Assessment of Groundwater Recharge Using WetSpass-M and MODFLOW Coupling in Jedeb Watershed, Upper Blue Nile Basin, Ethiopia

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ABSTRACT: Currently, the demand for water is rising, and as a result, the groundwater is declining. Water supplies are not sufficient for agricultural productivity, environmental preservation, or ecosystem services, resulting in an unbalanced water budget in the basin. The goal of this paper is to assess the groundwater recharge in the Jedeb sub-basin using WetSpass-MODFLOW coupling. A spatially distributed water balance model is developed to simulate long-term average recharge depending on land cover, soil texture, topography, and hydro meteorological parameters. The groundwater model is iteratively connected to the recharge model in order to simulate recharge. This means that the depth of the groundwater affects the recharge estimate and vice versa. The average yearly evapotranspiration, surface runoff, and groundwater recharge were determined using WetSpass-M to be 574, 898, and 99 mm, respectively. Groundwater recharge accounted for 6.3% of precipitation, while actual evapotranspiration and surface runoff accounted for 36.4% and 57% of precipitation, respectively. In such seasonal variations, the groundwater level in the Jedeb Sub-basin was studied under various stress conditions (dry season, wet season, and annually). The groundwater level distribution varied from 2,052.3 to 3,063.06 m in the summer stress period (recharge). While in the winter stress period (recharge), the groundwater level varied from 2,051.41 to 3,061.92 m, and the groundwater level due to the annual stress period (recharge) varied from 2,053.76 to 3,064.5 m. With a correlation coefficient of .89, which is an acceptable fit between the simulated and observed heads in steady state for all stress periods (summer, winter, and annual recharge). The contribution of this study could be used as baseline information for regional water resource experts, policymakers, and researchers for further investigation.

KEYWORDS: Groundwater recharge, Jedeb watershed, MODFLOW, WetSpass-M model

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Introduction

Groundwater, the greatest freshwater resource in the world, is crucial for irrigation, meeting rising residential water demands, and weathering droughts, which appear to be happening more frequently as a result of climate change and variability (Islam & Karim, 2019).

The process of adding water to the groundwater storage beneath the surface of the earth, indicated by a shift in the water table level, is known as groundwater recharge (Han et al., 2017). Understanding recharge processes and their quantification is vital for sustainable management and protection of groundwater resources (Xu & Beekman, 2019). Nevertheless, it is among the most challenging water budget elements to assess with a sufficient degree of accuracy. This is particularly true in areas with a wide heterogeneity of geological, topographical, and hydro-climatic conditions. There is no assurance that a method applied successfully will There is no assurance that a method applied successfully in one location will yield acceptable results in another, as recharge processes differ greatly between locations (Xu & Beekman, 2019). Various techniques are used to estimate recharging. Selecting the right approach, however, is frequently difficult. Space/time scales, range, and the dependability of recharge estimates are crucial factors to take into account while selecting a technique, all of which are dependent on the study's objectives (Singh et al., 2019).

There is a growing competitive demand for water in the Jedeb watershed for irrigation and agriculture. The area's groundwater recharge analysis has not been predicated on physically disparate approaches to long-term average estimation. The mapping and quantification of the subbasin's groundwater recharge areas did not guide the scientific study conducted there. Both the components of the water balance and the distribution of the hydraulic head in relation to stress were not accurately described. Given the rapid population development and growing reliance on groundwater, a thorough understanding of proper and efficient groundwater management in the subbasin and groundwater recharge was essential. The first edition of the WetSpass model could only reproduce the yearly and seasonal fluctuations. This limitation has been resolved in the updated version of WetSpass-M, which uses monthly climate data to replicate monthly variance.

Accordingly, WetSpass-M is able to provide a more accurate assessment of water balance components throughout time and space through the use of large monthly-scale data. Because climates tend to vary widely across topography, any hydrological model simulation at a monthly time step is more appropriate for the assessment of water resources than one at the seasonal or annual scale (period and type).

Assessing the long-term spatial distribution of the monthly, seasonal, and annual components of the water balance as well as

