and due to the tectonic folds and fractures (DEVECON, 1993).

Interpretation of subsurface hydrogeology is possible wherever there is a well log or bore test. Lithological log of wells can indicate high porosity and permeability area and can be important in defining the hydrostratigraphic unit for better understanding of subsurface aquifer. Well log data in the wellfield are collected from previous reports and different drilling companies (Appendix 7). The data show that the geological units are highly variable in lateral and vertical extent. This vertical extent caused by dolerite dykes intruded in the sedimentary formations. In areas where these intrusion dolerites exist, extensive tilting and fracturing of sedimentary layers have occurred. In almost all well log data, massive and less permeable dolerite is encountered at depth which acts as a barrier to groundwater flow (Gebrerufael, 2008). As obtained from previous reports, cross section constructed from well log lithological data indicates that vertical and lateral distribution of dolerite intrusion is highly variable (Figure 4.1). In some areas the dolerite is in shallow depth (PW7) and even exposed at surface where as, in other areas within limited horizontal distance it is found deeper (PW8) and even absent with depth (PW9).

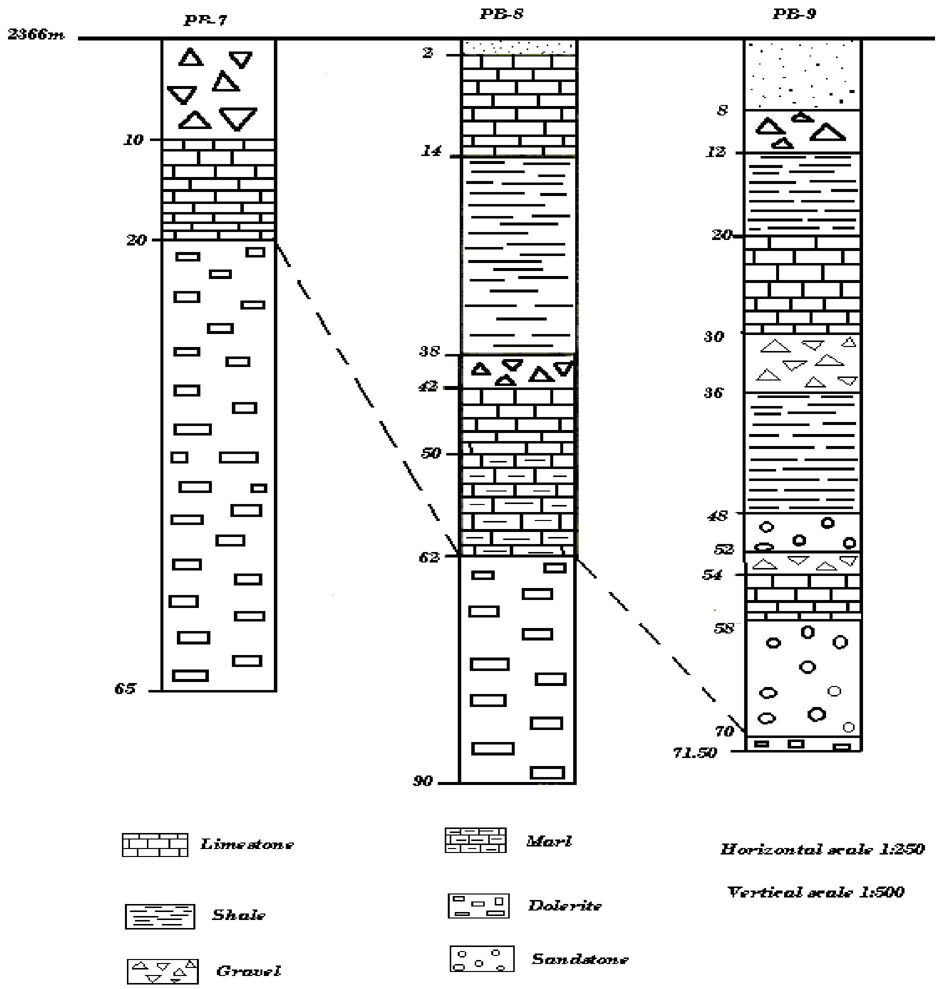


Figure 4-1: Lithological units showing depth to dolerite (after Yehdego, 2003)

4.1.3. Geophysics

Geophysical measurements are used to determine the extent and nature of the geological material beneath the surface, thickness of aquifers and their confining layers, in order to construct a cross-section across the catchment and the depth to water table. The correlation of geophysical data with the well logs is generally more reliable than either type of information used by itself (Fetter, 2001). Electrical resistivity methods are intensively used in the field of hydrogeology for evaluating groundwater aquifers and their hydrogeological conditions. VES is applied in the study of layering below the surface. Previously geophysical investigation was carried out in Aynalem and surrounding catchment for the assessment of groundwater (WWDSE, 2006). A total 107 VES soundies were carried out and 13 of them were conducted near the existing wells, in order to calibrate or estimate the resistivity values range of the major geological formations around them. The interpretations of the VES data were made based on the well log data (lithological and geophysical logging data). For the present study these geophysical data (VES) were collected in order to support in identification of aquifer thickness, geological cross-sections and the hydrostratigraphic units. From the resistivity survey conducted near the water wells, resistivity value ranges for the major formations have been deduced in Table 4.1. The geophysical data are shown in Appendix 10.

Table 4.1 Resistivity value ranges of the major geological formations (afte WWDSE, 2006)

No.	Estimated resistivity range (Ωm)	Main geological formation	Description	Remarks
1	0 - 60	Shale	10-25, wet and 25-60 dry	
2	60 - 280	Limestone	Weathered and fractured	Water bearing
3	200 - 450	Limestone dominant	Hard, less fractured	
4	100 - 300	Dolerite	Decomposed to weathered	
5	300 - 600	Dolerite	Slightly fractured	
6	>600	Dolerite	Massive, hard	Dry

4.2. Numerical groundwater model

4.2.1. Code selection

In order to understand the groundwater system and mathematically simulate the Aynalem wellfield in response to recharge and discharge (pumping), numerical modelling was performed using the MODFLOW. This is a modular-three dimensional finite-difference groundwater model of the U.S. Geological Survey, to describe and predict the behaviour of groundwater flow systems (McDonald and Harbaugh, 2000). MODFLOW simulates the effect of wells, rivers drains, head dependent boundaries recharge and evapotranspiration. The code is based on the flow equation of Darcy and mass continuity equation. The partial differential equation on which MODFLOW is based can be written as follows:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right)-W = S_s \frac{\partial h}{\partial t} \quad (4.1)$$

Where:

k_x, k_y and k_z	=	Hydraulic conductivity along *x, y,* and *z* respectively [LT^{-1}]
h	=	Hydraulic head [L]
W	=	Flux per unit volume of sources and/or sink [T^{-1}]
S_s	=	Specific storage [L^{-1}]
t	=	time [T].

The simplified conceptual model is two dimensional (x, y). Numerical modelling can be performed under steady state conditions where the magnitude and direction of the flow are constant with time or under transient state condition where the magnitude and direction of the flow velocity changes with time.

4.2.2. Lateral and vertical aquifer boundaries

Boundary conditions are mathematical statement, specify the dependent variable (head) or the derivative of the dependent variable (flux) at the boundary of the problem domain (Anderson and Woessner, 1992). The boundary condition can be physical boundaries formed by an impermeable body of rock, large water bodies or result of hydrological condition of groundwater divides or stream lines.

Boundary conditions of the modeled area were defined based on information acquired from the geology, topography and flow system existing in the area. Physical boundaries including impervious geologic formations, fault escarpments, topographic and surface water divides are used in defining the boundaries of the model domain. Aynalem sub-catchment is physically separated by dolerite ridge lines from adjacent sub-catchments of Chelekot and Ilala (Figure 4.4). The dolerite ridge lines form the northern, southern and eastern boundary of the study area. These natural features act as no-flow boundaries as they are considered coincident with groundwater divides and groundwater fluxes across the water divides are assumed negligible. The western outlet of the wellfield was assigned as general head a boundary assuming that the groundwater is outflow from the aquifer is through this boundary (Figure 4.5). At the bottom of the layer, no-flow boundary was assigned assuming that the boundary coincides with the massive dolerite sill (Figure 4.6).

Figure 4-2: The General Head Boundary model area at the western outlet.

Figure 4-3: Dolerite outcrop in the study area forming ridges

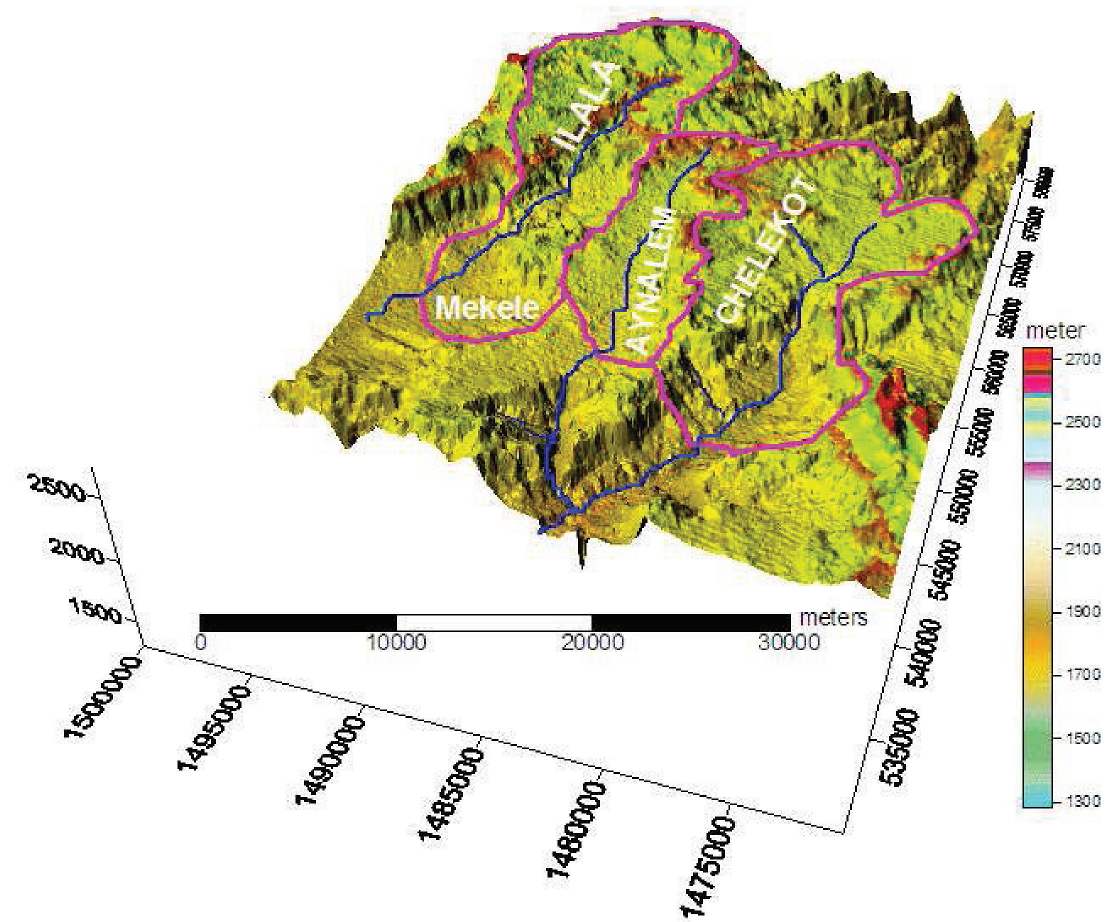


Figure 4-4: Topographic maps Mekele valleys (after Gebrerufael, 2008)

In order to simplify the field situation of the model area, depending on geophysical and lithological well log the limestone unit and the fractured and weathered dolerite were considered as an aquifer of 50 m thickness. Whereas, the interebedded shale and massive dolerite are considered as an impermeable lower boundary, the water table is considered as upper boundary (Figure 4.6).

The following simplifying assumptions were made for the model area of Aynalem wellfield:

- The geological formations are considered horizontal;
- The Aynalem river is gaining river from the Aynalem wellfield in average
- Groundwater flow from adjacent catchments is negligible
- Groundwater evapotranspiration from Aynalem groundwater is insignificant

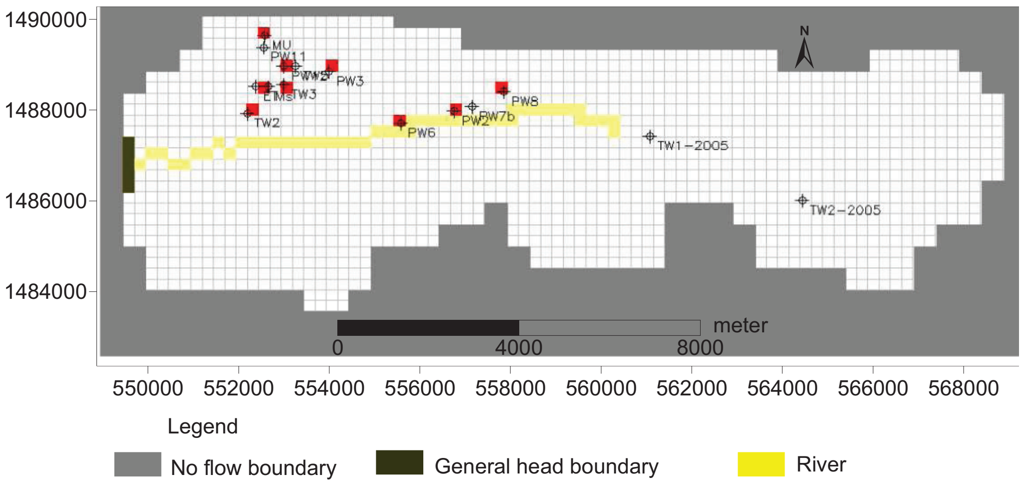


Figure 4-5: Boundary conditions of study area

In the Aynalem wellfield the distribution, occurrence and flow of groundwater is highly governed by dolerite sills (WWDSE, 2006). The occurrence of dolerite sills in depths classifies the groundwater into a shallow and a deep aquifer. This study only considers the shallow aquifer with 50 m thickness based on the lithological and geophysical boundaries discussed above. Due to the lack of data for the deep aquifer system, the deep aquifer is not included in this study. The simplified concept system of the sub-catchment is shown in Figure 4.6.

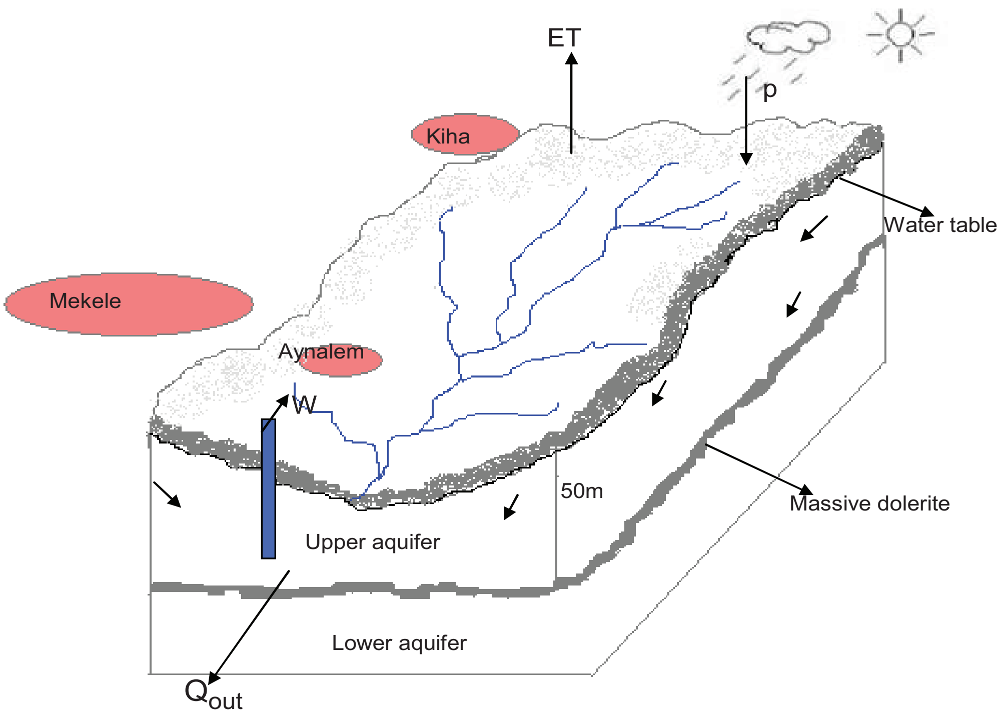


Figure 4-6: Simplified representation of study area

4.3. Steady-state model

The steady state model of Aynalem wellfield was developed and calibrated by Gebrerufael (2008) in his MSc thesis. The horizontal extent of the model domain is 8 by 20 km bounded by 548820 to 569251 m UTM East to 1482054 to 1490288 m UTM North. The model domain area is reduced into 104 square kilometres due to irregular shape of the catchment. The steady-state model was set up as one layer two dimensional with confined to semi-confined aquifer. The model area is discretized to one layer with regular grid of 250m by 250m, 32 rows and 82 columns consisting of 1492 active cells. Based on resistivity and seismic data, the geological and geophysical logs and well completion data obtained from previous reports, the following hydrostratigraphic units were determined: limestone-shale marl intercalation, limestone and dolerite. The top and bottom elevation of the aquifer system are defined based on the lithological logs and a DEM extracted from the ASTER image. All the horizontal boundaries of the Aynalem aquifer correspond to natural water divides, except the outlet in the western part of the catchment that is 1250 m wide. The water divides were assigned as laterally no-flow boundary to adjacent catchment. The western outlet of the catchment is assigned as a General Head Boundary (GHB).

4.3.1. Water balance components

4.3.1.1. Groundwater recharge

Groundwater recharge of the Aynalem catchment is received from direct rainfall and seasonal flood by the surrounding topographic elevated ridges of the catchment. The groundwater recharge process of Aynalem catchment is highly controlled by topography, geology and structure which direct the infiltrated water towards the discharge area (Gebrerufael, 2008). The groundwater recharge was estimated using the chloride mass balance method as 30 to 40 mm year^{-1} (4.5 to 6% of the average annual rainfall). The recharge was uniformly applied to the top most active cell using the recharge package of MODFLOW. The recharge obtained after model optimizing was similar with the result of chloride mass balance method which is 42 mm year^{-1} (6% the average annual rainfall).

4.3.1.2. Groundwater discharge

Groundwater is discharged from the Aynalem aquifer by well abstraction, seepage as spring into Aynalem River and swamps and groundwater flow through the western outlet. Aynalem River is the only river in catchment and it is well connected with aquifer of the wellfield system which feeds water as springs and seepages along the river banks. During the field campaign we observed that springs flowing into the river in through the contact of permeable and less permeable layers. Groundwater abstractions through wells are the main groundwater discharge at this time from the aquifer. On average 7346 m^3 groundwater is abstracted from the wellfield daily. Groundwater outflow through the western outlet by a saturated aquifer depending on the hydraulic gradient in the wellfield under natural condition is about 12960 m^{3}day^{-1} (Gebrerufael, 2008), which was calculated by applying Darcy law. This value was calculated with an average transmissivity value of 540m^{2}day^{-1} which was obtained from pumping test results of previous report. But from the end of 1990s the condition was changed, the groundwater outflow was declined because of increase abstraction of groundwater with pumping wells.

4.3.2. Steady-state model calibration

The steady- state model was calibrated without pumping and with pumping scenario. First the model was calibrated to check the model reliability in generating field condition, when it is subjected only to natural regime without pumping. Static water level records were used to calibrate the steady-state model without pumping. Average groundwater levels of three years monthly data were used to calibrate the steady- state model with pumping (Gebrerufael, 2008). The model was calibrated through trial and error by varying the transmissivity and comparing the calculated and observed heads. With uniform transmissivity the simulated heads deviated significantly from the observed heads but after dividing into different transmissivity zones the best fit results were obtained (Gebrerufael, 2008). The transmissivity values obtained from the steady-state model calibration are lower than the transmissivity values obtained from pumping test of pervious studies. After adjusting the hydraulic parameters, the root mean squared error as performance indicator was found to be 6.42 m. The calibration result was presented in graphical form and tables. The scatter plot observed vs. calculated heads for the non-pumping and pumping scenario are indicated in Figure 4.7.

