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ORIGINAL ARTICLE

Numerical modeling of groundwater flow system in the Modjo River catchment, Central Ethiopia

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Abstract

In recent years, groundwater pumping has increased for domestic, industrial, and irrigation use in the Modjo River catchment. Understanding changes in groundwater levels is crucial for the sustainable use and management of aquifer. This study investigates the groundwater flow system and aquifer response to increased groundwater pumping and reduced recharge using the calibrated steady-state groundwater level and budget as a baseline. The groundwater flow corresponds to the direction of the Modjo River flow, following the topographic gradient. The simulated groundwater budget indicates that recharge from precipitation and surface water (crater lakes and river) are the main inflow to the aquifer, while the outflow from the aquifer is due to groundwater pumping, natural subsurface flow to downstream area, and base flow. Analysis of the different scenarios reveals that both an increase in well pumping and a decline in recharge resulted in a decrease of the base flow to Bishoftu crater lakes and Mojo River, and to the downstream subsurface flow. In conclusion, increasing human demand for groundwater and variability in recharge will affect groundwater contribution to surface water and ultimately will be a source of concern in the future for both environmental flows and groundwater management.

Keywords Groundwater recharge · MODFLOW · Modjo River · Central Ethiopia

Introduction

Groundwater has increasingly been used to meet water demand for agriculture and other domestic water supplies (Guppy et al. 2018). According to Siebert et al. (2010), about 70% of pumped groundwater is used for irrigation worldwide. In recent decades, groundwater pumping for irrigation has increased (Wada et al. 2012). Groundwater pumping reduces groundwater storage and base flow to surface water (Gleeson and Richter 2017). Many researchers have used MODFLOW, a simulation program for groundwater flow, to investigate groundwater flow and dynamics in various parts of the world (Namaghi et al. 2015; Khadri and Pande 2016; Lachaal and Gana 2016; Bushira et al. 2017; Prasad and Rao 2018; Azerf and Bushira 2020), the impact of intensive groundwater withdrawal on environmental flows (Winter et al. 1999; Gerten et al. 2013; Zhou et al. 2013; De Graaf et al. 2017; Wang et al. 2018), to predict future stresses on the groundwater system (Hao et al. 2014; Zekri et al. 2015; Sahoo et al. 2017), and to investigate groundwater–surface water interaction (Urbano et al. 2006; Yang et al. 2015, 2017). Several studies have combined the groundwater flow model with the management model to maximize the pumping rate under imposed constraints (Jonoski et al. 1997; Ayvaz and Karahan 2008; Ebrahim et al. 2016; Kawo et al. 2018).

In the Modjo River catchment, groundwater has been widely pumped for domestic, industrial, and crop irrigation. Understanding variations in groundwater budgets under anthropogenic stress is crucial to sustainably use groundwater resources (Enku et al. 2017). The need to understand

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the groundwater flow system and the aquifer's response to future stress in the study area is driven by three factors: (1) in recent decades, groundwater pumping has increased to meet the growing water demand (WWDSE 2008). (2) Groundwater contributes to Modjo crater lakes (Kebede et al. 2001; Kawo and Shankar 2018) and these crater lakes have been used for water-based recreation and eco-tourism for many decades. High rainfall variability may have an impact on aquifer recharge and base flow in the Awash River basin (Bekele et al. 2017). This could have an impact on groundwater levels and base flow and could lead to indirect recharges from crater lakes and the Modjo River. (3) Modjo River catchment is located in the upper Awash River basin and many industries are located in this area (Kawo and Shankar 2018), which causes pollution of surface water and water reservoirs in the upper Awash River basin (Yohannes and Elias 2017; Eliku and Leta 2018; Shankar and Kawo 2019).

Changes in groundwater recharge and overuse can harm the ecosystem (Zhou et al. 2013). Understanding groundwater budgets under increasing human pressures are vital to sustainably use groundwater resources. Despite the importance of groundwater for human development and environmental flows, the aquifer's response to induced human activities is not well studied in the study area. Also, the impacts of increasing groundwater pumping on Crater lakes and Modjo River and changes in groundwater budget under induced human activities are seldom addressed in the study area. Therefore, in this study, aquifer responses to increasing groundwater pumping and decrease in recharge were investigated using the calibrated steady-state groundwater levels and budget as the baseline.

Materials and methods

Modjo River catchment description

Modjo River catchment is a sub-basin of the Awash River basin and situated in Central Ethiopia. It is situated approximately 40–70 km from Addis Ababa in the south-easterly direction, in Oromia Regional State, East Shewa Zone (Fig. 1). The elevation of the catchment ranges between 1603 m above mean sea level (amsl) in the flat lowland part to 3070 m amsl at the top of the mountain ridge. According to data from 1984 to 2014, obtained from the Ethiopian National Meteorology Agency, the mean annual rainfall in the catchment is 868.4 mm/year. The mean monthly of Modjo river flow (1998–2005), and average monthly rainfall (1984–2014) in the Modjo River catchment are shown in Fig. 2. The highest river discharge is between June and September, which is the main rainy season in the study area.

Geology and hydrogeology

The study area is covered by diverse volcanic products of the Quaternary rift volcanic (Tamiru and Antonio 1995). Figures 3 and 4 show the geological map and categories of productive aquifers in the Modjo River catchment, respectively. Larger portions of the study region are covered by lacustrine sediments and pyroclastic *Chefe donsa* rocks. Alluvial and lacustrine deposits in the Ada'a plain, especially around the Bishoftu lakes and Modjo areas, are constituted by coarse sediments and are highly permeable (WWDSE 2008). The Chefe Donsa Pyroclastics, Nazaret unit (Welded ignimbrites) have poor permeability except at the weathered and fractured zones. Except in the weathered and fractured zones, the localized acid volcanic units and Quaternary Bede Gebaba volcanic unit have also low permeability (WWDSE 2008).

The aquifers of the study area consist of weathered and fractured volcanic rocks and Quaternary alluvial and lacustrine deposits (Kebede 1987; Alem 2006; Kebede et al. 2007; Yitbarek et al. 2012). According to WWDSE (2008), the Quaternary alluvial and lacustrine aquifer has high groundwater potentials and exists in the flat part of the catchment. The productive Basaltic aquifer is overlain by the Quaternary alluvial and lacustrine aquifer (Yitbarek 2009; Yitbarek et al. 2012).

