

# Characterizing regional groundwater flow in the Ethiopian Rift: A multi-model approach applied to Gidabo River Basin

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## Abstract

Being located in the tectonically active Ethiopian Rift, the hydrogeology of the Gidabo River Basin is complex due to the disruption of lithologies by faults and the variability and lateral discontinuity of the aquifers. Hydrogeochemical and isotopic data suggest that the aquifers within the rift floor receive a relevant contribution of groundwater recharged in the highland. However, the incomplete knowledge about the aquifer properties, the hydraulic behavior of the faults, and the boundary conditions cause uncertainties in this conceptual hydrogeological model. To account for these uncertainties fourteen different numerical models with a stepwise increase from 7 to 40 adjustable parameters were developed, calibrated against the same hydraulic head observations, and ranked according to the Akaike information criteria (AIC and AICc) and Bayesian information criterion (BIC). Based on the information criteria five plausible models were identified, all of which were successfully verified against the river baseflow. The highest likelihood is attributed to a model with eleven adjustable parameters that does not explicitly account for the fault zones; other plausible models considering faults as semi-barriers achieve a slight improvement in model fit but have lower likelihood due to the increased number of calibration parameters. Thus, the effect of faults on groundwater flow needs further investigation, particularly at a local scale.

On a regional scale, the hydraulic head distributions of the plausible models agree reasonably well with the equipotential map interpolated from well observations. The estimated transmissivity values range between 30 m<sup>2</sup>/day and 1350 m<sup>2</sup>/day and generally increase from the mountains towards the rift floor. The water budget shows that 75 % of the groundwater recharge supplies baseflow to the rivers. The remaining water infiltrates to the deeper aquifers where less than 1 % is abstracted by pumping wells and the rest flows towards Lake Abaya. Within the rift floor, the majority of inflow to the aquifers is from direct recharge; nevertheless, 35 % of the inflow is contributed by mountain block recharge (lateral groundwater flow from the escarpment and highland). The results of this study strongly advocate the idea to incorporate alternative plausible models instead of relying on single models in the practice of groundwater modeling especially in areas of complex hydrogeology and limited data availability.

Die Hydrogeologie des im tektonisch aktiven Äthiopischen Graben gelegenen Gidabo-Flusseinzugsgebiets ist aufgrund der störungsbedingten Unterbrechungen der Lithologien sowie der Variabilität und lateralen Diskontinuität der Aquifere komplex. Hydrogeochemische und Isotopen-Daten weisen darauf hin, dass in den Aquiferen der Grabensohle ein relevanter Beitrag von Grundwässern vorliegt, die im Hochland neugebildet werden. Die unvollständige Kenntnis der Aquifereigenschaften, der hydraulischen Wirkung der Störungen und der Randbedingungen führen jedoch zu Unsicherheiten in diesem konzeptionellen hydrogeologischen Modell. Um diese Unsicherheiten zu berücksichtigen, wurden vierzehn verschiedene numerische Modelle mit einer stufenweisen Zunahme von 7 auf 40 anzupassenden Parametern aufgebaut, in Bezug auf dieselben beobachteten Standrohrspiegelhöhen kalibriert und entsprechend der Akaike-Informationskriterien (AIC und AICc) und des Bayesschen Informationskriteriums (BIC) eingestuft. Anhand der Informationskriterien wurden fünf plausible Modelle identifiziert, die alle anhand des Basisabflusses der Flüsse erfolgreich überprüft wurden. Die höchste Wahrscheinlichkeit wird einem Modell mit elf anzupassenden Parametern zugewiesen, das nicht explizit die Störungen berücksichtigt. Andere plausible Modelle, die Störungen als Geringleiter berücksichtigen, erzielen eine geringfügig bessere Modellanpassung, haben aber aufgrund der höheren Anzahl der zu kalibrierenden Parameter eine geringere Wahrscheinlichkeit. Die Wirkung der Störungen auf die Grundwasserströmung bedarf daher insbesondere im lokalen Maßstab weiterer Untersuchung.

Im regionalen Maßstab stimmen die mit den plausiblen Modellen erhaltenen Potentialverteilungen mit der aus Beobachtungen interpolierten hinreichend überein. Die ermittelte Transmissivität variiert zwischen 30 m<sup>2</sup>/d und 1350 m<sup>2</sup>/d und nimmt generell vom Hochland zur Grabensohle zu. Die Wasserbilanz zeigt, dass 75 % der Grundwasserneubildung den Basisabfluss der Flüsse speist. Das verbleibende Wasser infiltriert in tiefere Aquifere, wo weniger als 1 % durch Pumpbrunnen entnommen wird und der Rest zum Abaya-See abströmt. Der Hauptteil des Zuflusses zu den Aquiferen innerhalb der Grabensohle erfolgt durch direkte Neubildung; der laterale Grundwasserzustrom von der Grabenflanke und dem Hochland („Mountain Block Recharge“) beträgt dennoch 35 % des Zuflusses. Die Ergebnisse dieser Arbeit befürworten die Idee, bei der Grundwassermodellierung vor allem in Gebieten mit komplexer Hydrogeologie und beschränkter Datenverfügbarkeit anstelle eines einzelnen Modells alternative plausible Modelle einzubeziehen.

## 1. Introduction

The Main Ethiopian Rift (MER) represents a complex hydrogeologic setting composed of volcanic rocks of different type and age that are laterally discontinuous and intersected by faults (e.g., Kebede, 2013). In addition to its geological complexity, the rift setting is characterized by great physiographic differences between the rift floor and the highland. In particular, the highland receives high rainfall and hence high groundwater recharge, whereas the recharge rates in the rift floor are much lower, typically below 100 mm/a (Kebede et al., 2010). As a consequence, the question arises to which extent and how the water recharged in the highland may contribute to the replenishment of the aquifers within the rift floor. Following Wilson and Guan (2004) two potential mechanisms can be distinguished: On the one hand, streams originating from the highland might lose water (infiltrate) when they reach the rift floor, thus providing “mountain front recharge”. On the other hand, there might be groundwater flow from the highland toward the rift floor, which is called “mountain block recharge”.

Hydrogeochemical and isotope data provide strong evidence for a significant contribution of mountain block recharge in the central and northern part of the MER (Kebede et al., 2008, 2010; Bretzler et al., 2011). Likewise, groundwater samples from Gidabo River Basin, located within the southern part of the MER (Figure 1a), display depleted values of  $\delta^{18}\text{O}$  and  $\delta\text{D}$ , indicating the contribution of water recharged in the highland (Degu et al., 2014; Mechal, 2015). The purpose of this work is to examine if the conceptual understanding resulting from this finding is consistent with hydrological and hydrogeological data available for Gidabo River Basin. As a first step towards this goal Mechal et al. (2015) employed the semi-distributed hydrologic model Soil Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2011) to obtain an estimate of the spatial distribution of groundwater recharge within this catchment. In this model, the total recharge is split into two components, a deep aquifer recharge that is lost from the catchment and a shallow aquifer recharge contributing to baseflow within the particular sub-catchment. In the given case, the calibrated model suggests that 14% of the total recharge is lost from the catchment via a deep aquifer. Conceptually, this may be interpreted as groundwater flow into Lake Abaya, which borders Gidabo River Basin to the West (Figure 1b). However, the uncertainty in the values of the water balance components used for model input and calibration may easily account for this percentage too. This work therefore attempts to support or falsify the conceptual model suggesting significant mountain block recharge into the rift floor and groundwater outflow into Lake Abaya using a numerical groundwater flow model. Specifically, it will be tested if a model built on these hypotheses yields reasonable values of aquifer transmissivity and baseflow when calibrated to measured hydraulic heads, which were not considered in the hydrological modeling.

Although the regional-scale groundwater model developed

here relies on the above outlined general conceptual understanding of the hydrogeological setting within the MER, many details of the hydrogeological environment are prone to multiple interpretations and system conceptualizations. Particularly, the hydrogeological framework and impact of major features (e.g. faults and rivers) are poorly known; point measurements of subsurface properties and groundwater heads are sparse relative to the large modeling domain, spatially limited and prone to error. Incomplete or biased system representation that may possibly arise from a lack of understanding or incomplete knowledge of the boundary conditions and model parameter distributions render uncertain model results. One approach to account for these uncertainties is the consideration of more than one conceptual model. Alternative models, for example, may include variations in the structure of hydrogeologic units, boundary conditions, and parameter fields.