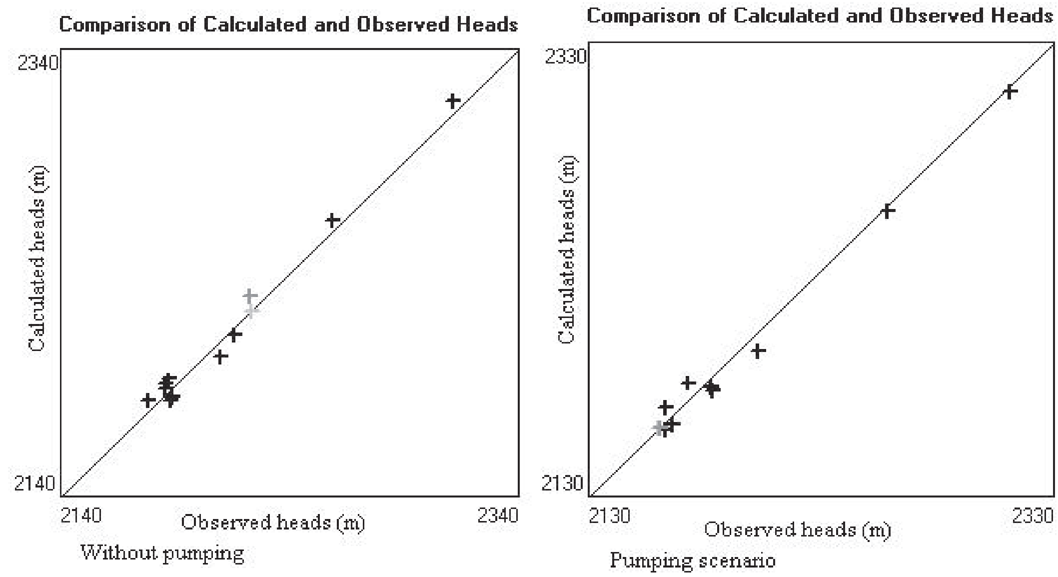


Figure 4-7: Scatter plot steady state model (after Gebrerufael, 2008)

4.3.3. Water budget of steady state model

The groundwater of the Aynalem wellfield was quantified on the basis of the calibrated steady-state model output for non-pumping and pumping scenario (Gebrerufael, 2008). The water budget components include recharge which is the only inflow and outflow to the river, a head dependent outflow through the western boundary and well abstraction (for the pumping scenario) which are outflow components. The inflow and outflow components were of similar order in both cases.

4.4. Transient state model

In transient problems the groundwater heads are a function of time. This applies to problems such as determining the change in head around a pumping well or growth of groundwater mound beneath a recharge basin (Fetter, 2001). A transient simulation typically begins with steady state initial conditions and ends when a steady state is reached. Transient simulations produce a set of heads for each time step. As discussed in section 1.5, transient model can be partially transient or fully transient. The fully transient model is the most reliable but also the least explored probably due to demanding input data. This study has been conducted using water level and recharge data that allow for a fully transient model. Discharge of groundwater by evapotranspiration from saturated zone is not considered in the model, since the saturated zone extends to 40m below the surface and since there are hardly any trees in the area.

4.4.1. Groundwater heads

Groundwater heads are the only observed data for model calibration. In Aynalem wellfield more than 15 wells are operational but only seven boreholes have records of temporal groundwater heads. Groundwater levels are measured from pumping wells. Due to this the groundwater monitoring data is highly affected by transient pumping effects during water level measurements.

4.4.2. Hydrostratigraphic units

A one layer model with regular square grid of 250 x 250m was used. The available geological map and cross-section, geophysical and geological logging and resistivity Vertical Electrical Sounding from previous reports were used to define the hydrostratigraphic units. For the finite difference schematization of the study area, 106 square kilometres was discretized into a uniform square grid of 250 by 250 m, comprising of 32 rows and 82 columns 1705 active cells.

4.4.3. Hydraulic conductivity

When the transient model was run for the first time, the hydraulic conductivity value was kept unchanged as calibrated in the steady state model by Gebrerufael (2008). However, the hydraulic conductivity was also adjusted during the calibration of the transient state model.

4.4.4. Aquifer storativity

The aquifer storativity largely influences transient model calibration and model prediction, which are very important in groundwater management. Well test of pumping wells with one or more observation wells are standard methods to obtain aquifer storativity. In the Aynalem wellfield a detailed group of pumping test was not performed. This makes it difficult to get the aquifer storativity. A well test with observation wells was only carried out in three locations. Using these wells the storage coefficient was determined as initial input for the transient-state model and optimized manually during model calibration.

4.4.5. Time discretization

Selection of the simulation time step is a critical step in the model design because the values of the space and time discretization strongly influence the numerical results (Anderson and Woessner, 1992). Time discretization into stress periods and discretization into time steps is an important step in transient modelling as it strongly influences the numerical results (Fresilassie, 2002). Stress period in MODFLOW are the blocks of time of variable lengths used in simulations of each time step. Stress period and time steps should not be too large to miss important changes in hydraulic heads, has also they should not be too small either, as this may be result in too detailed calculations and the model solution will take along time (Magombedze, 2002). The time discretization in MODFLOW for the Aynalem wellfield refers to the period from January 2003 to December 2007. The length of stress period was chosen after analysis of temporally variable recorded water levels, groundwater abstraction and temporally variable rainfall and groundwater recharge. As discussed in section 2.3, most of the rainfall falls in July to September and also small rainfall falls in spring (March, April and May). By taking into consideration the hydrological cycle, the period from January 2003 to December 2007 was divided into 20 stress period of three months length. Each stress period also divided into one month length time step.

4.4.6. Groundwater recharge

The quantification of recharge in the study area was made by the WATBAL_GW method. The WATBAL_GW requires time series inputs of effective precipitation, potential evapotranspiration and river runoff and groundwater level for calibration purpose. As output the WATBAL_GW model provides actual evapotranspiration, direct runoff, surface runoff, and subsurface runoff, base flow relative depth of soil moisture and groundwater level. The summation of base flow and subsurface runoff gives net groundwater recharge (Chapter 4 for detailed description). The result of the WATBAL_GW was used as initial input for the MODFLOW and was adjusted in the model calibration.

Table 4.2 Summary of length of stress period and recharge obtained from WATBAL_GW

Stress period				Time step	Recharge	
no.	Start	End	Days		10^{-5}m/day	10^{-2}mm/day
1	01-Jan-03	31-Mar-03	90	3	4.44	4.44
2	01-Apr-03	29-Jun-03	90	3	3.99	3.99
3	30-Jun-03	30-Sep-03	93	3	11.00	11.00
4	01-Oct-03	29-Dec-03	90	3	7.66	7.66
5	29-Dec-04	31-Mar-04	93	3	4.46	4.46
6	01-Apr-04	29-Jun-04	90	3	3.67	3.67
7	29-Jun-04	30-Sep-04	93	3	7.87	7.87
8	01-Oct-04	29-Dec-04	90	3	5.90	5.90
9	30-Dec-05	29-Mar-05	90	3	3.55	3.55
10	31-Mar-05	30-Jun-05	93	3	3.93	3.93
11	01-Jun-05	28-Sep-05	90	3	12.40	12.40
12	29-Sep-03	30-Dec-03	93	3	9.09	9.09
13	31-Dec-06	29-Mar-06	90	3	5.30	5.30
14	30-Mar-06	30-Jun-06	93	3	6.79	6.79
15	01-Jul-06	28-Sep-06	90	3	17.20	17.20
16	29-Sep-06	29-Dec-06	93	3	12.30	12.30
17	30-Dec-07	29-Mar-07	90	3	7.33	7.33
18	30-Dec-07	30-Jun-07	93	3	5.35	5.35
19	01-Jul-07	28-Sep-07	90	3	16.00	16.00
20	01-Oct-07	29-Dec-07	93	3	0.00	0.00

4.4.7. Evapotranspiration

Evapotranspiration generally constitutes significant amount in the water budget next to precipitation. The amount of water that disappears as evapotranspiration after the precipitation from the land surface and from shallow part of the unsaturated zone was considered in the computation of recharge in the WATBAL_GW model. For the saturated aquifer, it is assumed that influence of evapotranspiration is limited to a depth of several meters above the water table. Moreover only a very small area is covered with tress (small stands of trees) around Aynalem. Evapotranspiration from the saturated zone is therefore not considered in the conceptual model.

4.4.8. Groundwater abstraction

Abstraction data was available from Mekele water supply office. For the period from 2003 to 2007 total monthly abstracted volumes for the functional wells were available (Appendix 4). Groundwater abstracted from Aynalem aquifer is mainly used for domestic and industrial use. Using the available data on well abstraction, the number and location of active wells was established for each stress period. The well abstraction was entered into MODFLOW by well package for each stress period.

4.5. Transient state model calibration, water balance and sensitivity analysis

Calibration is the process of adjusting the input data to a groundwater model until the calculated heads of the model match the observed heads. Calibration is accomplished by finding a set of parameters, boundary conditions and stresses that produce simulated heads and fluxes that match the field measured values within pre-established range of error (Anderson and Woessner, 1992). Calibration can be carried out by manual trial and error or by automatic parameter estimation like PEST and the model must be run several times in order to obtain the most optimal solution. Because of many uncertainties, different conceptual and low data quality, to calibrate the model manual (trial and error) was applied.

4.5.1. Transient state model calibration

Although the model appeared to perform well at steady-state, most practical applications of modelling in groundwater management are dynamic, involving decision over time. For such applications steady state modelling is not sufficient and transient state model, which incorporates the time elements, must be used also (Shaki and Adeloye, 2007), and a transient state calibration similar to the steady state one was carried out.

The transient calibration was carried based on the groundwater level data of seven piezometers. In the first transient state model calibration was used to optimize the spatial variability of storage coefficient based on predefined values obtained from pumping test. In the second step improvement and fine-tuning was performed by trial and error adjustment of recharge (R). The adjustment of recharge was based on recharge obtained from WATBAL_GW model. Water levels measured in some of the wells PW2 and PW6 are erratic and believed to be outliers due to measurement errors (Gebrerufael, 2008; WWDSE, 2006), these wells were left out during steady state calibration. In the transient model the same problem occurred and these wells were also left out from calibration. It should be noted that most of the water level measurements are associated with errors due to the following reasons: there are no observation wells; the piezometric measurements are carried out on the pumping wells and errors during recording. These combined errors affect the calibration of the transient state model.

During transient state model calibration, the aim was not only to obtain the lowest root mean squared error of the difference between the calculated and observed heads, but also to have good fit to the pattern of rise and fall of groundwater levels as measured in five wells. The final calibrated and measured hydrograph heads are shown in Figure 4.9 and graphs groundwater heads result from the MODFLOW is indicated in Appendix 9.2.

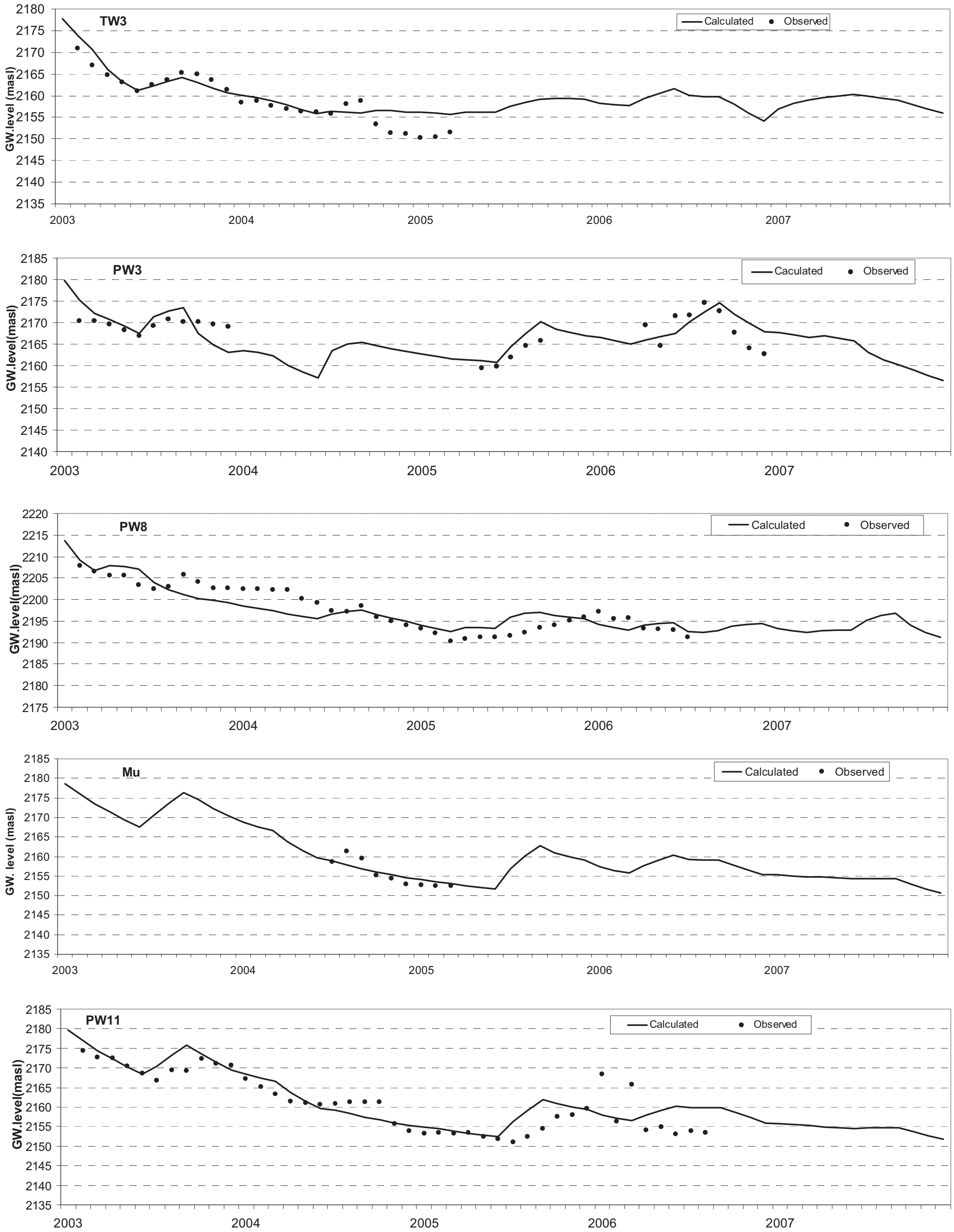


Figure 4-8: Observed and Simulated Groundwater heads of transient state model

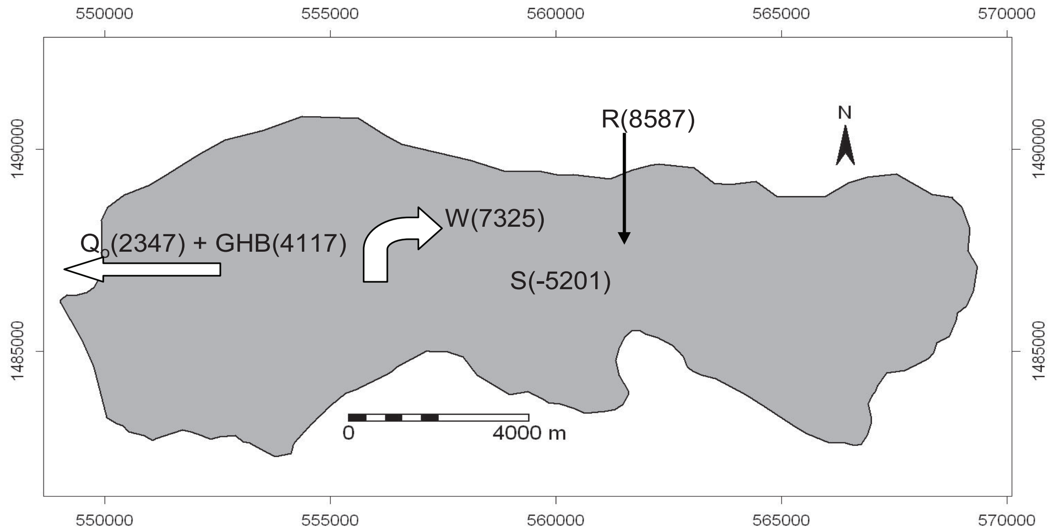
4.5.2. Water balance

The water balance Aynalem aquifer was evaluated from the transient state model of MODFLOW groundwater flows such as recharge, groundwater storage, groundwater abstraction, base flow to river (drain package), groundwater outflow at the downstream end of the catchment (western outlet) was assigned as general head boundary, while the water budget was estimated for each stress period. In the simulation period, the highest recharge occurred during the stress period 15 (0.4 mm/day) in July to September 2006 and lowest recharge is occurred in the dry season and it is almost zero in that period. This corresponds to the amount of rainfall which shows there is direct response to rainfall. The increase of groundwater abstraction from the aquifer, results in a decrease of the hydraulic gradient. As a result the flow of water to rivers and through the western outlet was declining. The water budget generated by the transient state model for each stress period is shown in Table 4.3. The detailed water budget at the end of each stress period is indicated in Appendix 9.1. Daily average groundwater flows for each component are shown in Figure 4.10. The temporal variability of each flow of the transient state model is shown in Figure 4.11. This model results an average base flow of Aynalem River of about 2347 m^3/day (Table 4.3), but there is no river gauging at the outlet of the river to verify the result. Base flow from the aquifer to Aynalem River decreases by some 68%, during the period January 2003 to December 2007.

Table 4.3 Water budget of model simulation

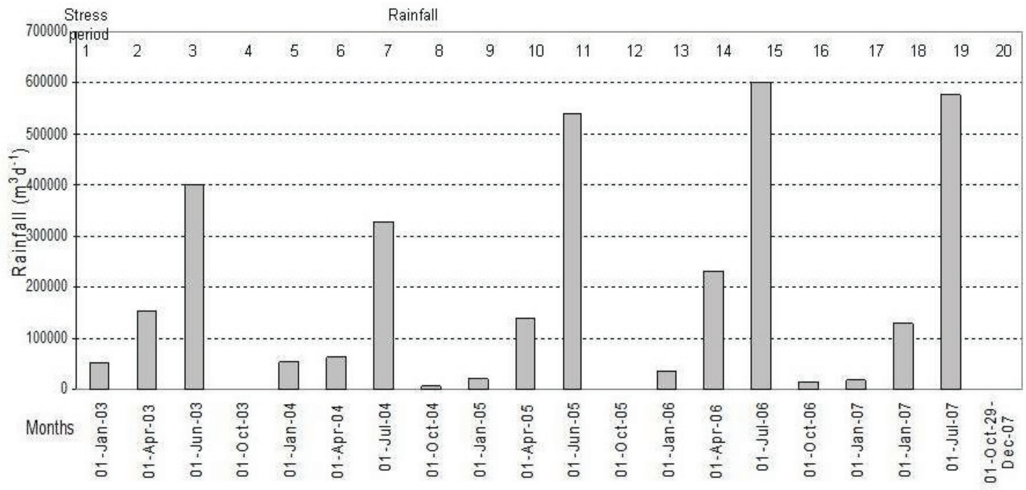
Stress period				Rainfall	Recharge	Storage	Well	Drain	GHB
no.	Start	Ends	Day	m^3 day^{-1}					
1	1-Jan-03	31-Mar-03	90	51940	78	-16692	7103	5075	4592
2	1-Apr-03	29-Jun-03	90	154407	170	-15581	7161	4123	4467
3	30-Jun-03	30-Sep-03	93	399837	10036	-4203	6277	3559	4403
4	1-Oct-03	29-Dec-03	90	942	14	-15135	7787	3075	4288
5	29-Dec-04	31-Mar-04	93	52772	6379	-8232	7650	2736	4224
6	1-Apr-04	29-Jun-04	90	62422	4289	-10240	7954	2429	4146
7	29-Jun-04	30-Sep-04	93	326890	18418	4512	6927	2767	4212
8	1-Oct-04	29-Dec-04	90	4593	558	-13204	7465	2209	4088
9	30-Dec-05	29-Mar-05	90	20022	3375	-9956	7526	1825	3980
10	31-Mar-05	30-Jun-05	93	139282	3498	-8291	6314	1578	3896
11	1-Jun-05	28-Sep-05	90	540364	14586	1810	7260	1592	3924
12	29-Sep-03	30-Dec-03	93	1482	860	-12267	7727	1492	3908
13	31-Dec-06	29-Mar-06	90	36864	5698	-6676	7205	1314	3855
14	30-Mar-06	30-Jun-06	93	230237	19215	6717	7044	1515	3939
15	1-Jul-06	28-Sep-06	90	600196	41988	27664	7541	2508	4276
16	29-Sep-06	29-Dec-06	93	14019	5055	-10195	9148	1992	4110
17	30-Dec-07	29-Mar-07	90	17196	7690	-4994	6840	1810	4034
18	30-Dec-07	30-Jun-07	93	129708	5059	-5815	5309	1618	3947
19	1-Jul-07	28-Sep-07	90	578171	24775	11111	7436	2117	4111
20	1-Oct-07	29-Dec-07	93	0	0	-14359	8824	1604	3931
Ave/tot			1827	168067	8587	-5201	7325	2347	4117

