GROUND WATER FLOW SIMULATION OF THE LAKE TANA BASIN, ETHIOPIA

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ABSTRACT

With the intention to capture the groundwater contribution into Lake Tana, a case study was conducted at the Gumera River sub-basin, one of the five sub-basins that drain into Lake Tana. The Gumera sub-basin was delineated using 90-m SRTM digital elevation model (DEM) using ArcHydro tools. The sub-basin boundary and the stream outlets are used as boundary conditions acting as the divide line of the groundwater flow into and out of the other watersheds while stream networks are used as internal drainage lines. Input parameters are obtained from past studies and also based on experts' experience. Upon reviewing the basin's geological information, unconfined subsurface flow condition is considered and it was simulated using MODular three-dimensional finite-difference ground-water FLOW model (MODFLOW). The result indicates that head contours are aligned to the streams showing their relationship as a subdued form of the surface water flow which are dictated by the drainage lines. The result depicted that groundwater outflow follows the surface water outlet. The result suggested the need to account contribution from the sub-basins on to the base flow, and to estimate groundwater inflow from the floodplain separately. The contribution from the floodplain was conceptualized by steady state flows of unconfined aquifer justified by the slow changes of groundwater level in the floodplain. The result has shown that 0.1 Billion Cubic Meter (BCM) is flowing annually across the perimeter of the Lake Tana. Four wells in the low and mid-altitudes were used to calibrate the head distribution. The study has given clues to further validate for inverse methods of parametric and flow estimation.

Key Words: Lake Tana, groundwater, modeling, Blue Nile, MODFLOW

INTRODUCTION

The Tana basin constitutes 3.1 million ha fresh water body that receives subsurface flow from the 16,500 km^2 drainage area (Kebede, 2005), (Figure 1). The lake serves for fishery, navigation and hydropower purposes. The downstream side of it is breeding places of the fish species which makes it sensitive to any intervention that affects the subsurface flow in any way. Despite its ecological and economical importance, little is known about the potential of subsurface water and its carrying capacity in the basin.

The research gaps and scarcity of monitoring data to understand the subsurface flow in the Tana Basin is reported by Kebede et al.,(2005). This has contributed to the knowledge gap on the groundwater quantification and sensitivity analysis to anthropogenic and climate-induced changes. This paper highlights the importance of identifying options to simplify and understand the process using simulation models. Given the ease of capturing geological data and conveniently measuring base flow with spatial and temporal scale of interest, it is arguable that a shift of focus is necessary to understand future possibilities of ground water parametric estimation through numerical and stochastic modeling approaches.

Unlike the physical models, numerical and stochastic models would find their way of replicability at different watersheds helping long-term calibration (Gelhar, 1993, Rubin, 2005). For this purpose, it was intended to study the capability of the MODular three-dimensional finite-difference ground-water FLOW model (MODFLOW) in subsurface flow estimation for the Lake Tana groundwater flow system.

