



Numerical groundwater flow modeling of the Kombolcha catchment northern Ethiopia

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Abstract

Intensive groundwater extraction is a changing groundwater system. It is also the main challenge for future groundwater availability. In this study, numerical groundwater flow model was developed in Kombolcha catchment, Ethiopia by using MODFLOW-OWHM. To address this concern, the conceptual model was built by analyzing the hydrogeological data. The groundwater model was calibrated under the steady-state condition to produce the best match between the simulated and observed hydraulic head. The simulated outflow of the MODFLOW model was 358,221.09 m³/day which is nearly equal to 358,221.08 m³/day of groundwater inflow with a difference 0.01 m³/day and zero discrepancies. The subsurface inflow covers the most percentage (76%) in the budget and surface outflow contributes about 66% of the total groundwater outflow. The model result shows that the Kombolcha aquifer system is highly sensitive to change of hydraulic conductivity. Prediction of this aquifer behavior for increasing well withdrawal and decreasing recharge scenarios has been carried out. The effect of increasing withdrawal by 25, 50 and 100% results in a decline of groundwater level by 6.77, 12.15 and 24.37 m, respectively, whereas the effect of decreasing groundwater recharge by the same percentage of withdrawal results in a decline of groundwater level by 4.27, 6.34 and 11.25 m, respectively. This model can be as a tool to understand the aquifer system and sustainable utilization of groundwater resources.

Keywords Conceptual model · Numerical model · MODFLOW-OWHM · Steady-state condition

Introduction

Groundwater is the most valuable natural resource which supports human health, economic development and ecological diversity. It is an important natural resource widely used for meeting domestic, industrial and agricultural requirements (Nigussie and Sebhat 2016). In recent years, population, industries and agriculture activities are increasing very rapidly; thus, utilization of groundwater resources is increasing over the world (Crowe et al. 2004). In Ethiopia including Kombolcha, groundwater is intensively extracting without a detail investigation of the groundwater system.

However, the real-world groundwater system is complex; thus, it is difficult to understand the groundwater system

(Marnani et al. 2010). Conceptual model development is powerful to simplify the complex groundwater system. A reliable and representative conceptual model is vital for a numerical groundwater flow model which reduces error (Anderson et al. 2015; Mengistu et al. 2019). The numerical model used to understand groundwater system change and flow direction (Zhou and Li 2011). It used to evaluate recharge, discharge and aquifer storage. The model is helpful to analyze the response of the groundwater system and to predict future conditions. Most studies i.e., Koohestani et al. (2013), Edet et al. (2014), Satapona et al. (2018), Igboekwe et al. (2008), Sathish and Elango (2015) and Gao (2011) investigate groundwater resource using numerical groundwater flow model. Numerical models solve groundwater flow problems using a computer program called MODFLOW (Malekzadeh et al. 2019 and Post et al. 2019).

MODFLOW is a computer program that numerically solves the groundwater problems for porous media by using a Finite Difference Method (FDM) (Harbaugh and McDonald 1984). Oljira (2006) confirms that FDM is a superior method that designing and understanding is easier and has

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less mathematical complexity. According to Kumar et al. (2018), FDM provides good MODFLOW efficiency. In this study, FDM of MODFLOW was used to develop a numerical groundwater flow model under steady-state conditions. The study also gives an insight into the response of the aquifer, under different scenarios decreasing recharge and increasing withdrawal.

Study area description

Kombolcha catchment is set in the Borkena sub-basin of the Awash River basin. It is located at the border of the Awash River basin. The total area of the catchment is 68 km², that bounded between geographic coordinates of 10° 55'4" to 11° 9'18" E latitudes and 39° 41'5" to 39° 46'22" N longitudes. The location of the study area is shown in Fig. 1. Kombolcha catchment is located in the

semi-arid area. The mean monthly precipitation is between 92 mm to 290 mm and the mean monthly potential evapotranspiration ranges from 91 mm to 109.4 mm from 1980 through 2018.

Hydrogeology and geology setting

Hydrogeology

As hydrogeology of the study area studied by ADSWE (2016), it is formed from alluvial units consisting of clay, silt, sand and gravel. It is found by underlain and bound by the volcanic rocks. It is strongly influenced by fractures and faults trending from north and west to south direction. The thickness of the aquifer varies from 100 m at the south and 250 m in the west and north part of the study area.