Within such a multi-model approach, information criteria can be used to rank the alternative models, eliminate those that are inappropriate, and obtain weighted parameter estimates or predictions (Neuman, 2003; Neuman and Wierenga, 2003; Burnham and Anderson, 2004; Ye et al., 2004; Poeter and Anderson, 2005). Among the numerous information criteria, we can distinguish two principal groups: (1) information theoretic criteria based on the idea that all models only approximate reality, such as Akaike Information Criteria (AIC and AICc) (Akaike, 1974; Hurvich and Tsai, 1989) and (2) Bayesian Information Criterion (BIC) based on the idea that within our ensemble of models, we can find the “true” model (Schwarz, 1978). Both groups of criteria consider how closely the model results reproduce the observations and how many parameters the models contain. Models having a low number of parameters while showing low deviation to the observations are generally favored. These models are associated with relatively small values of a given criterion and therefore ranked higher than those associated with larger values.

The performance of multi-model analysis with aid of information criteria (AIC, AICc and BIC) has been tested in a variety of applications ranging from synthetic cases (e.g. Poeter and Anderson, 2005) to real world conditions (e.g. Engelhardt et al., 2014). In this work, we employ the model discrimination and selection techniques in the context of alternative models implemented for the regional groundwater system in Gidabo River Basin to enhance our understanding of model uncertainty. We assume that the alternative models are possible approximations of the “true” model; therefore the second-order information theoretic criterion for AIC, which is AICc, is preferred for model discrimination purpose. AICc performs better than AIC when the number of parameters increases relative to the size of the sample (Burnham and Anderson, 2002; Poeter and Anderson, 2005). AIC and BIC are also computed and compared with the result obtained with AICc.

The proposed approach is applied to a regional-scale groundwater model of the Gidabo River Basin, situated in the south eastern MER (Figure 1). The lithological units building up the aquifer system are highly variable and laterally discon-

tinuous. Spatially, the extent of weathering and fracturing of the rocks is variable resulting in strongly heterogeneous aquifer properties. Even though there are plenty of wells in the area, pumping tests were performed only in a few of them which are primarily concentrated in the rift floor. As a result, the spatial distributions of the hydraulic properties of the aquifers are not well known. The aquifers are assumed to be dissected by numerous faults. The complexity of the impact of faults related to e.g. their type and orientation on the hydrogeologic system in the MER is shown by Ayenew et al. (2008), Kebede et al. (2008) and Furi et al. (2010). In particular, based on isotopic data, Kebede et al. (2008) suggested an opposed impact of transverse faults and marginal graben on the regional groundwater flow acting as channels from the mountain region to the rift floor and barriers, respectively, in a northern part of the MER. Based on hydrochemical and isotopic investigations, Mechal (2015) suggests that faults within Gidabo River Basin act as semi-barriers to groundwater flow across the faults. However, the hydraulic behavior of the faults is still not well understood. The faults are not restricted to the Gidabo River Basin but rather pass through the adjacent catchment to the north (Awassa Lake Basin; Figure 1) causing further uncertainty in the boundary condition between the two basins. Similarly, the catchment is characterized by a dense drainage system arising from the upper escarpment flowing to Lake Abaya, but information about the stream-aquifer interaction is lacking. Some studies (Ayenew, 2003; Ayenew et al., 2009) in the MER show the existence of strong stream-aquifer interaction as rivers flow from the highland to the rift floor. However, except the width and head of the rivers, the stream bed properties which control the strength of the interaction have not been studied yet. The complicated hydrogeologic conditions and lack of data thus lead to significant uncertainties in the conceptual model of the Gidabo River Basin.

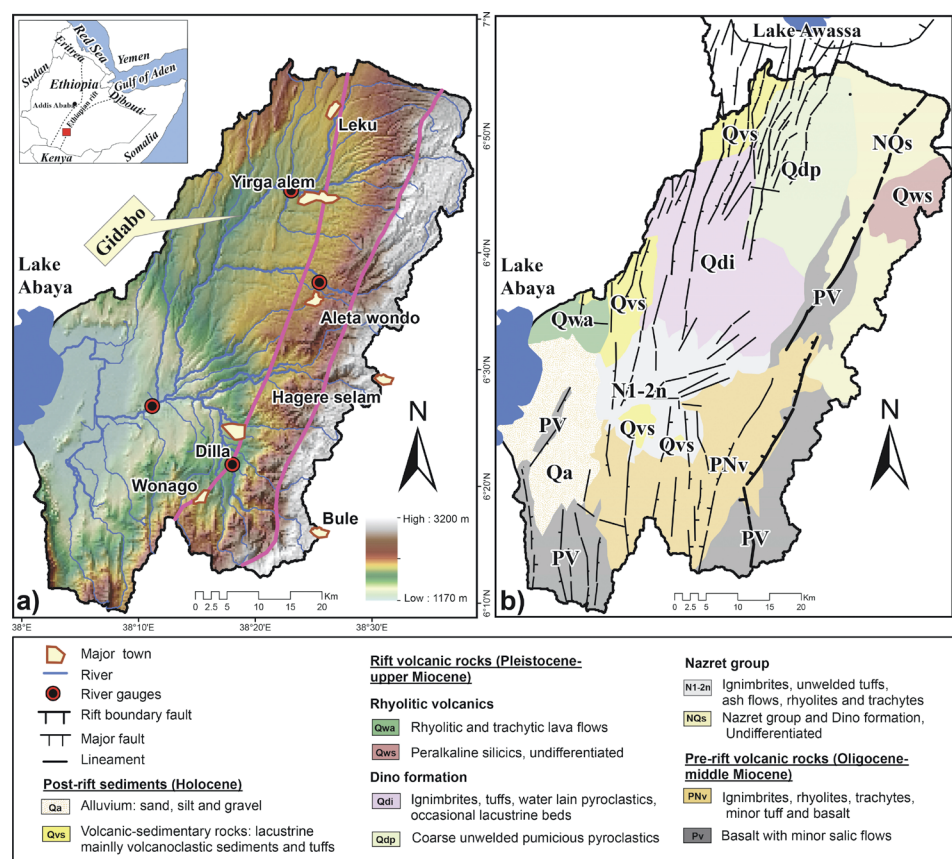
Therefore, the goal of this study is to explore and improve the existing conceptual understanding of the hydrogeology within this area in terms of transmissivity distribution, boundary condition, and fault and river conductance such that they can be incorporated into groundwater

flow predictions. Accordingly, 14 alternative groundwater flow models are developed ranging from simple approximations to more elaborated models by gradually increasing the amount of adjustable model parameters. The plausibility of the alternative models is evaluated by calibrating the models against the same observation data and estimating probabilities of the individual models using an information criterion as discussed above. AIC, AICc and BIC were computed for each model approach. Finally, the best model is selected using AICc to study the regional groundwater flow in the Gidabo River Basin including (1) the general groundwater flow pattern and the effects of faults, (2) the transmissivity distribution, and (3) the water budget comprising estimates of the various recharge and discharge components, particularly including mountain block recharge and groundwater outflow to Lake Abaya.

## 2. Study area

### 2.1 Location, physiography and climate

The Gidabo River Basin is located in southern Ethiopia in the eastern margin of the MER (Figure 1a). The catchment is bounded between latitude 6°8' N to 6°57' N and longitude 38° E to 38°38' E, within UTM zone 37 and covers 3302 km<sup>2</sup> drainage area which extends from the center of the rift floor



**Figure 1:** a) The location and the physiographic regions of the study area. The purple irregular lines mark the subdivision of physiographic regions: Highland, Escarpment and Rift floor. The inset map shows the location of the study area within the Ethiopian rift system. b) The simplified geological map of the Gidabo River Basin (compiled after Mechal, 2007; Halcrow, 2008; GSE, 2012). The neighbouring catchment in the north including Lake Awassa is also depicted.

to the mountains of the rift boundary. It is characterized by very diverse spatial variation of topographic features with an altitude range of 1175 to 3200 m a.s.l. forming three major physiographic regions: rift floor, escarpment and highland. The highland occupies a narrow strip in the eastern part of the catchment forming a flat to undulating landscape that is slightly dissected with some depressions characterized by seasonal drainage. The escarpment is very steep and marked by major border normal faults. The mountainous escarpment is highly dissected terrain with a dense drainage system. The rift floor is strongly deformed by faults and characterized by rough morphology with narrow uplifted blocks, valleys and swampy depressions.

The drainage system of the basin is strongly influenced by the morphology, which in turn is dependent on the geological phenomena. The stream networks commonly show dendritic drainage pattern and the flow is east-west almost perpendicular to the strike of the escarpment in the upstream regions of highland and escarpment. However in the southern and northern rift floor the flow deflects to the northwest and southwest direction, respectively, finally flowing towards Lake Abaya and displays a sub-parallel pattern in the down course sections. There seems to be a strong relationship between the main stream course and geologic structures in the area (Figure 1).