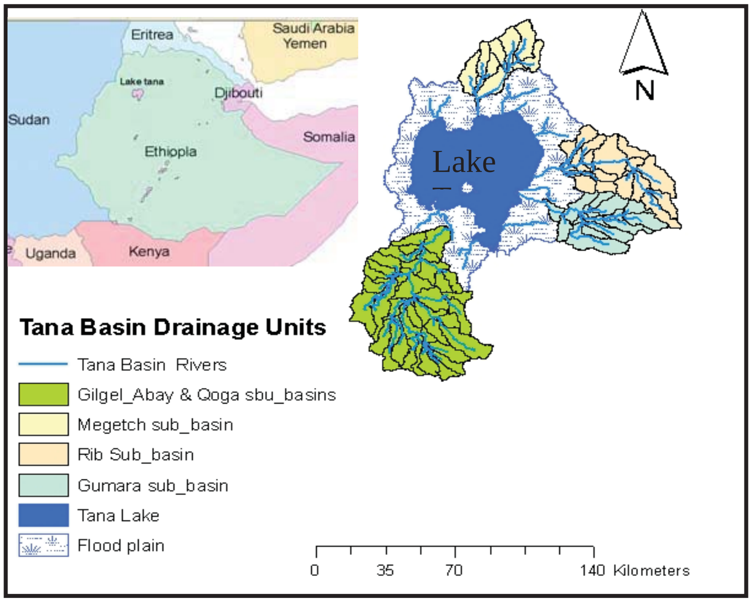


Figure 1. The Lake Tana drainage system and contributing watersheds.

The specific objectives of this study are to (a) understand regional and basin level ground water flow in the Lake Tana basin and (b) evaluate MODFLOW application for simulation of the groundwater flow in the Lake Tana basin.

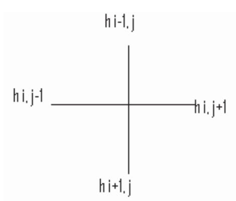
Review

Physical models in combination with geochemical tracers are traditionally used to quantify groundwater flow and analyze the flow pattern (Anderson and Wossener, 1992). The use of tracers to understand the subsurface inflow and outflow from Lake Tana has given fundamental clues of potential inflows and outflows within and out of the basin (Kebede et al. 2005). However, these traditional methods specifically, the physical models are known for their cost and less replicability. The comparability of numerical and stochastic models with physical models for parametric estimation of ground water flow is reported by Gelhar (1993), suggesting their cost effectiveness and replicability without compromising the data.

Gelhar (1993) suggests techniques to tackle the uncertainty over the simulation models through distributed hydrogeological models. Apparently, the differentiation of the distributed hydrogeological modeling units would be based on topography and aquifer type. As a case in point hydrogeologic units could have differing flow patterns identified as fracture Darcian flows (Anderson and Wossener, 1992).

For complex physical models, use of the MODFLOW, which is built on finite difference methods, is encouraging while the numerical finite difference methods could be sufficient to address unsophisticated simple physical models with sound boundary and initial conditions (Anderson and Wossener, 1992). The finite difference (finite element) is the numerical method used for subsurface flow analysis using interfaces such as Matalab. Numerical methods by Poisson’s equation and the discretized format for iteration is expressed as follows (Wang and Anderson, 1982)

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{E}{T} \qquad \text{Steady state} \qquad (1)$$



$$h_{i,j} = [h_{i+1,j} + h_{i-1,,j} + h_{i,,j+1} + h_{i,,j-1} - E*DX^2/T\ ] /4 \qquad (2)$$

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t} + \frac{E}{T} \qquad \text{Transient} \qquad (3)$$

$$h_{i,j,t} = [h_{i,j,t-\Delta t} + (T\Delta t/S)\ [h_{i+1,j,t-\Delta t} + h_{i-1,,j,t-\Delta t} - 4\ h_{i,j,t-\Delta t} + h_{i,,j+1,t-\Delta t} + h_{i,,j-1,t-\Delta t}\ ] + E*DX^2/S\ ] /4 \qquad (4)$$

where h = head; T = transmissivity; E = evapotranspiration, S = storativity, DX = grid interval, t = time.

Geology of the Basin

As part of the modeling framework, the knowledge on the structural geology, hydrogeology, and geomorphology of the basin remains a key factor for parameterization of inputs and also identify assumptions. Lake Tana basin is a junction point of three grabens centering Lake Tana which were active in the mid tertiary and quaternary and run from Gondar, Dengel Ber and Debre Tabor (Chorowicz et al., 1998). The lake is dammed by dyke swarms that run NW-SE, NE-SW, ESE –WNW (Hautot et al., 2005) and a 50 km lava flow cutoff at the outlet of the Blue Nile River to a possible depth of 100m (Chorowicz et al., 1998). Quaternary lacustrine sediments and alluvial deposits are evident at the head and toes of the basin namely Chilga, Debretabor and Fogera plains overlain on the flood basalts. The simplified geological cross-section by Hautot, et al., (2006) shows that the underlying formations beneath the 250m thick basaltic grabens are Adigrat and Nile Gorge sand stones and Ashengi, Aiba and Tarma Ber formations that go 1-2 km deep.