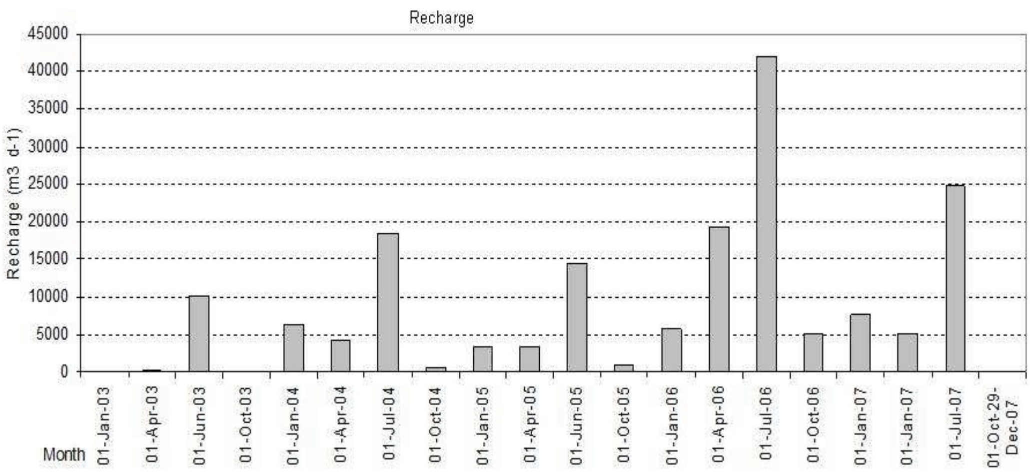
GHB= General Head Boundary in the western outlet
Ave/tot= Average/ total

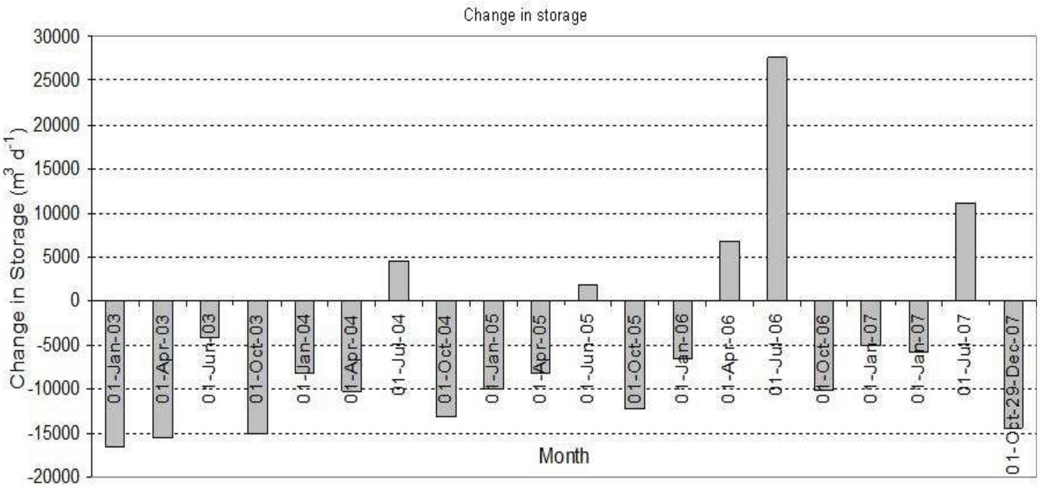


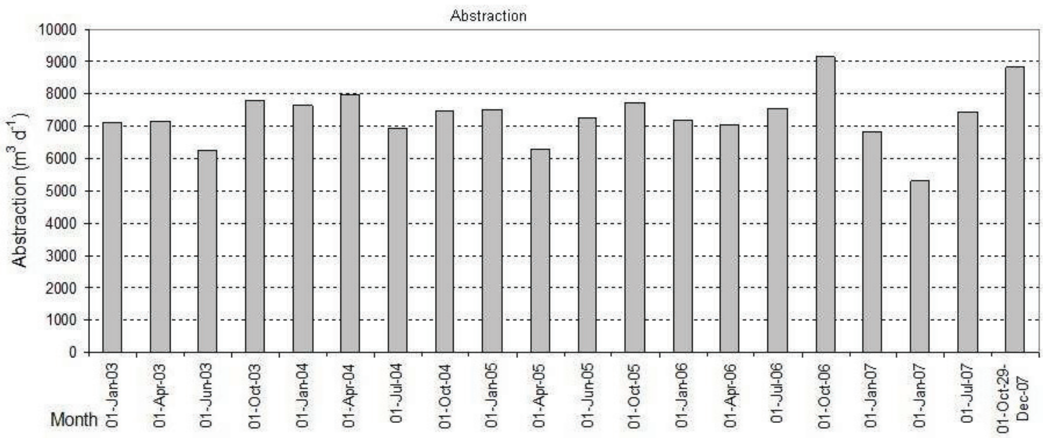
R: Recharge, Q_o: Groundwater flow to river (Drain), GHB: Groundwater outflow in lower boundary, W: Well abstraction, S: Change of groundwater storage. Unit ($m^3 day^{-1}$)

Figure 4-9: Daily groundwater balance of Aynalem aquifer.






Change in storage
Change in Storage (m3 d-1)
30000
25000
20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
Month
01-Jan-03
01-Apr-03
01-Jun-03
01-Oct-03
01-Jan-04
01-Apr-04
01-Jul-04
01-Oct-04
01-Jan-05
01-Apr-05
01-Jun-05
01-Oct-05
01-Jan-06
01-Apr-06
01-Jul-06
01-Oct-06
01-Jan-07
01-Jan-07
01-Jul-07
01-Oct-29-Dec-07


Abstraction
Abstraction (m3 d-1)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Month
01-Jan-03
01-Apr-03
01-Jun-03
01-Oct-03
01-Jan-04
01-Apr-04
01-Jul-04
01-Oct-04
01-Jan-05
01-Apr-05
01-Jun-05
01-Oct-05
01-Jan-06
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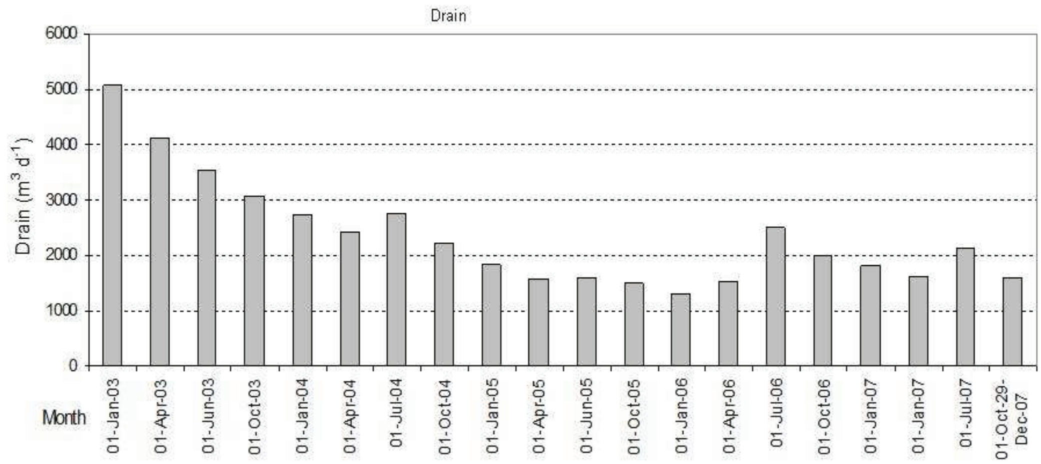
01-Jul-06
01-Oct-06
01-Jan-07
01-Jan-07
01-Jul-07
01-Oct-29-Dec-07


Drain
Drain (m3 d-1)
6000
5000
4000
3000
2000
1000
0
Month
01-Jan-03
01-Apr-03
01-Jun-03
01-Oct-03
01-Jan-04
01-Apr-04
01-Jul-04
01-Oct-04
01-Jan-05
01-Apr-05
01-Jun-05
01-Oct-05
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01-Oct-29-Dec-07

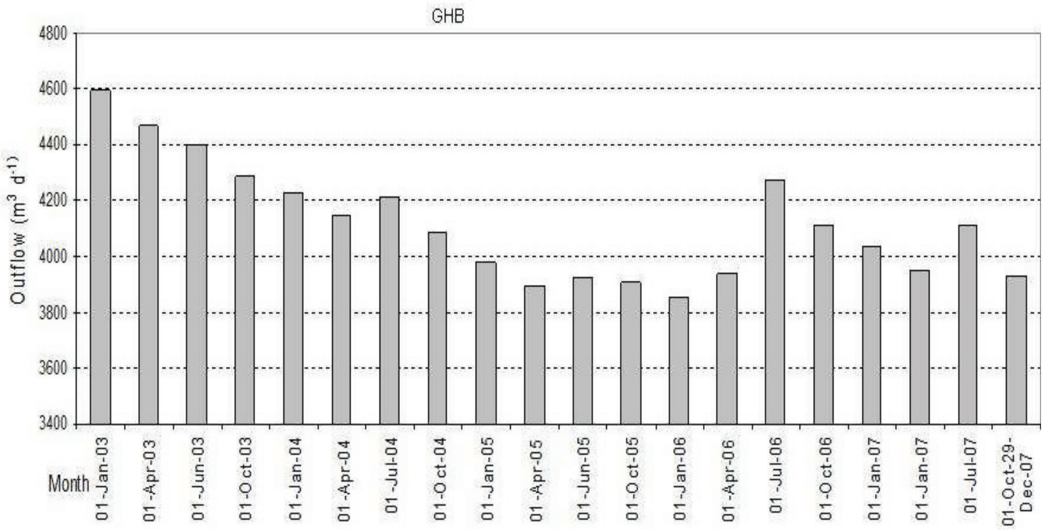


Figure 4-10: Water budget components of the transient state model.

4.5.3. Sensitivity analysis

The sensitivity analysis was performed by systematically changing aquifer and hydrologic parameters from the optimized values and evaluating the change on the model result. Groundwater recharge, storativity and transmissivity were each varied separately to assess the impact on the model output. Since in calibration of the model creates zones of aquifer parameters (transmissivity and specific storage) and recharge, only consider the average values the different zones for the sensitivity analysis (Figure 4.14). To observe the change of the groundwater table by changing the these parameters, put an observation well at the centre of the field assuming that the change in groundwater table in the observation well represents the average change in the wellfield (Figure 4.12). Since the catchment has one outlet, flat topography, geometrically simple, uniform recharge, the change of groundwater table in the observation well can give an estimation of the wellfield.

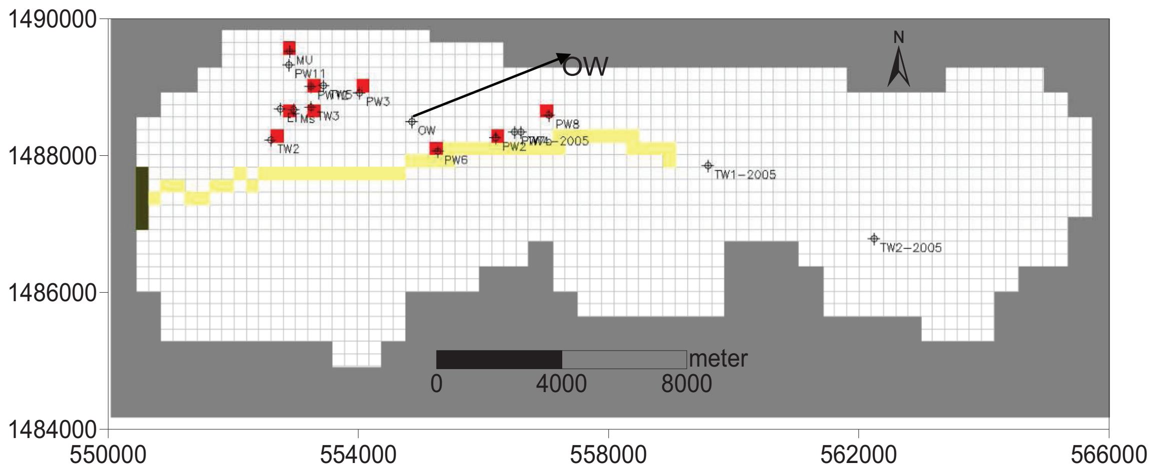


Figure 4-11: Location of observation well for sensitivity analysis

The parameter values were changed from the average simulated values by 10%, 25% and 50% to the left and to the right and compare the change in hydraulic gradient in the observation well located at centre of the wellfield. A small change of groundwater storativity from the simulated average values has greater influence on the water table than transmissivity and recharge. Change of time series recharge by 50% from the simulated values the water tables changes in magnitude with average values 2.5 meter (Table 4.4) and the time series recharge change by 50% is indicated in Figure 4.13 and the sensitivity analysis graph for the aquifer parameters are indicated in Figure 4.14. The results of the sensitivity for each parameter are summarized in Table 4.4. The sensitivity result indicates that the transient modelling is very well capable of producing accurate storage values provided of course the aquifer parameters (recharge and transmissivity) and geometry (boundaries) are valid.

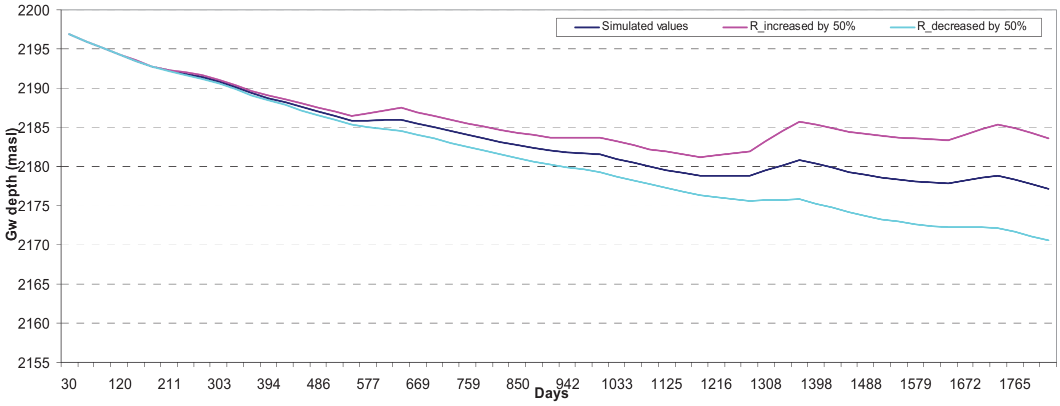


Figure 4-12: Groundwater depth result change recharge by 50%

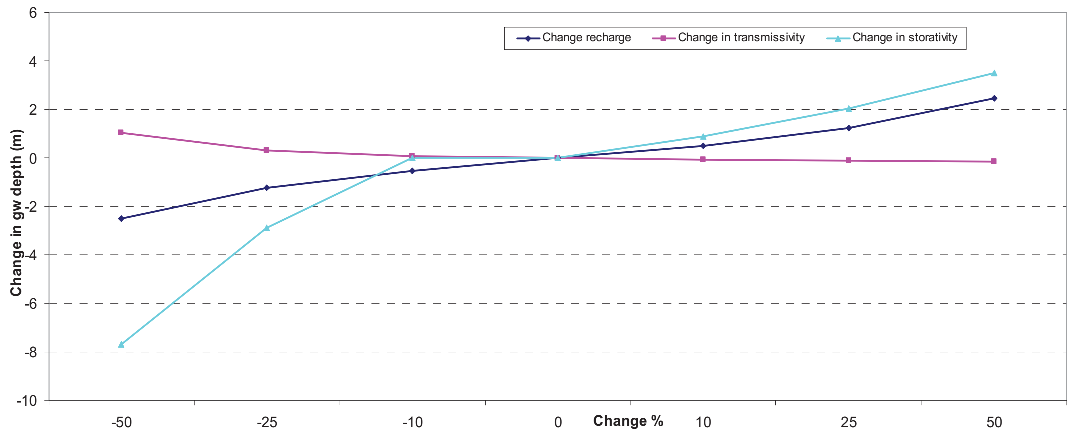


Figure 4-13: Sensitivity analysis recharge, storativity and transmissivity

Table 4.4 Transient state model senstivity result

Aquifer parameters	Optimimized value	Change in %	Change in hydraulic head	Remark
Specific storage	$0.000024m^{-1}$	-50%	-7.69	3 zones
		-25%	-2.90	(Figure 4.14 A)
		-10%	0.00	
		0%	0.00	
		10%	0.90	
		25%	2.05	
		50%	3.51	
Recharge	$30mmy^{-1}$	-50%	-2.51	3 zones, only
		-25%	-1.25	boundary shown
		-10%	-0.52	no value is given
		0%	0.00	because time series
		10%	0.50	(Figure 4.14B)
		25%	1.25	
		50%	2.48	
Transmissivity	$54m^2$/day	-50%	1.04	8 zones
		-25%	0.31	(Figure 4.14 C)
		-10%	0.09	
		0%	0.00	
		10%	-0.07	
		25%	-0.12	
		50%	-0.15	

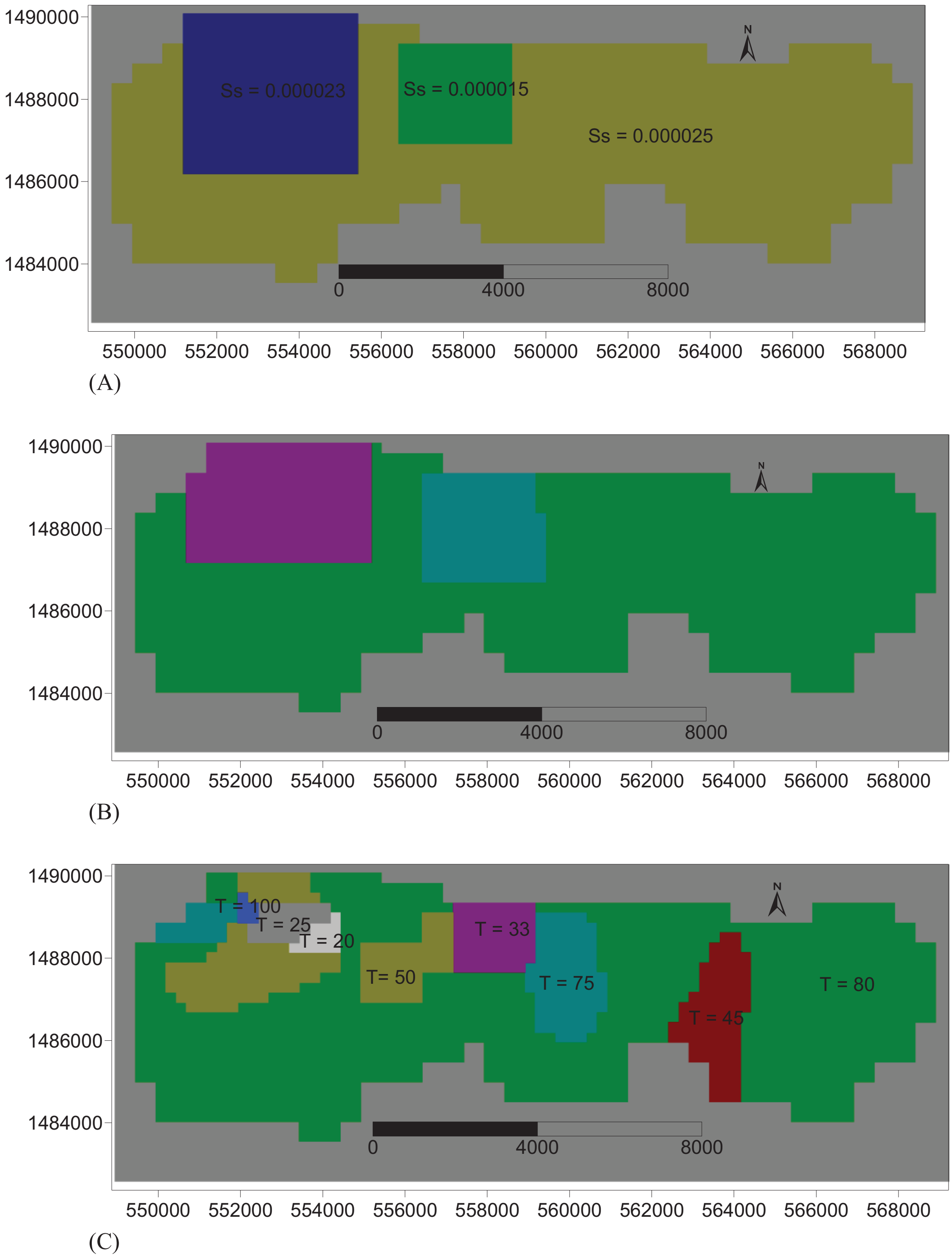


Figure 4-14: Zone maps of specific storage, m^{-1} (A) recharge (B) and transmissivity, m^3/day (C)

5. Groundwater Prediction and Scenario Development

5.1. Introduction

Predictive modelling facilitates assessment of the response of the aquifer to different stress conditions and provides a predictive tool for the management of the resources in terms of temporal and spatial distribution of abstraction. Scenarios are an important tool for decision making in situation of high uncertainty. They can assist in evaluation of different possible future circumstances and their implications for decision making in the present. Due to increase abstraction of groundwater and less recharge in the Aynalem Aquifer, the water table is declining and partial shortage of water has occurred, especially in the dry periods. To predict the aquifer response for different stress conditions three scenarios were developed.

5.2. Grid refining

Simulation groundwater modelling often requires a refined grid size to achieve accurate solution in areas of interest where hydraulic gradient vary in space. The need for a locally refined grid in groundwater models generally stems from three practical requirements: (1) Accurate modelling of hydraulics near pumping or injecting wells, where smaller grid spacing is required in regions where hydraulic gradients vary significantly over short distances. (2) Contaminant transport modelling where smaller grid spacing is often required to accurately model sharp fronts (3) Accurate modelling of a detailed representation of hydrologic and hydrogeologic features such as rivers and stratigraphy (Mehl and Hill, 2002). In the Aynalem wellfield the abstraction wells are clustered in the northwestern part of the wellfield. To see the change in groundwater head the grid of the model area was refined into 125 by 125 grid size locally in areas where more wells exist. Later the entire model is refined into that size in the scenario development for better prediction of aquifer response for different stress conditions. The simulated contour map of the refined grid is shown in Figure 5.1.