Data and methods

Data collection

The Digital elevation model (30 m resolution) of the Modjo River catchment was downloaded using path/raw from the US Geological Survey website (https://earthexplorer.usgs.gov/). Temperature, precipitation, and wind speed data were collected from the Ethiopian National Meteorological Agency (NMA). Meteorological data are converted to special grid maps for WetSpass modeling. Potential evapotranspiration (PET) was computed using the Penman–Monteith combination method. Monthly computed PET values were used to map the summer and winter PET grids. Data on soil, land use, and land cover used as inputs to the WetSpass model were obtained from the Ministry of Water Resources and Irrigation Energy (MWRIE). The soil map was grouped into hydrological soil groups to evaluate permeability and infiltration capacity. Geological map, borehole completion report, pumping test data, groundwater level, and lake level data were collected from various sources (Ethiopian Waterworks Design Supervision Work and Enterprise, Oromia Water Resources Bureau, and Oromia Water Works Design and

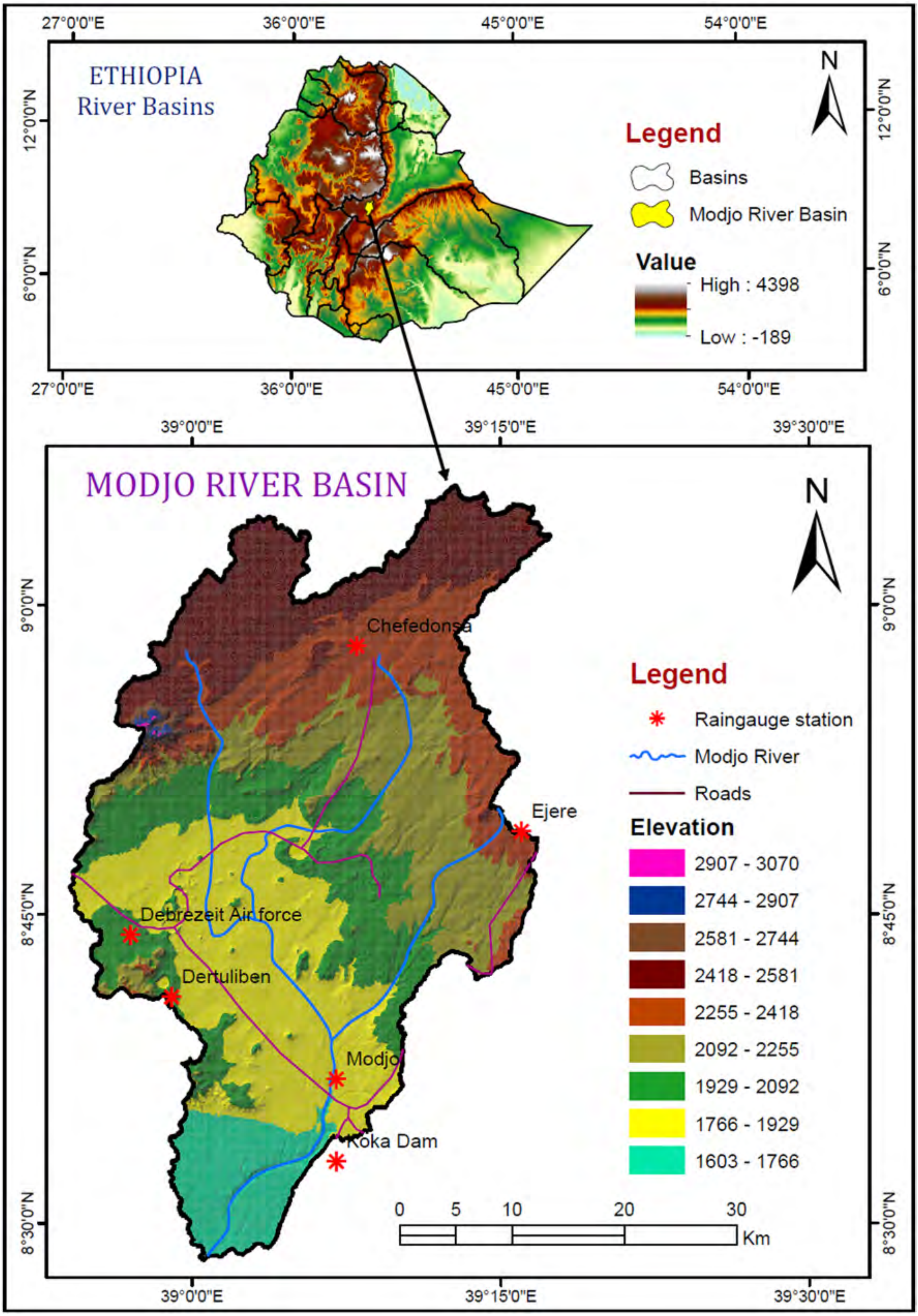

Fig. 1 Location and topography of the study area

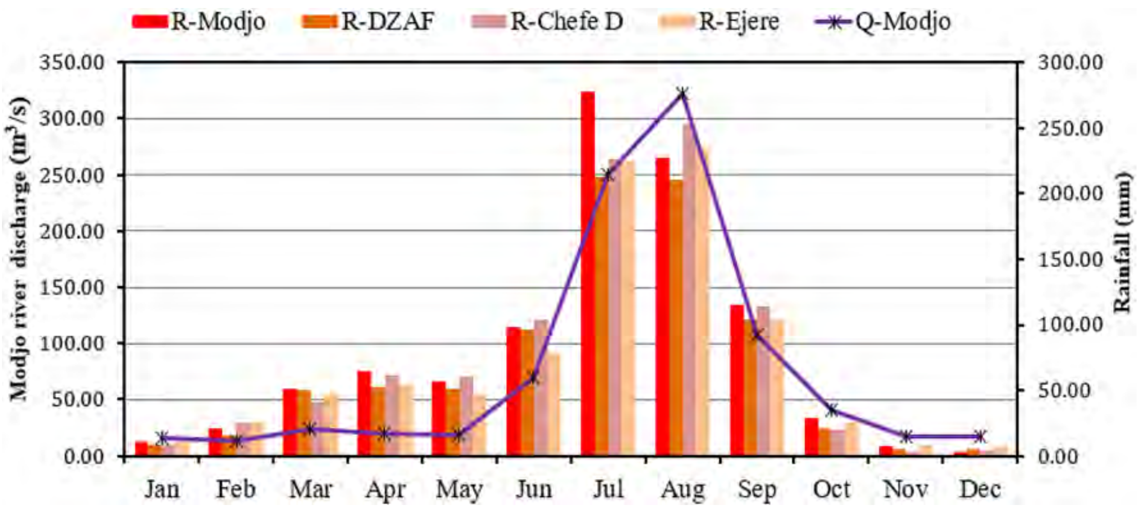

Fig. 2 Mean monthly flow for Modjo Riverand an average rainfall of selected stations in the Modjo river catchment for the period 1984–2014

Supervision Enterprise) to construct and calibrate groundwater flow model.

Steady pumping model setup

In this study, MODFLOW-2005 code (Harbaugh et al. 2005) was used to investigate the aquifer response to increased groundwater pumping and reduced recharge in the Modjo River catchment. For this simulation, a single vertical layer was considered and discretized with a grid spacing 200 by 200 m, which resulted in 365 columns and 250 rows. The higher elevation of the aquifer is interpolated using kriging methods while the lower elevation is allocated based on the elevation of the deepest pumping wells drilled in the study area. Constant head boundary conditions were applied to all Bishotu crater lakes (Fig. 5). The water surface elevations of Bishoftu Guda (1864 m), Hora (1860 m), Bishoftu (1856 m), Hado (1870 m), and Chelelka (1890 m) were given in the constant head area. According to WWDSE (2008), the aquifer of the study area receives subsurface inflow from the Southern, Southeastern, and Western parts. Thus, the general head boundary was used in these areas to simulate subsurface inflow and outflow from the aquifer. No-flow boundary was assumed for areas of impermeable aquifer unit boundary. The River package implemented in the MODFLOW-2005 was used to simulate the interactions between the aquifer and the Modjo River. The Modjo River was divided into sections and the following parameters were assigned for each section of the river: river bed hydraulic conductivity, width of the river, head, and elevation of the riverbed bottom.