The underlying basaltic graben serves as a cutoff against seepage loss from the lake as it is confirmed upon the absence of geochemical mixing outside of the basin (Kebede et al., 2005). On the contrary, a regional groundwater inflow is identified from a possible aquifer that extends from mount choke (South of Lake Tana basin), confirming its signature of geochemical mixing at Andasa springs. Even then with the circumscribing course of the Blue Nile River gorge the amount delivered to Lake Tana is not well known. The contribution from Guna aquifer (East of Tana basin) is found to have negligible contribution for lack of evidence of geochemical mixing within the basin (Kebede et al., 2005). The minor geochemical mixing obtained at Wanzaye, $\delta^{18}O$ (3.2%), is attributed to the mixing from the cold springs of Debretabor than the Guna aquifers (Kebede et al., 2005). In summary these evidences help to assume that major subsurface inflow to Lake Tana is from the basin itself.

The inflow within the basin is characterized by quick hydrological response through the fractures of the faulted blocks dipping towards the Lake Tana from all directions with strike NNE, SSW (Kebede et al., 2005). This is observable from the normal and lateral slip faults of the structural geologic map (Figure 2) by Chorowicz et al., (1998) which are confirmed from satellite images. Looking at the geological structures and topography of the Tana basin quick response of the subsurface flow within the basin is evident.

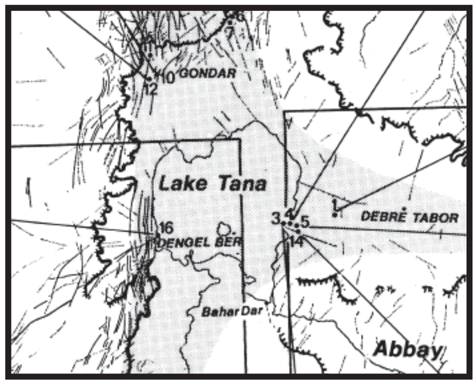


Figure 2. Normal and lateral slip faults in the Tana basin from Chorowicz et al., 1998.

METHODOLOGY

Two modeling exercises were conducted: one at a representing sub-basin called Gumera and the other at Lake Tana floodplains. For the Gumara Sub-basin, a one dimensional flow profile is simulated on the MATLAB interface based on analytic solutions (Wang and Anderson, 1982). The digital elevation model (DEM) was used as a guiding line to observe the topographic profile and hence model the ground water as a subdued form of it. A separate 2-D flow simulation on the floodplains was also designed using finite difference method which involved iteration techniques. The 2-D flow model was simulated using MODFLOW software. In all the cases, steady state flow patterns are simulated.

Model Set Up

The model set up for the two dimensional sub-basin model with MODFLOW was conducted by setting the watershed boundary as no flow zones, and the streams as internal drainage lines. The outlet is represented by a pumping well with equal discharge amount as the stream flow as shown in Figure 3a. Secondary data of input variables collected from BECOM and reported in Kebede et al., (2005) is applied on grid basis

(Figure 3b). This includes transmissivity determined from pumping test by BECOM. Quoting form BECOM, Kebede et al., (2005) stated that the transmssivity of the Tana grabens and alluvial deposits are 100 to 200 m^2/day and $700m^2$/d, respectively while on the back side of the western Tana escarpments it is only $1m^2$/day. The evapotranspiration was estimated using Penman's method (Ward, 1995). Leakance to the confined aquifer is assumed 5% of the precipitation with conservative expert judgment and incorporated in the evapotranspiration parameters (as a loss). Hydraulic head data from two shallow wells developed in year 2006 by the district were used for calibration.