As a result of the wide topographic differences in the region, three distinct climatic zones are formed; humid in the highland with altitudes above 2400 m a.s.l., sub-humid in the escarpment with altitudes between 2400 and 1800 m a.s.l. and semi-arid in the rift floor below 1800 m a.s.l. In the highlands and escarpment bounding the rift floor rainfall exceeds 1600 mm/year, while the lowest altitude of the rift floor receives much less rainfall, often below 800 mm/year. Precipitation is characterized by a bimodal pattern with maximum peaks during April and May ("small rainy" season) and during September and October in the "heavy rainy" season. The average monthly temperature varies from 21-25 °C in the rift floor to less than 11.5-13.5 °C in the high altitude plateau.

## 2.2 Geology

The overall geological framework of the Gidabo River Basin (Figure 1b) is part of the geological architecture of the MER which was propagated during the Miocene-Quaternary period. It is mainly the product of different episodes of volcanic eruptions accompanied by tectonic events and sedimentation processes. The volcanic series and geological structures of the MER including the study area have been extensively described (WoldeGabriel et al., 1990; Boccaletti et al., 1998; Acocella et al., 2003; AG consult, 2004; Korme et al., 2004; Kurz et al., 2007; Mechal, 2007; Halcrow, 2008; GSE, 2012). In general, the lithologies of the area can be divided into three major groups: pre-rift volcanic rocks, rift volcanic rocks and post-rift sediments. The pre-rift rocks (Oligocene-Middle Miocene) occur mainly in the escarpment, highland and to a lesser extent in the rift floor. This group mainly comprises basalt (PV) and ignimbrite

(PNv) and represents the oldest rocks in the area. Rift volcanic rocks (Upper Miocene-Pleistocene) are mainly exposed in the rift floor and dominated by silicic volcanic rocks. A thick succession of stratoid silicics comprising predominantly ignimbrites with subordinate unwelded tuffs, ash flows, rhyolites and trachytes, which is commonly known as the Nazareth group (N1-2n) form parts of the rift floor and also outcrops in the escarpment and highland. In the rift floor, the Nazareth group is unconformably overlain by younger volcanic rocks called Dino formation which comprises coarse unwelded pumiceous pyroclastics (Qdp) and a complex mixture of different pyroclastic materials such as ash, tuff and ignimbrite (Qdi). Rhyolitic lava flows, composed of stratified ash, pumice and rhyolite flows (Qwa) mainly occur to the north of Lake Abaya along the axial zone of the rift but similar prominent volcanoes also have erupted pumice and unwelded tuffs forming volcanic mountains in the highland (Qws). Post-rift sediments (Holocene) such as alluvial (Qa) and lacustrine sediments (Qvs) mainly occur along the lower reaches of the Gidabo River and as patchy deposit along the axial zone of the rift, respectively.

The volcanic sequences and sediments in the area are densely dissected by extensional fault systems resulting from the rifting process (Figure 1b). The major fault types are normal faults having generally similar strike but some dip to the east and others to the west. Chronologically they can be grouped into two distinct fault systems. The older, Oligocene-Miocene, NE-SW trending fault system which characterizes mainly the rift margin and the younger, Quaternary-present, NNE-SSW trending set of faults affecting the rift floor, usually referred to as the Wonji fault belt (WFB). The rift margin is well developed and it is defined by a more or less continuous system of boundary faults with a single vertical displacement (> 1000 m) to the rift floor, whereas the rift floor faults are characterized by short, closely spaced, active faults that exhibit minor vertical throw (5-100 m). Main geological units and major stratigraphic sequences with associated fault systems are shown in figure 1b.

## 3. Hydrogeological conceptual model

The bottleneck for building a robust hydrogeological conceptual model of the Gidabo River Basin (and many other catchments) is the lack of sufficient hydrogeological and hydraulic data such as drilling logs, pumping test data and information on static groundwater levels. However, based on the limited data available, a simple conceptual model of the Gidabo River Basin has been developed, making a number of simplifying assumptions.

The aquifers of the investigation area are largely the product of volcanic eruptions, weathering and fracturing. Volcanic eruptions occurred in the area at different times and different locations. As a result the rocks have been subjected to different degree of weathering and fracturing. Between the different eruption time periods, the rocks have been weathered and eroded with subsequent deposition of alluvial materials resulting in multi-layer aquifers with a range



of unconfined to semi-confined layers. Based on well data obtained from Sidama, Gedeo and Borena Zone Water Resource Development Offices, interlayered weathered and fractured basalts and ignimbrites are the major aquifers in the highland and escarpment while a mixture of pyroclastic flows (ignimbrite, pumice, tuff and ash), alluvial and lacustrine deposits in the rift floor. These rocks constitute a multi-layer aquifer system, where the thickness of the individual layers varies between a few to 30 m. However, laterally continuous units cannot be identified from the existing well-lithologic logs, which are located at distances in the order of hundreds of meters to kilometers. Generally speaking two major aquifer systems can be distinguished: upper permeable layers characterized by deeply weathered and fractured rocks overlain by predominantly permeable soils, alluvial, and lacustrine sediments, and deeper semi-confined layers consisting of volcanic rock sequences.

The two major aquifer systems can also be observed from the hydrochemical and isotopic studies carried out in the region showing the existence of two major flow systems: shallow and deep groundwater flow systems (Mechal, 2015). The shallow circulating groundwater is characterized by low electrical conductivity (EC) and temperature close to surface temperature. The deep circulating groundwater is characterized by high EC and elevated temperature of more than 10 °C above the shallow groundwater temperature. However, concurrently both aquifer systems are severely disturbed by various deep seated faults indicating that they are hydraulically connected. The hydraulic connection of the two major aquifer systems is further supported by their isotopic signature. The tritium ( $^3\text{H}$ ) and  $\delta^{18}\text{O}$  content of the two groundwater flow systems do not reflect significant difference showing mixing behavior. Therefore in the absence of a conceivable extended confining layer and because of the high degree of fracturing, a good hydraulic connection is assumed to exist between the two major layers. Thus the two major layers are in a simplified manner represented in regional scale as a single layer with a spatially varying transmissivity.

The catchment is bounded by the continuous rift boundary fault to the east, a series of step faults to the west and volcanic hills to the south. Groundwater at the eastern and southern boundary exhibits very low EC indicating that these parts of the basin represent the recharge area. The western part of the catchment is bordered by prominent right stepping NNE-SSW trending normal faults resulting in a high local relief in the rift floor (Figure 1). Groundwater in this region generally flows parallel to faults towards Lake Abaya following the elevation gradient therefore groundwater inflow or outflow is assumed to be negligible. Portions of the western catchment coincide with the Lake Abaya (Figure 1a). In the northern catchment adjacent to Lake Awassa Basin (Figure 1b), there are intense faults passing through the two basins and shattered rocks related to the Awassa caldera collapse. Groundwater outflow from the upper Gidabo River Basin to Lake Awassa Basin is suspected to occur (Yasin, 2002; Mussie, 2007) based on

the existence of high yield springs (Loke palace, 30 l/s, and Gemeto, 40 l/s) emerging through highly fractured rocks of the Awassa caldera rim which cannot be explained by the recharge within the basin. Detailed water level measurements close to the water divide between the two basins and the low tritium content (1.56 TU) exhibited in Loke palace spring with respect to surrounding water points (average value of tritium content 3.19 TU) further signify a slight shift of the groundwater divide towards the Gidabo River Basin and the existence of possible groundwater outflow from upper Gidabo to Lake Awassa Basin. However, compared with the size of the Gidabo River Basin the outflow appears to be small and likely to be negligible within the scope of this work.

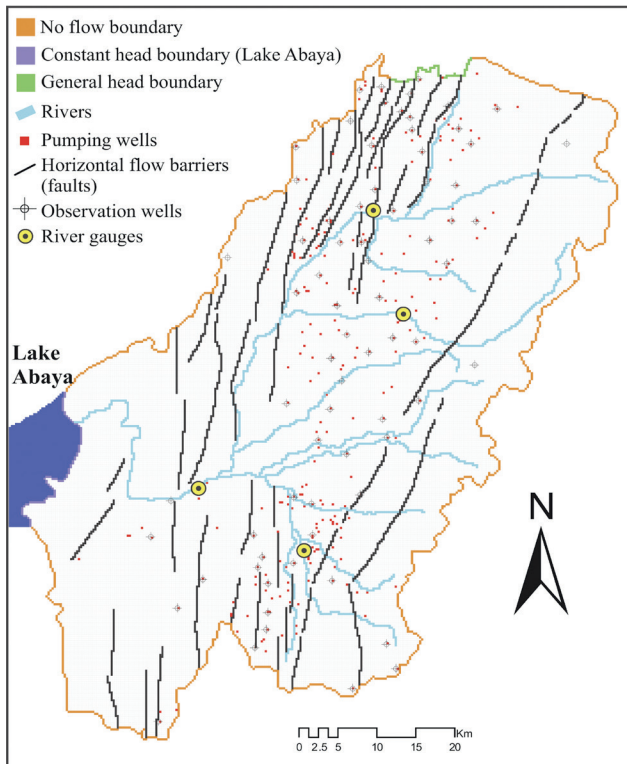
#### 4. Numerical model

A steady-state two dimensional groundwater flow model of the Gidabo River Basin was constructed based on the code MODFLOW-2005 (Harbaugh, 2005). The area of the model domain is 3302 km<sup>2</sup>; therefore the model has a regional character. The model domain is considered as a single layer with a specified transmissivity and discretized into squared grid cells of 250 m dimensions resulting in a total of 52832 active cells (Figure 2).