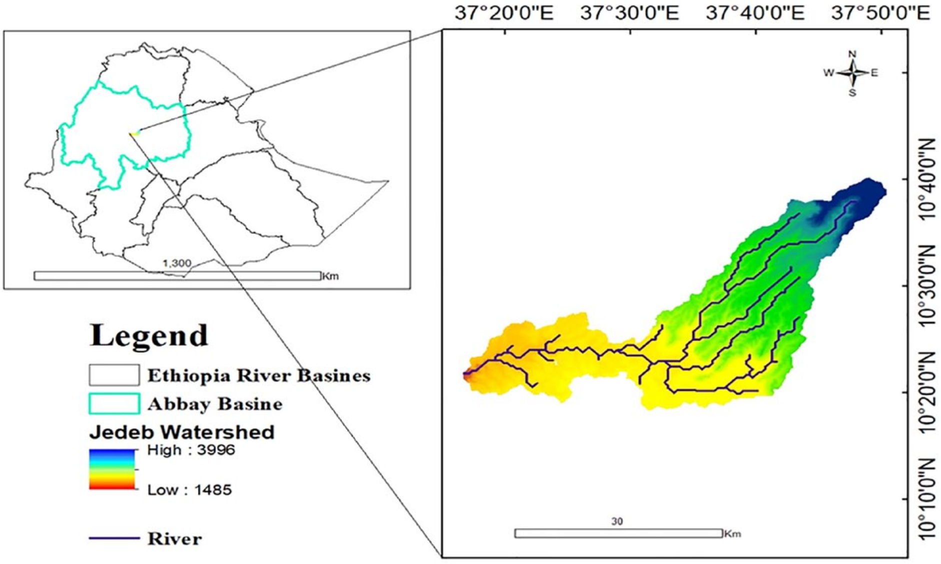

Figure 1. Location map of Jedeb watershed.

the spatial groundwater levels was the main objective of this study. For a steady-state groundwater model, the spatial distributed recharge output of the WetSpass-M model can enhance the prediction of the simulated groundwater level and the locations of discharge and recharge areas (Bezabih & Alemayehu, 2022). In this case, WetSpass-M and the groundwater model perform simulations one after the other while exchanging inputs of groundwater and recharge values, respectively. This results in a stable solution for the groundwater level and discharge areas. MODFLOW was used to simulate the hydraulic head distribution using the groundwater recharge distributions acquired by WetSpass-M (Bezabih & Alemayehu, 2022). A fuller understanding of the temporal and spatial changes of water balance components, in particular actual evapotranspiration, surface runoff, and recharge, is necessary for the sustainable and efficient management of water resources in the Jedeb subbasin.

Materials and Methods

Description of the study area

Jedeb watershed is located in the East Gojjam zone of Amhara Regional State, northwestern Ethiopia. The watershed encompasses four districts: Sinen, Machakel, Debre Elias, and Gozamin. Jedeb watershed is found about 20 km from Debremarkos and 320 km from Addis Ababa. The Jedeb River originate from the Choke Mountains at an elevation of 4,000 m a.s.l. and drain to the Abay/Blue Nile basin. It covers an area of 830 km^2. It is one of the tributaries of the Upper Abay River basin, and it is located in the northwestern highlands of Ethiopia, within 10°18′N to 10°39′N and 37°20′E to 37°53′E (Figure 1).

WetSpass-M Model

This study uses the most recent version of the WetSpass-M model to assess the monthly, seasonal, and annual spatial distribution of the components of the water balance (Amiri et al., 2022; Anteneh et al., 2023; Gelebo et al., 2022; Hirbo Gelebo et al., 2022; Salem et al., 2019). Each raster cell's spatial distribution of LULC, soil texture, elevation, slope, and meteorological parameters is considered by the model. They can therefore perform their calculations using the recharge output obtained from WetSpass-M. For SteadyState groundwater models, the distributed recharge output of the WetSpass-M model can enhance the model's capacity to forecast simulated groundwater levels and the locations of discharge and recharge zones (Bezabih & Alemayehu, 2022; Dowlatabadi et al., 2023).

Four main classes—vegetable, bare soil, open water, and impermeable surfaces—are identified by the model to represent the watershed's land use and cover. The model computes the specific raster output of water balances (WBs) by adding all raster cells of vegetated, bare soil, open water, and impervious area components in the catchment. The summation of individual raster cells of WBCs provides robust information on the spatial and temporal variation of total WB for specific hydrological regions. The processes are described using a combination of empirical and physical correlations. Ces équations sont utilisées pour définir la totale water balance of a raster cell en ajoutant ensemble les components de la water balance of vegetated, bare soil, open water, and impervious surfaces.

$$\mathrm{ETraster} = \mathrm{avETv} + \mathrm{asEEs} + \mathrm{aoEo} + \mathrm{aiEi} \tag{1}$$

$$\mathrm{Sraster} = \mathrm{avSv} + \mathrm{asSs} + \mathrm{aoSo} + \mathrm{aiSi} \tag{2}$$

$$\mathrm{Rraster} = \mathrm{avRv} + \mathrm{asRs} + \mathrm{aoRo} + \mathrm{aiRi} \tag{3}$$

Where ETraster, Sraster, Rraster are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell respectively, each having a vegetated, bare-soil, open-water, and