Hydraulic conductivity

Horizontal hydraulic conductivities were analyzed and mapped based on geology and available pumping test data in the study area. Figure 6 shows horizontal hydraulic conductivities zones of the study area. According to Waterloo Hydrogeology (2006), vertical hydraulic conductivity (V_k) of the aquifer is 1/10th of the horizontal hydraulic conductivity (V_h) of the aquifer. Therefore, in this study, 1/10th of the V_h was applied for V_k of the aquifer.

Groundwater recharge estimation

The spatial variation of groundwater recharge in the Modjo River catchment was computed using the Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-steady State (WetSpass) model (Batelaan and De Smedt 2007). The WetSpass model uses land use and land cover, groundwater depth, precipitation, potential evapotranspiration, wind speed, temperature, soil, and slope as inputs to estimate annual and seasonal groundwater recharges (Batelaan and De Smedt 2007; Zomlot et al., 2017). The detail on the input parameters and description of the WetSpass model is presented in Batelaan and Desmedt (2001, 2007). Input data to compute the spatial distribution of groundwater recharge in the Modjo River catchment are presented in Fig. 7. The calculated spatially distributed groundwater recharges were applied to the aquifer using the recharge package implemented in the MODFLOW-2005.

In the next paragraphs, the inputs to the modeling are described such as the steady pumping model, hydraulic conductivity, groundwater abstraction model, and finally, the scenarios that have been selected are described in detail.

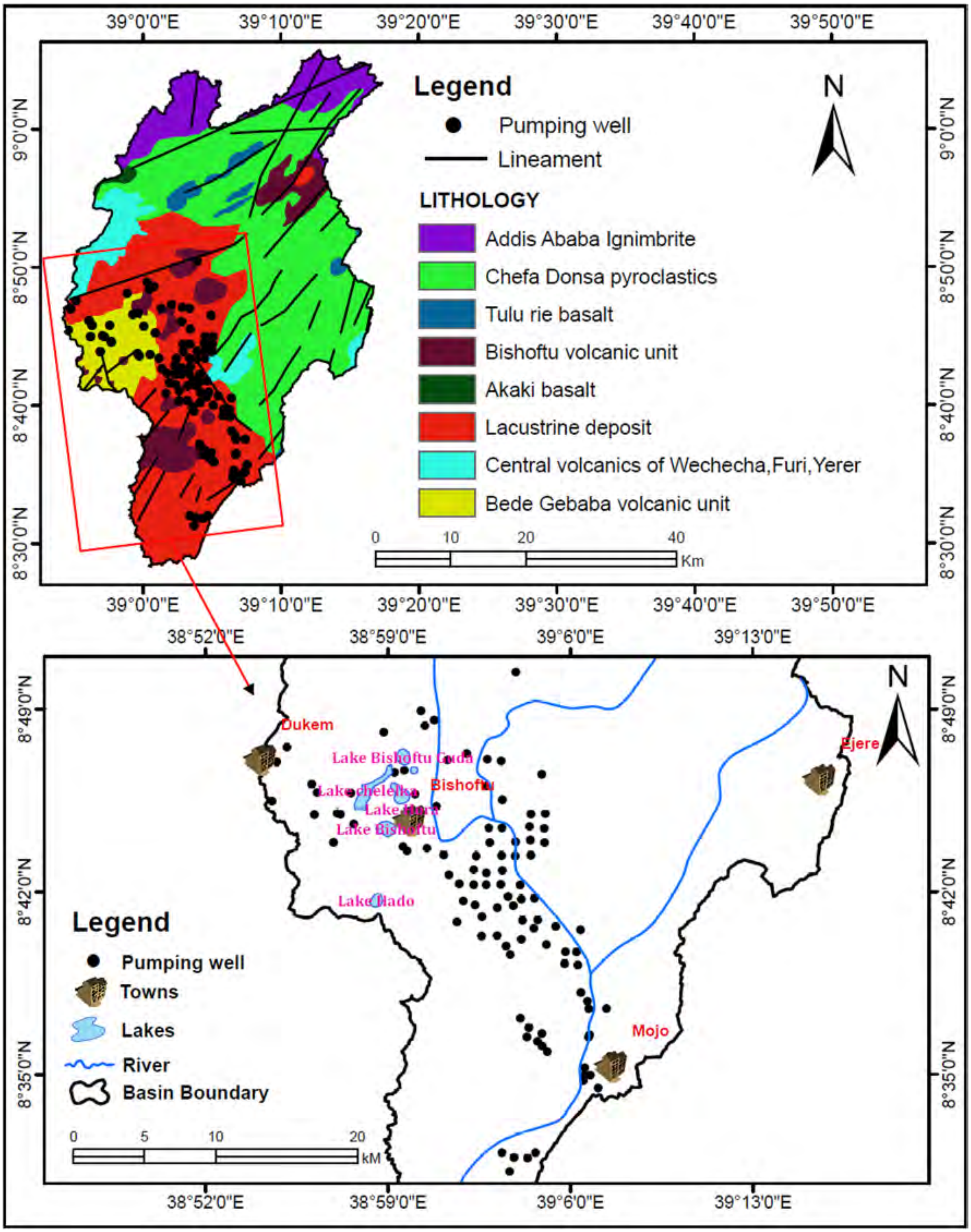

Fig. 3 Geological Map and pumping well location in the Modjo River catchment

Groundwater pumping

A daily pumping rate from the aquifer of the study area was specified using the Well package implemented in the MODFLOW-2005. The locations and rates of each pumping well in the model are shown in Figs. 3, 8, respectively.

Scenario analysis

Two scenarios have been built for this study area: Scenario 1 entails an increase in groundwater pumping and Scenario 2 entails a reduction in groundwater recharge.