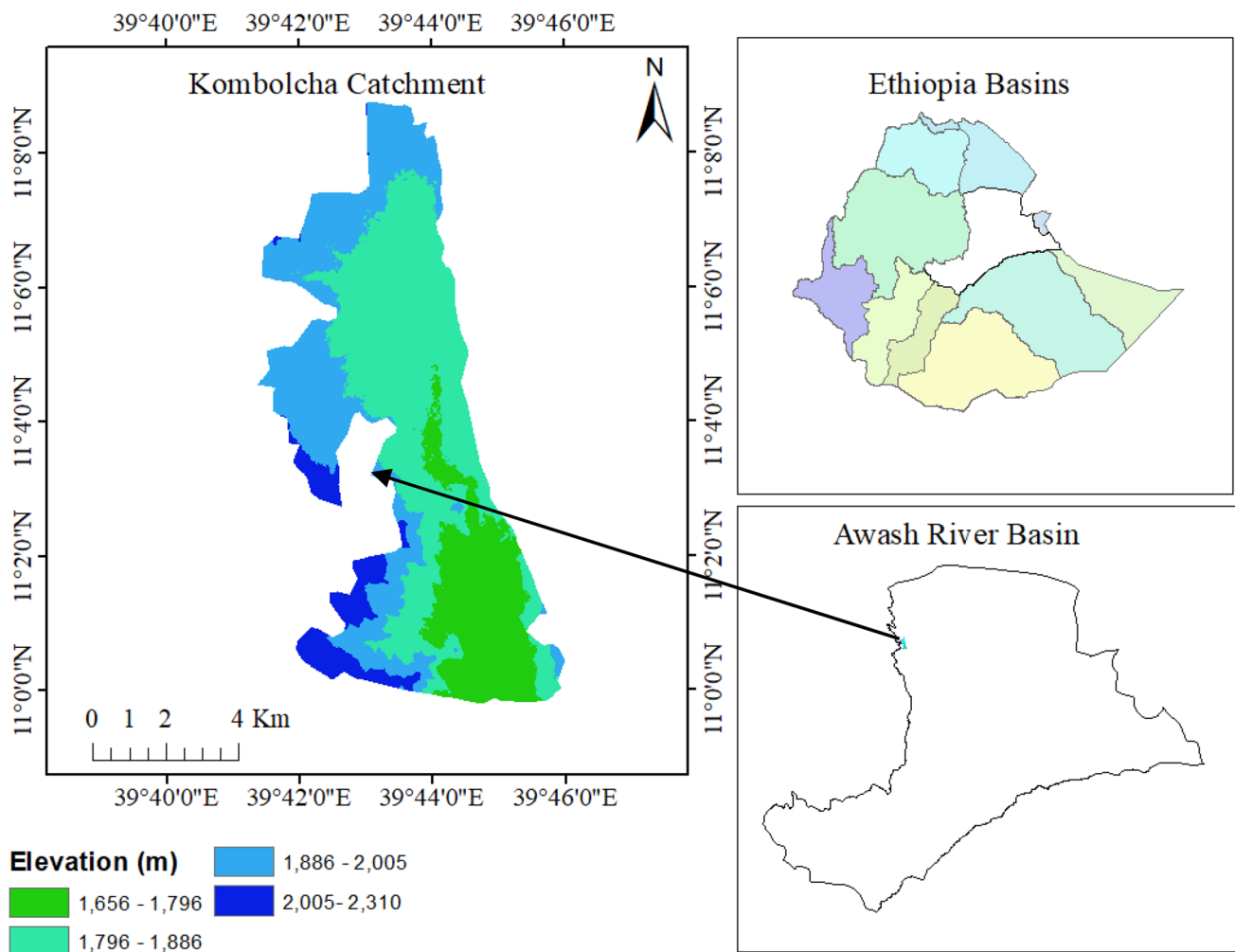


Fig. 1 Study area description map

Geology

The geological formation of Kombolcha catchment and its surroundings is categorized in Miocene-Pleistocene (tectonic events) volcanic successions which are intersected by normal faults and fractures. The study area is a part of the Main Ethiopian Rift valley, and the geological setup arises from the evolution and development history of the Ethiopian Plateau and Rift system (ADSWE 2016).

The geological map shows in Fig. 2 indicate that the study area and its surroundings are characterized by Alaji rhyolite, Termaber basalts, Aiba basalts, alluvial deposit, Albuko rhyolite, Mable rhyolite and Granite intrusion geological formations.

Method and data collection

Methods

In this study, the numerical groundwater flow model was developed with the application of the finite difference MODFLOW computer program. Secondary and primary data were used to develop a groundwater flow model. All the collected

data were carefully set into Microsoft Excel, ARC GIS, etc. and exported into different formats for better representation in the model. The general overview of the methods used in this study is shown in Fig. 3.

Data collection

Numerous data with different types were collected, homogenized and integrated from different resources. The Kombolcha catchment was delineated using the shuttle Radar Terrain Mapping (STRM) digital elevation model (DEM) with 30 m resolution from the US Geological Survey (USGS). Soil, LULC, geological and hydrogeological maps were obtained from the Ministry of Water Resource and Irrigation Energy (MWRIE) and Food Association and Organization (FAO). Thirty boreholes data were collected from Amhara Design Supervision Work and Enterprise (ADSWE), Kombolcha Water Supply Project Office (KWSPO) and Kombolcha industry park (KIP).

Numerous data with different types were collected, homogenized and integrated from different resources.

Conceptual model development

Hydrostratigraphic unit

The hydrostratigraphy unit was defined according to the aquifer thickness. Using data from the selected well boreholes in Kombolcha, one-layer hydrostratigraphy unit is considered as present throughout the study area. It is an unconfined aquifer. The hydrostratigraphy unit of Kombolcha catchment is characterized by fractures and faults which is bounded and underlaid by volcanic formation as shown in Fig. 4.

Boundary conditions

Groundwater flow modeling in the aquifer system is governed boundary conditions of the aquifer system. In this study, boundary conditions of the aquifer system were defined using ADSWE (2016) identification. Thus, the eastern side of the study area is bounded by mountains (Rhyolite types of volcanic rock), with very low porosity. Water takes a long time to reach in the system; thus, this side is treated as a no-flow boundary. The rest part of the study area except faulted and fractured zone parts also considered as a no-flow boundary as shown in Fig. 5b.

The northern side of Kombolcha catchment coincides with Tita, Azwa Gedel and Amora Gedel mountain ranges. The mountains are characterized by volcanic rock, and it is affected by faults and fractures. ADSWE (2016) confirms that the faults and fractures act as conduits for subsurface