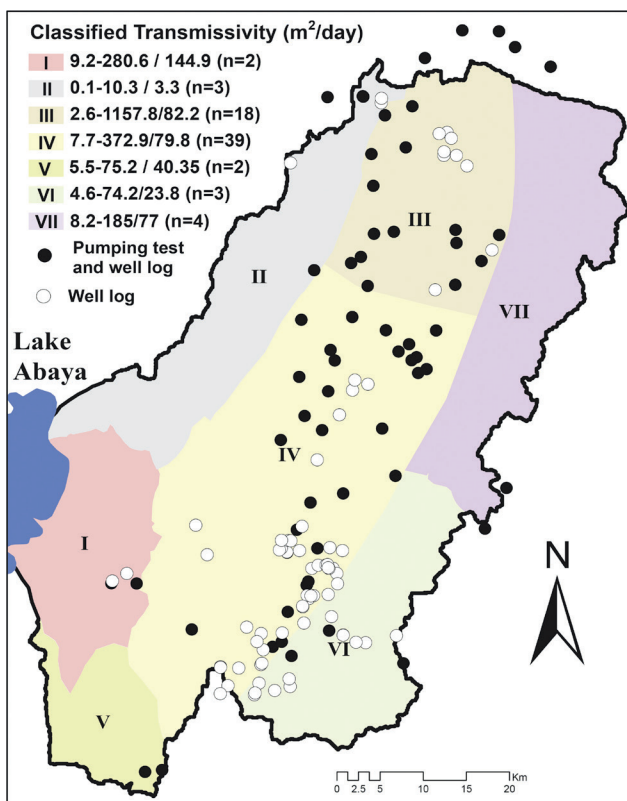
The spatial distribution of the hydraulic properties of the aquifer is hardly known. The surface geology as shown in figure 1b therefore served as a first criterion for the delineation of transmissivity zones. Yet, in some areas the results from pumping tests data obtained from Sidama, Gedeo and Borena Zone Water Resource Development Offices display a wide range of transmissivity values within the same lithology. Therefore, the zonation was further modified based on the pumping test data as well as on the information about aquifer geology (from well lithology). As a result, seven zones were identified for which it is assumed that despite their internal heterogeneity they can be reasonably represented by one transmissivity value at the regional scale. The transmissivity range and average value for each zone is shown in figure 3. The average values are used as initial estimates in the model calibration. In order to assess if a higher or lower number of transmissivity zones might be more appropriate several model set-ups with modified zonation (from one to ten zones) were calibrated and compared using information criteria.

Except for the northern and western boundaries, the catchment boundary is treated as a no flow boundary (Figure 2). Following the speculation of groundwater outflow, the northern boundary is treated as general head boundary in two model scenarios. Portions of the western boundary where it coincides with the Lake Abaya are considered as constant head boundary taking the average lake level as a reference (1169 m a.s.l.; Awulachew, 2001).

Various MODFLOW-2005 packages were used to simulate the effects of faults on groundwater flow, recharge, stream-aquifer interaction and well withdrawals. The Horizontal Flow Barrier (HFB) package (Hsieh and Freckleton, 1993) was utilized to simulate the effect of faults on groundwater flow.



**Figure 2:** Model geometry, boundary conditions, perennial rivers and river gauging stations, pumping and observation well locations.

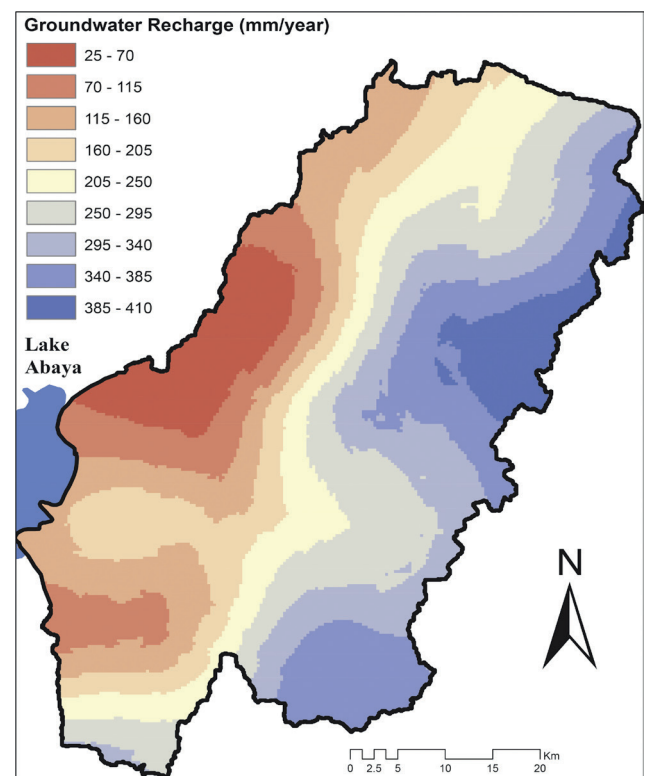


**Figure 3:** Classified transmissivity map based on the geology (Figure 1b), well-lithologic log, and pumping test data. The transmissivity range/average values for the different zones/n = number of pumping test data considered for a zone: I) Lacustrine sediments, ignimbrite and basalt, II) Pyroclastics and ignimbrite, III) Pumiceous pyroclastics, IV) Ignimbrite with minor basalt, V) rift floor basalt, VI) highland basalt and VII) Rhyolite and rhyolitic ignimbrite.

The HFB package essentially simulates the fault via a conductance term between two horizontally adjacent finite-difference cells. The HFB package is based on the assumption that the fault is vertically oriented and that the flow through the adjacent cells is horizontal. The fault hydraulic properties are input as a conductance,  $K=K_f/c$ ; where  $K_f$  and  $c$  are the fault hydraulic conductivity and thickness in the direction normal to flow, respectively. It is important to note that faults are considered in the model as barriers only. Faults functioning as conduits are not considered at this stage yet.

The recharge distribution was estimated using the semi-distributed hydrologic model Soil Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2011). The hydrologic model accounts for the spatial heterogeneity in climate, topography, land use and soil of the Gidabo River Basin and was calibrated and validated using time series of river discharge. A detailed description of the temporal and spatial variability of groundwater recharge is presented in Mechal et al. (2015). Figure 4 shows the long term annual average recharge rates (1998-2010) obtained from the SWAT model. It shows a remarkable decrease of recharge from the highland (410 mm/year) towards the rift floor (25 mm/year) reflecting the great differences in climatic conditions as well as soil and land use characteristics. This long-term average of the annual groundwater recharge distribution was used for the groundwater flow model.

The Gidabo river drainage system is extensive arising from the highland and flowing towards Lake Abaya following the surface topographic gradient. Attributed to the bimodal



**Figure 4:** Spatial variation of simulated long term (1998-2010) average annual recharge in the Gidabo River Basin (Mechal et al., 2015).

rainfall distribution and higher annual rainfall, the majority of the rivers originating from the escarpment and highland are perennial while those in the rift floor are intermittent and appear only during high rainfall events. In the high rainfall zone of the highland and escarpment, part of the recharge contributes to the baseflow of the streams along the rift boundary fault. The sustained flow throughout a year in the perennial rivers is evidently related to this groundwater contribution. The “River” package (McDonald and Harbaugh, 1988) was used to simulate the hydraulic connection between groundwater and rivers by allowing rivers to gain or lose water through the riverbed material based on the difference between the hydraulic head and the river stage. Model cells were designated as river cells along major streams (Figure 2). Initial estimates of river bed conductance were obtained from hydrogeological properties.

The groundwater within the study area is mainly used for drinking water by means of shallow and a few deep wells close to the main towns. A total of 301 pumping wells are considered, with a variable pumping rate ranging from 10.8 to 36 m<sup>3</sup>/day. There are no injection wells. Groundwater abstraction from the aquifer was simulated using the “Well” package (McDonald and Harbaugh, 1988) to withdraw water from each well at a specified rate.