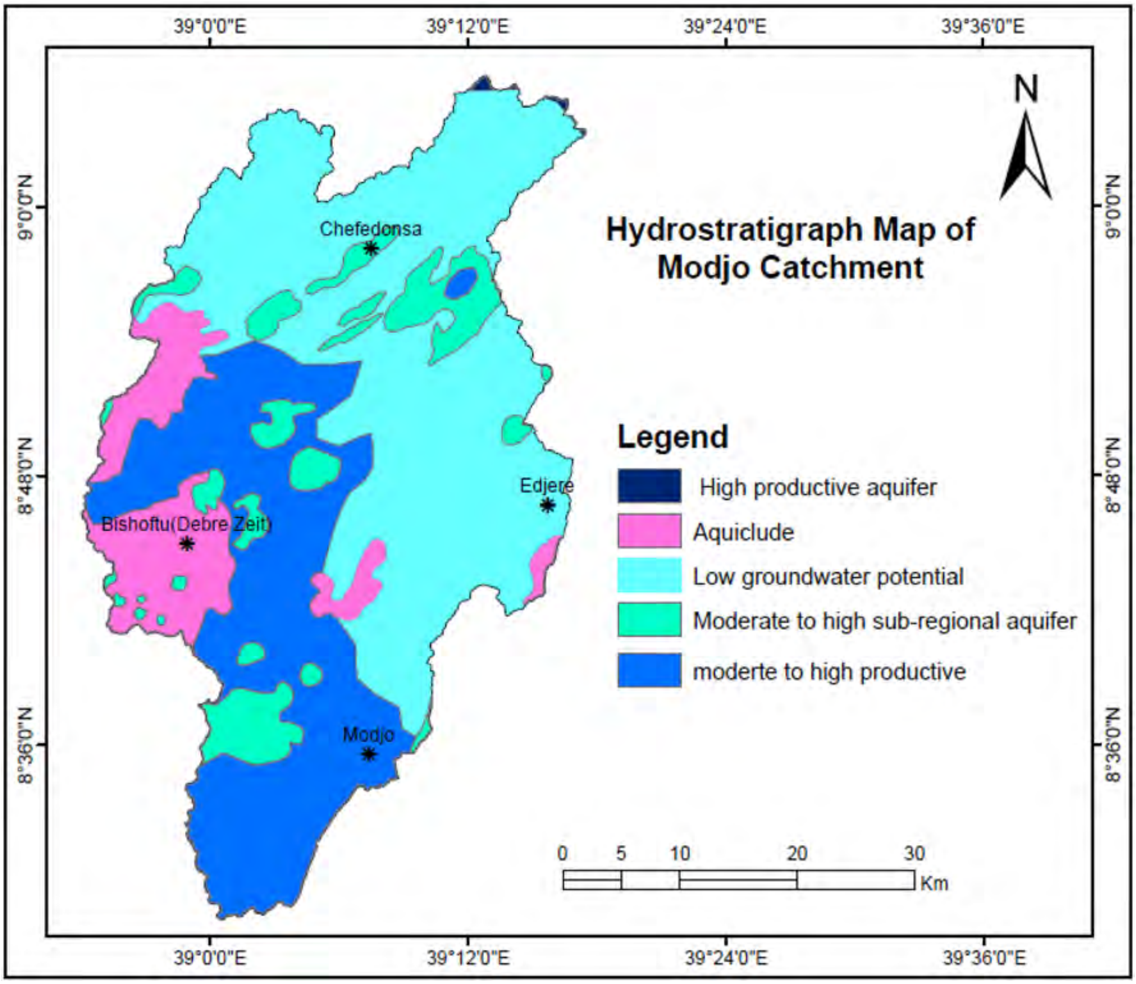

Fig. 4 Hydrogeological map of Modjo River catchment (Modified from WWDSE 2008)

Scenario 1: increase in groundwater pumping

The water demand is increasing over time due to population growth and urban and industrial expansion in the Modjo River catchment. Industries based in the catchment area causing migration of population to cities in search of a job. Knoema (2017) stated that the urban population of Ethiopia grew from 8.3 to 20.3% between 1968 and 2017. Furthermore, as a result of industrial and urban liquid waste discharges, surface water is highly polluted in the study area. Hence, the need for groundwater exploitations is increasing over time in the Modjo River catchment.

In this study, current groundwater pumping rates were increased by 20%, 40%, and 50%, and the aquifer response to the increased withdrawal rates were assessed using groundwater budgets and groundwater levels under the steady model as a baseline.

Scenario 2: reduction in groundwater recharge

Recharge and base flow varies over time, and the dynamics within a basin are affected by climate change, geological formation, slopes, type of soils, and vegetation. Anthropogenic activities such as deforestation, expansion of agricultural land, urbanization, and pollution may affect the groundwater recharge rate and quality. These, in turn, affect base flow to surface water. According to Price (2011), factors that increase recharge to the aquifer are instrumental to base flow while factors that increase evapotranspiration result in a decrease in base flow. Taye et al. (2018) investigated the impact of climate change on water resources in the Awash River basin and have reported hydro-climatological variability and increased water deficiency in all seasons under the projected climate. Urbanization in the Upper Awash River Basin is taking place at an exponentially high rate due to

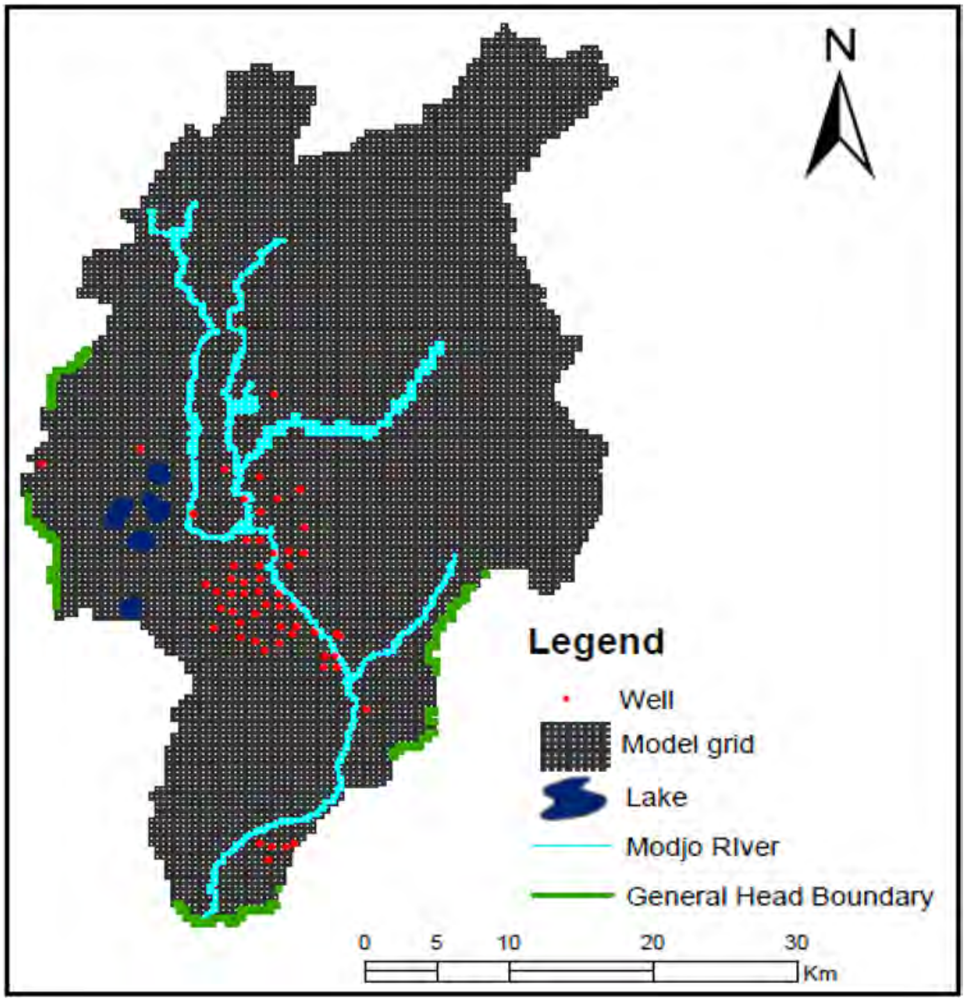

Fig. 5 Location of boundary condition, Lakes and Rivers in the steady-state pumping model

its proximity to the capital city of Addis Ababa. In addition to hydro-climatological variability, the urbanization taking place in the highland area would have an impact on groundwater recharge. Therefore, in this scenario, the current recharge rate is reduced by 25% to examine the aquifer's response.