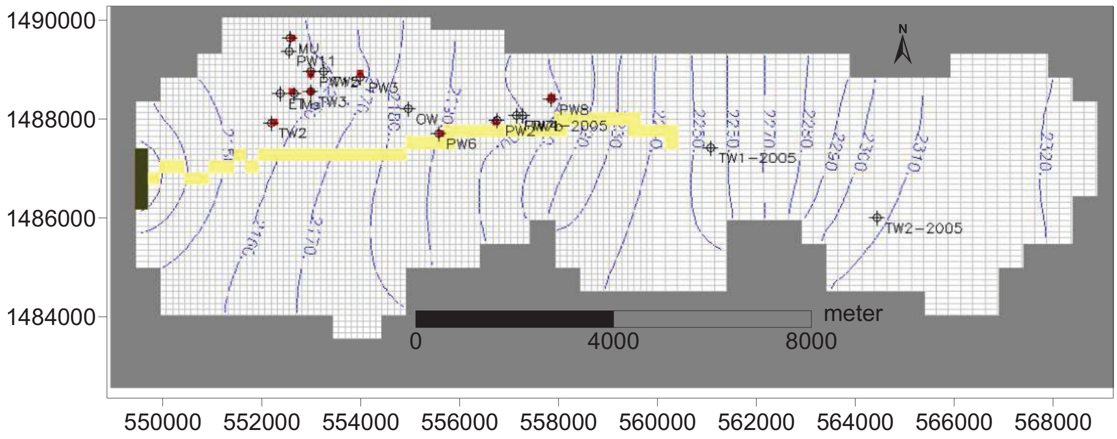


Figure 5-1: Simulated contour map of refined grid locally

5.3. Scenario development

Transient model calibration was used to evaluate the aquifer response to different stress conditions like groundwater abstractions and recharge with the objective of predicting water table drawdown. Three scenarios are used to evaluate the aquifer response to different times, recharge and for future abstraction of the aquifer in the catchment.

- Scenario one: only recharge is applied
- Scenario two: effect of abstraction for five and ten years
- Scenario three: effect of adding new wells

The assumptions applied for the simulation of the different scenarios are:

- Groundwater heads and flux values of the calibrated transient state model are considered as initial condition for each scenarios,
- Groundwater recharge is equal to as in the simulation period in transient state model
- Pumping rate will be average abstraction rate of each well
- The average drawdown in observation wells would be the average drawdown of the water table in the wellfield.

5.3.1. Scenario one

Scenario one is used to evaluate the response the Aynalem aquifer for recharge without abstractions. To observe the aquifer response to recharge without abstraction two observation wells were placed in the wellfield depending on the distribution of pumping wells. With four years of recharge without abstraction, the water table rise with an average value of 26 meter. More wells in the wellfield were clustered in the northwestern part of the catchment and as such there is a pressure drop locally in this area. Simulation results indicate that the water level in the northwestern part is not fully recovered in the four years recharge without abstraction. Base flow to the Ayanlem River in four years of recharge without pumping of groundwater from the aquifer increases from 1604 m^3day^{-1} to 4716m^3day^{-1} which is almost the same as the base flow in 2003. The results of the two observation wells are summarized in Table 5.1 and Figure 5.3.

Table 5.1 Groundwater heads applying recharge only

	Location		Groundwater heads (masl)		
Observation wells	UTM_E	UTM_N	Initial	After four years	Rise in level (m)
OW1	553216	1488750	2153	2179.55	26.11
OW2	556989	1488254	2185	2210.26	25.15
Average rise in level					25.63

5.3.2. Scenario two

In the Aynalem wellfield groundwater is abstracted with more than fifteen operational wells but abstraction data is not well monitored. To predict the groundwater level for the next five and ten years of period with continuous abstractions groundwater from the existing wells and assuming that abstraction data will be well monitored. Depending on the distribution of pumping wells three observation wells are put to observe the drawdown for five and ten years of abstractions. After pumping for these years with an abstraction rate of 12403 m^3day^{-1} (with the same recharge to the periods of transient model simulations) the groundwater table declines on average 15.26 and 26.55 meters respectively. The groundwater drain to Aynalem River declined from 1604 to 126 m^3day^{-1} and 24 m^3day^{-1} in five and ten years pumping of the aquifer respectively. Observation well two (OW2) placed in the centre of the wellfield, shows higher drawdown than the other two observation wells. The results of each observation well are indicated in the Table 5.2 and Figure 5.3 below.

Table 5.2 Groundwater heads after 5 and10 years continuous abstraction for the existing wells

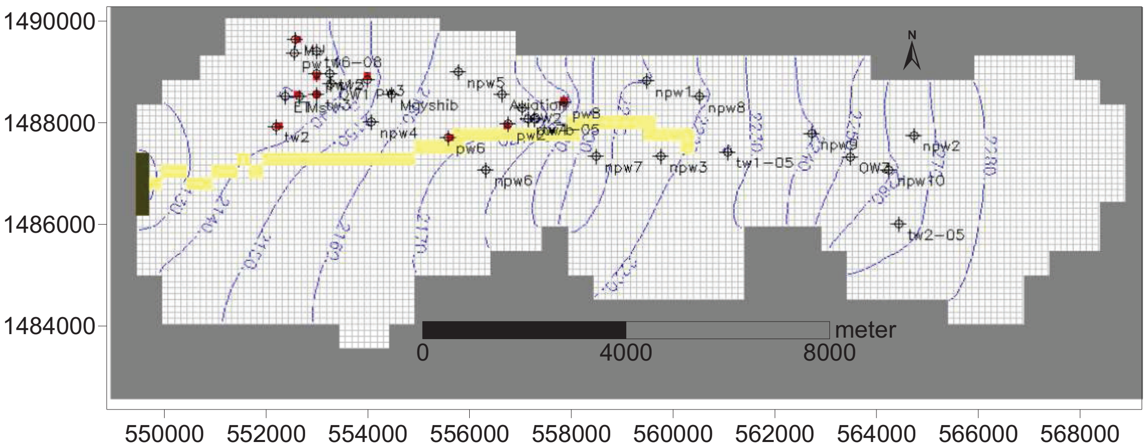
	Location		Groundwater heads (masl)			Drawdown (m)	
Obser. wells	UTM_E	UTM_N	Initial	After 5 years	After 10 years	After 5 years	After 10 years
OW1	553216	1488750	2153.4	2141.20	2131.18	12.24	22.26
OW2	556989	1488254	2185.1	2164.69	2152.81	20.42	32.30
OW3	563479	1487244	2292.5	2279.40	2267.37	13.11	25.08
Aver.dd						15.26	26.55

5.3.3. Scenario three

In the Aynalem wellfield new wells are being drilled. Scenario three was simulated to observe the drawdown of groundwater table for the coming five and tens years with abstraction groundwater by existing wells and adding of some hypothetical new wells. Pumping 18000 m^3day^{-1} shows that the drawdown reaches 30 m after five years and 53 meter after ten year. The base flow (drain) from the aquifer decreases from 1604 to 104 and 3.5 m^3day^{-1} and groundwater flow from the saturated aquifer decrease from 4117 to 3318 and 2575 m^3day^{-1} for the same number of years respectively. The results of the groundwater heads after pumping for five and ten years are shown in Figure 5.3 and contour maps for ten years of abstraction in Figure 5.2.

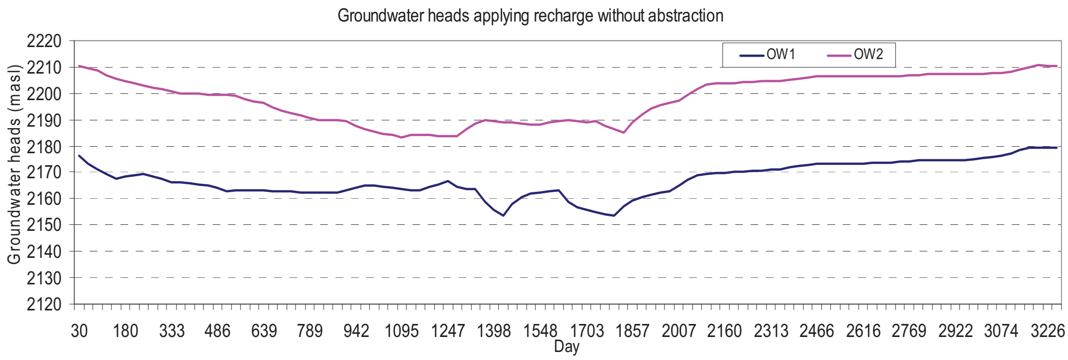
Table 5.3 Groundwater heads after 5 and 10 years continuous abstraction for the existing and new wells

Obser. wells	Location		Groundwater heads (masl)			Drawdown (m)	
	UTM_E	UTM_N	Initial	After 5 years	After 10 years	After 5 years	After 10 years
OW1	553216	1488750	2153	2137.39	2122.31	16.05	31.13
OW2	556989	1488254	2185	2152.13	2129.32	33.00	55.79
OW3	563479	1487244	2292.5	2251.71	2221.67	40. 74	70.77
Aver.dd						29.92	52.56



npw1, npw2, ...= new pumping well

Figure 5-2: Contour map of groundwater heads ten years abstraction of exiting wells and new wells



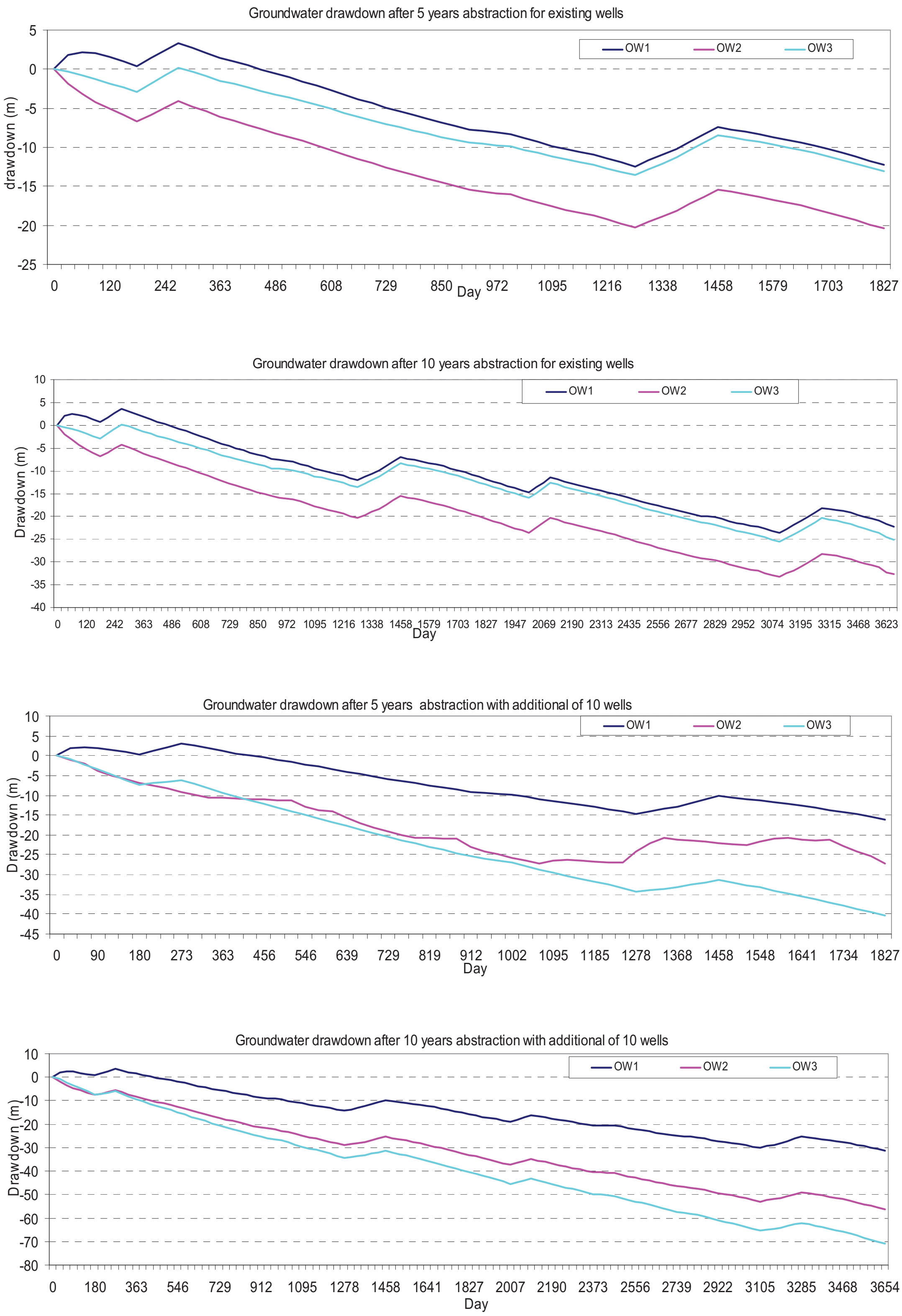


Figure 5-3: Groundwater table condition results of different scenarios

6. Discussion, Conclusion and Recommendation

The objective of this study was to assess the groundwater resources using transient state modelling. The transient state modelling was developed by data integration of different sources with spatial and temporal variable recharge and storage. Based on the results obtained the following comments can be made.

6.1. Discussion

The groundwater recharge was calculated with WATBAL_GW model for 16 years of meteorological data (1992 to 2007) and served as input for the transient state model. The groundwater recharge was optimized in the transient model through calibration result in an annual recharge of 30 mm/year (5% of the total annual rainfall). The recharge result from the WATBAL_GW model simulation indicates 32 mm/year (5% of the total annual rainfall of the 16 years average rainfall). Since the transient state model was only simulated for a five year period (2003 to 2007) and the rainfall in this period was lower than the previous years, the result of the recharge estimate with transient is lower than the recharge estimated with WATBAL_GW which was simulated for sixteen years (1992 to 2007). Taking into account the variation of rainfall the estimated recharge with the WATBAL_GW and the recharge estimated with the transient model calibration is in the same range.

As discussed in section 1.5.2 and section 2.6, the efforts estimate groundwater recharge of the Aynalem catchment was by different methods. Hussien (2000), Samuel (2003) and Teklay (2006) uses water balance method whereas Gebrerufael (2008) used chloride mass balance to calculate the groundwater recharge. The recharge estimated by Hussien (2000) and Samuel(2003) results in the range of 9% of the total annual rainfall. The recharge estimated by Gebrerufael (2008) and Teklay (2006) with the chloride mass balance and water balance respectively was in the range of 4.5 – 6% of the annual rainfall. In this work the recharge estimated is some 5% of the annual rainfall.

A transient model was developed for the Aynalem wellfield with spatially and temporally variable groundwater recharge and aquifer storativity. The transient model was calibrated in two steps. The first step was to adjust the aquifer storativity based on the value obtained from the pumping test through optimisation in the transient model calibration. Second the groundwater recharge was adjusted in each stress period based on the value obtained in the WATBAL_GW. From the transient model calibration the specific storage was found as 0.000015, 0.000023, and 0.000025 m^{-1}. According to the WWDSE (2006) the storage coefficient of Aynalem aquifer varies between 10^{-3} to 10^{-4} and is in line with result in this work. In the calibration of the transient model five wells were used. As can be observed from the graph of the observed and simulated heads of the groundwater levels, the calculated heads match the observed heads closely. In the observed heads there are gaps in recording the water level and also an outlier in the data. These outliers may be due to errors in water level measurements. Under the transient state simulation, it is shows that water level fluctuations correlate with changes in annual rainfall. The highest recharge occurs in the rainy season (August and July) but in the dry season the recharge is very low. There are several indications that the calibrated model is plausible:

- The simulated and observed water levels match closely.
- The water balance of model simulated corresponds closely to the water balance of WATLBAL_GW.
- Groundwater flow directions simulated by the model are reasonable and in concordance with the conceptual model
- The distribution of aquifer parameters (transmissivity and storativity) makes sense with geological distributions

Nevertheless, there are some uncertainties involved in the model:

- As previously discussed, water levels are only measured in a few pumping wells and these wells are mainly clustered in the northwestern of the wellfield.
- Water levels were measured in pumping well which introduces errors in transient water level measurement. Well abstraction data are also not well collected.
- There are public and private wells which pump significant amount of groundwater but they are not monitored. These affect the model by minimizing well abstraction.

The water balance components of an aquifer include groundwater inflow (recharge) and groundwater outflow (well abstraction, groundwater outflow to rivers and flow of groundwater across boundaries). Similarly, the groundwater flow conditions in the Aynalem aquifer is controlled by groundwater recharge, groundwater abstraction (pumping rates) and groundwater flow to the Aynalem river and groundwater outflow through western boundary. From the transient model simulation results the groundwater recharge of the aquifer system is estimated at some 30 mm/year (5% of the annual rainfall). Groundwater from the aquifer discharged with well abstraction is estimated at 25 mm/year, drain to Aynalem River 8mm/year and the groundwater outflow through western outlet is some 14 mm/year. Based on the water balance of the five years (2003 to 2007) of model simulation, the Aynalem aquifer was depleted in average of 17 mm/year. The groundwater balance simulated with WATBAL_GW for sixteen years periods (1992 to 2007) also show that the Aynalem aquifer is depleted with an average of 2.3 mm/year. Since 1999/2000 more wells were drilled in the Aynalem wellfield and more groundwater is abstracted while the groundwater recharge was decreasing during this period, faster depletion of the aquifer storage has resulted. As can be observed in Figure 6.1, a cone of depression is created locally.

Validation of the calibrated model is not possible because too short a series of observed data is available and this is already used in the calibration of the model. The difficulties in model validation are:

- Monitoring of river flow has stopped since 2001 and only ten years of records are available.
- Early abstraction records are missing
- Well abstraction was not regular, records are poor

- Several conceptual models are constructed for the Aynalem wellfield. The WWDSE (2006), has made a two layer model aquifer on regional scale, where as Zeru (2008) has proposed a 20 layer model in his MSc thesis.
- Deep drilling program is underway

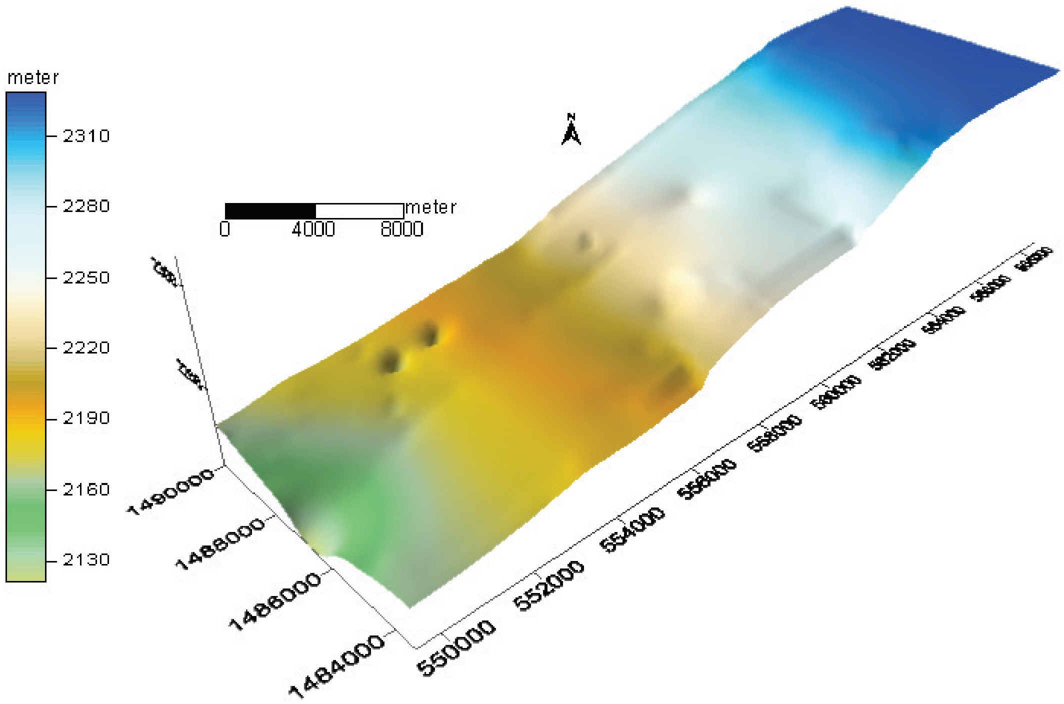


Figure 6-1: Local cone of depression due to abstraction of groundwater.

6.2. Conclusion

The objectives of developing a transient groundwater model and calibrating this model by comparing the simulated with observed groundwater heads have been achieved. The study answered the research question of developing a transient model with spatio-temporal input data and estimates the storativity of the aquifer. For the transient groundwater model, the spatio-temporal data includes groundwater recharge, groundwater abstraction, groundwater flow to rivers and groundwater base flow. All the groundwater fluxes were found reliable in the calibration of the transient state model.