#### 4.1 Model calibration

The groundwater flow models were calibrated to measured groundwater level data. Water level measurements (108 hydraulic heads) were carried out in two field seasons (July–September 2012 and 2013). Within this time period, representing the heavy rain season, at each well one hydraulic head measurement was made. Hence, information about the temporal variability of the water table is not available. All of these wells are used for water supply and not designed as observation wells. Before the commencement of the measurement, the pumping wells were stopped to allow recovery. The accuracy of the global positioning system (GPS) used to determine location and elevation of the wells was approximately between 3–5 m.

Moreover, water level data was collected from pumping test records where direct water level measurement was not possible. However, among the whole set of water level data only 72 trusted observations in terms of quality of the data and time of measurement were used for calibration (Figure 2). Nevertheless, the full set of data points and additional helping points (e.g. close to Lake Abaya estimated based on the lake water level) were used for the preliminary interpolation of the water level to have rough information on the spatial distribution of hydraulic heads that can be compared to the simulated hydraulic head in the entire catchment (which includes regions with sparse data).

The non-linear parameter estimation code PEST (Model-Independent Parameter Estimation and Uncertainty Analysis; Doherty, 2010) was used for the automated model calibration. PEST minimizes discrepancies between model simulated outputs and the corresponding measurements by minimizing

the weighted sum of squared differences between the respective values. Parameters adjusted automatically during the calibration process include transmissivity, fault and river bed conductance.

The groundwater flow to the rivers obtained from the calibrated model was compared to river discharge measurements at four locations obtained from Ministry of Water, Irrigation and Energy of Ethiopia (Aposto, Kolla, Bedessa and Meassa gauging stations; Figure 2). The river gauging stations are well distributed in the catchment and more than 75 % of the catchment area is gauged at the Meassa station. An automatic base flow filter program (Lyne and Hollick, 1979; Nathan and McMahon, 1990) was used to separate the river discharge into surface runoff and baseflow component. The average baseflow in the time period 1998–2010 (corresponding to that of the recharge calculation) was used for comparison with the baseflow simulated by the model.

#### 4.2 Alternative models

The alternative models were developed based on consideration of the uncertainties associated with the current understanding of the hydrogeology of the area. A significant issue of concern in developing the conceptual model of the Gidabo River Basin is the distribution of transmissivity, stream-aquifer interaction, the effects of faults and the boundary conditions. To address this uncertainty, 14 possible alternative models were generated. Based on the existing information a base model with seven transmissivity zones, two fault sets (eastward and westward dipping faults) with different conductance, and four river bed conductance zones (all small rivers joining Gidabo River and three segments of Gidabo River) was developed initially (Model 4 in Table 1). Thirteen alternative models were developed either by increasing, lowering or eliminating the parameters from the base model. Model 1–5 were developed by increasing the number of transmissivity zones from a single homogeneous zone to 10 zones to consider the effects of aquifer heterogeneity on the model performance. To examine the effect of the faults on groundwater flow models 6–9 consider settings with no faults, only the eastward dipping set of faults (ignoring the westward), the two sets of faults (both east and westward) having identical properties and individual faults behaving differently. Models 10–12 include no river, one major river Gidabo, ignoring the smaller streams) and individual rivers with variable stream bed properties. Model 13 considers the general head boundary to account for the possible outflow to Lake Awassa Basin at the northern boundary, and Model 14 is the most complex realization, which includes 40 parameters. The details of the alternative conceptual models with their number and type of parameters are given in Table 1. All models were calibrated to the same data set of hydraulic heads and compared to the observed river baseflow. The model with the smallest information criterion (AIC, AICc, and BIC) is regarded as the most likely model.

Number and type of adjusted parameters during model calibration

Model	Transmissivity zone	Fault leakance	River leakance	General head boundary	Total number of paramters	Comment
1	1	2	4	–	7	Aquifer heterogeneity
2	2	2	4	–	8	
3	3	2	4	–	9	
4	7	2	4	–	13	
5	10	2	4	–	16	
6	7	–	4	–	11	Effect of faults
7	7	1	4	–	12	
8	7	1	4	–	12	
9	7	15	4	–	26	
10	7	2	–	–	9	Stream-aquifer interaction
11	7	2	3	–	12	
12	7	2	14	–	23	
13	7	2	4	1	14	Goundwater outflow
14	10	15	14	1	40	Most complex realization

**Table 1:** Alternative models analyzed with AIC, AICc and BIC. Note that Model 4 is the base model.

## 5. Model selection criteria

Having many predictors with many possible interactions, one could come up with several possible models that fit equally well the observed data and make it difficult to find a good model among the candidates. Thus a criterion or a benchmark is needed to rank or compare models. As previously stated, several model selection criteria have been proposed in order to enable choosing wisely among the different possibilities. The most popular model selection criteria applied in the field of hydrogeology are AIC, AICc and BIC. It is not our aim here to provide an in depth discussion of each method. Considerable literature exists discussing the origin, philosophy and application of the methods (e.g. Burnham and Anderson, 2002; Ye et al., 2008; Burnham et al., 2010). We briefly outline the approaches with regard to this work. Akaike's Information Criterion (AIC) is based on Kullback-Leibler (K-L) information,  $I(f,g)$  (Kullback and Leibler, 1951). This is interpreted as the information,  $I$ , lost when full truth,  $f$ , is approximated by a model,  $g$ . Given a set of candidate models  $g_i$ , one might compute K-L information for each of the  $R$  models and select the one that minimizes information loss that is, minimize  $I(f,g)$  across models. This is a compelling approach. However, for groundwater models, K-L information cannot be computed because the truth and the optimal effective parameters (e.g., hydraulic conductivities, boundary heads, and fluxes) are not known (Anderson, 2003).

Akaike (1973, 1974) provided a simple way to estimate expected K-L information, based on a bias corrected, maximized log-likelihood value; the resulting statistic has two terms and is commonly referred to as AIC. This was a major breakthrough (Parzen et al., 1998).

$$AIC = n \log(\sigma^2) + 2k \quad (1)$$

Soon thereafter, a version of equation (1) was developed that accounts for cases when  $n/k < 40$  (Sugiura, 1978; Hurvich and Tsai, 1989) and is referred to as the corrected Akaike Information Criterion (AICc) which is calculated using the following equation (2):

$$AICc = n \log(\sigma^2) + 2k + \frac{2k(k+1)}{n-k-1} \quad (2)$$

BIC (equation 3) was derived in a Bayesian context by Schwarz (1978) as an asymptotic approximation to a transformation of the posterior probability of a candidate model (Cavanaugh and Neath, 1999). BIC is similar in form to AIC and AICc:

$$BIC = n \log(\sigma^2) + k \log(n) \quad (3)$$

Where  $\sigma^2$  is the estimated residual variance,  $n$  is the number of observations, and  $k$  is the number of estimated parameters for the model. Here, the estimator of  $\sigma^2 = WSSR/n$ , where WSSR is the weighted sum of squared residuals.

The first term of AIC, AICc and BIC (equations 1, 2 and 3) measures the goodness of fit between predicted and observed system states. The smaller this term is, the better is the fit. The terms containing  $k$  measure model complexity. The criteria thus embody (to various degrees) the principle of parsimony, penalizing models for having a relatively large number of parameters if this does not lead to a corresponding improvement in model fit. As such, the goodness of fit term in the equations for AIC, AICc and BIC is the same; only the approximation of the bias differs (penalty term).

Generally, model selection criterion values themselves are not meaningful. Instead, the differences between model criterion values are used to analyze alternative models. The differences are called delta ( $\Delta_i$ ) values and, for a given set of



models, are calculated relative to the model with the smallest criterion value. Thus, using AICc as an example, the delta values are calculated as

$$\Delta i = AICc - AICc_{min} \quad (4)$$

for each model,  $i$ , in a set of  $R$  models being analyzed, where  $AICc_{min}$  is the minimum AICc value of all the models in the set. For AIC and AICc,  $\Delta i$  represents the K-L information loss of model  $i$  relative to the best model in the set.

There is still debate about when a model can be considered uninformative (Burnham et al., 2010; Richards et al., 2011), but as a coarse guide, models with  $\Delta i$  values  $< 2$  are considered to be essentially as good as the best model, and models with  $4 < \Delta i < 7$  should probably not be discounted (Richards, 2005). Above this, model rejection might be considered, and certainly models with  $\Delta i$  values  $> 10$  are considerably poorer than the best AICc model and thus considered implausible (Burnham and Anderson, 2002).