Results and discussion

Water balance

Table 1 shows the annual water balance of the Modjo River catchment. Annual evapotranspiration in the Modjo River catchment ranges between 412 and 595 mm with a mean of 490.51 mm. It accounts for 57% of annual rainfall in the Modjo River catchment. The surface runoff ranges from 40 to 322 mm (mean and standard deviation is 172 and 68 mm, respectively). It accounts for 20% of the annual rainfall. The result of the water balance shows that a high amount of water is lost, from a groundwater recharge perspective, through evapotranspiration and surface runoff, which accounts for about 77% of the total rainfall.

Groundwater recharge

The groundwater recharge in the Modjo River catchment is shown in Fig. 9. The annual recharge to the aquifer ranges between 57 and 347 mm with a 197 mm mean value (23% of the annual precipitation). It is observed that annually 197 mm of the total precipitation recharges the aquifer while the remaining portion of the annual rainfall is lost as surface runoff and evapotranspiration from the catchment (Table 1). High groundwater recharge occurs primarily during the summer periods (which are the main rainy seasons in the study area), while low recharge rates occur during the winter.

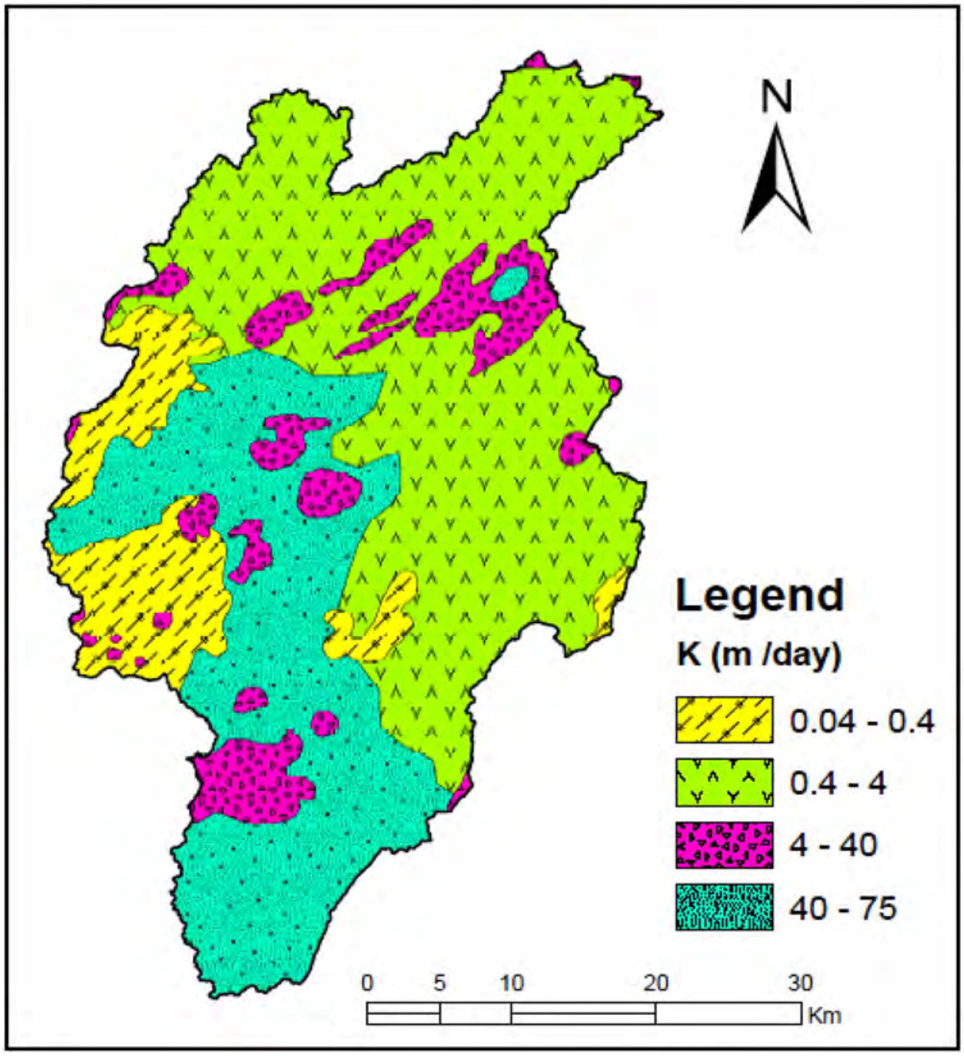

Fig. 6 Hydraulic conductivity map of the study area

Ground recharges are observed to be variable over space. The northern, northeastern, and southeastern around Chefe Donsa and Modjo typically have high annual groundwater recharge which ranges between 250 and 347 mm. These areas have coarse sediments, deeply weathered, and fractured volcanic units (WWDSE 2008). On the contrary, the Western parts of the basin around Dertu Liben town of the catchment have fewer amounts of recharge ranges between 56 and 153 m. Moderate groundwater recharge ranges between 153 and 250 mm in the middle, eastern, northwestern, and southern parts (around Ejere and Bishoftu areas).

It is observed that groundwater recharge is low in urban areas (Bishoftu and Modjo) as a result of increasing the impervious areas and alteration of soil hydro-properties by urban expansion. Hence, urbanization in the catchment will result in reductions of recharge in the future.

MODFLOW result

Calibration

The model was calibrated to match the calculated hydraulic head to the hydraulic head observed. Figure 10 shows a scatter plot of observed and simulated groundwater levels in the Modjo River catchment. The correlation coefficient found to be 0.99, showing a good fit between calculated groundwater heads and observed groundwater levels.

Groundwater budget

The groundwater budget was used to assess the inflow and outflow of the aquifer in the study area. The inflow to the aquifer originates from three directions: (1) direct recharge