The transient simulation shows there is a local drawdown in the western part of the wellfield. It seems necessary to redistribute a number of wells in the area to minimize local pressure drops. Otherwise groundwater abstraction will lead to groundwater mining especially in the dry months. Long period drought will cause a serious decline of groundwater levels and possible unrecoverable exhaustion of groundwater reserves locally.

Decline of groundwater levels is caused by increased groundwater abstractions with less recharge. The transient state model shows that due to increase pumping of groundwater, there is a local drawdown of water table in the western part of the wellfield. To reduce this drawdown into natural condition, an average of groundwater recharge of 30 to 32 mm/year is needed for four years without abstraction. On the other hand groundwater pumping of 18000 m^3/day (twice the present abstraction) from the aquifer shows an average drawdown of 53 m after ten years and the groundwater level in the wellfield then becomes nearly equal to the groundwater head in the outlet.

The results of the transient model show that important water balance components are groundwater recharge and groundwater abstraction from pumping wells. Finally the aquifer storativities have been estimated accurately by both WATBAL_GW and transient state model and also with sensitivity analysis of the transient model.

6.3. Recommendation

The transient modelling of the Aynalem aquifer has been formulated and the model was calibrated against actual monitoring data. Finally, for future studies the following recommendations have been made.

- Groundwater monitoring data is vital in calibrating of transient model and to understand the aquifer response to abstraction and recharge. However, in the Aynalem wellfield not all wells are monitored, for better prediction of the aquifer it is important to monitor wells with good measuring instruments and professional future researches.
- Groundwater abstraction is mainly situated in the northwestern part of the wellfield which creates a local drop in groundwater level. It is necessary to stop drilling of new wells in this area and expand the wellfield to the eastern part of the wellfield.
- For better prediction of the groundwater sustainability it is advisable to start groundwater modelling in a three layer model (unsaturated, shallow phreatic aquifer and deep semi-confined aquifer). This can be done if data is available for the unsaturated and saturated zone and detailed pumping tests of the deep aquifer are carried out.
- The transient model is limited only to the shallow aquifer of 50 m thickness. Complete modelling of the aquifer including the deep aquifer would provide better prediction of aquifer response to recharge and abstraction but such has not been possible here because of the lack of the necessary data. It would be therefore helpful for future studies if a hydrogeological database is established which can provide the required data for research.
- Note that the amount of outflow from the aquifer (groundwater abstraction) is larger than the inflow into the aquifer (groundwater recharge) which clearly reflects the need of water supply. Hence it is necessary take into account groundwater balance in future development of the wellfield
- For better assessment of the groundwater of Aynalem aquifer well monitoring by automatic level recorders has to be implemented. Continuous recording of abstraction data and daily weather data are also necessary. The conceptual models must be updated after a couple of years when more data have become available.

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Appendices

Appendix 1 Climatic data for the Mekele Airport station

(Long.39^{o}31', Lat. 13^{o}28' and Alt.2257m.a.s.l.)

Appendix 1.1 Average Monthly Maximum Temperatures (^{0}C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	21.7	23.3	24.4	25.4	26.0	27.6	23.2	20.4	22.8	22.5	20.2	20.8
1993	20.7	21.8	23.6	22.2	24.0	25.3	22.3	22.9	24.4	23.1	21.8	21.7
1994	21.9	22.9	24.2	24.9	26.1	25.7	21.3	21.0	22.5	23.1	21.9	21.3
1995	22.1	24.0	24.6	24.6	25.8	28.2	22.9	22.1	23.9	23.4	22.8	22.8
1996	23.1	24.9	24.9	25.6	24.8	24.4	23.2	22.5	24.9	23.7	22.1	21.6
1997	23.3	23.5	25.7	25.5	26.6	26.6	22.8	23.1	25.6	23.3	22.7	23.1
1998	23.7	25.2	26.1	27.3	27.0	27.8	22.4	21.3	23.9	23.3	22.2	21.8
1999	22.3	24.9	24.9	26.3	27.9	27.9	21.7	21.4	23.5	23.5	22.7	22.5
2000	22.2	23.9	24.7	25.6	27.5	27.6	23.6	22.4	23.9	23.6	22.7	22.4
2001	23.1	24.5	24.5	26.5	28.1	25.5	24.0	21.9	24.6	24.5	22.8	22.7
2002	22.3	24.6	25.8	26.6	28.7	27.3	25.5	23.3	24.8	24.8	23.5	23.4
2003	24.5	25.9	25.7	26.6	28.2	26.9	23.4	22.3	24.3	23.6	22.9	22.0
2004	25.0	24.0	25.0	25.9	28.2	26.5	24.8	22.9	25.1	21.3	23.0	22.9
2005	23.7	25.7	26.1	26.3	26.4	27.4	23.2	23.3	24.6	23.4	22.6	22.1
2006	23.6	25.2	25.5	25.0	26.0	27.1	23.6	22.3	24.5	23.9	22.7	22.4
2007	22.7	24.8	26.1	26.1	27.8	26.8	22.6	22.8	23.9	23.3	22.1	21.8

Appendix 1.2 Average Monthly Minimum Temperatures (^{0}C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	9.8	9.7	11.9	13.2	13.8	13.2	12.4	12.8	11.2	10.9	10.3	10.8
1993	9.6	9.6	11.7	12.5	13.1	13.0	12.7	12.6	11.7	12.1	10.8	9.4
1994	9.6	10.6	11.7	13.8	14.4	12.9	13.0	12.9	10.6	10.6	10.6	9.2
1995	9.3	9.8	11.9	14.0	14.5	13.7	12.7	13.3	11.2	11.0	10.1	10.4
1996	9.6	10.7	12.5	13.3	13.6	12.6	13.1	13.2	11.7	11.1	10.2	9.4
1997	9.3	10.1	12.5	13.0	13.6	14.4	13.2	12.7	12.4	12.4	12.3	10.4
1998	10.8	10.2	12.8	14.9	14.5	14.4	14.0	13.9	12.6	11.5	8.9	8.3
1999	9.3	10.6	11.1	13.5	13.9	13.7	12.8	12.9	12.1	11.5	9.5	9.5
2000	9.5	10.4	11.7	12.9	13.7	13.5	13.3	13.6	11.8	11.2	10.9	10.2
2001	8.1	10.2	12.2	13.8	14.5	13.3	13.4	13.4	12.1	11.8	10.8	10.3
2002	10.5	10.7	12.4	12.6	14.1	13.7	13.7	12.7	12.2	11.6	14.0	10.5
2003	8.7	11.7	12.3	13.7	15.1	13.5	13.8	12.7	11.7	10.7	10.6	9.3
2004	10.1	9.7	11.6	13.5	13.2	13.2	13.0	13.0	11.7	10.0	11.0	9.9
2005	9.0	11.3	12.5	13.5	13.8	13.3	13.5	12.8	12.2	10.4	10.7	8.5
2006	7.6	11.1	11.5	12.9	13.0	12.8	13.4	13.0	11.0	11.1	10.0	10.4
2007	9.4	11.4	11.4	12.4	14.0	14.1	13.0	12.7	11.1	9.8	9.8	8.5

Appendix 1.3 Monthly totals Rainfall (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1992	8.7	2.1	38.5	1.0	30.7	6.2	140.7	233.1	1.3	2.1	54.4	8.3	527.1
1993	11.7	7.7	63.9	135.0	74.7	69.0	217.2	106.5	15.2	20.0	0.0	0.0	720.9
1994	0.0	5.3	0.4	43.8	0.8	67.6	147.9	317.8	70.1	0.0	1.8	2.0	657.5
1995	0.0	5.9	31.2	29.2	27.1	6.8	268.2	237.7	51.4	3.0	0.0	2.7	663.3
1996	1.4	0.0	59.5	12.5	92.3	47.9	109.2	224.0	7.1	0.0	31.4	1.1	586.5
1997	0.0	0.0	20.4	32.6	29.8	32.4	243.1	100.5	16.3	59.9	15.7	0.0	550.8
1998	10.0	1.2	0.0	10.6	22.0	48.0	289.0	318.8	31.7	22.0	0.0	0.0	753.4
1999	22.1	0.3	10.9	0.0	0.0	7.4	293.6	359.2	22.8	0.9	0.0	0.0	717.2
2000	0.0	0.0	0.0	10.4	24.6	5.4	201.4	182.0	15.8	2.2	10.3	3.5	455.6
2001	0.0	0.0	38.1	18.7	8.7	65.5	267.9	226.3	9.2	2.9	0.0	0.0	637.3
2002	12.9	0.0	35.5	4.2	23.0	60.8	95.5	208.6	28.0	0.0	0.0	0.3	468.8
2003	0.0	25.9	18.2	8.4	35.2	87.5	125.6	201.8	23.4	0.7	0.0	0.1	526.8
2004	7.4	3.7	35.2	20.5	7.1	25.4	64.3	221.1	1.4	3.1	0.8	0.0	390.0
2005	0.0	1.4	15.6	48.9	55.1	18.2	110.5	314.0	34.3	0.0	1.3	0.0	599.3
2006	0.0	0.0	31.3	117.6	46.3	38.1	187.1	298.9	23.6	12.0	0.0	0.3	755.2
2007	1.1	2.3	11.2	34.5	22.2	57.1	272.6	139.7	78.6	0.0	0.0	0.0	619.3
Mean	4.7	3.5	25.6	33.0	31.2	40.2	189.6	230.6	26.9	8.1	7.2	1.1	602

Appendix 1.4 Average monthly relative humidity (%)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	55	49	47	38	34	32	73	86	66	57	61	50
1993	48	42	38	68	65	66	72	69	53	50	54	44
1994	44	47	46	35	28	39	68	74	55	34	48	42
1995	37	44	40	47	40	36	73	77	47	36	35	43
1996	47	37	42	34	43	49	60	70	44	33	39	34
1997	36	31	34	32	31	45	68	62	33	42	45	35
1998	45	33	33	29	36	28	69	76	48	36	28	29
1999	36	20	28	24	20	26	72	75	47	45	39	42
2000	30	21	34	29	26	30	63	73	44	42	38	35
2001	49	39	42	56	58	55	74	73	56	48	52	40
2002	46	51	49	43	38	42	71	78	57	45	54	55
2003	52	51	43	48	41	48	76	77	54	42	45	49
2004	49	42	36	46	22	39	60	73	43	39	41	48
2005	50	37	46	44	51	43	75	76	59	45	50	35
2006	49	55	52	52	48	45	74	82	59	56	61	67
2007	66	59	45	49	42	60	79	78	62	47	55	55
Averag	46	41	41	42	39	43	71	75	52	44	47	44

Appendix 1.5 Average monthly sunshine hours (hrs)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	8.2	9.1	9.0	9.5	9.8	8.1	5.0	3.8	6.9	7.9	8.3	9.0
1993	9.7	8.4	9.5	8.4	9.3	7.1	5.4	5.9	7.1	8.5	10.4	10.2
1994	10.3	9.9	9.0	9.5	10.1	6.4	4.4	5.1	7.9	10.5	9.8	10.2
1995	10.3	8.9	9.3	9.1	9.3	9.2	5.4	5.1	8.6	9.8	10.0	9.4
1996	9.0	9.6	8.2	9.2	8.4	5.9	6.1	5.7	7.7	9.8	9.0	9.9
1997	9.5	9.9	8.6	9.1	9.6	8.0	6.0	6.5	8.4	8.1	8.9	10.0
1998	8.4	8.7	9.1	9.4	9.4	7.3	4.9	4.1	7.1	9.2	10.2	10.3
1999	9.3	10.3	9.7	10.4	9.9	6.9	3.9	5.2	8.1	8.9	10.4	9.9
2000	10.1	10.0	10.0	7.8	9.6	7.7	6.7	5.3	6.9	9.0	9.0	9.4
2001	9.6	9.7	6.4	9.6	10.1	7.9	5.3	4.5	8.6	9.3	10.3	10.1
2002	9.3	10.1	8.9	10.4	10.6	11.9	6.2	7.4	8.5	10.3	10.0	9.6
2003	9.9	9.4	9.6	9.3	10.5	6.8	4.3	4.4	8.3	10.5	10.3	10.2
2004	9.8	10.0	10.1	8.8	10.9	6.7	5.9	5.8	7.8	10.1	10.2	10.1
2005	9.6	10.7	9.7	9.8	9.7	8.6	5.4	5.5	7.9	10.4	10.2	10.8
2006	10.6	10.3	8.1	9.0	9.9	6.6	4.9	4.0	7.3	9.5	10.3	9.4
2007	9.4	9.4	9.7	9.8	9.5	7.2	5.6	5.8	7.7	10.6	10.3	10.7
Averag	9.6	9.7	9.0	9.3	9.8	7.6	5.3	5.2	7.8	9.5	9.8	9.9

Appendix 1.6 Average monthly wind run, u_2 (m/s)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	3.47	4.31	4.45	3.75	2.88	1.99	2.04	1.67	1.91	3.13	3.55	3.95
1993	3.53	4.33	3.86	3.86	4.00	3.08	2.64	2.03	1.48	1.85	3.10	3.52
1994	3.84	3.67	3.69	3.78	4.08	3.00	2.14	1.86	1.82	1.67	2.95	3.48
1995	3.51	3.73	4.38	4.10	4.00	2.92	2.46	1.86	1.93	3.35	3.36	3.65
1996	3.58	4.00	3.79	4.08	2.96	1.92	2.04	1.64	2.00	3.34	3.57	3.73
1997	4.42	4.87	3.86	3.79	3.63	2.25	1.68	1.39	2.32	3.65	3.78	3.78
1998	3.52	3.20	4.36	4.78	3.42	2.39	2.33	2.31	1.58	2.67	3.30	3.59
1999	3.46	5.70	3.86	4.25	2.90	2.83	1.86	2.20	1.49	2.66	3.38	3.58
2000	3.71	4.43	4.72	3.44	2.99	2.17	2.05	1.89	1.71	2.80	3.12	3.27
2001	2.83	3.52	3.22	3.74	2.67	1.89	2.31	1.56	1.79	2.83	3.15	3.53
2002	3.49	3.61	3.19	3.43	2.67	2.01	1.54	1.52	1.96	3.02	3.35	3.09
2003	3.86	3.34	3.81	3.63	3.07	2.01	1.99	1.61	1.49	3.60	3.89	4.06
2004	3.11	4.51	4.85	3.74	2.69	1.87	2.01	1.48	2.01	3.26	3.96	4.83
2005	3.36	4.61	4.51	4.46	2.95	3.78	2.11	1.48	1.45	2.82	3.63	4.20
2006	3.98	4.26	3.79	4.04	2.91	2.00	1.71	1.65	1.47	3.15	3.81	3.85
2007	3.86	4.10	4.63	4.12	2.80	2.56	1.72	1.47	1.40	2.55	3.57	3.53
Averag	3.6	4.1	4.1	3.9	3.2	2.4	2.0	1.7	1.7	2.9	3.5	3.7

Appendix 2 Monthly Discharge of Aynalem River upper part of the catchment

(i.e 69km^2): UTM, E-553925, N-1486922

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	**I**	0	0	0.02	0	0.07	0	0.17	0.79	0.037	0	0.021	0
	II	0	0	0.127	0	0.36	0	0.52	2.027	0.074	0	0.074	0
	III	0	0	0	0	0	0	0	0.004	0	0	0	0
1993	**I**	0	0	0	0.103	0.08	0.007	0.17	1.079	0.443	0.015	0.01	0
	II	0	0	0	0.409	0.2	0.038	0.2	9.096	4.148	0.011	0.037	0
	III	0	0	0	0	0	0	0	0.038	0.005	0	0	0
1994	**I**	0	0	0	0.002	0	0.04	0.19	3.838	1.934	0.031	0	0
	II	0	0	0	0.023	0	0.36	0.76	15.151	7.587	0.023	0	0
	III	0	0	0	0	0	0	0	0.012	0.006	0	0	0
1995	**I**	0	0	0.004	0	0.01	0.101	0.15	0.545	0.986	0.016	0	0
	II	0	0	0.027	0	0.07	0.234	0.2	0.959	3.812	0.012	0	0
	III	0	0	0	0	0	0	0	0.019	0.004	0	0	0
1996	**I**	0.01	0.002	0.001	0	0.02	0.081	0.35	0.215	0.038	0.001	0	0
	II	0	0.001	0.001	0	0.22	0.216	2.47	0.272	0.038	0.001	0	0
	III	0	0.001	0	0	0	0	0	0.005	0.001	0	0	0
1997	**I**	0	0	0	0	0.05	0.04	1.7	0.513	0.256	0	0	0
	II	0	0	0	0	0.41	0.027	10.2	1.349	0.675	0	0	0
	III	0	0	0	0	0	0.007	0	0.001	0.001	0	0	0
1998	**I**	0	0	0	0	0	0.273	2.02	2.346	0.489	0.178	0.204	0.147
	II	0	0	0	0	0	1.096	4.71	6.829	1.349	0.086	0.104	0.074
	III	0	0	0	0	0	0	0.01	0.007	0.083	0.058	0.05	0.027
1999	**I**	0.05	0.007	0	0	0	0	0.98	3.897	0.972	0.471	0.243	0.146
	II	0.03	0.012	0	0	0	0	1	6.682	2.797	1.958	0.104	0.074
	III	0.01	0	0	0	0	0	0	0.093	0.115	0.104	0.074	0.038
2000	**I**	0.05	0	0	0	0	0.002	0.18	0.813	0.042	0.001	0	0
	II	0.04	0.001	0	0	0	0.009	0.72	0.959	0.093	0.002	0	0
	III	0	0	0	0	0	0	0	0.002	0.004	0	0	0
2001	**I**	0	0	0	0	0	0	1.32	2.217	0.196	0.062	0.034	0.002
	II	0	0	0	0	0	0	6.25	5.449	0.115	0.044	0.023	0.002
	III	0	0	0	0	0	0	0	0.044	0.038	0.005	0.004	0

I = Monthly Runoff in Mm^3

II = Maximum Discharge in m^{3}s^{-1}

III = minimum Discharge in m^{3}s^{-1}

Appendix 3 Monthly water level for monitoring wells (m)

Year	Month	PW3	PW6	PW8	PW11	TW3	PW2	MU
2003	Jan							
	Feb	35.24	29.5	34.4	24.6	24.4	58.1	
	Mar	35.4	29.5	35.7	24.9	28.3	44.5	
	Apr	36.1	29.5	36.6	27	30.5	77	
	May	37.5	29.5	36.7	28.7	32.2	78	
	Jun	38.7	29.5	39	30.7	34.2	82	34.7
	Jul	36.4	29.5	39.9	28	32.7	76	
	Aug	35	29.5	39.3	28.1	31.6	73.4	
	Sep	35.6	29.5	34.2	25.2	29.9	74	
	Oct	40.5	29.5	33.5	26.3	30.2	75	
	Nov	36	29.5	33.8	26.8	31.5	80	
	Dec	35.6	29.5	35	30.3	33.8	85	
2004	Jan	52.4	29.5	36.1	32.2	36.7	89	
	Feb	57.8	29.5	37.2	34.2	36.4	88	
	Mar	58	30	39.5	35.9	37.6		
	Apr	59.1	31	40.1	36.3	38.3		
	May	59.1	32	42	36.8	38.8		
	Jun	59.1	33	43.1	36.5	39	91.5	
	Jul	53.4	33.8	44.9	36.1	39.4	94.4	39.8
	Aug	59	32	45	33	37.2	94.7	37.0
	Sep	60	32.5	43.8	36.1	36.4	95.9	38.9
	Oct	60	36.9	46.4	41.7	41.8	96	43.3
	Nov	60	37.7	47.4	43.6	43.9	96	44.0
	Dec	60	37.4	48.3	44.2	44	96	45.4
2005	Jan	60	37	49	44	44.9	96	45.8
	Feb	60	37.2	50.1	44.2	44.8	96	46.0
	Mar	60	37.2	52	44	43.7	96	46.0
	Apr	55.5	34.5	51.5	45			42.9
	May	46.2	35.1	51.1	45.5			
	Jun	45.9	35	52.2	46.5			
	Jul	43.8	34.3	54.7	44.9			
	Aug	41	33	53	43			
	Sep	40	32.9	48.9	39.9			
	Oct	25	31.7	48.3	39.5			
	Nov	24.6	30.6	47.2	37.9			
	Dec	24.2	30.3	46.3	28.9			
2006	Jan	25	30	45	41			
	Feb	26.7	29.3	46.8	31.7			
	Mar	33.2	29.4	46.5	43.4			
	Apr	36.3	29.5	48.93	42.44			
	May	41	30.4	49.25	44.3			
	Jun	34.15	30.45	49.33	43.45			
	Jul	34	31	51	44			
	Aug	31	31	45	37			
	sep	33	31	51	37			
	Oct	38	31	37	33			
	Nov	41.6	30.5	36.8	31.6			
	Dec	43	31	37	33			

Appendix 4 Monthly well abstractions for monitoring wells (m3)