To better interpret the AICc values for a given set of  $R$  models and treat them as probabilities, Burnham and Anderson (2002) defined the Akaike weights ( $w_i$ ), by norming the relative measure of the likelihood of a model, so that they sum up to 1. The Akaike weights are expressed as

$$w_i = \frac{\exp^{-0.5\Delta i}}{\sum_{j=1}^R \exp^{-0.5\Delta j}} \quad (5)$$

Where  $j$  is the counter of models,  $\Delta i$  denotes the AICc difference of a specific model to the smallest AICc of all considered models (equation 4) and  $R$  gives the total number of considered models.

## 6. Results

### 6.1 Model calibration and ranking

Model complexity was varied from the base model (Model 4) resulting in various model realizations from 7 (Model 1) to 40 (Model 14) adjustable model parameters (Table 1). All the candidate models were calibrated to the same observation data (72 hydraulic head values) and attained the best possible fit at their respective complexity level (Table 2). When considering more parameters the model fit gradually improved up to 11 parameters where it reached nearly a constant level with differences between observed and calculated values (Figure 5a). This may be related to model structure error and parameter zonation. The increases in the number of transmissivity zones (Models 1-5) and the incorporation of existing rivers with variable river bed conductance (Models 10-12) improved the model fit. However, the fit is nearly the same for models with or without faults (Models 6-9). In general, the increase in the complexity of the models showed improvement in the model fit but linearly penalized due to over-parameterization. On the other hand the simplified models are under fitted although less penalized (Figure 5a).

Table 2 lists the model selection criteria (AIC, AICc and BIC) calculated based on the results from the model calibration following the method of Ye et al. (2008) as well as the model probabilities estimated using Equation 5. They are computed to rank the alternative models and select the most likely model approach. As Equations 4, 7, and 9 have to be minimized, the lowest information criterion value indicates the best model. The information criterion is a relative measure, i.e. the absolute values are meaningless and only the differences to the best model are relevant (AIC  $\Delta i$ , AICc  $\Delta i$  and BIC  $\Delta i$ ; Table 2).

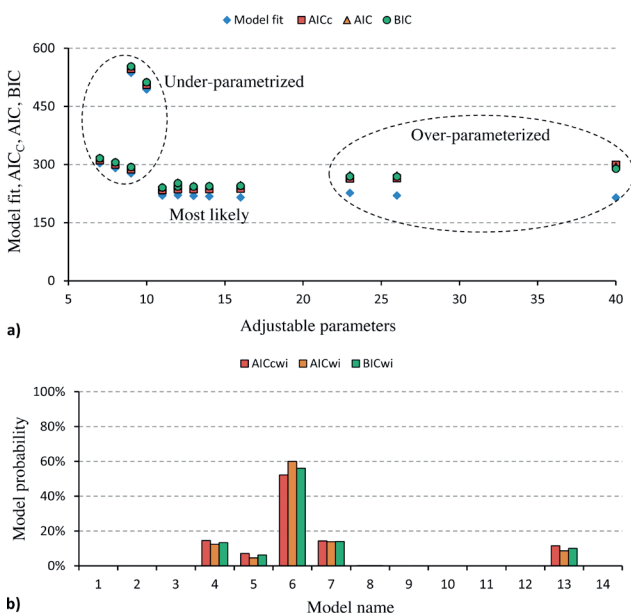
The model ranking is quite similar among the different criteria. All information criteria (AIC, AICc, BIC) selected Model 6 (no faults) as the best and Model 10 (no rivers) as the worst model. AIC and BIC rank the models identically. However, minor differences occurred in the AICc model ranking as compared to AIC and BIC (Table 2). AIC, AICc and BIC statistics indicate that models with less than seven transmissivity zones and fewer rivers are clearly inferior. This suggests, as expected, that the aquifers are heterogeneous and the rivers are an integral part of the groundwater system within Gidabo River Basin. On the other hand, models with or without fault barriers show similar values suggesting that the faults as barriers are less significant in the head distribution at the regional scale. In the following, we will focus on the AICc ranking. However, AIC and BIC are presented here (Table 2) to corroborate the observation of Ye et al. (2008) and Poeter and Anderson (2005) that they perform similarly in applications.

Relative Akaike weights (AICc  $w_i$ ) according to Equation 5 were computed for all models to express the likelihood of a model. A likelihood of 100% means that only one model is regarded to represent the "optimal option". A likelihood of 0% corresponds to a model that has absolutely no support. In our case, the model selected as the most likely (Model 6) by AICc obtained the largest likelihood of 52.2% followed by Model 4 (15%), Model 7 (14%), Model 13 (12%), and Model 5 (7%) (Table 2; Figure 5b). All other models have no support and are assessed according to the AICc weights either as under-parameterized (Models 1, 2, 3, 10, 11) or over-parameterized (Models 8, 9, 12, and 14). Among the candidates, 5 models showed a probability above 0; however, the results (hydraulic heads, transmissivity and water budget) do not show significant differences. Therefore, the best model selected by AICc with a likelihood of 52.2% is used for further analysis. The results of the remaining models are addressed in the discussion.

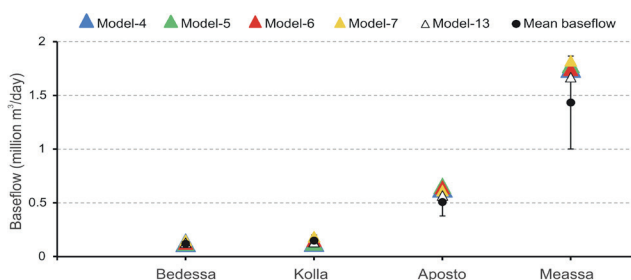
After calibration, the baseflow to the rivers obtained by the model was compared with the result of a baseflow separation at four river discharge stations (Bedessa, Kolla, Aposto, and Meassa). Figure 6 shows the comparison with the mean and the range of the long term baseflow (1998-2010). The groundwater flow into the rivers obtained by the five models having non-zero probabilities according to table 3 is within the ranges of the observed baseflow (Figure 6). The baseflow simulated by the best model selected by AICc (Model 6) is quite close to the mean values at Bedessa (107%) and Kolla (88%) stations but overestimates the baseflow at the Aposto (125%)

Model	Adjustable parameters (k)	Model fit	AICc $\Delta i$	AIC $\Delta i$	BIC $\Delta i$	AICc wi (%)	Rank
1	7	303.45	77.25	75.37	75.94	0	12
2	8	290.95	66.21	64.87	65.30	0	11
3	9	277.15	53.91	53.07	53.36	0	9
4	13	219.24	2.54	3.16	2.87	15	2
5	16	215.18	3.99	5.10	4.38	7	5
6	11	220.08	0.00	0.00	0.00	52	1
7	12	221.00	2.59	2.92	2.78	14	3
8	12	229.68	11.27	11.60	11.46	0	6
9	26	220.40	31.16	30.32	28.18	0	8
10	9	536.42	313.17	312.34	312.63	0	14
11	10	493.57	271.88	271.49	271.64	0	13
12	23	226.83	30.42	30.75	29.04	0	7
13	14	217.94	3.03	3.86	3.43	12	4
14	40	214.82	65.63	52.74	48.60	0	10

**Table 2:** List of models, number of adjustable parameters, model fit, differences ( $\Delta i$ ) of the AIC, AICc and BIC values to the optimal model (Model 6), and likelihood of the flow models from the Akaike Weights (AICc wi). The dark grey bar indicates the best (most likely) model; lighter grey bars indicate other likely models.



**Figure 5:** a) AIC, AICc and BIC and model fit of the calibrated models with respect to complexity, b) model discrimination using model probabilities calculated using Equation 5.



**Figure 6:** The comparisons of long term (1998-2010) mean and the range of baseflow (bars indicating the range) with simulated baseflow of the most likely model realizations at Aposto, Kolla, Bedessa and Meassa stations.

and Meassa (123 %) stations. However, the deviation from the mean value is within the error of the river discharge measurements and separation techniques.