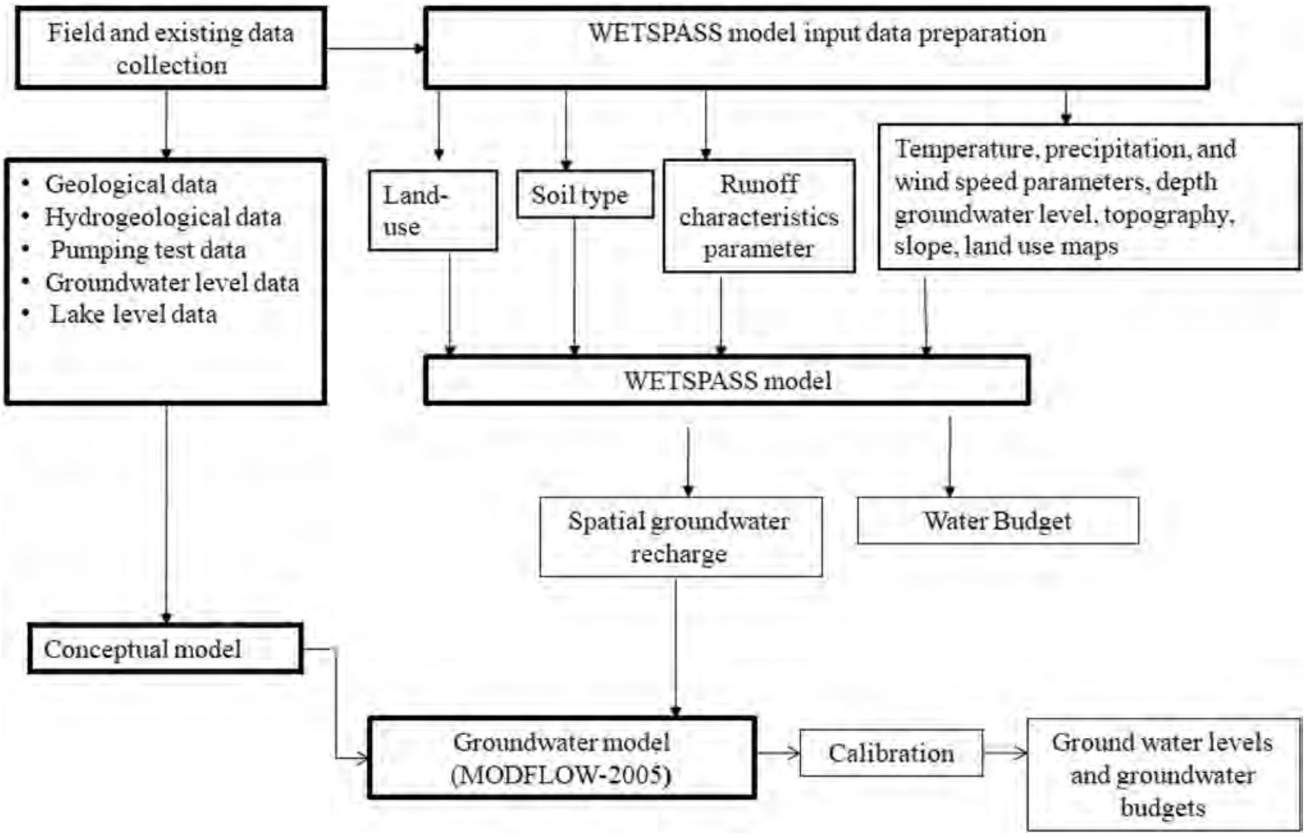

Fig. 7 Research methodology followed to estimate groundwater recharge and data used to investigate the aquifer response to increased groundwater pumping and reduced recharge in the Modjo River catchment

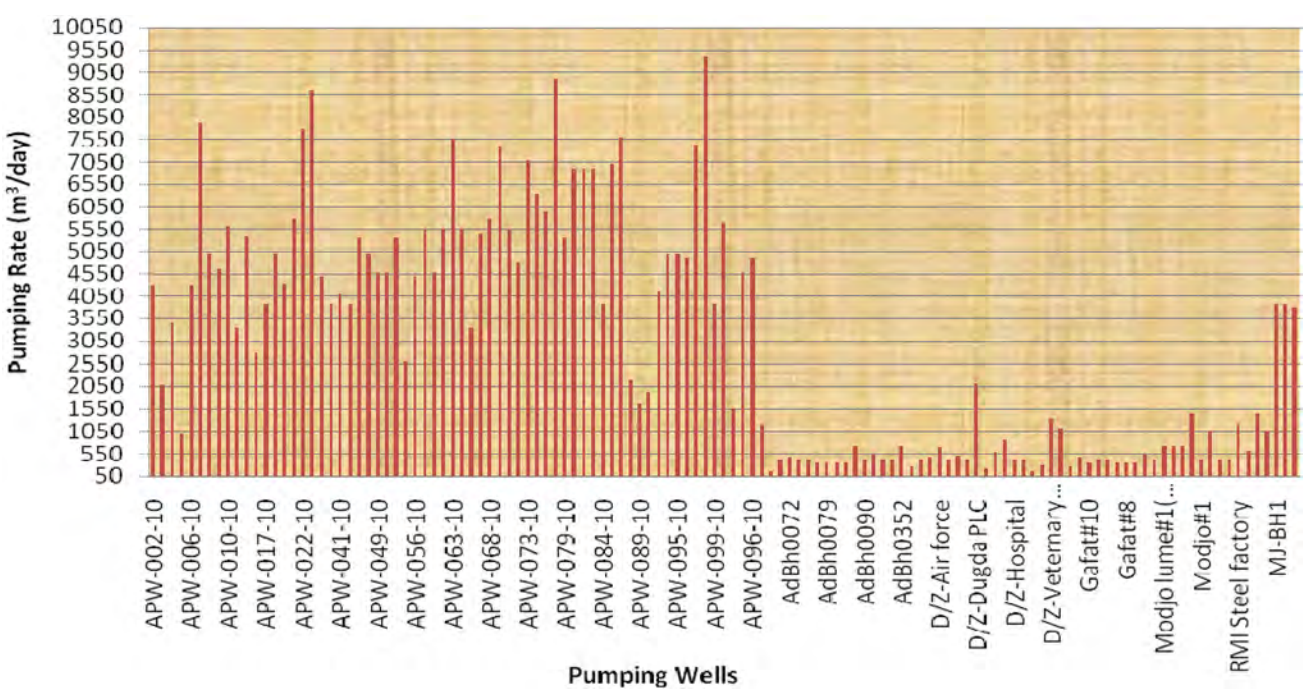

Fig. 8 Pumping rate in the Modjo River catchment (WWDSE 2008)

Table 1 Annual water balance of Modjo river catchment (mm)

Parameters	Minimum	Maximum	Mean	Std.dev
Rainfall	743	1004	862	45
Evapotranspiration	412	595	490	34
Surface runoff	40	322	172	68
Recharge	56	347	197	47

Recharge = rainfall − et − surface runoff

from precipitation and infiltration through the vadose zone, (2) indirect recharge from the river and crater lakes, and, (3) lateral subsurface inflows (Table 2). The aquifer recharge from rainfall and crater lakes account for 46% and 51% of the total water inflow, respectively. The river leakage and subsurface lateral inflow from the high land area accounts for 0.8% and 1.4% of the total inflow, respectively.

The outflow from the aquifer occurs through pumping wells, discharge to surface water, and subsurface lateral outflow to downstream. The groundwater discharge to crater lakes accounts for 48% of the total aquifer outflow (Table 2). The total groundwater pumping from the aquifer and subsurface outflow to downstream area accounts for 20% and 21% of the total outflow from the aquifer, respectively. The base flow accounts for 11% of the total outflow from the aquifer. Modjo River originates from the northern highlands area and flows towards the south (rift floor). The rivers gain as well as lose water along its flow path. Ayenew and Tilahun, (2008) investigated lake–groundwater interactions in central Ethiopia and have suggested that groundwater feeds the rivers in the highland area whereas lakes and rivers recharge aquifer on the rift floor.

Interaction between groundwater and crater lakes is significant. The flux between lakes and aquifers depends on the levels of groundwater and crater lakes. The inflow from crater lakes to the aquifer varies with the seasons due to the fluctuation of crater lakes. Crater lakes recharge aquifers during rainy seasons, while groundwater flows into lakes during dry seasons (WWDSE 2008).