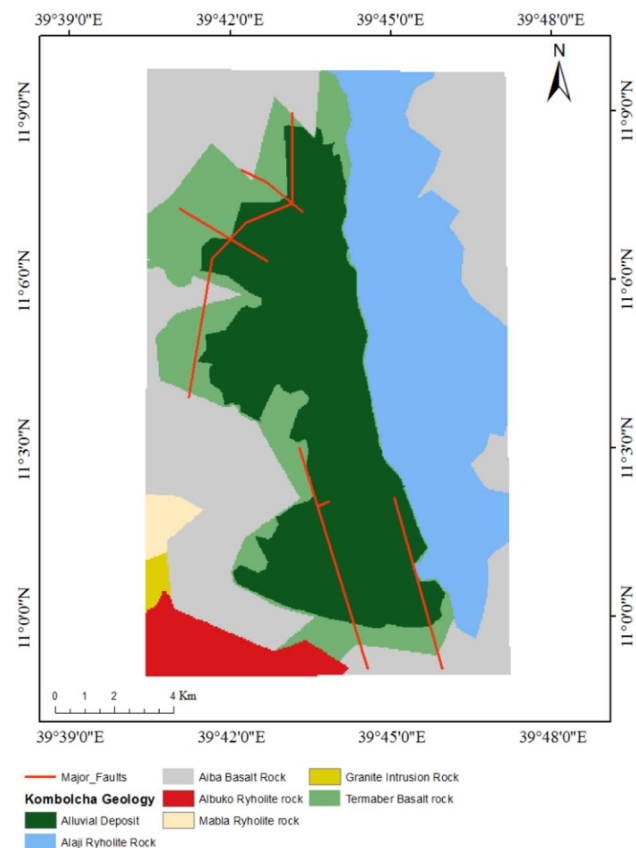


Fig. 2 Geological and hydrogeological map of Kombolcha catchment

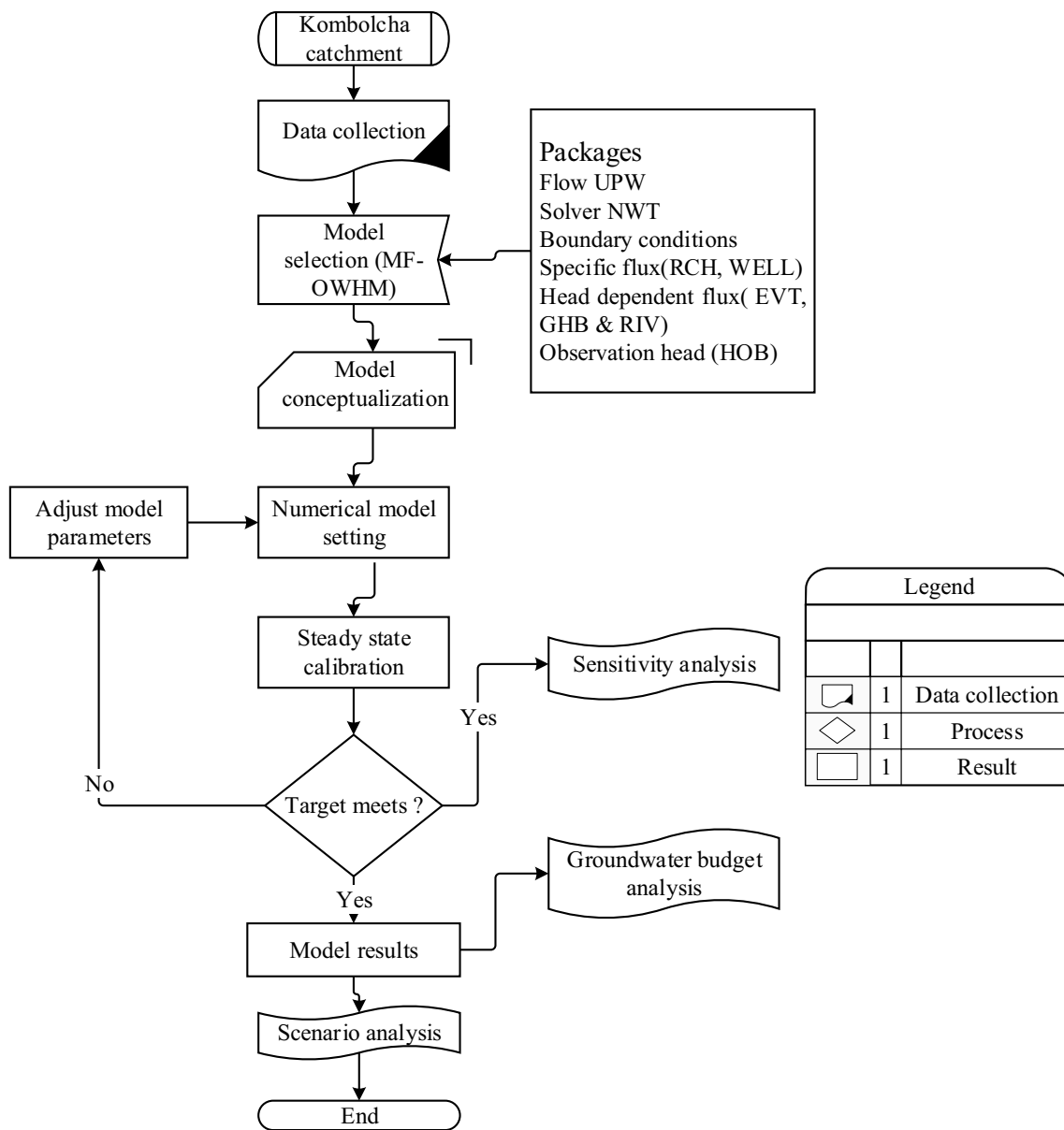


Fig. 3 General flowchart for methods applied and the process followed during the study

inflow to the groundwater system. This part is represented by a head-dependent boundary. The rest part of the study area (west, west-south, south, southeast) is a mountainous area that is also influenced by faults and fractures. Thus, the zonal head-dependent boundary also considered to those parts (Fig. 5b).

The recharge zones for the study area (Fig. 5a) were obtained from Amhara design and supervision work enterprise (ADSWE) and inputted as a recharge (RCH) package in MODFLOW. According to (ADSWE 2016) report recharge zone, one and two have to exist in this area with the same value of 900 mm/year. The highest recharge receiving zone area with large faults and fracture area is zone three.

It is located western part of the study area which is mostly covered by open grass with a little forest. The recharge value is about 3711 mm/year. Recharge zone four also found the western part that covered by sparse forest with a recharge value of 973 mm/year. The fifth zone receives higher recharge next to recharge zone three is located westeastern part. It is a highly fractured area covered by a sparse forest. The recharge value in this area is to be about 1953 mm/year. The rest recharge zone obtained from (ADSWE 2016) is zone six which is located in the southern part of the study area left side of broken a river outlet. Its geology is volcanic rock basalt covered by annual cropland. The annual groundwater recharge was measured in mm/year, and that is correct