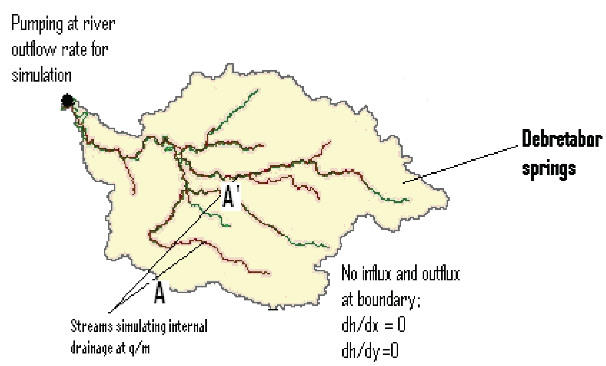


Figure 3a. Boundary conditions and internal drainage.

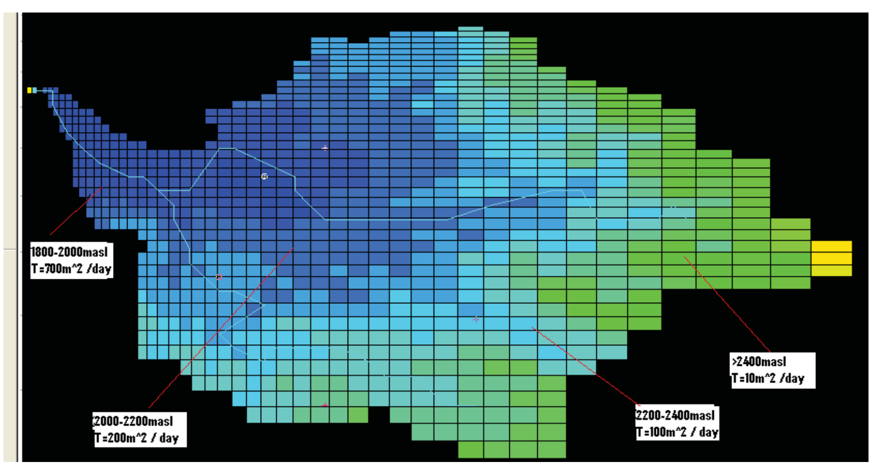


Figure 3b. Distributed inputs of transmissivity and elevation for the Gumera sub-basin.

Analysis

The Shuttle Radar Terrain Mapping (SRTM) DEM data with 90m resolution from U.S Geological Survey (USGS) (USGS, 2007) is used to delineate the Tana basin. Watershed analysis tools of ArcHydro (Maidment, 2002) were used to process the raw data, fill sinks, and generate stream network and watersheds. Four sub-basins namely Rib, Gumera, Megech, and the Gilgel Abay-Koga were delineated. This has helped to do analysis on separate sub-basins and also capture the Tana plain separately from the other sub-basins. A GIS layer of Gumara sub-basin was developed that MODFLOW uses as flow boundary condition and the streamlines were used as 'drains'.

RESULTS AND DISCUSSION

Subsurface Flow from Gumara Sub-Basin

Vertical Cross Section Analysis

A radiometrically corrected Landsat Enhanced Thematic Mapper Plus (ETM+) imagery of the study area was enhanced by a high pass filter (HFF) to identify fractures. The results were in agreement with the structural maps developed by Chorowicz et al.,(1998). Based on these evidences of fracture flow dominance over the sub-basin, a one dimensional overview of the flow profile was simulated using finite difference methods with Matlab interface to look at the flow cross-section in one dimension. Based on the topographic profile map from the DEM that indicates 3 rising shelves at a regular contour interval of 200 m from the 1820 to 2400 m amsl (Figure 3b) the simulation was done across the A-A` shelve. For this purpose, a simplified form of the Poisson's equation (Wang and Anderson, 1982) (1) is reduced to Laplace equation taking the form

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \qquad (5)$$

Based on observations on the morphology, stream network and slope classifications from the DEM, both linear as well as the sinusoidal fitting of the groundwater level as a replica of the topography was tested. And the sinusoidal subdue of the groundwater is found fitting to the internal drainage conditions. This is in agreement with the BECOM hypothesis that (quoted in Kebede et al., 2005) the ground water could be in a perched form with high water table and flux around streams.