## 7. Discussion

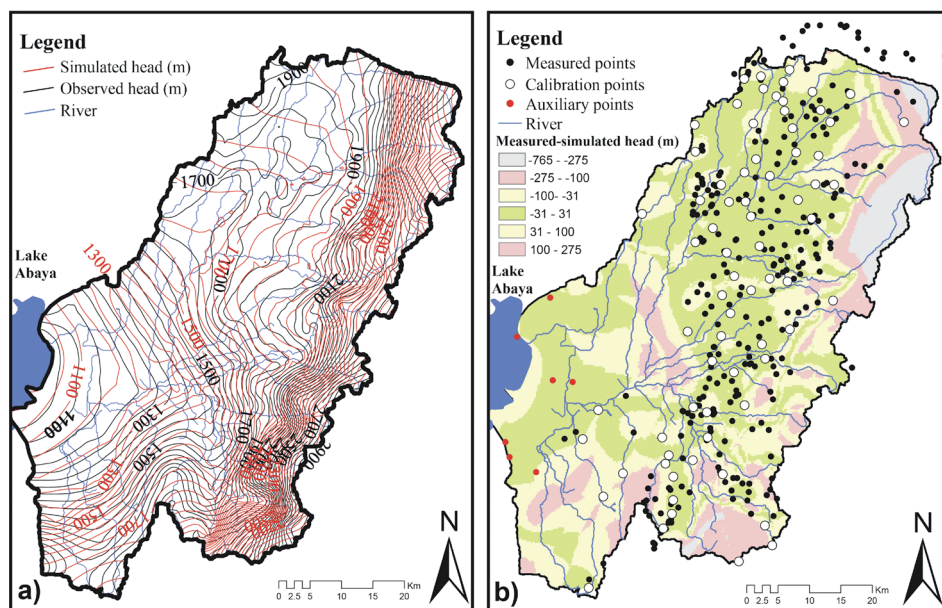
### 7.1 Groundwater flow and the effects of faults

The spatial distribution of hydraulic heads (equipotential lines) obtained with the best (most likely) model (Model 6) selected by AIC, AICc, and BIC is shown in figure 7a compared to interpolated equipotential lines based on the hydraulic head data available. Both equipotential lines indicate that groundwater generally flows from the upland areas in the east towards Lake Abaya to the west, which corresponds to the surface water flow direction. For the calibration points, the correlation coefficient, a measure of goodness of fit, of the measured vs. computed heads is 0.99 which shows a good concordance between observed and simulated hydraulic heads (Figure 8); the root mean square error (RSME) is 31 m. The deviation of measured from simulated heads (Figure 7b) appears to be higher when the simulated equipotential lines are compared to the spatial interpolation of the entire data set including not only the calibration points but also measurements considered to be inappropriate for some reason (e.g., wells representing shallow, local aquifers, measurements taken in different time period, etc.) The highest deviation is observed in the upland and some patchy locations in the rift floor where there is lack of data and therefore the data interpolation highly uncertain. However, for the majority of the catchment, the deviation is still within the range of the above mentioned error. In general, the range appears large for local considerations, but is reasonable at the scale of the catchment, where hydraulic heads exhibit a range of approximately 2000 m. The general pattern of the model-estimated head distribution thus agrees reasonably well with the equipotential map constructed from hydraulic head observations.

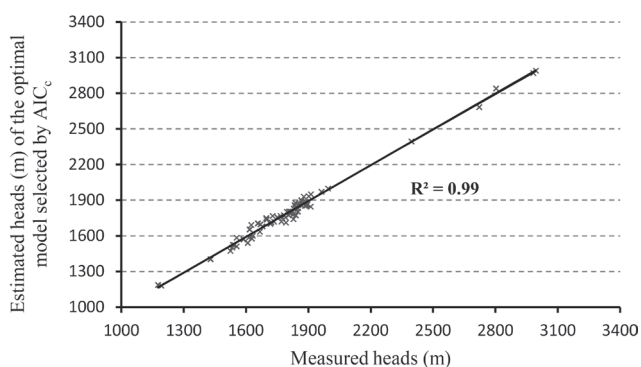
The most likely model (Model 6) selected by the information criteria does not explicitly consider faults. However, the other plausible models (Models 4, 5, 7 and 13) that consider faults as barriers have similar or even slightly better model fits than the model favored by the information criteria. This suggests that the impact of faults on the groundwater flow cannot be fully disregarded.

Faults affect the groundwater flow of the study region mainly as a result of fault induced topography and change in fault zone

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**Figure 7:** a) Comparison of the simulated equipotential lines of Model 6 and those interpolated from all the observed hydraulic heads. b) The difference between measured and simulated heads (measured-simulated heads).



**Figure 8:** Scatter plots of computed (Model 6) versus the 72 observed hydraulic heads in m (a.s.l.) in the study area.

properties, for example juxtaposition of the highly permeable aquifer unit against one or more low permeable units. Fault induced topography such as horst-graben structures and a series of right stepping faults are a very common phenomenon in the rift floor mainly affecting shallow aquifers. The change in the fault zone properties seems to have modest effect on groundwater flow as the faults appear to act as semi-barriers. In this investigation area such effects are potentially highly relevant at the local scale but appear to be less important at the total catchment scale considered by the groundwater flow model. Comparatively, in other investigation areas such as e.g. Colorado, USA (Marler and Ge, 2003), Canada (Gleeson and Novakowski, 2009) and Japan (Illman et al., 2009) faults act as effective barriers at regional scale. In the Gidabo River Basin the presence of multi-layer aquifers might enable the groundwater different options to pass through the fault zones. Nevertheless, in the northwestern part of the catchment, where the equipotential lines obtained from the well observations indicate that the local groundwater flow is directed eastward against

the general topography, which is not fully matched by any of the calibrated models (e.g. Model 6 in Figure 7a). The observed flow pattern is related to the prominent right stepping faults rising above 2000 m a.s.l. in the rift floor and might be more adequately reproduced by the anisotropic hydraulic behavior of faults (e.g. Caine et al, 1996) where they can act as a conduit parallel to the fault plane instead or in addition to the barrier for flow perpendicular to the fault considered in this work.

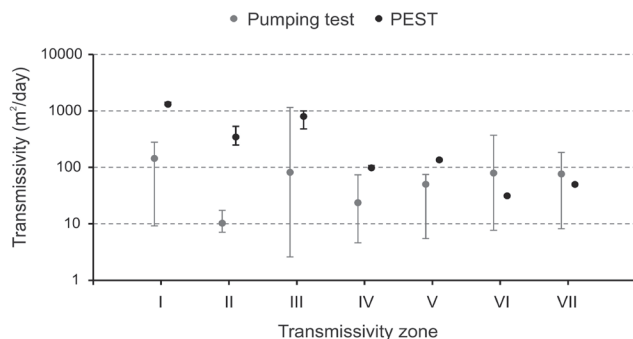
## 7.2 Transmissivity distribution

The existing information about the aquifer properties

is very limited as mentioned earlier. The transmissivity values were identified for zones of the model that were determined before the calibration process. For each zone, initial values were estimated based on pumping test data and geological interpretation. The number of these zones was changed gradually from a single homogeneous aquifer to 10 different zones (Models 1-5; Table 1 and 2). As expected, the model fit was significantly improved as the number of zones increased, but the information criteria suggest that the improvement in the model fit when the number is increased from 7 to 10 is not sufficient to justify the higher number of calibration parameters.

Figure 9 shows the average and range of the calibrated transmissivity values of the best (Model 6) and other plausible models (Models 4, 5, 7 and 13). The values of each zone do not show significant differences among the models and range between 30 m<sup>2</sup>/day and 1350 m<sup>2</sup>/day. The estimated values generally increase from the mountains towards the rift floor. This could be related to the increase in the intensity of the fracturing towards the rift floor (Figure 1b) and the occurrence of highly permeable rocks such as pumice and lacustrine sediments in the rift floor. In most regions, the transmissivity resulting from the calibration of the groundwater model is distinctively higher than that derived from pumping test data. However, towards the eastern part of the catchment the differences decrease and for the two most eastern transmissivity zones (zone VI and VII) the results from the pumping tests and the model calibration agree well. The observed differences could be related to partial penetration of the aquifer since the wells rarely exceed a depth of 200 m. Another possible explanation is that the (single-well) pumping tests provide transmissivity estimates at a local scale, which do not reflect the large-scale effects of the fault system. In contrast, the catchment model

needs to account for such large-scale effects, which might increase the transmissivity (e.g. Clauser, 1992; De Dreuzy et al., 2001; Carrera et al., 2005). In the present study, this leads to transmissivity values larger than those obtained at local scales. As indicated in the previous section, some faults might act as conduits parallel to the fault plane, i.e. they might be represented by additional transmissivity zones (e.g. damage zones) extending along the fault (e.g. Evans et al., 1997; Seaton and Burbey, 2005; Ruelleu et al., 2010; Leray et al., 2013; Winkler and Reichl, 2014). The transmissivity of these zones would be expected to be high and thus that of the other zones could be lower than in the present model. Whether or not this will lead to a better agreement with the pumping test results and an improvement in terms of the model evaluation based on information criteria needs further investigation.



**Figure 9:** Comparison of the transmissivity estimates based on pumping test data and geological interpretation and those obtained by automatic calibration of the plausible models (Models 4, 5, 6, 7 and 13).

### 7.3 Water budget: Groundwater recharge and discharge

The water budget refers to the quantification of the inflow to and outflow from parts or the entire model domain. The inflow includes direct recharge from precipitation, leakage from rivers as well as lateral inflow of groundwater. Outflows include baseflow to rivers, well withdrawals, and lateral groundwater flow into adjacent subdomains or across the model boundary (Lake Abaya; in Model 13 and 14 also the northern boundary). Table 3 summarizes the steady-state water budget of the entire model domain and of the two subdomains representing the upper catchment (escarpment and highland) and the rift floor.