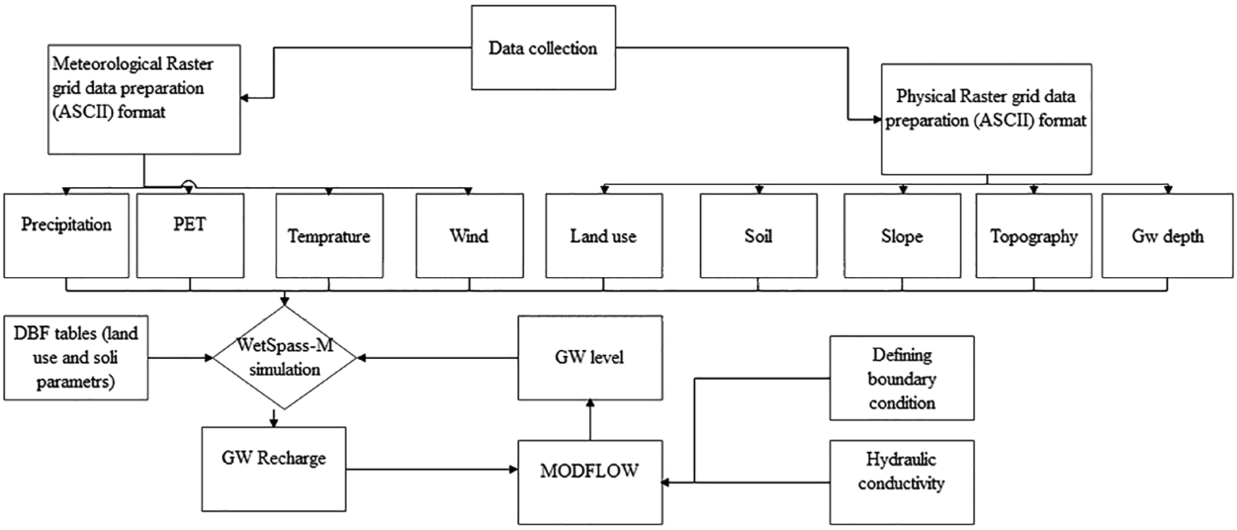

Figure 2. General framework of the research study.

impervious area component denoted by av, as, ao, and ai, respectively. Precipitation is taken as starting point for the computation of the water balance for each of the above-mentioned components of a raster cell. The other processes (interception, runoff, evapotranspiration, and recharge) have been calculated in an orderly manner; which becomes a prerequisite for the seasonal time scale to quantify the processes. The water balance for the different components was treated thereafter.

Methods

The research methodology was designed in recursive and adaptive ways that enable a robust investigation of the research problem and achieve its intended objectives. Consequently, there are four main steps to the research technique. In the first stage, the collection and preprocessing of spatial and hydrometeorological data were conducted. The activities in this stage include satellite image downloading and processing, land use and land cover classification, accuracy assessment, DEM processing to develop topography and slope maps, and gridding soil maps at common spatial resolution for the study area.

The second step involved creating the grid maps for the model's input, which included information on temperature, groundwater depth, wind speed, precipitation, evapotranspiration, land use, and soil. Additionally, lookup tables for the parameters of the runoff coefficient, soil, and land use were created.

In the third stage, the WetSpass-M model was simulated for the watershed using meteorological and biophysical data gathered and processed in the previous stages. The WetSpass-M model simulation produced monthly, seasonal, and annual averages of groundwater recharge, surface runoff, and actual evapotranspiration in the Jedeb catchment.

In the final fourth stage, the WetSpass-M model was calibrated and validated using groundwater level data by coupling the model with a MODFLOW groundwater flow model of the study area. Next, the MODFLOW model was fed with groundwater recharge data derived from the WetSpass-M model. The resulting groundwater depth of the MODFLOW head output is then used as input to WetSpass-M for refining the estimation of recharge. The MODFLOW model was calibrated using groundwater level data collected from the study area with the objective of minimizing the variance of residual between observed and simulated groundwater levels at various observation wells over the study area.

The overall research methodology framework developed for the estimation of groundwater recharge for the Jedeb watershed using the GIS-based WetSpass-M and MODFLOW model is schematically illustrated in (Figure 2).

Materials and software used

The major software and resources used in this research study were ERDAS Imagine 2014, ArcGIS 10.4, wetSpass-M model, MODFLOW, zonal statistics as table tools in ArcGIS, dep meter, and GPS. The input data of WetSpass-M model are listed below Table 1.

Input Data for WetSpass-M

There are two types of necessary input data for the WetSpass-M model: parameter tables and GIS grid maps (Amiri et al., 2022; Anteneh et al., 2023; Hirbo Gelebo et al., 2022; Salem et al., 2019). Rainfall, potential evapotranspiration (PET), average temperature, wind speed, topography, soil, groundwater depth, and LULC type are all included in GIS grid maps. Due to the disparate data sources and formats discovered, the data must be transformed using a spatial analysis method specific to the type of data. Because it can be quickly and easily constructed for a specific purpose using sparse and limited measurement data, this interpolation method is used. Frist, the model input grid maps were prepared at the spatial resolution of 12.5 m × 12.5 m the coarser biophysical factor. The hydro-meteorological observations in the watershed were very sparse, and their grid maps with a resolution of 12.5 m were unable to clearly show

Table 1. WetSpass-M Input Parameters.