Fig. 4 Schematic drawing of Kombolcha catchment conceptual modeling

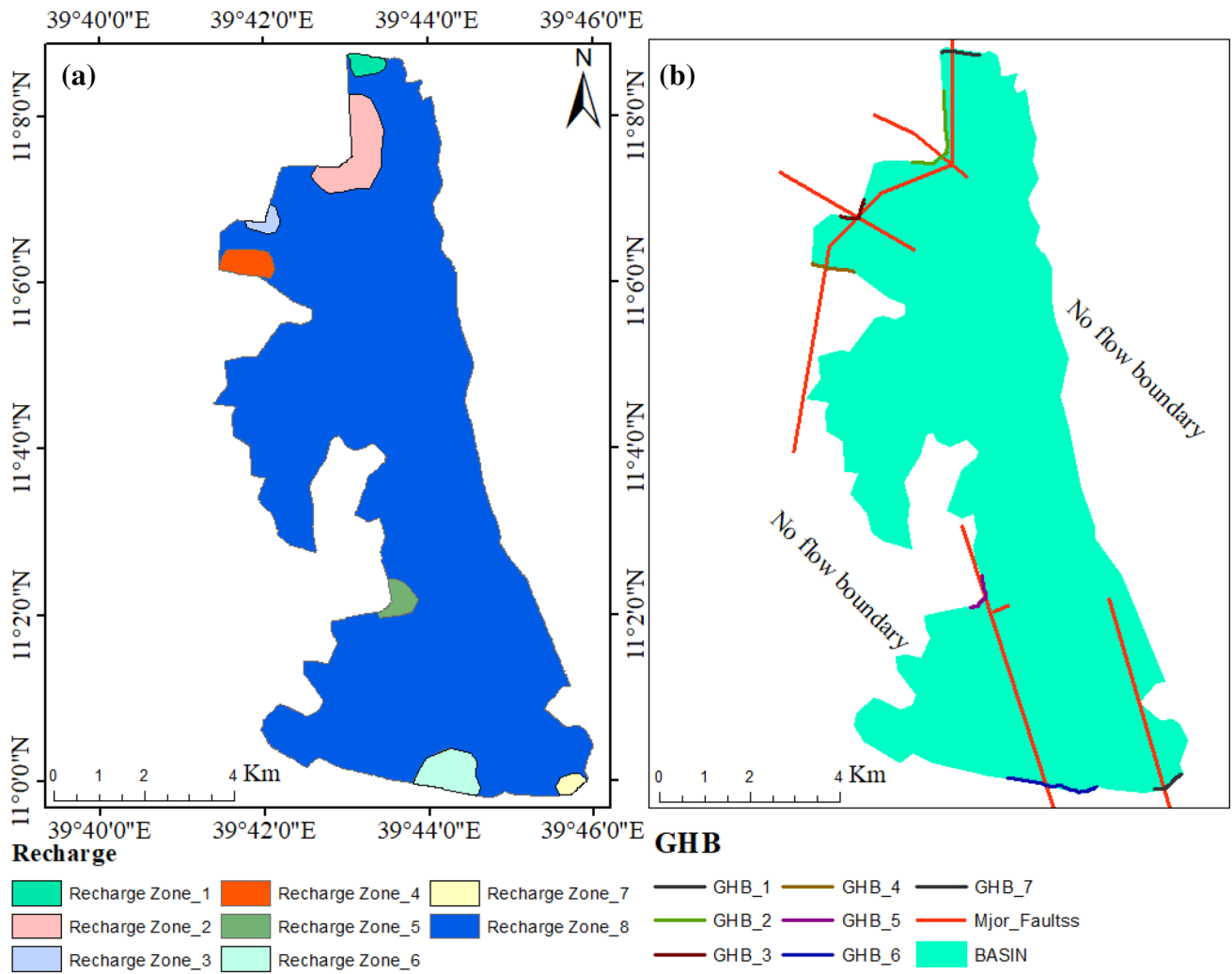
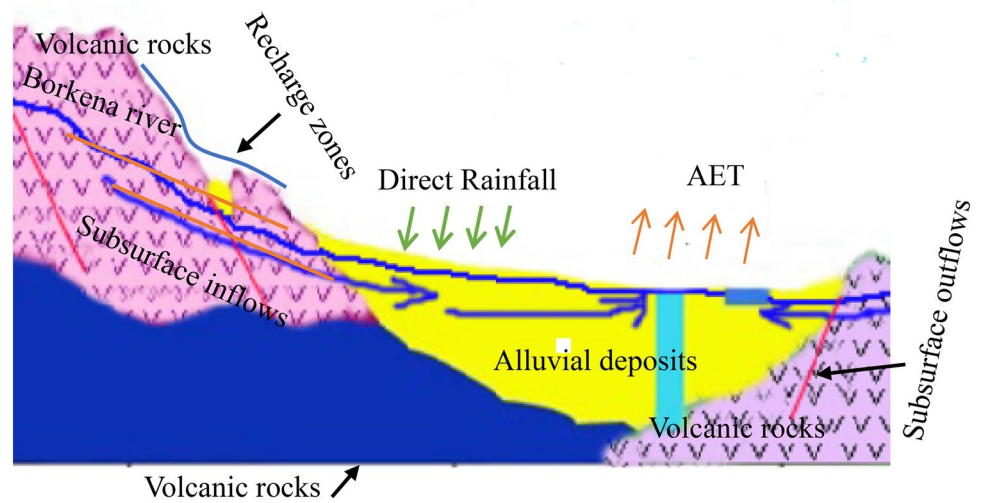


Fig. 5 Spatial distribution of the study area **a** Recharge zones and **b** General head boundary (GHBs)

expression. The zone that is expected to receive the lowest recharge due to urbanization effect is zone seven which covers most of the total study area (about 95%). The source of water for this zone is direct rainfall. It is covered by different LULC characteristics, where settlement is found. The value of recharge obtained from water balance estimation is to be 147.65 mm/year which is 12.94% of total rainfall.

Hydraulic conductivity

Hydraulic conductivity of the study area was interpolated using kriging techniques obtained from thirty well completion reports (Table 1). The result shows that aquifer hydraulic conductivity ranges from 0.62 to 7.52 m/day. Higher hydraulic conductivity was found in the northern part of the study area, which is about 7.52 m/day, and it declines toward a south direction.

Groundwater inflow and outflow sources

The sources of groundwater inflow to the Kombolcha aquifer system include from direct rainfall, recharge from mountains, subsurface inflow (zonal through faults and fractures) and seepage from Borkena river. The sources of groundwater outflow are through well withdrawal (Table 1) for different purposes like human consumption, industry, and irrigation, subsurface outflow, as seepage losses from aquifer system to Borkena river and evapotranspiration. The daily average values are assigned to the model using Well, recharge, General Head Boundary, River and Evapotranspiration packages.

2-D groundwater flow numerical model development

Governing equations

Two-dimensional steady-state groundwater flow can be mathematically represented given Eq. (1) which based on, Darcy's law and the principle of conservation of mass (Anderson et al. 2015).

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) - W = 0 \quad (1)$$

where K_x and K_y are the values of hydraulic conductivity along x and y coordinate, h is the hydraulic head, W is a volumetric flux per unit volume and represents sources or sinks or both of water such as well discharge, recharge and water removal from the aquifer by drain per day.