2003												
WELL	Jan.	Feb.	Mar	April	May	Jun	July	August	Sep.	Oct.	Nov.	Dec.
PW2	14721	2181	0	26815	36241	31459	32475	36739	35440	36995	32655	33615
PW3	49350	48225	50400	57491	52025	22865	12882	5812	48080	54300	42909	45234
PW6	5627	7212	5627	7212	5627	7212						
PW7											5696	1674
PW8	61577	58562	62435	5541	58338	58174	57892	58886	62020	64230	57522	58405
PW11							12998	6867	8820	9297	9645	9015
PW12	55793	34061	55793	55793	30912	30912						
TW 5							6130	5683	6729	6920	6560	6358
TW 3	2205	4662	10717	13304	17532	17143	17382	16770	16629	20970	18751	18346
MU	17598	15590	11150	18830	11150	14161	14300	14300	9210	9210	9210	9210
TW2	19138	20370	15043	14373	15043	22927	21937	18240	0	6420	19446	19859
ET							6316	19839	19345	20476	19224	19080
Ms	4081	2387	4785	5220	2387	5812	4297	3107	4721	13817	11889	11263

2004												
WELL	Jan.	Feb.	mar	April	May	Jun	July	August	Sep.	Oct.	Nov.	Dec.
PW7b							35380	34286	31517	30962	32627	33746
PW2	32968	29703	28636	23914	21837	14452	10972	14115	35056	35845	35320	34819
PW3	42079	40760	36223	33733	31482	71671	9489	9883	14070	14354	13398	10987
PW4							15603	15603	15471	16129	15959	15471
PW8	60126	61651	66614	63714	67381	58248	60745	58418	55562	60262	58951	60010
PW11	5638	6034	15325	14114	12482	10636	6023	2868	9467	5679	4997	3815
TW5	6528	5724	4943	5464	5363	4783						
TW3	18603	17750	18528	17800	18755	17903	14644	13959	11633	10313	10130	10025
MU	14000	14300	13862	13062	14400	13940	14005	12813	14377	12798	13485	13070
Tw2	23711	24955	30354	29691	31773	28650	28838	23406	21651	24997	24015	24228
ET	20574	19654	19351	19322	19024	19459	17358	9000	9000	9000	9000	9000
Ms	11182	10648	11027	11284	10515	11058	5623	7811	7141	6413	6038	5477

2005												
WELL	Jan.	Feb.	mar	April	May	Jun	July	August	Sep.	Oct.	Nov.	Dec.
PW7b	34695	34154	35661	30684	30173	27595	77069	40601	58488	61834	60351	59764
PW2	36663	35352	33856	34248	34049	26149	32929	30785	38278	37795	37780	36787
PW3	12726	12819	12603	11804	11176	10614	11303	1742	16410	17331	16500	12568
PW4	14720	15603	15454	16	16762	16908	16796	17026	17991	18213	1738	16950
PW8	60289	58831	60765	54704	52798	48744	29844	27805	36885	39240	38927	37276
PW11	4361	3391	5838	5593	6150	5556	5154	5802	6931	5969	4323	1843
TW3	10441	9197	9391	4356	10545	6677	5555	2164	2164	2164	2164	2164
MU	13915	13123	13886	13408	13831	13444	13940			7905	12636	15195
TW2	24959	24281	26502	22953	10472	26225	30419	29407	30243	31974	30932	31196
ET	9000	9000	9000		10308	15275	16432	15133	20346	19087	17540	16527
Ms	5633	5500	5633	5378	5378	5378	5030.89	5144.56	5580.3	9054.2	7580.7	7352.67

2006												
WELL	Jan.	Feb.	Mar.	April	May	Jun	July	August	Sep.	Oct.	Nov.	Dec.
PW7b	56042	33145	34194	53498	53499	53499	19903	23752	25193	27990	38987	24495
PW2	35409	33910	34654	35370	35370	35370	25051.4	22851	32294	34937	22509	41891
PW3	13067	11170	11596	12409	12410	12410	14777	21002	19021	18920	18374	18821
PW4	16627	16329	16824	15388	15388	15388	14943	17544	25615	17874	19523	20499
PW8	35197	48632	49717	38169	38169	38169	50665	54784	58903	47964	34852	55280
PW11	3347	5321	5513	4911	4911	4911	4672	6673	5702	5098	5728	5860
TW5									45878	41709	46049	46222
TW3	13922	2164	2405	2164	2164	2164	12527	10964.4	10142	11149	10348	10178.4
MU	14078	14289	14289	10259	10259	10259	13094	15525	15300	13854	14170	15817
Tw2	31248	27898	28692	30223	30223	30223	21112	16415	27577	32476	37125	36722
ET	13922	12150	12715	15984	15984	15984	15278.4	14865.2	16667	17935	15432	14633

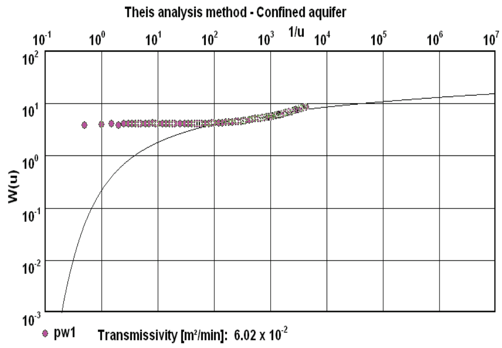
2007												
WELL	Jan.	Feb.	Mar.	April	May	Jun	July	August	Sep.	Oct.	Nov.	Dec.
PW7b	34112	27487	32138		31806	29320	29093	40227	1258	1432	26824	35527
PW2	34665	36558	33882	34237	16528	21743	31253	32979	36309	34072	35281	36867
PW3	12971	13191	11216	10621		8189	14837	17419	17534	17949	15179	11003
PW4	16719	16342	16654	16144	16960	14013	17402	630	18929	18560	19041	18604
PW8	54993	56215	48632	55396	53815	44316	39230	15309	57831	53853	54801	58142
PW11		3989	5321	4842	5334	5147	5609	5981	4170	3115	4193	3113
TW5							41254	78905		41709	29380	27727
TW4-2005							30593	21170		34388	42049	43547
MU	14086	5888	14289	13683	15217		10709	9659	13228	13996	15417	15414
Tw2	30454	28483	27220		26190	26337	15236	15718	14706	6824	14034	18945
ET	14499	13601.3	13689	11769	15105.3	16906	21007	15488	17977	23176	23176	23176

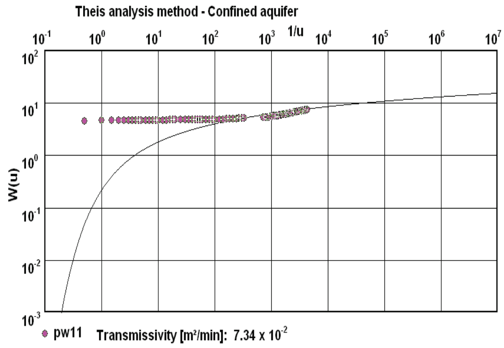
Appendix 5 Detailed information of wells in Aynalem aquifer

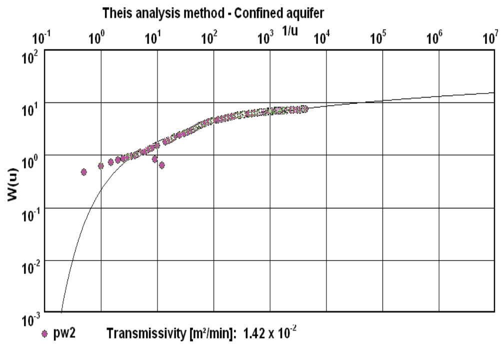
	Location						
Local Name	UTM-E	UTM-N	Elevation(m)	T (m^2/d)	Aquifer thickness	K (m/d)	Major aquifer
PW-12	553549	1488948	2208	1138.4	14	81.3	lmst/dolerite
PW-3	553941	1488821	2214	3120.63	28	111.5	lmst/dolerite
PW-11	552490	1489376	2208	967	13	74.4	lmst/dolerite
PW-1	556050	1487809	2211	138.84	30	4.6	lmst/dolerite
Adi-seleste	555901	1486423	2252	217	12	18.1	lmst/dolerite
PW-4	553706	1488251	2210	91.67	30	3.1	dolerite
PW-5	554336	1487216	2189	1.02	45	0.02	dolerite
PW-6	555526	1487648	2221	4757.2	30	158.6	lmst/dolerite
PW-8	557809	1488359	2237	3504.7	24	146	lmst/dolerite
PW-2	556722	1487915	2227	24	8.5	2.82	lmst/dolerite
PW-9	558268	1488286	2243	51.04	16	3.2	lmst/sst
PW-7	557115	1487967	2233	1839.5	20	91.96	lmst/dolerite
TW1-2005	561057	1487352	2277	1750	65.6	26.68	limestone
TW2-2005	564439	1485877	2311	100	72	1.39	limestone
TW4-2005	557234	1488028	2228	100	54	1.85	limestone
TW5-2005	552970	1488153	2206	170	60	2.83	limestone
AR-1	556406	1488604	2215	409	14	29.2	limestone
AR-2	555787	1489875	2256	723	18	40.2	lmst/dolerite
Lesper	551526	1487025	2143	27.4	24	1.14	lmst/dolerite
TW4	553140	1488452	2178	24.4	19	1.28	dolerite
TW5	552880	1489018	2183	127	28	4.54	lms/dole/sst
Tesfayelive	552112	1484834	2226	402		57.5	limestone
TW1	553845	1487586	2193	23.3	19	1.25	dolerite
TW6-2006	549453	1485160	2133	65.3	40	1.6	

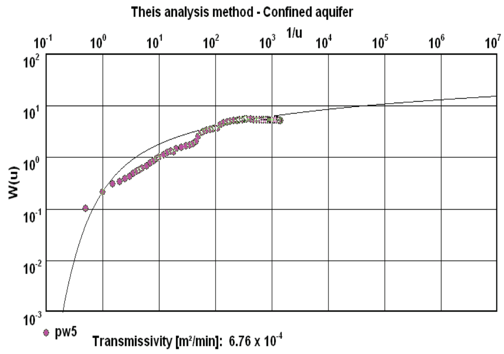
Appendix 6 Pumping test curve matching by different methods

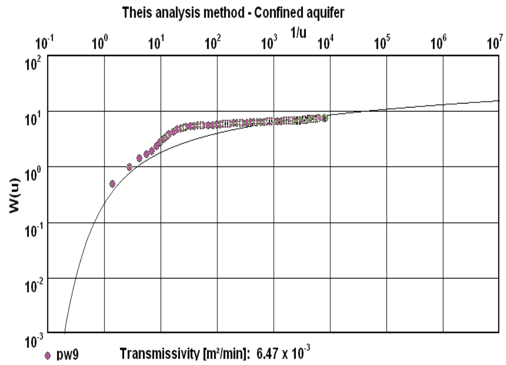
Appendix 6.1 Pumping test analysis of Theis method- confined aquifer

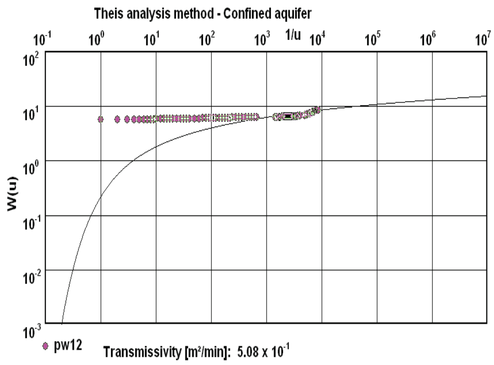




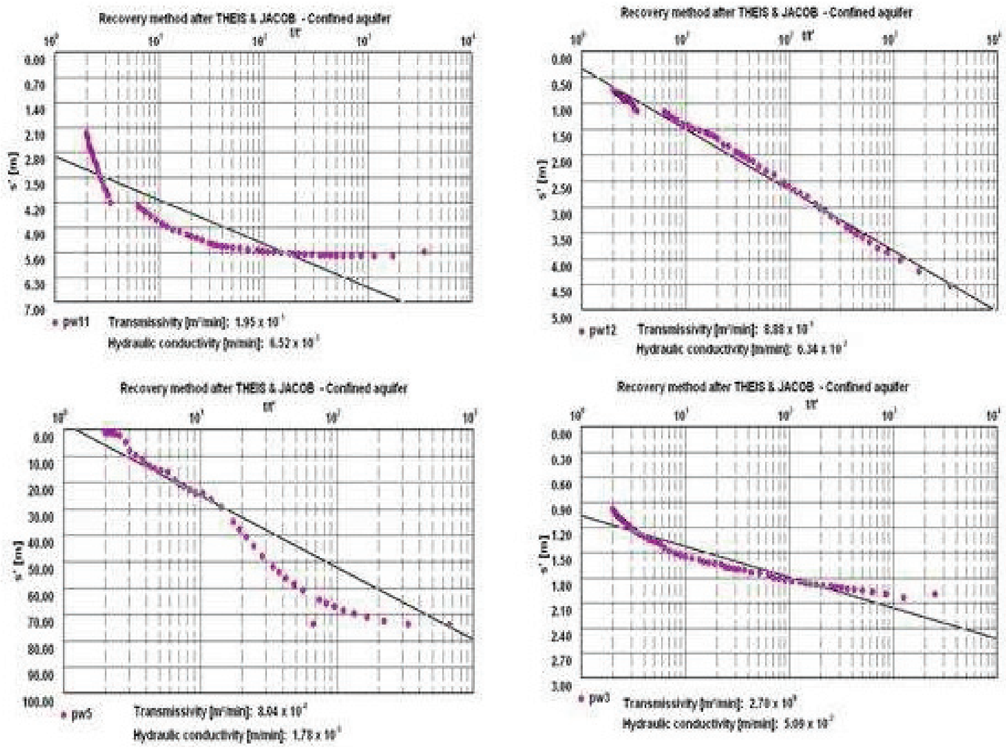




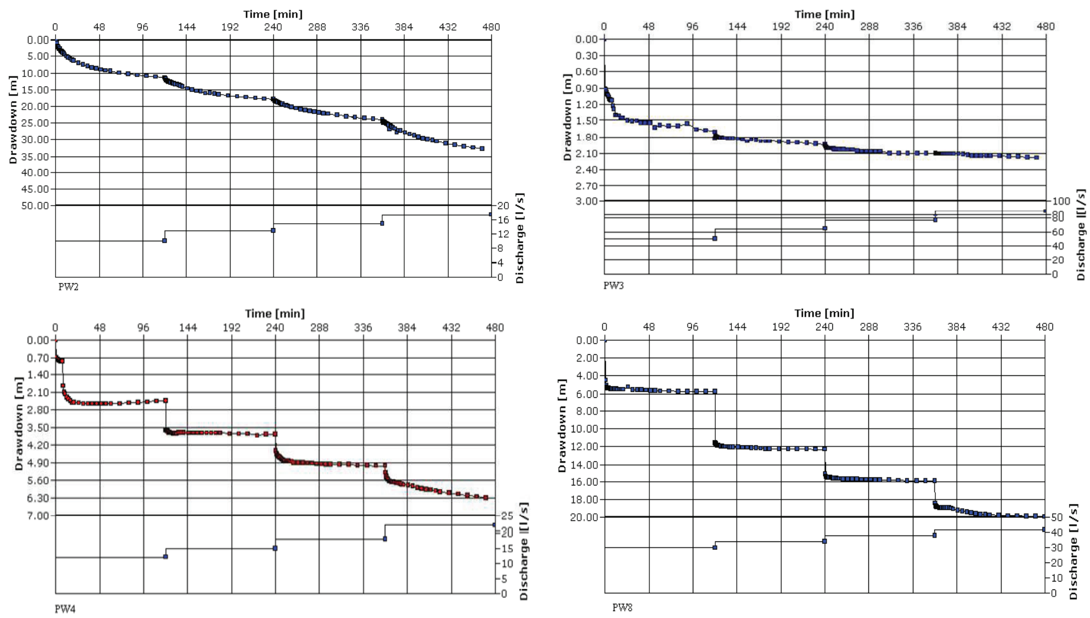




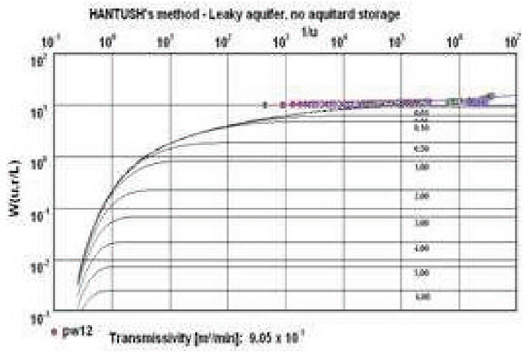
Appendix 6.2 Recovery method after Theis & Jacob-confined aquifer

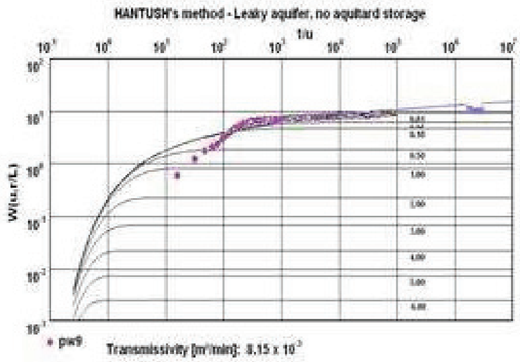


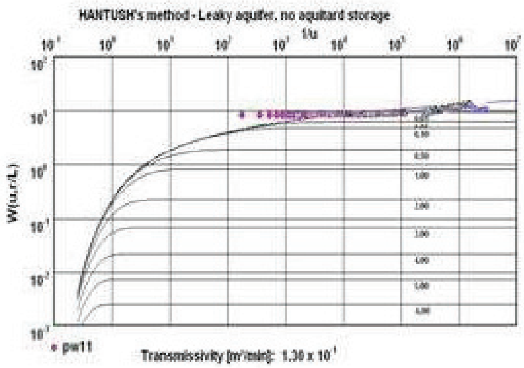
Appendix 6.3 Step test of drawdown and discharge of pumping wells

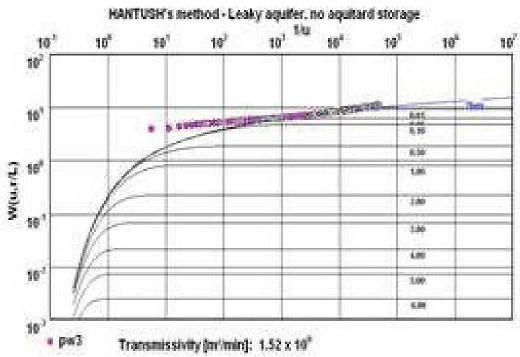


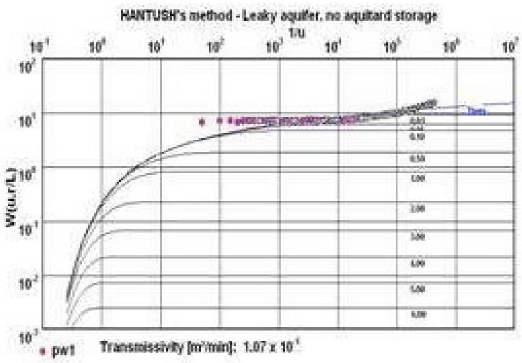
Appendix 6.4 Hantush method-leaky aquifer no aquitard storage