INPUT VARIABLES	SOURCES
1. Topography	DEM (12.5 m × 12.5 m) resolution
2. Slope	DEM (12.5 m × 12.5 m) resolution
3. Land use land cover	Landsat 8 (www.earthexplorer.com)
4. Soil textural class	Bureau of Agriculture Bahir Dar
5. Temperature (monthly)	National Meteorological Agency
6. Precipitation (monthly)	National Meteorological Agency
7. PET (monthly)	Estimated by using R-programming
8. Wind speed (monthly)	National Meteorological Agency
9. Depth to groundwater	Direct measurement from existing boreholes
10. Soil parameter, runoff coefficient, and land use parameters	WetSpass user guide

the spatial variability in the data (Demissie et al., 2023). As a result, the grid maps used in the model were further resampled to a spatial resolution of 30 m, and it was discovered that during model simulation, this spatial scale produced coherent outputs. After the preparation of all hydro-meteorological and biophysical maps, they were resampled at 30 m × 30 m resolution and later transferred into ASCII files ready to be used in the model.

Topography and slope

Jedeb watershed is characterized by different types of topography, with its elevation in the catchment ranging from 1,485 to 3,996 m above mean sea level (Figure 3a). The upstream part of the watershed is characterized by mountainous and highly separated terrain with steep slopes, while the central and downstream parts are characterized by an undulating topography and gentle slopes. The slope map of the basin is directly derived from the topography map using the "derive slope" module in ArcMap 10.4. The slope ranges from 0° to 71°, with a mean of 8° and a standard deviation of 6° (Figure 3b).

Soil texture

One of the primary physical elements that regulates runoff and recharge is soil. The amount of water that may be stored in the soil and the degree of hostility with which it flows into deep strata are both determined by the permeability of the soil, which is a function of soil infiltration capability. The textural map of the study area was collected from the Agriculture Bureau in Bahir Dar as a shape file that considers the physical properties of soils, including texture and accessible water content, for every type of soil, including bulk density, hydraulic conductivity, and organic carbon content. The major types of soil groups in the study area were loam, clay, and sandy loam. They cover 84.85% of loam, 5.12% of clay, and 10.033% of sandy loam (Figure 4).

Land use/land cover (LULC)

Groundwater recharge or infiltration is significantly impacted by the type of LULC (Amiri et al., 2022; Siddik et al., 2022). Another useful use of the LULC is estimating the values of vegetative parameters such as the leaf area index (LAI) and evaporative zone depth. Surface evaporation and transpiration

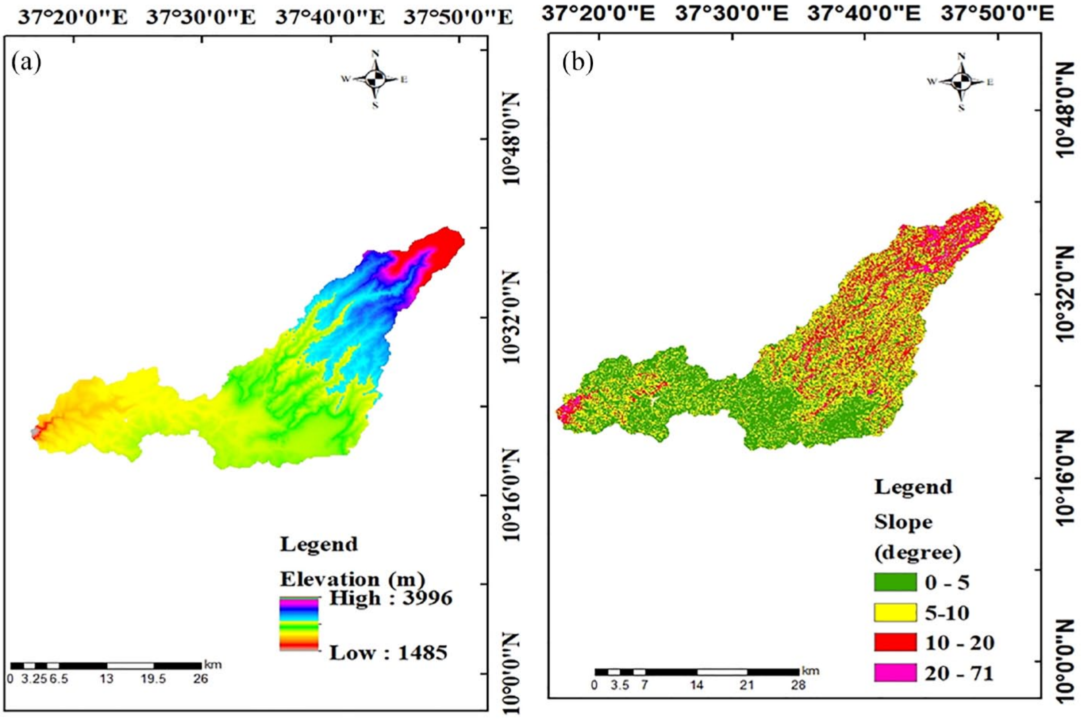

Figure 3. (a) Elevation and (b) slope map of Jedeb watershed.