Groundwater model selection

MODFLOW in Model muse graphical user interface is a well-documented computer program and can be implemented easily. The model is easy to understand (freely available on internet address) (Kumar 2019). It can simulate groundwater flow with fast, good convergency and accurate solutions (Yang et al. 2011). MODFLOW simple to learned and modified to represent more complex features of the flow system (Nyende et al. 2013; Fouad and Hussein 2018). The model can be readily incorporated into future studies for optimal groundwater management (Xu et al. 2011). It is modifiable from time to time when timely and sufficient data are available. MF-OWHM (One Water Hydrologic Flow Model) is the complete modified version.

MF-OWHM is a MODFLOW based integrated hydrologic model that simulates, analysis and manages groundwater occurrence and movement (Harbaugh and McDonald 1984). It provides more options for hydraulic properties and evaporation than other MODFLOW versions. MF-OWHM is a model code that includes new features like, Surface Water Routing Process (SWR), Riparian-Evapotranspiration (RIP-ET) and other flow packages. It is compatible with a solver (UPW & NWT) and it is felexible to simulate head-dependent fluxes (subsurface inflow and outflow) than other models. MF-OWHM suitable for a small catchment with flat topography (Harbaugh and McDonald 1984).

Model discretization

The range of Kombolcha catchment in west–east and north–south is 5.5 km and 11 km, respectively, with a modeled catchment area of 68 km². In this study, the model domain was discretized using a block centered approach in which the head is calculated at the center of the nodes. The model domain discretized into 71 columns and 171 rows using a uniform grid spacing of 100 by 100 m. Nodes that falls within the modeled area is called active nodes and nodes that fall outside the modeled area called inactive nodes. The active cells of the study area were 12,141. Nodes outside of the domain called inactive cells and assigned by 0. Inactive cells could not apply for groundwater flow modeling.

Top and bottom layer

The node values of groundwater-surface elevation were extracted from DEM with 30 by 30 m resolution then it considered as the model top in MODFLOW. According to the (ADSWE 2016) report, the thickness of the Kombolcha aquifer system reaches up to a maximum value of 250 m. Bottom layer elevation of this study area was fixed

Table 1 Groundwater well withdrawal locations, rates and hydraulic conductivity values (ADSWE 2016)

No.	Well ID	Location			Withdrawal (m ³ /day)	Hydraulic conductivity (m/day)
		X	Y	Elevation (m)		
1	BH-1	579,647	1,226,175	1836	288.00	0.8
2	BH-4	579,345	1,226,470	1836	720.00	2.9
3	BH-5	578,542	1,226,092	1840	590.40	3.1
4	BH-6	578,233	1,226,301	1844	1440.00	3.0
5	BH-7	579,513	1,225,734	1833	1584.00	7.6
6	AWWCE	578,936	1,225,892	1851	864.00	2.7
7	Tex-2	578,679	1,225,237	1843	135.36	1.2
8	Tex-3	578,655	1,224,977	1847	288.00	2.0
9	Tex-5	578,703	1,224,887	1847	288.00	0.9
10	Tex-7	579,053	1,225,221	1832	345.60	3.7
11	Kospi-2	577,613	1,225,879	1875	80.06	0.6
12	Kospi-3	578,959	1,225,361	1840	230.40	2.2
13	IP 1	578,323	1,228,083	1858	851.62	3.7
14	IP 2	577,849	1,227,885	1859	650.30	7.3
15	IP 3	577,833	1,228,381	1860	736.70	7.5
16	KCPW#2	579,067	1,226,406	1831	1440.00	1.6
17	PW1	578,537	1,226,089	1850	411.84	1.7
18	PW2	578,231	1,226,297	1852	411.84	2.6
19	PW3	579,350	1,226,465	1840	414.72	3.9
20	KBH1	579,379	1,226,203	1830	1468.80	5.2
21	KBH2	578,913	1,226,081	1837	864.00	3.1
22	PW3N	579,565	1,226,611	1848	414.72	3.9
23	PW2N	578,528	1,226,346	1850	411.84	2.6
24	PW1N	578,718	1,226,240	1859	411.84	2.0
25	well one	579,376	1,226,205	1835	288.00	3.0
26	well two	578,936	1,226,045	1843	230.40	2.7
27	hot	578,240	1,225,670	1860	208.80	1.5
28	Kmetal	579,428	1,223,639	1820	345.60	1.6
29	Kospi-1	577,636	1,225,730	1874	80.06	1.8
30	MI.50#3	577,915	1,226,833	1856	1152.00	2.0

by subtracting the thickness of aquifer system from model top elevation.

Results and discussions

Model calibration error assessment

Calibration is the process of adjusting model parameters within the expected range until the difference between model-simulated head and the observed head is within selected criteria of performance (Aynalem 2015; Oljira 2006). A trial and error calibration method was used to provide suitable results where the groundwater hydraulic head was obtained from nine observation points and used for calibration.

The steady-state observed and simulated heads were examined for correlation using the scatter plot and

calculating coefficient of correlation (*r*). The scatter plots show that the observation points are randomly distributed and fall in a 45° solid line which represents a good fit between observed and simulated head changes. The correlation coefficient (*r*) was 0.9964 as shown in Fig. 6. A comparison of head data in all observation points indicates a good match between the observed and simulated head values.

The residuals calculated as the difference between observed and simulated heads in all observation indicated in Fig. 7. The residual varies from the lowest −0.08 at BGI4 well point to the highest 2.28 m at KIPO2 well point. The overall residual error was negative which indicates there was an overestimation of the groundwater level by the model.

$$\text{Mean Error (ME)} = \frac{1}{n} \sum_{i=1}^n (hm - hs)_i \tag{2}$$

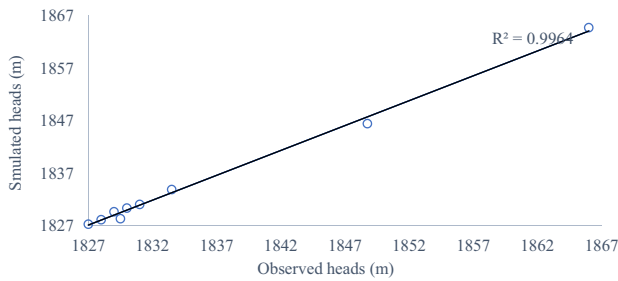


Fig. 6 Scatter plot of head distribution of observed and simulated head in Kombolcha catchment

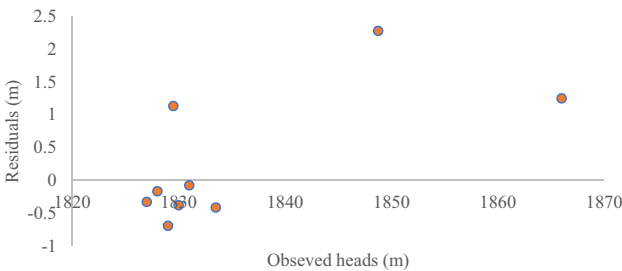


Fig. 7 Residuals vs observed heads of steady-state simulation

$$\text{Mean Absolute Error (MAE)} = \frac{1}{n} \sum_{i=1}^n (hm - hs) \tag{3}$$

$$\text{Root Mean Square Error (RMSE)} = \left[\frac{1}{n} \sum_{i=1}^n (hm - hs)^2 \right]^{1/2} \tag{4}$$

where N is number of points where comparisons are made, hm is the observed hydraulic head at some point i , and hs is the simulated hydraulic head at the same time.