The sinusoidal head variation is captured through Toth solutions (Wang and Anderson, 1982) and applied with a constant head at the two boundaries setting the foot of the valley bottom at zero, and the streams at their own elevation from DEM. Based on one year observation an annual average head of 20m at the upstream (A) is considered. The model is run with Matlab interface whose outcome is a sub-basin head profile (Figure 4) and the flow pattern (Figure 5). The head profile is on a 30m thick unconfined aquifer with head at 20m on the upstream. The head is at 1m interval while the topographic relief is at 10 meters vertical interval. The horizontal grid follows the topographic interval of 100m.

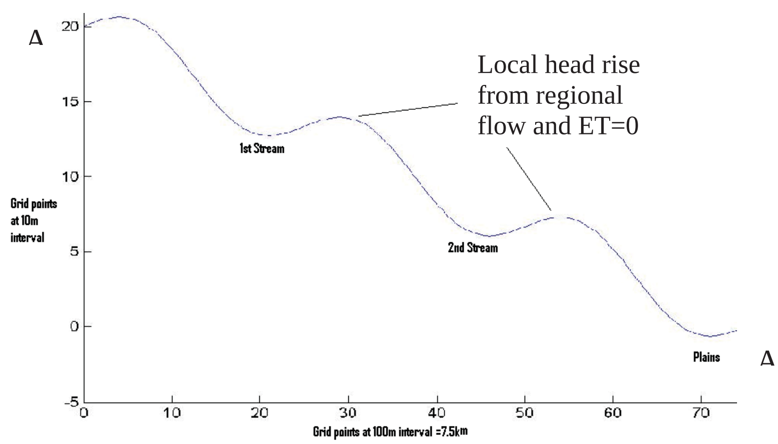


Figure 4. Regional flow model for the cross section of A-A\` of Figure 3a on the sub-basin.

A flow-net analysis estimates an interception of 65% of the groundwater as base flow by the streams (Figure 4). Also, the local watershed and sub-basin flow mix on stream lines is noticeable from the flow profile (Figure 5). Even the remaining 35% should diverge with other influxes from other areas and recur in the downstream. In other words the subsurface flow contributes to Lake Tana as the base flow than as direct subsurface flow into the lake. To confirm the result, the ideal solution could be use of tracers (Fetter, 1988), however, in the absence of such experiments, 2D modeling with calibration of wells is opted.

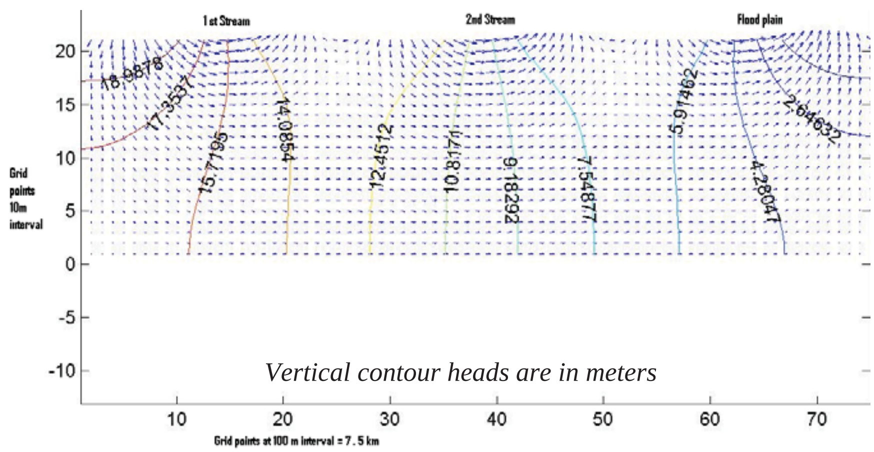


Figure 5. A vertical cross-section sub-basin level flow on cross-section A-A.