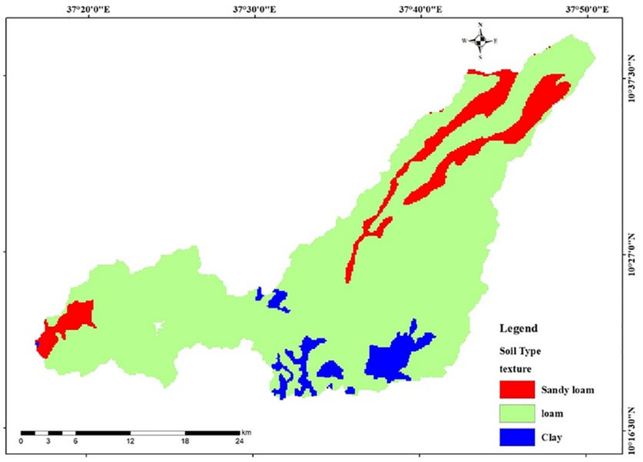

Figure 4. Soil map of the study area.

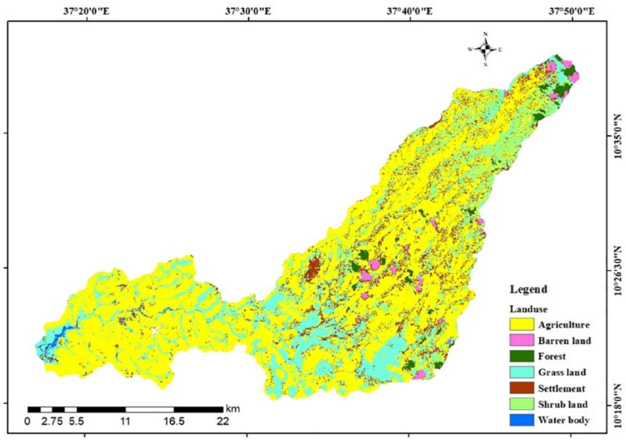

Figure 5. Land use land cover map of the study area.

are both regulated by the LAI parameter (Amiri et al., 2022). The land use and land cover data for the watershed was downloaded from the United States Geological Survey Global Visualization Viewer website (https://earthexplorer.usgs.gov). Satellite images for the study area were obtained at path 166 and row 53 on February 8, 2020. Using the standard ERDAS IMAGINE supervised image classification method, seven different types of land use have been identified for each watershed. These are agricultural (cultivated land), forest land, grass land, shrubs (bush land), settlement (urban), water, and barren land. Each class accounts for 60% agricultural land, 5% forest, 15% grass land, 10% shrub land, 5% settlement, 2% water, and 3% barren land, respectively (Figure 5).

Groundwater depth

Groundwater depth (static water level) is one of the input parameters for the WetSpass-M model to estimate the recharge of the study area. The static water levels are obtained from existing inventoried wells construction completion reports of archives of different organizations. However, for model calibration purpose the water level is measured directly from

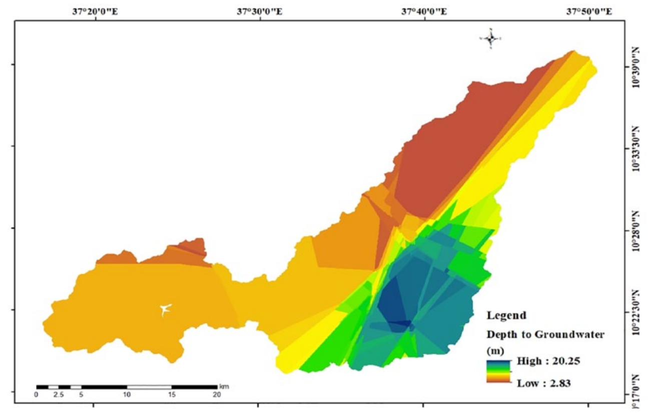

Figure 6. Groundwater depth map of Jedeb watershed.

non-pumping borehole and boreholes having operational observation pipe that allows insertion of deep meter. Based on the inventoried borehole water level data, a depth-to-groundwater map is prepared using kriging spatial interpolation, exported in ASCII format, and applied to the WetSpass-M model. For this study, the groundwater depth grid map was produced by using 40 wells that were present in the watershed and near the watershed. The minimum groundwater depth is 2.83 m and the maximum depth is 20.25 m, with a mean and standard deviation value of 8.3 and 4.2, respectively (Figure 6).