Error is common in the groundwater flow modeling process, basically due to the assumption made and the hydrogeological condition of the aquifer. According to error assessment criteria (Eqs. 2, 3 and 4), the calculated values of ME, MAE and RMSE are 2.59, 6.73 and 8.98, respectively, as shown in Table 2 which was with an acceptable limit of 5% tolerance of Kombolcha aquifer depth (12.5 m). Besides, the calibration satisfied the justification of Anderson and Woessner’s (1992) model error criteria, where the maximum absolute values of model residual (2.28 m) should be less than 10% of total head change (3.9). MAE (0.75) is less than 2% of total head change (0.78) and the ratio of RMSE to the total head difference is 2.56 which is lower

Table 2 Comparison of observed and simulated heads under steady-state condition

Obs_Name	X	Y	Obs head (m)	Simu head (m)	Obs-Simu	/Obs-Simu/	(Obs-Simu) ²
BGL_2	579,473	1,225,113	1829.00	1829.70	− 0.70	0.70	0.48
BGL_3	579,416	1,224,967	1830.00	1830.38	− 0.38	0.38	0.15
BGL_4	579,894	1,224,686	1831.00	1831.08	− 0.08	0.08	0.01
ELFORA	579,541	1,225,432	1828.00	1828.17	− 0.17	0.17	0.03
K_TANN	579,618	1,225,606	1866.00	1864.75	1.25	1.25	1.56
KBH_11	578,379	1,226,203	1848.75	1846.47	2.28	2.28	5.19
KBH_22	578,913	1,226,081	1833.50	1833.92	− 0.42	0.42	0.17
KTW_9	579,143	1,225,434	1829.50	1828.37	1.13	1.13	1.28
W_3	578,987	1,226,326	1827.00	1827.33	− 0.33	0.33	0.11
Sum					2.59	6.73	8.98
				Calculated	ME	MAE	RMSE
				Change head 39	0.29	0.75	1
				Median	− 0.17	0.42	0.17
				STD	1.01	0.70	1.67
				Min	− 0.7	0.08	0.01
				Max	2.28	2.28	5.19

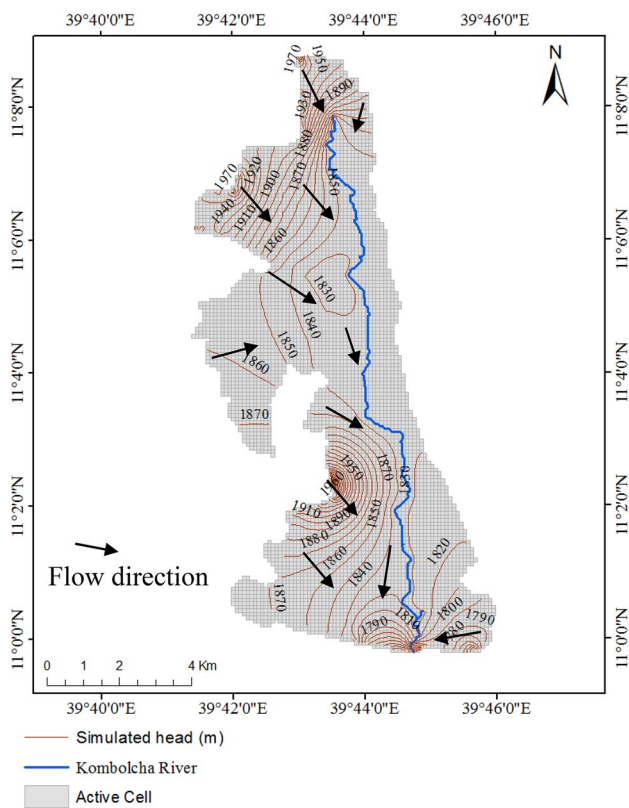


Fig. 8 Simulated head and flow direction

Table 3 Groundwater balance of the entire model domain in m³/day

Flow terms	In (m ³ /day)	Out (m ³ /day)	In–Out
Wells	0.00	17,646.90	– 17,646.90
Recharge	37,287.65	0.00	37,287.65
River Leakage	50,131.57	59,066.06	– 8934.49
Evapotranspiration	0.00	45,664.14	– 45,664.14
Head Dep Bounds	270,801.88	235,843.98	34,957.89
Sum	358,221.09	358,221.08	0.01
Discrepancy (%)	0.00		

than 10% of the total head difference (3.9). These results support the statement of good calibration results of the steady-state model.

Groundwater simulated head and flow direction

The maximum simulated head was observed in the upper part of Kombolcha Industry Park, whereas the lowest simulated head was toward the outlet of the catchment. As shown in Fig. 8, the simulated groundwater head was dropped from north, west, southwest and southeast to the southern direction. The groundwater flows continuously, which indicates that the aquifer system is hydrologically connected.

Water budget of the model domain

Groundwater budget is a process of quantifying the inflow and outflow terms in groundwater modeling. The water balance (Table 3) as per the input parameters shows that a total volume of 358,221.09 m³/day water joins the groundwater system yearly and a volume of 358221.08 m³/day water leaves the groundwater system under steady-state condition. The difference between groundwater inflow and outflow was 0.01 m³/day. The percentage of discrepancy approaches to zero which indicates that the model is running under a perfectly steady-state condition.