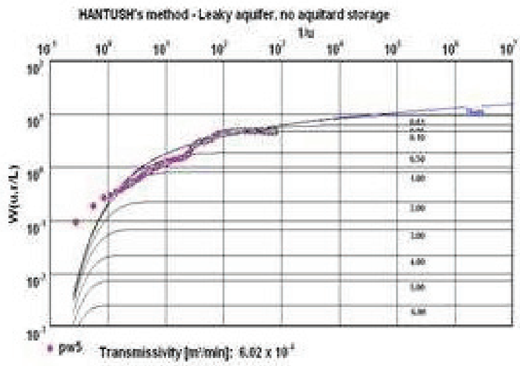




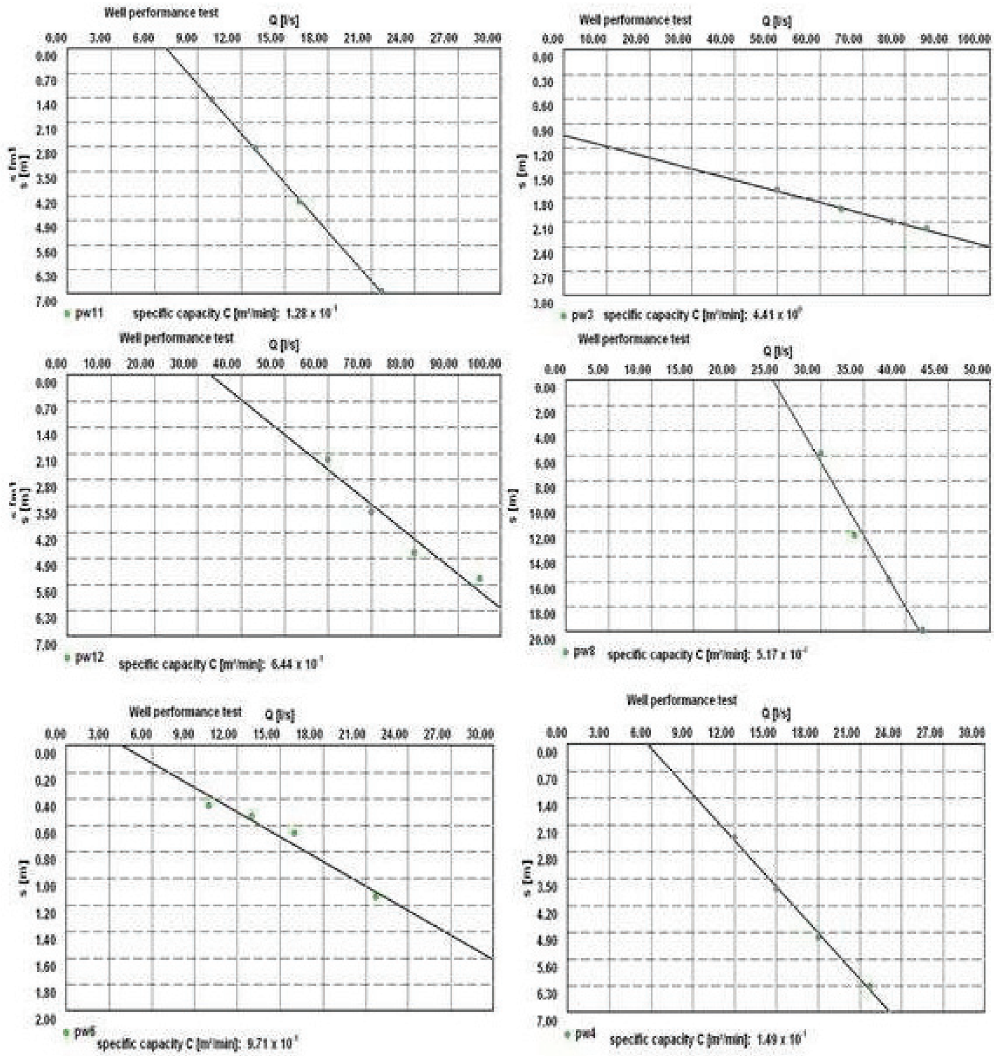






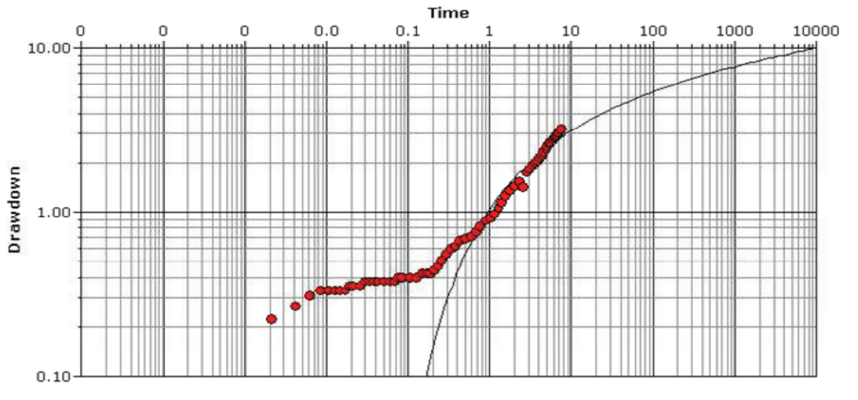


Appendix 6.5 Well performance test



Appendix 6.6 Pumping test of pumping well with observation well (log-log and linear)

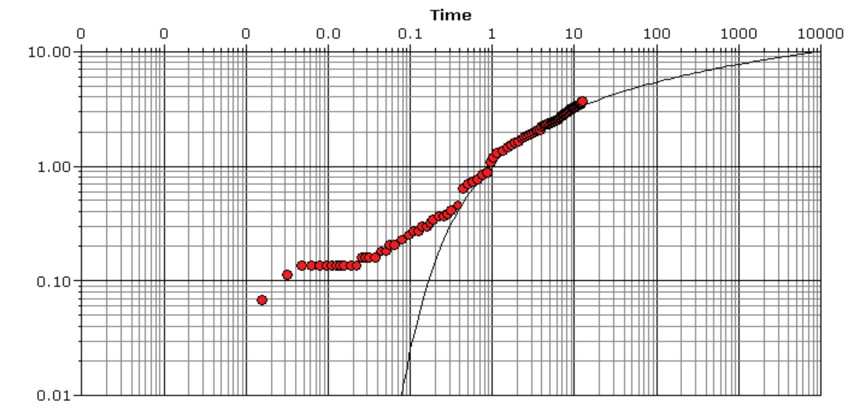
Analysis Performed by:	theis	Analysis Date: 10/22/2008
Aquifer Thickness: 14.00 m	Discharge Rate: 95 [m³/d]	



Calculation after Theis

Observation Well	Transmissivity [m²/d]	Hydraulic Conductivity [m/d]	Storage coefficient	Radial Distance to PW [m]	
PW12	3.57×10^{1}	2.55×10^{0}	3.27×10^{-10}	0.2	
PW3	1.67×10^{1}	1.19×10^{0}	1.59×10^{-5}	412.06	
Average	2.62×10^{1}	1.87×10^{0}	7.96×10^{-6}		

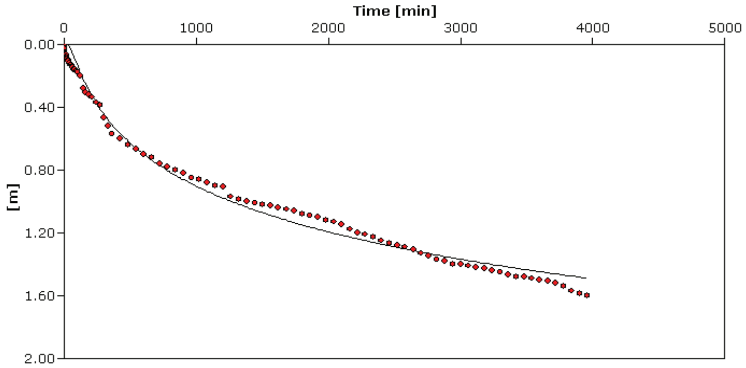
Analysis Performed by: gebrehaweria	theis	Analysis Date: 10/20/2008
Aquifer Thickness: 34.00 m	Discharge Rate: 42 [l/s]	



Calculation after Theis

Observation Well	Transmissivity [m²/d]	Hydraulic Conductivity [m/d]	Storage coefficient	Radial Distance to PW [m]	
pw9	6.53×10^{2}	1.92×10^{1}	6.56×10^{-4}	464.77	

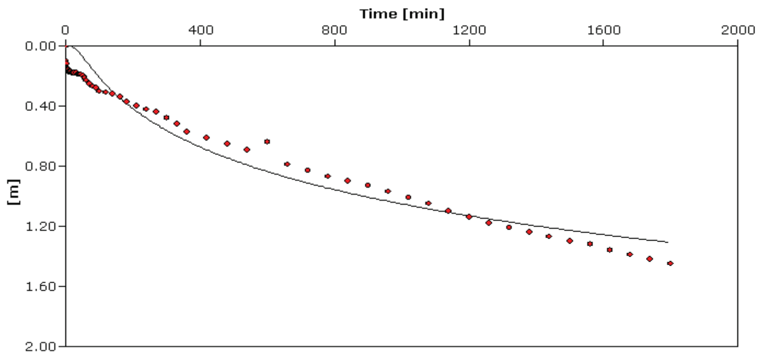
Test Conducted by:		Test Date: 10/20/2008
Analysis Performed by: gebrehaweria	time vs drawdown	Analysis Date: 10/20/2008
Aquifer Thickness: 34.00 m	Discharge Rate: 42 [l/s]	



Calculation after Theis

Observation Well	Transmissivity [m²/d]	Hydraulic Conductivity [m/d]	Storage coefficient	Radial Distance to PW [m]	
pw9	6.53×10^{2}	1.92×10^{1}	6.56×10^{-4}	464.77	

Test Conducted by:		Test Date: 10/22/2008
Analysis Performed by: gebre	Time vs. drawdown	Analysis Date: 10/22/2008
Aquifer Thickness: 14.00 m	Discharge Rate: 95 [m³/d]	



Calculation after Theis

Observation Well	Transmissivity [m²/d]	Hydraulic Conductivity [m/d]	Storage coefficient	Radial Distance to PW [m]	
PW3	1.67×10^{1}	1.19×10^{0}	1.59×10^{-5}	412.06	

Appendix 7 Detailed well history and lithological logs

1. Well index-TW4, depth-94m, SWL-24.50m, well diameter-8", casing type-open well, UTME-559405, UTMN 487676, elevation-2262 m

Depth (m)	Lithology
0-12	Limestone; weathered and fractured
12-94	Dolerite; weathered and fractured with secondary precipitate

3. Well index–PIZ-1S, Well depth –133m, Water strike- 67; 107, SWL-36.58, Well diameter- 6 ", Well Casing - 2" pvc, Screen Position - 109 -133 m, drilling date – 27/02/2004, UTM E – 553320, UTMN – 1488680, elevation-2203

Depth (m)	Lithology
0-2	Silty clay
2-5	Silt
5-14	Rock fragments of limestone
14-17	Dolerite; highly weathered
17-20	Dolerite; moderately weathered
20-65	Dolerite; Dolerite, fresh
65-85	Dolerite; highly fractured with calcite precipitate
68-95	Dolerite; fresh
95-105	Dolerite; moderately weathered and fractured
105-108	Limestone; highly weathered and fractured
108-117	Limestone; dark, highly fractured
117-133	Limestone; with intercalation of shale

2.Well index-Kiha new hospital, drilling diameter- 8 ½ inch, depth – 59 m, SWL=16.2 m, Q= 1.75 l/s, draw dawn – 22.27m, Transmissivity – 5.53m²/day, drilling date –15/12/98, location: UTME-558144, UTMN-1490672

Depth (m)	Lithology
0-3	Top soil with limestone cobble
3-4	Dark blue limestone, weathered
4-12	Weathered whitish limestone and variegated clay stone
12-15	Black dolerite
15-21	Shale with blue limestone interbedded
21-36	Whitish greenish shale with some crystalline doleritic layer interbedded
36-46	White crystalline limestone fractured (aquifer)
42-59	Black dolerite

4.Well Index – PW6, well depth-75m, SWL-19.73m, well casing-open well, well diameter -7 7/8 ", drilling date - 23/12/1997, UTME - 55552, UTMN – 1487648, elevation-2221m

Depth (m)	Description
0 - 4	Sandy clay
2 - 6	Highly weathered sandy limestone
6 - 26	Highly weathered sandy limestone very white
26 - 35	Black weathered limestone
35 - 52	Weathered dolerite
52 - 75	Massive dolerite

19.Well Index-TW5, well depth-100 m, SWL-16.93m, well casing- open well, well diameter –12.25 ", drilling date – 30/06/1992, UTME - 553207, UTMN – 1488955, Elevation-2206m

Depth (m)	Description
0 - 2	Light brown soil
2 - 15	Weathered and fractured dolerite
15 -72	Dark fresh dolerite fractured
72 - 85	Fresh dolerite with secondary mineral fractured
85 - 100	Light brown fresh sandstone, fractured fresh, black limestone

5.Well index- PIZ-3D,
depth 128m,
water strike-36, 89,124,
SWL-24.08,
well diameter-6”,
well casing - PVC 2",
Screen position - 104-128,
UTME-559410,
UTMN-1487663,
Elevation-2259

Depth (m)	Lithology
0-5	Sandy clay on the top black cotton soil
5-11	Dolerite; highly decomposed
11-20	Limestone; highly weathered
20-26	Limestone; moderately weathered
26-38	Limestone; fractured, with calcite precipitate
38-68	Shale; dark colour
68-89	Limestone; dark with intercalation of shale
89-95	Limestone; highly fractured
95-101	Limestone; assimilated with dolerite
101-113	Dolerite; fractured
113-119	Dolerite; massive
119-123	Dolerite; fractured
123-128	Dolerite; fresh

6.Well Index – PIZ,
well depth – 101m,
water strike - 36; 89,
SWL– 24.50 m,
well casing-PVC 2",
well diameter - 6 ",
Screen position - 77- 101m,
UTME – 559405,
UTMN-1487676,
Elevation-2262 m

Depth (m)	Lithology
0-5	Rock fragment; at the top sandy clay
5-20	Dolerite; highly decomposed
20-26	Limestone fragment
26-35	Limestone; fractured, light colour, with calcite precipitate
35-41	Limestone; with shale intercalation
41-68	Shale; very dark
68-83	Limestone; light colour, with shale intercalation
83-92	Limestone; dark colour
92-101	Limestone assimilated with dolerite (contact zone)

7.Well index – PW2,
well depth – 117.5 m,
water strike – 109, SWL-31.30m,
well casing- open well,
well diameter - 12.25 ",
drilling date - 18/06/1997,
UTME-556722,
UTMN-1487915,
elevation-2227m

Depth (m)	Lithology
0-1.5	Top soil, clay
1.5-5	Highly weathered dolerite
5-11	Moderately weathered dolerite
11-38	Massive dolerite
38-44	Slightly fractured dolerite
44-109	Massive dolerite
109-114	Highly fractured dolerite
114-117.5	Moderately weathered limestone

13.Well Index - PW7,
well depth-65m,
water strike-20 m,
SWL-8.1m,
well casing-Open well,
well diameter- 12.25 ",
drilling date-18/01/1998
UTME – 557115,
UTMN -1487967,
Elevation-2233m

Depth (m)	Description
0 - 2	Black cotton soil
2 - 10	rock fragment mainly limestone
10 - 14	Black limestone
14 - 18	Fresh dolerite
18 - 20	Marley limestone, highly fractured with calcite precipitation
20 - 28	Highly fractured dolerite
28 - 40	Moderately fractured dolerite
40 - 65	Massive dolerite

8.Well Index-7b,
well depth-51m,
water strike – 135, SWL-46.95m,
well casing- open,
well diameter - 9 5/8",
UTME-557108
UTMN-1487962,
Elevation-2232m

Depth (m)	Lithology
0-4	Clay; sandy
4-8	Limestone; highly weathered
8-14	Limestone; dark, moderately weathered
14-20	Limestone; highly fractured and weathered
20-25	Limestone; very dark
25-37	Dolerite, slightly weathered
37-61	Dolerite; slightly fractured but, dry
61-131	Dolerite; with porphyritic texture
131-137	Limestone assimilated with dolerite (contact zone)
137-141	Limestone; highly weathered
141-145	Limestone; highly fractured with calcite precipitate
145-149	Limestone; marly
149	Limestone; dark

9.Well Index – PW10,
well depth – 98 m,
well diameter -12.25 ",
drilling date - 04/04/1998,
UTME-554135,
UTMN - 1489476
Elevation-2202m

Depth (m)	Description
0 - 2	clay & marl
2 - 6	Rock fragment
6 - 10	Highly weathered limestone
10 - 32	Dark limestone
32 - 42	silt stone
42 - 50	sandstone
50 - 51	weathered dolerite
51 - 98	Fresh dolerite

11.Well Index-PW3,
well depth-120 m,
water strike -SWL-20.55m,
well casing-open well,
well diameter - 12.25 ",
drilling date -15/08/1997.
UTME-553941,
UTMN -1488821,
elevation-2214m

Depth (m)	Lithology
0-2	Sandy clay
2-11	Highly fractured & moderately weathered limestone
11-29	Highly weathered & fractured limestone with sub angular limic gravel
29-33	Gravely to sandy rounded and angular poorly sorted limestone and sandstone composition
33-35	Gravely to sandy limestone
35-36	highly fractured limestone black colour
36-39	Black limestone moderately with calcite precipitation
39-47	limestone highly fractured with calcite precipitation, black color
47-57	Fractured and weathered dolerite
57-88	Massive dolerite
88-92	Highly fractured dolerite
92-112	Moderately fractured dolerite
112-120	Massive dolerite

22.Well index-TW5-2005,
SWL-29m, 31m, 30m,
water strike-from 50-80,98m
UTME-552970,
UTMN-1488153,
Elevation-2206m

Depth (m)	Lithology
0-9	Black cotton top soil
16-16	Highly weathered dolerite
16-64	Moderately weathered dolerite
64-98	Massive dolerite
98-136	Fractured limestone
136-147	Massive limestone

10.Well index-PW1,
well depth-120m,
water strike -21; 65; 105,
SWL-1.22 m,
well casing-8",
well diameter-12",
drilling date - 24/05/1997
UTME-556050,
UTMN-1487809, e
levation-2211m

Depth (m)	Lithology
0-4	sandy clay
4-15	Gravely sand, angular
15-25	Limestone; highly weathered with marl or shale intercalation
25 -45	Limestone; highly fractured and moderately weathered
45-57	Sand; fine grain light in colour
57-63	Calcareous limestone
6371	Fractured limestone with shale intercalation
71-103	Dolerite; massive
103-115	Highly fractured dolerite
115-120	Fresh dolerite

12.Well Index-PW4,
well depth-120 m,
SWL-15.15m,
well casing-open well
well diameter-12.25 ",
drilling date - 24/08/1997.
UTME-553706,
UTMN – 1488251,
elevation-2210m

Depth (m)	Lithology
0-2	Top soil; Sandy clay
2-11	Highly fractured weathered limestone
11-15	Moderately weathered light grey fosliferous limestone
15-21	Moderately weathered limestone
21-25	Black limestone
25-31	Moderately weathered limestone
31-37.5	Moderately weathered dolerite
37.5-49.5	Fractured dolerite with calcite filling
49.5-57.5	Slightly fractured dolerite
57.5-71.5	Fresh dolerite
71.5-73.5	Slightly fractured dolerite
73.5-77.5	Fresh dolerite
77.5-89.5	Slightly fractured dolerite
89.5-95.5	Fresh dolerite
95.5-120	Dolerite fresh, slightly fractured at the bottom

16.Well Index – PW8,
well depth-89.9m,
water strike - 38m,
SWL-19.31m,
well casing -open well,
well diameter-12.25",
drilling date -10/02/1998
UTME-557809,
UTMN-1488359
Elevation-2237m

Depth (m)	Description
0 - 2	Sandy clay
2 - 10	Weathered limestone; white colour
10 - 14	Black limestone
14 - 38	Darky shale
38 - 42	Rock fragment mainly limestone, sandstone and shale
42 - 50	Black limestone
50 - 62	Marl with calcite with precipitation
62 - 89.9	Massive dolerite

18.Well Index – PW12,
well depth-80m,
water strike -28 m,
SWL-14.97m,
well casing -open well,
well diameter-12.25",
drilling date - 10/04/98
UTME-552945,
UTMN – 1488948,
Elevation-2208m

Depth (m)	Description
0 - 4	sandy clay
4 - 20	Weathered sandstone with rock fragments
20 -30	Weathered limestone. marl
30 - 34	Weathered dolerite
34 - 80	Dolerite fresh

15.Well Index – PW9,
well depth-71.5m,
water strike - 58 m,
SWL-16.26 m
well casing - 8" steel casing,
well diameter -12.25 ",
drilling date - 02/03/1998
UTME-558268,
UTMN-1488286,
Elevation-2243m

Depth (m)	Description
0 - 2	Black cotton soil
2 - 8	Sandy clay
8 - 12	Rock fragment mainly limestone
12 - 20	Shale darkly
20 - 30	Shale & limestone
30 - 36	Gravel, limestone origin
36 - 48	Siltstone
48 - 52	Sandstone grey colour
52 - 54	Unsorted gravel
54 - 58.5	Highly fractured limestone
58.5 - 70	Sandstone, fractured
70 -71.5	Dolerite massive

17.Well Index – PW11,
well depth–75m,
water strike -62 m,
SWL-9.8 m
well casing-Open well,
well diameter - 12.25”,
drilling date - 28/03/1998,
UTME-552490,
UTMN -1489376,
Elevation-2208m

Depth (m)	Description
0 - 2	Top soil, clay
2 - 6	Sandy clay fine grain
6 - 8	Highly weathered dolerite
12 - 48	Dolerite; slightly weathered
48 - 52	Massive dolerite
52 - 62	Highly fractured dolerite with calcite precipitation
62 - 66	Sandstone
66 - 68	Dolerite; fractured
68 - 75	Sandstone; fractured light in color

20.Well Index-TW1,
well depth-83.5m,
SWL-6.6 m,
well casing - steel 12”,
Drilling-date-14/08/1992,
UTME-552490,
UTMN-1489376,
Elevation-2208m