Meteorological data

This data includes four parameters (rain, temperature, wind, and evaporation) as inputs to the Wetspass M 1.3 model. Twelve raster maps were created for each climate parameter on a monthly basis; the total number of these maps was 48. All raster maps were converted to American Standard Code for Information Interchange (ASCII) files in order to be input correctly into the model. These rasters' have a cell size of 30 m × 30 m in order to run the model conveniently.

Development of groundwater flow model

The groundwater flow model was created using ModelMuse software. For the purpose of creating model input files for MODFLOW, a graphical user interface (GUI) called ModelMuse was developed (Chowdhury & Rahnuma, 2023). The model's construction consists of a set of possible assumptions that reduce the real situation and result in a conceptual model that is appropriate for the modeling goal. Concerning the modeled area, the following assumptions were made: (i) the system was assumed to be in a steady state all year round; and (ii) the extent of the geological formations of concern was assumed to be horizontal. ModelMuse was used to create a one-layered MODFLOW model using the basin's grid, which consists of 2,046 rows and 1,342 columns. The lower layer's bottom was aligned with the bedrock elevation, while the upper layer's top surface was set to match the elevation of the groundwater surface.

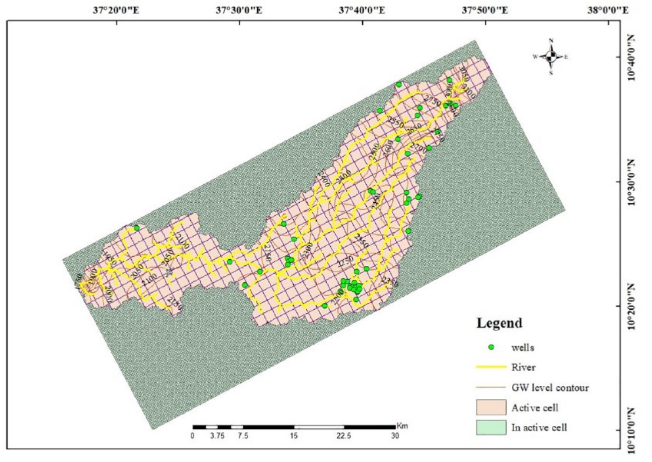

Figure 7. MODFLOW model grid design.

It requires two input packages to build a model: (i) model properties and (ii) model boundary conditions. Aquifer parameters and initial heads are among the model property inputs. Only horizontal hydraulic conductivities were significant since the groundwater flow model was single-layered. Initial heads were measured directly from existing boreholes and interpolated within the model to produce initial heads for the whole model. To interpolate the observation heads, the inverse distance weighting (IDW) method was employed. Recharge was used as a boundary condition in this study.

For the purpose of model calibration, observation wells were added to the model. This work required the use of 40 observation wells. The import tool was used to import observation wells into MODFLOW. Calibration was performed using a built-in software package within ModelMuse known as PEST, which stands for parameter estimation. Compared to a manual method, PEST enables the modeler to optimize parameters significantly more quickly. PEST allows the model to be calibrated based upon hydraulic conductivities, storage coefficients, and recharge (Vengust et al., 2023). For this study, automatically calibrated hydraulic conductivities were used to increase the accuracy of the modeling. The purpose of this program is to minimize an objective function, such as the sum of the square residuals. Though this approach is advantageous for that, it gives a statistical degree of uncertainty and saves time. Figure 7 shows the MODFLOW grid design and well locations.

Coupling of surface water model and groundwater flow model

Because of its lumped nature, the WetSpass model is essentially restricted in terms of dealing with groundwater flow. MODFLOW, on the other hand, has problems identifying the distributed groundwater recharges, which are the principal inputs to the groundwater model (Aslam et al., 2022; Bezabih & Alemayehu, 2022). Until the rates of recharge and hydraulic heads stabilize, MODFLOW and WetSpass guarantee data interchange (Aslam et al., 2022; Bezabih & Alemayehu, 2022). The first simulation was run using the WetSpass-M model with a variety of input data. MODFLOW was used to simulate groundwater head using the calculated groundwater recharge, which is then fed into WetSpass-M. Hydraulic conductivity of the aquifer, hydraulic head of aquifers, aquifer thickness, and WetSpass-based groundwater recharge were given as input data in MODFLOW, and the groundwater level was estimated and transferred to WetSpass-M. The spatiotemporal characteristics of the study region were adequately represented. The current state and future conditions of the hydrology (components of the water balance, system water budget, and groundwater level) were examined using a coupled model of this kind of Jedeb sub basin. Understanding the groundwater flow characteristics that will be used as a decision support system (DSS) for water resource management requires integrating WetSpass-M and MODFLOW (Aslam et al., 2022; Bezabih & Alemayehu, 2022).