According to the model result, head-dependent flux is an important term that contributes 76% of total groundwater inflow. The rest 10% and 14% of groundwater inflows are the contributions of recharge and river leakage, respectively (Fig. 9). The majority of the groundwater (66%) leaves the system through head-dependent flux (subsurface outflow). The groundwater also leaves from the aquifer system through River leakage which accounts for 16% of groundwater outflow. The rest 5% and 13% of groundwater outflows from the system through well withdrawal and evapotranspiration as shown in Fig. 9b.

Any stress to the groundwater system under the future utilization would affect groundwater balance. Groundwater flow direction can be altered due to the intensive exploitation.

Model sensitivity analysis

Sensitivity analysis was carried out to understand how the change in some parameters affects the model outputs. In this study, sensitivity of hydraulic parameters (hydraulic conductivity, recharge and well withdrawal) on groundwater head through a change of Root Mean Square Error (RMSE) was conducted. The calibrated model was tested for increasing and decreasing the three hydraulic parameters values by 25%, 50% and 75% as shown in Table 4 and Fig. 10.

The model is highly sensitive during decrement hydraulic conductivity value by 75% which resulted in a rise of RMSE by 22.87. The model is moderately sensitive during decreasing hydraulic conductivity value by 50% which resulted in an increase of RMSE by 7.77. The decrement hydraulic conductivity values by 25% and increment by 75% show more or less moderately sensitive in which the RMSE raises by 2.93 and 2.94, respectively. For the rest condition, the model is less sensitive.

To observe how the model is sensitive to recharge, the recharge values of the whole area were increasing and decreasing by 25%, 50% and 75%. As shown in Table 4 and Fig. 10, the effect of decreasing recharge value by 75%

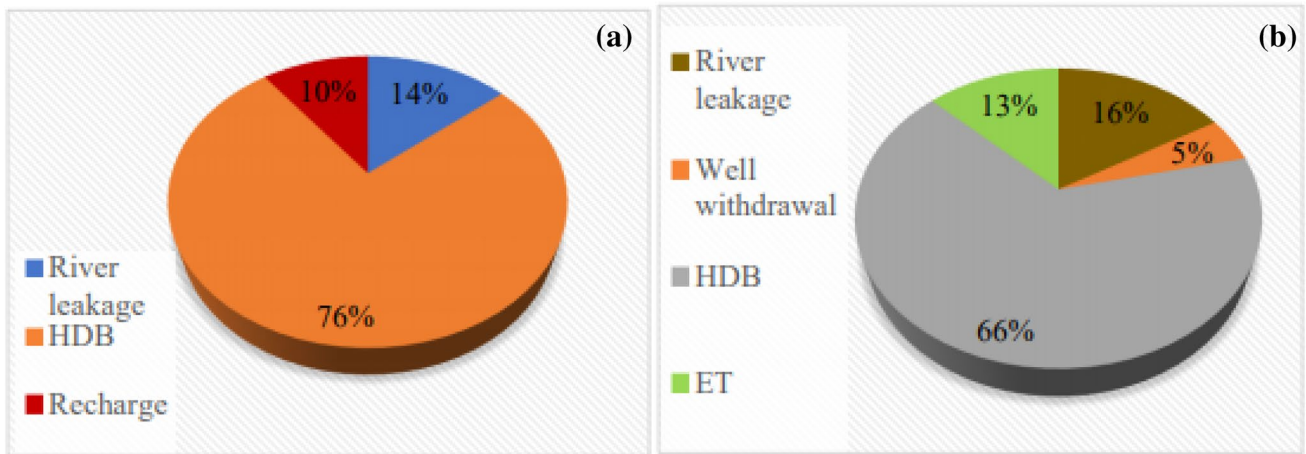


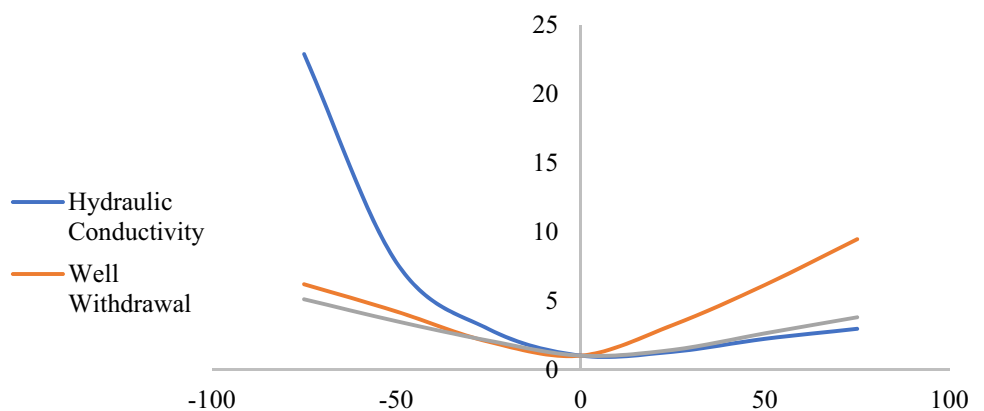
Fig. 9 Schematic description of the water budget of model domain **a** groundwater inflows, **b** groundwater outflows

Table 4 Result of model sensitivity analysis test through a change of RMSE

Change in parameters	RMSE values for the selected parameters		
	Hydraulic conductivity	Recharge	Well withdrawal
-75%	22.87	5.09	6.18
-50%	7.77	3.50	4.21
-25%	2.93	2.09	2.01
0	1.00	1.00	1.00
25%	1.28	1.42	3.22
50%	2.22	2.62	6.13
75%	2.94	3.78	9.45

results in a rising of RMSE by 5.09. Increasing the recharge value by 75% and decreasing by 50% result in a rising an RMSE by 3.78 and 3.5, respectively. However increasing recharge value by 50% and decreasing by 25% shows an increment of RMSE by 2.62 and 2.09, respectively. Increasing the recharge values by 25% result in raising of RMSE

Fig. 10 Sensitivity analysis of hydraulic parameters on head of groundwater through the change of RMSE



up to 1.42 which indicates the model is less sensitive to recharge.

The rest hydraulic parameter used for sensitivity analysis was well withdrawal. RMSE value was increased by 9.45 and 6.13 during incremental of well withdrawal by 75% and 50%, respectively. Whereas decrement of well withdrawal by 75% and 50% results rising of RMSE by 6.18 and 4.21, respectively, in this case, the model was moderately sensitive. For the rest condition, decrement and increment of well withdrawal by 25% result raising of RMSE up to 3.22 and 2.01, respectively, which the model is less sensitive.