Groundwater flow system

Modeling groundwater flow systems offer useful spatial knowledge for groundwater resource management. Figure 11 shows the simulated groundwater level. The shallow water levels in the high lands area coincide with poor permeability at shallow depth, while the deeper water levels coincide with permeable lacustrine and fractured volcanic aquifer in the flat plains of the study area. The flow of groundwater is from the highland towards the rift floor, so follows also the direction of the Modjo River flow. In this study area, the topography controls the general direction of the groundwater flow system.

Results about scenario building

In the following paragraphs, the results of the two modeled scenarios are presented. These results are also be considered in terms of the effects on groundwater quality.

Scenarios 1: increase in groundwater pumping

Groundwater is important for the environment and it maintains river discharge and lake level in the study area. However, the increase in groundwater pumping alters the direction of groundwater flow, decreases base flow to Crater Lakes and Modjo River, and affects groundwater quality. In this study, the current groundwater pumping rates were increased by 20%, 40%, and 50%, and the corresponding change in the water budget and groundwater level were assessed. Table 3 shows changes in base flow, changes in the subsurface outflow from the catchment, and the average change in groundwater heads to increased groundwater pumping from the aquifer. Increasing the existing pumping from the aquifer by 20% resulted in a corresponding reduction of 11% in base flow, a 2% reduction in the subsurface outflow from the catchment. There is a small shift in groundwater level in the well, and it is less decreasing (0.2 m) in wells around crater lakes and near the river. The maximum drop of the groundwater level is 21 m and the average drop is 3 m. Increase the existing pumping from the aquifer by 40% results in a decrease in 22% of the total surface water contribution, a decrease of the subsurface downstream flow by 5%. A decline of groundwater level ranges between 1 m (in the wells near lakes and river) and 24 m (in the wells far from surface water bodies). The average drop in groundwater levels is 5 m. Increase existing aquifer pumping by 50% results in a 53,359 m^3/day decrease in base flow, which is around 27% of the base flow of the calibrated steady-state model. The groundwater level is declined by 6 m (average) and 2 m around the vicinity of the lake. The groundwater level was 27 m and was found at wells far from the crate lakes and river.

Increased groundwater pumping resulted in decreased groundwater levels and increased inflows from surface water to the aquifer. Declines in groundwater levels at wells far from the Modjo crater lakes and Modjo River is significant. The declines in groundwater levels at the wells near Modjo crater lakes and the Modjo River are, however, insignificant. Intensive groundwater pumping from the aquifer to

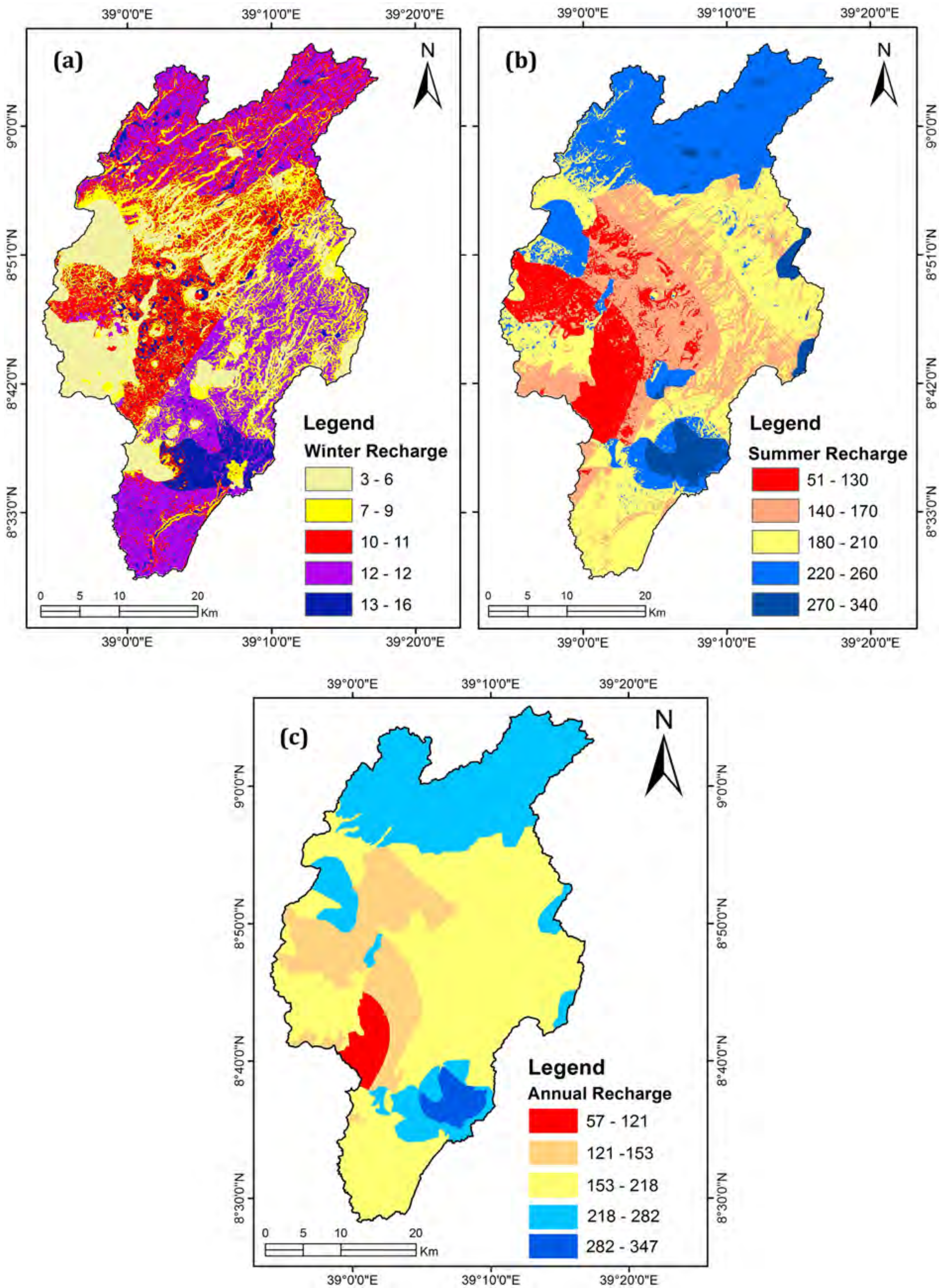

Fig. 9 Groundwater recharge map of Modjo River catchment: winter in mm/month (**a**), summer in mm/month (**b**), and annual recharge in mm/year (**c**)