Results and Discussion

WetSpass-M model simulation

The main outputs of the WetSpass-M model are raster maps of monthly groundwater recharge, surface runoff, and evapotranspiration for the period 1990 to 2021 Each pixel on these maps corresponds to the water budget component's magnitude (in mm). This research is the first to assess the spatial and temporal distribution of groundwater recharge in the Jedeb subbasin. The WetSpass-M results for water balance components used as an integrated groundwater modeling inputs and boundary conditions in the Jedeb sub basin. The monthly, annual, and seasonal Wetspass-M simulated water balance components of Jedeb sub basin shown in Table 2.

Evapotranspiration (ET)

The spatial mean monthly, seasonal, and annual evapotranspiration simulated by the WetSpass-M model is presented in Table 2. The entire actual evapotranspiration per pixel is determined via a WetSpass-M model by adding the evaporations from open water, impermeable surface area, bare soil, vegetated area interception, and transpiration of the vegetative cove. The simulated monthly long-term actual evapotranspiration of the Jedeb subbasin ranges from 1.06 to 115.8 mm/month as the lowest and highest values. The mean and standard deviation are 47.8 and 47.3 mm. The total annual actual evapotranspiration is determined by accumulating the simulated monthly actual evapotranspiration in the Jedeb subbasin. The maximum and minimum of the average annual evapotranspiration for the studied area by Wetspass-M simulation are equal to 463 and 638 mm, respectively (Figure 8c). The mean value represents 574 mm/year, which accounts for 36.4% of the annual precipitation loss in the watershed (1,578 mm).

In this watershed, the annual evapotranspiration was very high in forest areas (in the northern parts of the watershed),

Table 2. Monthly, Annual, and Seasonal Wetspass-M Simulated Components of Jedeb Sub Basin.

PERIOD	VALUE	PRECIPITATION (MM)	RECHARGE (MM)	EVAPOTRANSPIRATION (MM)	RUNOFF (MM)
Monthly	Range	9.1–336	0.05–14.96	1.06–115.8	2.76–205.8
	M	131.5	8.2	47.8	74.7
	SD	125.8	5.4	47.3	79
	Range	378.9–463.1	40–142	114–207	89–258
Winter	*M*	419.73	66	151	202
	SD	17.66	20.62	23.9	47
	Range	995.7–1,233	0–285	349–440	385–864
Summer	*M*	1,159	33	423	696
	SD	93.9	60.8	13	115
	Range	1,374.8–1,696	40–393	463–638	474–1,120
Annual	*M*	1,578	99	574	898
	SD	105	80.4	33.5	163

shrub areas, and grasslands. In this watershed, evapotranspiration was high in the highland areas of the watershed. This is due to high rainfall and high coverage of shrubs and forest in the highland areas.

Surface runoff

The WetSpass-M model calculates monthly surface runoff in mm/month using the runoff coefficient, which varies its value with vegetation type, soil type, and slope. The monthly, seasonal, and annual WetSpass-M simulated runoffs in the basin are presented in Table 2. The estimated monthly surface runoff varies from 2.76 mm/month to a maximum of 205.8 mm/month, with an average value of 74.7 mm/month and a standard deviation of 79 mm/month. The amount of surface runoff also shows variation in the summer and winter seasons. The annual surface runoff in the Jedeb watershed ranges from 474 to 1,120 mm/year (Figure 9c). The mean value represents 899 mm/year, which accounts for 57% of the annual precipitation loss in the watershed.

According to the annually simulated surface runoff of the catchment, the central and western parts of the watershed have the highest surface runoff due to the presence of clay soil, which has a low permeability that enhances surface runoff, and also rural settlements and agricultural land use types' areas where the probability for the formation of surface runoff is high. On the other hand, the south-western and northern parts have less surface runoff. This is caused by sandy loam and loam soil types associated with forest and shrub coverage of the area, which hinder surface runoff formation. All land uses with sandy loam and loam soil yield the lowest surface runoff, while rural settlements and agricultural land uses with clay soil yield the highest amounts of surface runoff in the catchment. This shows these soil types and land use classes have a great impact on the surface runoff of the Jedeb watershed and create an opportunity for the formation of groundwater recharge.

Groundwater recharge

The WetSpass-M model evaluates the long-term spatial distribution of monthly groundwater recharge for the Jedeb catchment as a residual term of the water budget components by subtracting the monthly surface runoff and actual evapotranspiration from the monthly rainfall. The WetSpass-M model evaluates the mean monthly long-term groundwater recharge of the Jedeb subbasin to be 0.05 and 14.96 mm as minimum and maximum values, respectively, with a mean value of 8.2 mm/month and a standard deviation of 5.4 mm/month (Table 2). On the basis of monthly simulated data, the average yearly groundwater recharge is calculated. The maximum, minimum, and mean values of annual groundwater recharge for the whole period are 393, 40, and 99 mm, respectively (Figure 10c). The average recharge accounts for 6.3% of the total average annual rainfall.