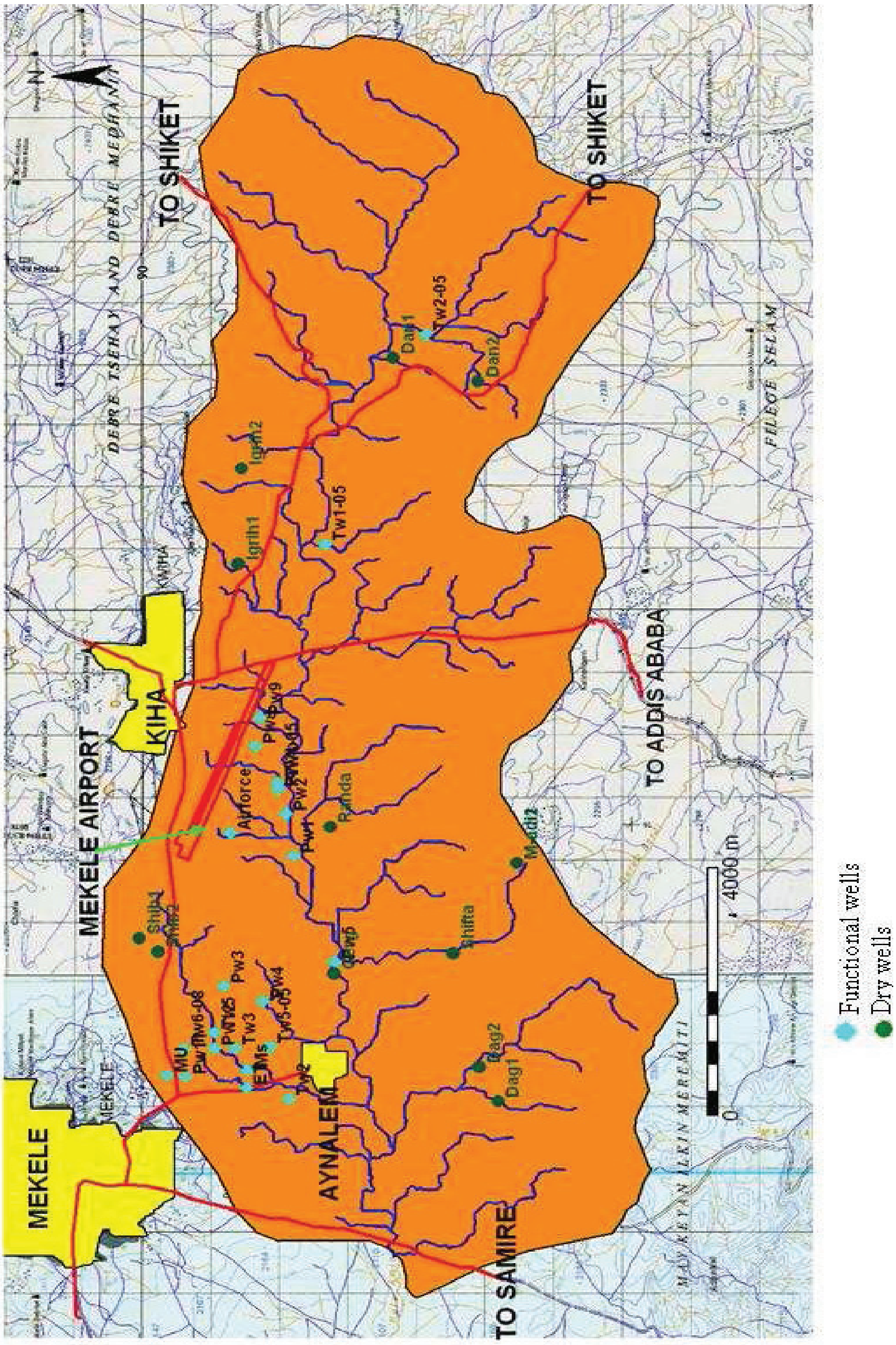
Depth (m)	Description
0 - 4	Black cotton soil
4 - 6	Marly clay
6 - 10	Shale with unconsolidated layer
10 - 22	Gravely sand with limestone pebbles
22 - 32	Shale, the lower part fractured
32 - 50	Limestone with marl, upper part fractured
50 - 52	Sand with gravel
52 - 60	Slightly weathered limestone
60 - 83.5	Black limestone; non fractured

21.Well index- Mekele University,
well depth-174 m,
well casing - 8”,
Drilling date – 17/12/2003,
UTME –552506,
UTMN – 1489646,
Elevation-2209m

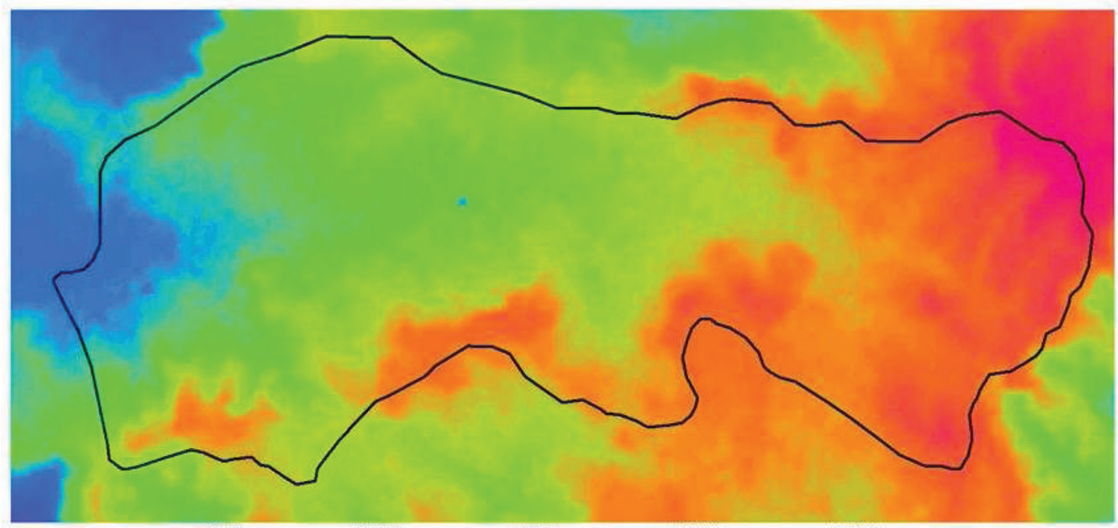
Depth (m)	Description
0 – 6	Top soil, black silty clay
6 - 18	Weathered and fractured dolerite
18 - 66	Fresh dolerite
66 - 70	Sandy limestone
70 - 80	Fresh Dolerite
80-126	Black limestone
126-164	Fresh massive dolerite
164-174	Black limestone

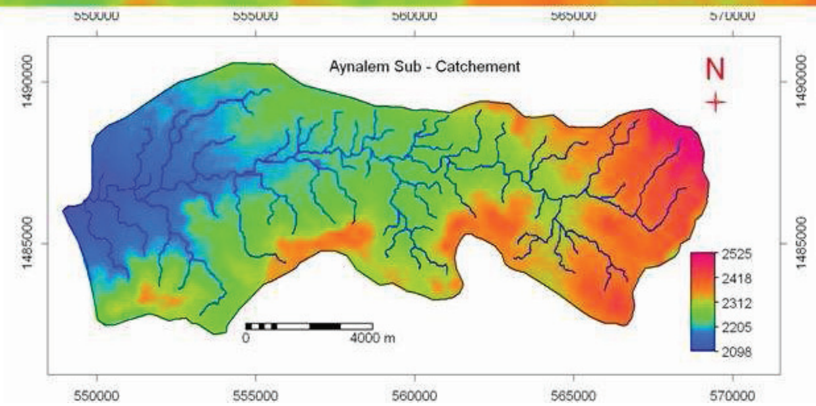
Appendix 8 Well location and base map of study area extracted from topo map and ASTER DEM

Appendix 8.1 Well location map



Appendix 8.2 Base map extracted from ASTER DEM





Appendix 9 WATBAL_GW models for simulation of groundwater recharge.

Appendix 10 Water budget and groundwater head MODFLOW simulation

Appendix 10.1Water budget from model simulation of at the end of each stress period (m^3/day)

STRESS PERIOD 1			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	16695.0	0.0	16695.0
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7103.0	-7103.0
DRAINS	0.0	5075.3	-5075.3
RECHARGE	78.4	0.0	78.4
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	4591.9	-4591.9
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	16773.3	16770.2	3.1
DISCREPANCY[%]	0.0		

STRESS PERIOD 2			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	15581.1	0.0	15581.1
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7161.0	-7161.0
DRAINS	0.0	4122.5	-4122.5
RECHARGE	169.7	0.0	169.7
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	4467.0	-4467.0
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	15750.9	15750.5	0.3
DISCREPANCY[%]	0.0		

STRESS PERIOD 3			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	6760.2	2558.4	4201.8
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	6277.0	-6277.0
DRAINS	0.0	3558.8	-3558.8
RECHARGE	10035.6	0.0	10035.6
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	4403.1	-4403.1
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	16795.8	16797.2	-1.4
DISCREPANCY[%]	0.0		

STRESS PERIOD 4			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	14926.0	0.0	14926.0
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7787.0	-7787.0
DRAINS	0.0	2863.2	-2863.2
RECHARGE	14.5	0.0	14.5
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	4285.6	-4285.6
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	14940.5	14935.9	4.6
DISCREPANCY[%]	0.0		

STRESS PERIOD 5			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	8228.5	0.0	8228.5
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7650.0	-7650.0
DRAINS	0.0	2736.2	-2736.2
RECHARGE	6378.6	0.0	6378.6
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	4224.2	-4224.2
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	14607.1	14610.4	-3.3
DISCREPANCY[%]	0.0		

STRESS PERIOD 6			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	10242.6	0.0	10242.6
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7954.0	-7954.0
DRAINS	0.0	2428.8	-2428.8
RECHARGE	4289.2	0.0	4289.2
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	4146.1	-4146.1
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	14531.8	14529.0	2.8
DISCREPANCY[%]	0.0		

STRESS PERIOD 7			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	1402.3	5915.2	-4512.9
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	6927.0	-6927.0
DRAINS	0.0	2767.5	-2767.5
RECHARGE	18417.9	0.0	18417.9
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	4211.8	-4211.8
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	19820.2	19821.6	-1.3
DISCREPANCY[%]	0.0		

STRESS PERIOD 8			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	12879.1	0.0	12879.1
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7465.0	-7465.0
DRAINS	0.0	1939.9	-1939.9
RECHARGE	557.9	0.0	557.9
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	4027.8	-4027.8
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	13437.0	13432.7	4.3
DISCREPANCY[%]	0.0		

STRESS PERIOD 9			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	9958.6	0.0	9958.6
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7526.0	-7526.0
DRAINS	0.0	1825.5	-1825.5
RECHARGE	3374.8	0.0	3374.8
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	3979.5	-3979.5
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	13333.4	13331.0	2.4
DISCREPANCY[%]	0.0		

STRESS PERIOD 10			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	8288.3	0.0	8288.3
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	6314.0	-6314.0
DRAINS	0.0	1578.3	-1578.3
RECHARGE	3497.8	0.0	3497.8
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	3896.3	-3896.3
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	11786.1	11788.6	-2.5
DISCREPANCY[%]	0.0		

STRESS PERIOD 11			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	1305.7	3113.0	-1807.3
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7260.0	-7260.0
DRAINS	0.0	1592.0	-1592.0
RECHARGE	14585.5	0.0	14585.5
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	3924.0	-3924.0
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	15891.2	15889.0	2.2
DISCREPANCY[%]	0.0		

STRESS PERIOD 12			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	11810.9	0.0	11810.9
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7727.0	-7727.0
DRAINS	0.0	1155.3	-1155.3
RECHARGE	859.6	0.0	859.6
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	3787.6	-3787.6
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	12670.5	12669.9	0.6
DISCREPANCY[%]	0.0		

STRESS PERIOD 13			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	6679.4	1.0	6678.4
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7205.0	-7205.0
DRAINS	0.0	1314.2	-1314.2
RECHARGE	5697.8	0.0	5697.8
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	3854.8	-3854.8
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	12377.2	12375.0	2.2
DISCREPANCY[%]	0.0		

STRESS PERIOD 14			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	0.5	6718.7	-6718.2
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7044.0	-7044.0
DRAINS	0.0	1514.7	-1514.7
RECHARGE	19214.6	0.0	19214.6
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	3939.1	-3939.1
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	19215.1	19216.5	-1.3
DISCREPANCY[%]	0.0		

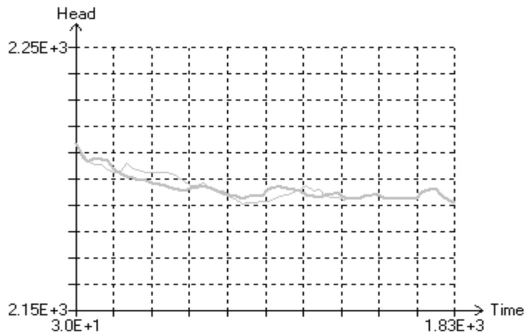
STRESS PERIOD 17			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	5376.1	380.2	4995.9
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	6840.0	-6840.0
DRAINS	0.0	1809.7	-1809.7
RECHARGE	7689.8	0.0	7689.8
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	4034.4	-4034.4
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	13065.8	13064.3	1.5
DISCREPANCY[%]	0.0		

STRESS PERIOD 18			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	5951.6	137.5	5814.1
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	5309.0	-5309.0
DRAINS	0.0	1618.4	-1618.4
RECHARGE	5059.1	0.0	5059.1
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	3947.1	-3947.1
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	11010.7	11012.0	-1.3
DISCREPANCY[%]	0.0		

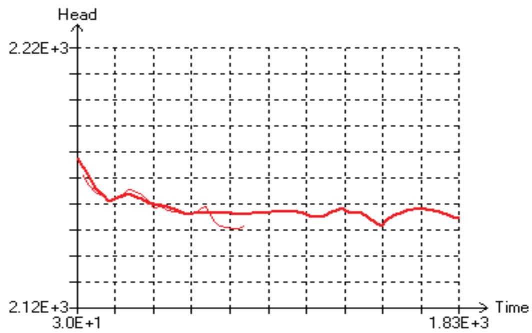
STRESS PERIOD 19			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	399.6	11512.3	-11112.7
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	7436.0	-7436.0
DRAINS	0.0	2117.3	-2117.3
RECHARGE	24775.4	0.0	24775.4
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	4110.7	-4110.7
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	25175.0	25176.3	-1.2
DISCREPANCY[%]	0.0		

STRESS PERIOD 20			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	14357.6	0.0	14357.6
CONSTANT HEAD	0.0	0.0	0.0
WELLS	0.0	8824.0	-8824.0
DRAINS	0.0	1603.6	-1603.6
RECHARGE	0.0	0.0	0.0
ET	0.0	0.0	0.0
RIVER LEAKAGE	0.0	0.0	0.0
HEAD DEP BOUNDS	0.0	3931.3	-3931.3
STREAM LEAKAGE	0.0	0.0	0.0
INTERBED STORAGE	0.0	0.0	0.0
MULTI-AQIFR WELL	0.0	0.0	0.0
SUM	14357.6	14358.9	-1.3
DISCREPANCY[%]	0.0		

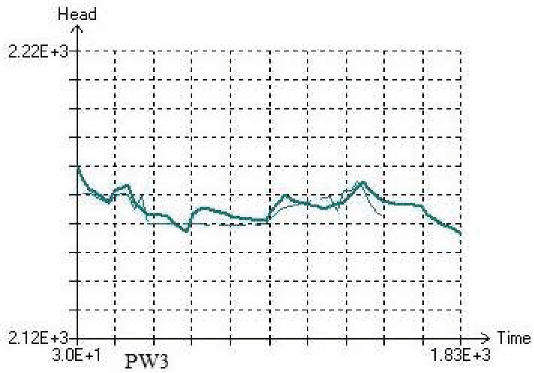
Appendix 10.2 Observed and simulated groundwater head (MODFLOW)



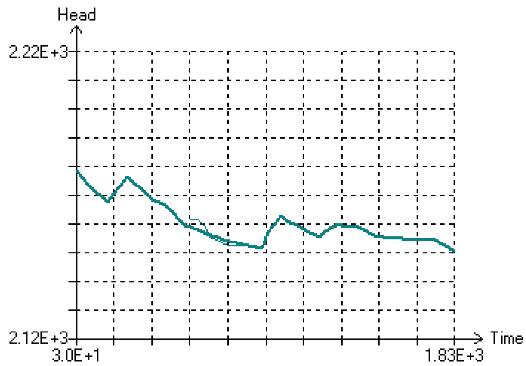
PW8



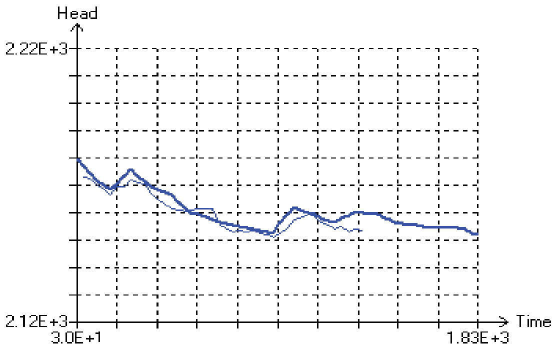
TW3



PW3



MU



PW11

Appendix 11 Geophysics data collected in the Aynalem wellfied (after WWDSE, 2006)

Location	VES_INDEX	X	Y	AB/2, m																	
				1.5	2.1	3	4.2	6	9	13.5	20	20	30	30	45	66	100	150	220	330	500
Ayn-PW2	2	556699	1487950	16	21.4	28.6	39.8	46	55.3	63.8	82.8	113	167	123	251	380	430.5	564.5	556	778	
Ayn-PW3	3	553948	1488840	36.11	42.74	47.86	56.76	72	85.24	67.5	74.6	67.2	59.5	65.9	57.2	69.1	91.6	127.5	158.3	264.2	333
Ayn-PW4	4	553733	1488269	30.5	32.8	34.8	38.2	40.4	43.6	46.2	47.7	48.1	53.3	55	65.11	82.9	107.9	134.3	192	259	290
Ayn-PW5	5	554336	1487216	11.5	10.6	13	17	24	36	54	78	65	97	117	146	214	280	441	566	733	823
Ayn-PW6	6	555529	1487625	18	19.6	20.9	24.1	27.1	35.4	41	50	54.8	67.9	62.2	81.9	95.7	124	176.5	229	289	378
Ayn-PW7	7	557177	1487962	8.2	10	14	17.5	23.7	33.3	44	57	53.1	70.1	76.3	102	131	160.5	195	244	299	360
Ayn-PW8	8	557809	1488320	60	63	71	79	80	80	67	61	61.5	63	67	71	78	101.5	126	158	222	
Ayn-PW9	9	558270	1488284	7.5	7.5	8.8	10.1	12.4	15.5	20	27	30	41	40	60	73	92.9	126	155	210.5	261
Ayn-PW10	10	554155	1489476	27.6	31.8	33.8	34.5	31.3	30.6	25.2	20.5	23	24	22.3	29	39.1	59.55	87	119	170	223
Ayn-PW11	11	552500	1489380	36.2	45.4	55.81	65.1	73.2	89.3	110	140.1	118	161.4	194	222	267	294.5	328.5	327	311	302
Ayn-PW12	12	553539	1488969	63.93	61.82	65.7	61.13	52.79	45.92	46.2	51.73	50.05	62.04		82	106	138.8	199	226	292	308
Ayn-PW3	3	552938	1488685	25.4	24.6	29.1	32.6	38.5	48.5	61.2	76.7	82.5	115.2	109	159	202.8	270.5	305	373	359	380
Aynalem	VES8	560300	1487907	144	137	163	201	232	287	327	370	383	437	408	433	331	283	239	179	147	
Aynalem	VES9	559524	1485930	12.7	19.3	26.7	35.5	36.3	34	30.9	35.8	32.9	40.5	38.2	39.8	39.3	52.7	74.45	99.9	195	
Aynalem	VES1A	553968	1489186	37.1	30.8	21.5	19.6	20.4	17.9	17.7	22.5	26.9	34.8	37.9	51.7	71.8	99.8	131	175	267	282
Aynalem	VESA	560970	1487125	167	97.3	89.5	105	137	125	133	140	156	185	177	196	230	249	245	223	191	146
Aynalem	VES3A	552105	1485822	43.3	26.9	29.4	27.6	26.9	20.2	20.3	24.8	18.5	30.6	23.9	29.4	38.4	57.6	77.95	87.2	119	106
Aynalem	VES5A	554622	1481122	92.4	67.5	60.9	50.2	39.6	49.5	47.1	46.5	54	50.4	51.6	46.8	49.3	63.1	80.1	97	134	186
Aynalem	VES6A	557206	1486256	30	26.6	38.8	48.2	59.3	67.3	81.3	47.9	44.9	46.9	45.5	46.3	46.3	61.8	75.95	101	160	233
Aynalem	VES7A	556056	1486119	35.2	16.5	15.6	12.4	15.3	15.4	18.6	29.4	26.4	51.2	43.9	54.9	65.4	81.2	109.5	123	145	160
Aynalem	VES8A	554835	1487532	34.6	34.5	45.1	53.3	63.6	59.7	68.4	77.9	75.7	84.3	79.5	79.9	85.3	99.3	139.5	190	279	311
Aynalem	VES22	553023	1488324	14.5	13.9	22.8	30.5	41.1	50.2	62.4	82.5	78.5	110	107	143	200	305	344	361	484	610

Appendix 12 Photo plates collected during field trip

New well drilling

Local people collecting water

Well in the wellfield

Groundwater level measuring

Measuring groundwater EC

GPS point collecting

EC measuring in Aynalem river

Shallow hand dug well

Weathered dolerite

Weathered dolerite

Black limestone outcrop

Black clay soil