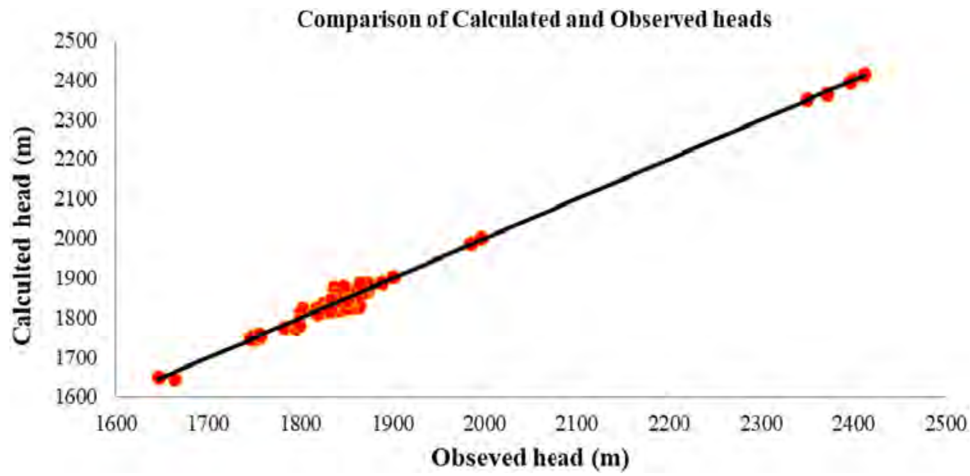

Fig. 10 Comparison between observed and model calculated groundwater levels

meet demand is expected to bring polluted water from the Modjo River into the aquifers and affect the groundwater system in the future. This will cause contamination of the aquifer and have a significant impact on the groundwater-dependent ecosystem. This will also increase the costs of groundwater treatment in the future. The optimization of groundwater pumping rates in the study area is, therefore, crucial to reduce the effect of groundwater pumping on the Modjo River and Crater Lakes.

Scenarios 2: reduce in groundwater recharge

The aquifer's response to reduced recharge was investigated by keeping current pumping rates constant. The scenario of a 25% reduction in recharge indicates that the overall water level drops by 14 m. Also, a reduction in groundwater recharge resulted in a decrease of 4% and 13% in groundwater outflow and base flow, respectively, compared to the steady-state water budget model. The groundwater level, base flow, and subsurface outflow from the aquifer are observed to be affected by a change in the recharge rate.

Table 2 Groundwater budget under the steady-state model

Inflow component	m^3/day	Percentage (%)
Subsurface boundary inflow	26,220	1.4
Recharge	860,595	46
Constant head in (lake inflow)	950,254	51
River leakage	15,344	0.8
Sum	1,852,414	
Outflow component		
Outflow to the downstream area	387,628	21
Abstraction	374,093	20
Discharge to river	197,392	11
Discharge to lakes	892,789	48
Sum	1,851,901	
In–out	513	
Discrepancy (%)	0.030	

Conclusions

Understanding spatial–temporal variation in groundwater and surface water interactions is important to reduce the impact of groundwater pumping on surface water and ecosystems in the study area. Increases in groundwater depletion affect both the groundwater flow mechanism and the base flow to surface water.

Simulations under varying groundwater pumping rates indicate that the increase in pumping greatly affects the groundwater flow process and alters hydrological fluxes in the Modjo River catchment. In addition, increasing groundwater pumping would also adversely impact groundwater-dependent ecosystems. Declines in groundwater levels will deteriorate the quality of groundwater and are likely to raise treatment costs in the future. In conclusion, intensive groundwater pumping is expected to reduce the level of the Bishoftu Crater Lakes, the Modjo River discharge, and disrupt the hydrological system in the study area. Therefore, potential risks need to be thoroughly investigated when a new groundwater well for water supply is located in the future. The steady-state model was used in this analysis because of data scarcity. A transient-state model is recommended to better simulate spatial–temporal variation in groundwater and surface interactions in the study area. Furthermore, an analysis of groundwater levels and storage variability under the transient-state model would provide valuable information for managing groundwater resources.

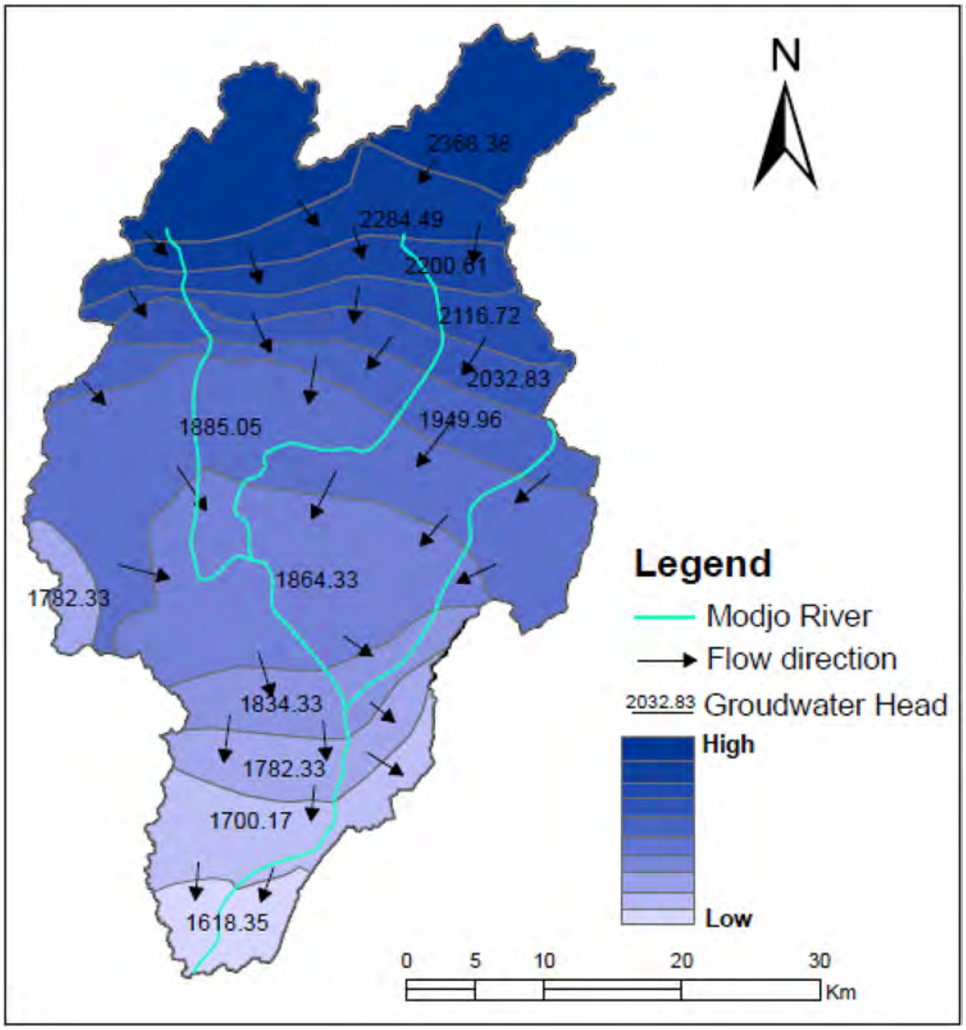

Fig. 11 Groundwater head distribution for the steady-state pumping model

Table 3 Change in base flow in %, change in subsurface outflow in%, and the average change of ground head in m to increased pumping rate

Increase in groundwater withdrawal from the calibrated steady-state value (%)	Change in base flow (%)	Change in the subsurface outflow from GHB (%)	The average change of groundwater head (m)
20	−11	−2	−3
40	−22	−5	−5
50	−27	−6	−6

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