Scenario analysis

One of the most useful advantages of developing a model is to predict the future possible change. In this study, two scenarios are investigated where the accuracy result depends on the validity of assumptions.

Effect of increasing groundwater withdrawal

In this study, withdrawal rates were increased by 25, 50 and 100% to study the response of the system. When the well withdrawal increased with 25%, the discharge rate increased by 4411.74 m³/day from the present discharge rate of 17,646.90 m³/day. The result shows the decline of groundwater level up to 6.77 m in the observation well KOIP2 in the upper part of the study area (around the new Kombolcha industry park). Similarly, during well withdrawal increment with 50% and 100% the discharge rate increased by 8823.45 and 17,646.90 m³/day, respectively. Thus, groundwater level decline by a maximum of 12.15 m in well KOIP2 and 24.37 m in well KOIP2 was observed, respectively. Generally, groundwater level fluctuation varies from 0.54 to 24.37 m.

When groundwater withdrawal rates increased stream leakages from the aquifer system and subsurface outflows significantly reduced. The loss of the groundwater through evapotranspiration in the study area also reduced. During withdrawal rate increment by 25, 50 and 100%, river leakage from the Kombolcha aquifer system was reduced by 1.04, 2.18 and 4.46%, respectively. The initial volumetric water river leakage from the Kombolcha aquifer system was 59,066.06 m³/day. Subsurface outflow reduced by 0.06, 0.12 and 0.26% from initial volumetric water values of 235,843.98 m³/day, and the evaporation loss also reduced by 2.72, 4.54 and 6.82%.

Effect of decreasing recharge

Three simulations (decreased by 25, 50 and 100%) were made by changing the recharge in the catchment. In the simulation with 25%, the initial discharging rate (37,287.65 m³/day) was reduced by 9321.91 m³/day and it was observed that groundwater level decline by maximum of 4.27 m in well KOIP2 which is located in the upper part of the study area. During recharge decrement by 50 and 100%, the initial discharging rate also reduced by 18,643.83 and 37,287.65 m³/day, respectively. Well KOIP2 shows 6.34 and 11.25 m decline in groundwater level under 50 and 100% decrement of recharge, respectively. In general, groundwater level fluctuation varies from 0.37 to 11.25 m.

Under 25, 50 and 100% reduction of recharge simulation, river leakage from the Kombolcha aquifer system was reduced by 4.19, 8.05 and 15.55%, respectively. Subsurface outflow was reduced by 0.57, 1.12 and 2.22%, respectively. Groundwater loss through evapotranspiration was also reduced by 2.22, 4.69 and 8.49%, respectively. The simulation of the model indicates that the east part of the study area shows smaller groundwater level fluctuation, whereas the upper part of the study is identified by higher groundwater fluctuation.

Conclusion

In this study, a numerical groundwater flow model was constructed to understand the Kombolcha aquifer system and to investigate the response of the system to future changes in stress. The conceptual model was developed based on the geology and hydrogeology of Kombolcha catchment. Single unconfined unit of alluvial deposit was considered consisting of poorly sorted clay, silt sand and gravel. The water groundwater divide was assumed to coincide with the surface water divide. The thickness of aquifer formation reaches up to 250 m in most parts of the study area.

The groundwater inflow to the Kombolcha aquifer system has occurred from zonal recharge, subsurface inflow and seepage from the Borkena river. Zonal recharge was estimated using the water balance method and obtained from previous work. The estimated value of recharge was 0.4045 mm/day whereas the total obtained recharge to be 25.58 mm/day. Subsurface inflow and seepage from the river were calculated by the MODFLOW model. Groundwater outflow from the study area includes well withdrawal, subsurface outflows, seepage from aquifer system and Evapotranspiration, where each value was calculated by the MODFLOW model.

The study area was discretized with an equal grid spacing of 100 m by 100 m, with 171 rows and 71 columns having 12,141 active cells. General head and no-flow boundaries were used to better representation of boundary conditions. The model was simulated under steady-state condition using MODFLOW-OWHM under model muse graphical user interface utilizing its Upstream Weighting Package (UPW) and Newton Solver (NWT) packages. The simulated inflow of the MODFLOW model was 358,221.09 m³/day which is nearly equal to simulated inflow (358,221.08 m³/day) with a difference 0.01 m³/day and zero discrepancies. The subsurface inflow covers the most percentage (76%) of the groundwater inflow, and surface outflow contributes about 66% of the total groundwater outflow.

The model was calibrated using the head measured in nine wells. It was calibrated using trial and error method in adjusting aquifer parameters until simulated and observed head get in the best match ($r^2 = 0.9964$). The model performance was evaluated using the statistical method: mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) and the values to be 2.59, 6.73 and 8.98, respectively. Sensitivity analysis was done to understand how some parameters affect the model outputs. In this section, hydraulic parameters including hydraulic conductivity, recharge and well withdrawal on groundwater head through the change of RMSE were conducted, where the model is highly sensitive to change RMSE in hydraulic conductivity.

As the model intended to study the future response of the hydrological system, two scenarios (incremental of good withdrawal and decremental of recharge) were used. Scenarios analysis was conducted to evaluate changes that might occur on groundwater head, subsurface outflow, River leakage and evaporation loss.

The well withdrawal rates were increased by 25, 50 and 100% which is equivalent to withdrawing 4411.73, 8823.45 and 17,646.90 m³/day over the whole catchment, respectively. Maximum groundwater level decline 6.77, 12.15 and 24.37 m was observed, respectively. River leakage was reduced by 1.04, 2.18 and 4.46% and subsurface by 0.06, 0.12 and 0.26%, respectively. Evapotranspiration loss also reduced by 2.72, 4.54 and 6.82%, respectively. The second scenario was decreasing the recharge to the aquifer system. The steady-state simulated recharge was decreased by 25, 50 and 100% to examine the response of the system, where the equivalent reduced recharge was 9321.91, 18,643.82 and 37,287.65 m³/day, respectively. The simulation result shows a maximum groundwater level decrement of 4.27, 6.34 and 11.25 m. This scenario simulation resulted in a decrease in river leakage by 4.19, 8.05 and 15.55%, respectively. The simulation also resulted in the decrement of subsurface outflow by 0.57, 1.12 and 2.22% and evapotranspiration by 2.22, 4.69 and 8.49%, respectively.

Data availability Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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