Two Dimensional Flow Analysis of Gumara Sub-Basin

With the intention to confirm the overall head distribution in the sub-basin, a 2D flow analysis was modeled using MODFLOW. The watershed boundary of the sub-basin was used as the boundary conditions of the model considering the watershed boundary as no flow zones, streams as drains, and watershed outlets as siphoning out wells at equal discharge as the stream outflow. In this analysis, both precipitation and evapotranpiration were considered as sources and sinks (recharge and out fluxes) and Poisson's equation was applied.

This hydrogeological simulation through forced boundary condition has shown that in both the dry and wet season the hydraulic head (Figure 6) is concentrated near the streams showing that the flow is a subdued form of the watershed drainage line into stream courses. Given the fact that the steam flow line is perpendicular to the contour lines, it proves that most of the groundwater flow is draining into the streams (Figure 6). This is in conformity with the 1D model indicating alignment of head distributions with the streams. Nevertheless, no local rise of heads is observed which might be attributable to the consideration of evapotranspiration and leakance.

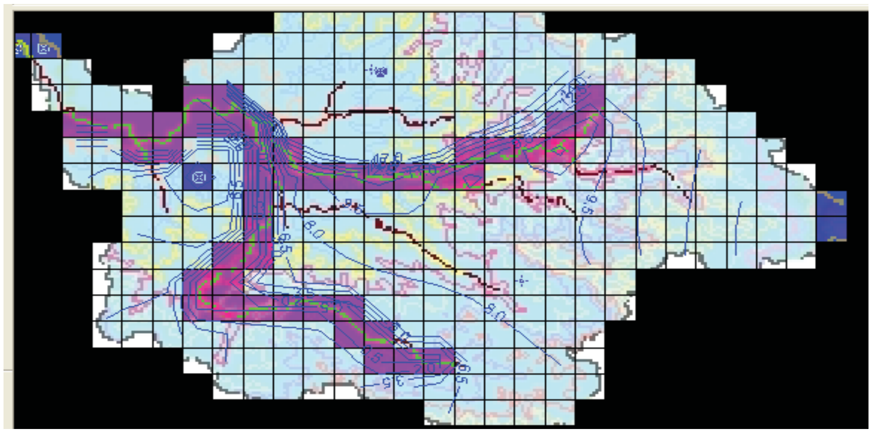


Figure 6. Head contour (blue lines) for Gumera sub-basin aligning with stream lines.

The model is run with two constant head calibrating wells. The analysis indicated that ground water input from the watershed could be captured from the base flow of the stream plus the flow through the thin unconfined section. Also this study confirms the facts established by Kebede et al.,(2005) that quick response of groundwater outflow and less retention due to the high fracture garben calling it “perched aquifer”.

Subsurface Flow in the Floodplain

The major outcome of the 2D study on Gumara sub-basin is that, while the groundwater inflow could be taken into account by the base flow, a separate contribution is identified from the floodplain that is flooded for months to its surface during the rainy season and starts to yield into the lake during the dry seasons. This contribution is from a 20 km section of floodplain which carves as a concentric circle centering Lake Tana (Figure 7). The flow from the plain across the perimeter is estimated using Poisson’s equation of steady state flow for unconfined condition. A finite difference model set up at the floodplain involved two major rivers, Rib and Gumara at 10 km apart, and the Lake Tana (20 km from the head).