The water budget obtained from the regional groundwater model shows that 75 % of the modeled groundwater recharge provides the baseflow of the streams draining Gidabo River Basin, only less than 1 % is abstracted by pumping wells and the rest represents groundwater inflow into Lake Abaya. The result shows that the rivers are gaining large quantities of groundwater from the aquifer in the majority of the catchment. This result of the groundwater model is similar to the finding from the hydrological SWAT model (Mechal et al., 2015), which suggests that 86 % of the total recharge flows toward the rivers and the remaining 14 % are deep recharge

leaving the catchment as groundwater outflow to Lake Abaya. The deviation in magnitude might be attributed to differences in representation of the catchment particularly close to Lake Abaya, where neither hydraulic head data nor discharge measurements are available. The calibrated transmissivity values of the two zones bordering Lake Abaya are clearly higher than those obtained from pumping tests (zones I and II in Figure 9). As explained above, potentially an alternative model that might be more in accordance with the pumping test data could be designed if the transmissivity within narrow belts parallel to the faults are assumed to be higher, whereas lower values are used elsewhere within these zones. Such a model might result in more baseflow to the rivers and less groundwater flow toward Lake Abaya. While this could be explored by further modeling studies, the validity of the results and their interpretation with regard to the groundwater contribution to Lake Abaya can only be assessed if additional data becomes available.

In some parts of the catchment (e.g., within the rift floor) gaining rivers can be identified from the simulated equipotential lines displayed in figure 7a. However, due to the scale of the map this is not always obvious, especially in the upland sections. A more detailed consideration of the stream-aquifer interaction at the local scale appears to be inappropriate here, as the spatial resolution and the accuracy of the water level data is too low for such a purpose. Among the alternative models, the models with only one major river (Gidabo River, Model 11) and without rivers (Model 10) are unable to capture the head distribution indicating the rivers are an integral part of the groundwater system (Table 2). The existing groundwater pumping rate is by far lower than the recharge. Groundwater flow into the Lake Abaya is found to be significant but less than the contribution from river baseflow. As the total river flow to Lake Abaya also includes surface runoff and interflow (which are not part of the water budget of the groundwater model), it is evident that Lake Abaya receives the majority of water from the rivers.

The total outflow from upper Gidabo River Basin to the adjacent Awassa Lake Basin has been estimated to be 1 % of the recharge using Model 13 (which has a likelihood of 12 %). Thus, compared with the other water budget components the outflow to the Awassa Lake Basin is small and found to be consistent with the previous studies (Yasin, 2002; Mussie, 2007). Despite being negligible at the catchment scale, the inter-basin flow might need further attention in local investigations close to the water divide.

In the study area, a significant portion of the recharge occurs along the mountain front (highland and escarpment). Parts of the water recharging the shallow aquifers discharge to the nearby depressions along the rift boundary fault contributing to the baseflow of the streams and springs. The remaining groundwater infiltrates into the deeper aquifers and joins the regional flow system towards the rift floor following the topographic gradient. Therefore, the rift floor aquifers receive inflow from two different sources: direct recharge



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Region	Flow component	Inflow (million m <sup>3</sup> / day)	Outflow (million m <sup>3</sup> / day)	Balance (million m <sup>3</sup> / day)
<b>Entire Gidbo River Basin</b>	Lake Abaya	0.000	0.56	-0.560
	Wells	0.000	0.005	-0.005
	Recharge	2.269	0.000	2.269
	River leakage	7.724	9.429	-1.705
<b>Upper catchment (Highland and escarpment)</b>	Horizontal exchange	0.046	0.615	-0.569
	Wells	0.000	0.002	-0.002
	Recharge	1.251	0.000	1.251
	River leakage	3.676	4.358	-0.682
<b>Rift floor</b>	Lake Abaya	0.000	0.560	-0.560
	Horizontal exchange	0.615	0.046	0.569
	Wells	0.000	0.003	-0.003
	Recharge	1.018	0.000	1.018
	River leakage	4.049	5.071	-1.023

**Table 3:** Estimated inflow and outflow components of groundwater fluxes for the entire basin as well as the upper catchment (highland and escarpment) and the rift floor separately based on the best model (Model 6).

from the local rainfall and indirect recharge from the escarpment and the highland. The latter usually is called mountain block recharge (Wilson and Guan, 2004). To compare these two components, the model domain is subdivided in two sub-regions, the upper catchment comprising the highland and escarpment as opposed to the rift floor. The water budget of these regions is presented in table 3. Within the rift floor the majority of inflow into the aquifers is from the direct recharge, while the mountain block recharge ("horizontal exchange" in Table 3) accounts only for 35 % of the total inflow to the rift floor. At first, this finding is surprising, as the recharge is very low in large parts of the rift floor but much higher in the upper catchment (see Figure 4). Yet, the aerial extent of the rift floor is larger than that of the upper catchment and, more importantly, more than half (55 %) of the recharge to the upper catchment is drained as river baseflow and thus not transformed to mountain block recharge. It is further noteworthy that the model results suggest that the river flow from the upper catchment does not provide a net recharge to the rift floor aquifer. Instead the rift floor aquifers provide a baseflow component to the river flow, which approximately balances the direct recharge received in the rift floor. Yet, while generally gaining baseflow from the aquifers both in the upper catchment and in the rift floor, locally the streams may lose water to the aquifers. However, similar to the discussion in the previous sections the catchment-scale groundwater flow model does not enable reliable assessments of such local effects.

## 8. Conclusions

In this work, the regional groundwater flow within Gidabo River Basin, which is part of the southeastern Main Ethiopian Rift, is characterized using a multi-model approach to account for the conceptual model uncertainty arising from the incomplete knowledge about the complex hydrogeology of the

area. An ensemble of fourteen alternative conceptual models is proposed comprising different representations of aquifer heterogeneity, boundary conditions, fault zones and river-aquifer interaction. Model ranking and discrimination techniques such as the Akaike information criterion (AIC and AICc) and the Bayesian information criterion (BIC) were calculated to identify the most plausible among the calibrated models.

The model ranking resulting from the different criteria is similar. All model selection criteria select five models as plausible ones and discard the other nine as they are either

under-parameterized or over-parameterized. The best model selected by AICc obtained a likelihood of 52 %, while the other four plausible models range from 15 % to 7 %. The baseflow simulated by these models is of similar magnitude and found to be within the ranges of the observed long-term baseflow. Likewise, the calibrated transmissivities, the groundwater flow pattern, and the water budget of these five models are very similar.

The simulated hydraulic head distributions of the plausible models agree reasonably well with the equipotential map constructed from head observations. The best model selected by AICc ignores faults; other possible models considering faults as semi-barriers achieve a slight improvement in model fit but have lower likelihood due to the increased number of calibration parameters. In general, the effect of faults on groundwater flow appears to be more important at a local scale but looks modest at the catchment scale considered in this work. The estimated transmissivity values range between 30 m<sup>2</sup>/day and 1350 m<sup>2</sup>/day and generally increase from the mountains towards the rift floor. In most regions, the calibrated transmissivity values were higher than those derived from pumping tests. These differences are most pronounced in the rift floor but vanish towards the highland. This might partly result from the partial penetration of the wells, but likely also reflects the effect of fault zones acting as conduits along the fault plane.

The water budget shows that 75 % of the groundwater recharge flows into the surface streams, thus sustaining river baseflow. The remaining water infiltrates to the deeper aquifers and mainly flows towards Lake Abaya, while only less than 1 % of the total recharge is abstracted by pumping wells. The water budget of the rift floor indicates that the majority of inflow is from direct recharge, while only 35 % is mountain block recharge originating from the upper catchment comprising the escarpment and the highland. These results support the

conceptual understanding suggesting significant mountain block recharge from the highland to rift floor aquifers, which is also indicated by hydrochemical and isotope data in this and other parts of the Ethiopian Rift. For the given catchment, the results further indicate a substantial groundwater flow into Lake Abaya. However, as there is neither a river gauging station nor any well in close vicinity of the lake that could be used to assess the validity of the model in this part of the catchment, this finding should be interpreted with caution and needs to be substantiated by further investigation.

The results of this study strongly advocate the idea to incorporate alternative plausible models instead of relying on single models in the practice of groundwater modeling especially in areas of complex hydrogeology and lack of data. The study provides valuable information about groundwater flow pattern, water budget, stream-aquifer interaction, and aquifer properties at the catchment scale, which is a prerequisite for the future development of groundwater resources in the area. However, the results obtained in this study will need to be complemented by more detailed investigations at a local scale to enable a proper water management.

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