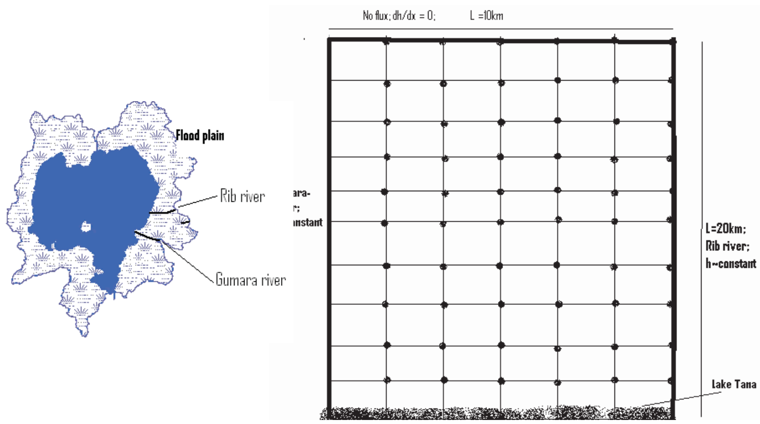


Figure 7. Model setup for the floodplains and grid points are for finite differences estimate.

The hydraulic head distribution from the simulation (Figure 8) for the dry and wet seasons indicate that subsurface flow is from the rivers towards the floodplains, higher heads near the rivers with decreasing gradient towards the main land. It is also found out that the floodplain receives about 0.16 billion cubic meters (BCM) from base flow of the rivers, while the flood itself contributes 0.1BCM to Lake Tana. The difference (6 millions m^3) is being stored in the floodplain. The hydraulic head is calibrated against shallow wells in the floodplain.

A 1D transient flow simulation for the wet season indicates the reversal of the head distribution. Apparently the recharge from precipitation played a significant role to reverse it.

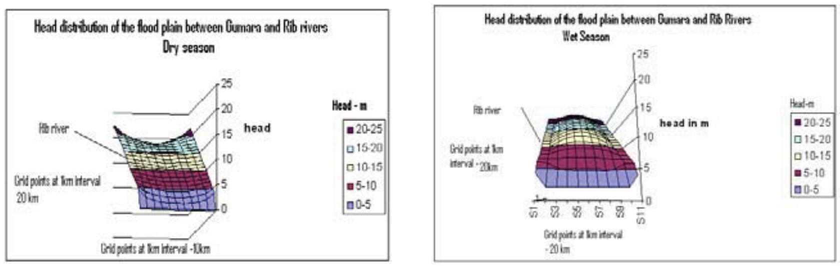


Figure 8. Simulated and calibrated head distribution for floodplain.

CONCLUSION

The main purpose of this study was to understand the ground water flow system of Lake Tana and quantify the flow. From the past studies, the hydrogeology of the basin and watershed analysis of the study area using ArcHydro, the boundary conditions were identified. This has enabled an understanding of the different hydrogeologic units and subsequently facilitates the model setup. The model setup for the Gumera sub-basin was made on MODFLOW 2002. The analysis depicted the alignment of the groundwater from sub-basins along the streams suggesting the need for separate analysis for floodplains. The subsurface flow from the floodplains is done using finite difference methods. Finally, the contribution of groundwater was accounted from the subsurface flows of the floodplains and the base flow from the sub-basins.

The simulation has improved the understanding of the groundwater flow system of the Lake Tana Basin both in upper catchments and the floodplains. This is achieved with the employment of MODFLOW whose advantages were found three fold: (1) Its capability of working with the GIS shape files and take up DEM data, (2) its simulation of the irregular boundaries of the sub-basin and (3) the utilities that simulate groundwater wells, internal drainage streams etc., which are vital for distributed hydrogeological modeling. Moreover, the utilities of MODFLOW such as PEST (parametric estimators) for forward and inverse modeling approach makes it inviting. The simplicity, flexibility and control of calibration points were an advantage.

ACKNOWLEDGEMENTS

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