The south-western and northern part of the Jedeb basin that receives high amounts of precipitation has higher annual and seasonal groundwater recharge. Also, forest and shrub in the south-western and northern parts of the Jedeb basin are characterized by high groundwater recharge due to the presence of permeable (loam and sandy loam) soils with apparently flat topography. On the other hand, the eastern and central part accounted for a lower rate of annual and seasonal groundwater recharge, attributed to the presence of settlement and agricultural land with less permeable loam and clay soil. In general, high values of groundwater recharge are observed in the forest and shrub with sandy loam soil. In general, all types of land use

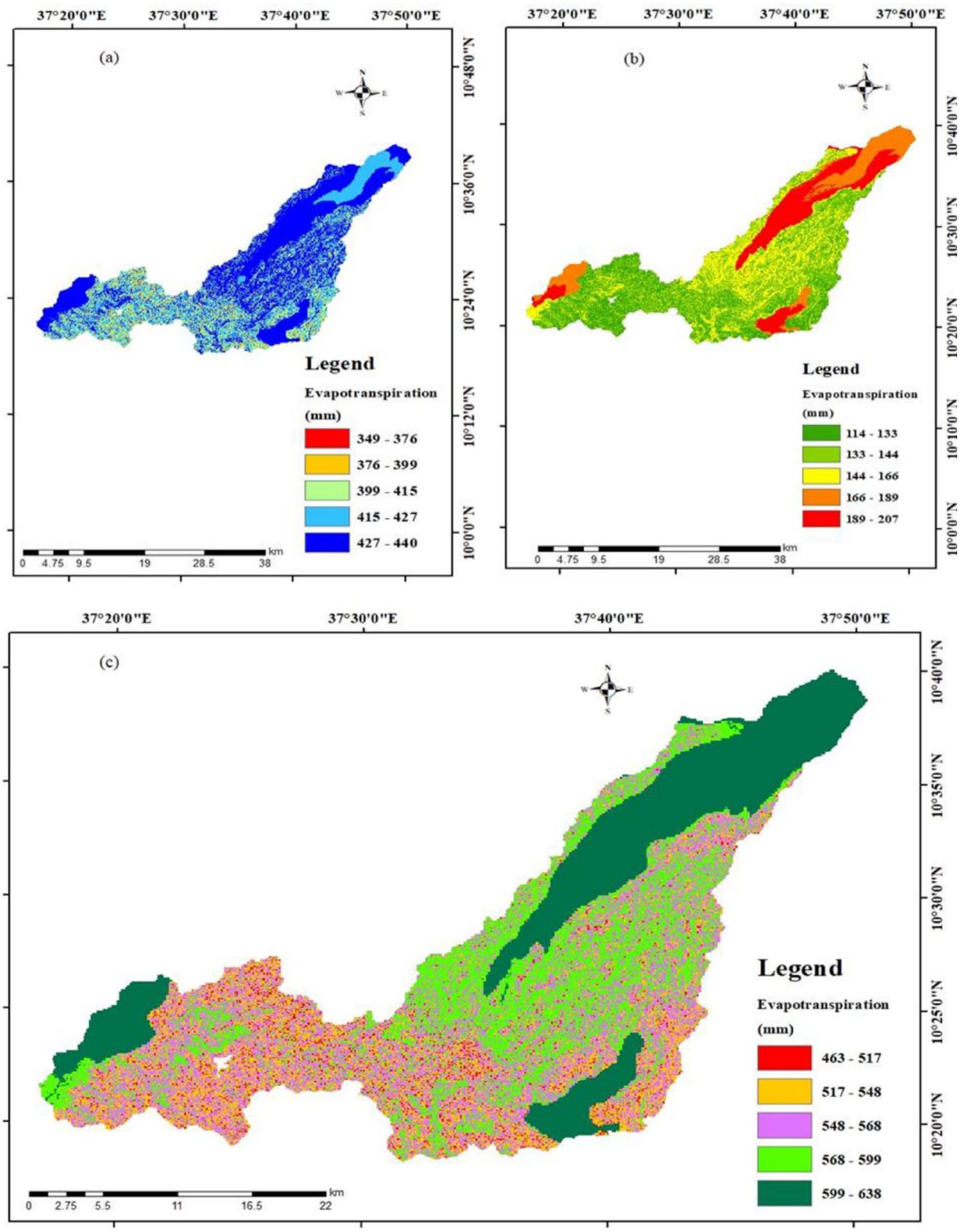

Figure 8. (a) Summer, (b) winter, and (c) annual simulated evapotranspiration of Jedeb watershed.

with loam, and clay soil have resulted low amounts of groundwater recharge.

Groundwater level (hydraulic head) distribution with respect to stress

The groundwater levee in Jedeb Sub-basin has been analyzed for different stress periods (dry season, wet season, and annually). After successful calibration of the MODFLOW model, calculated GW head levels were compared to observed head levels. The model result (Figure 11a) shows the groundwater level due to the summer/wet stress period (recharge) varied from 2,052.3 to 3,063.06 m. While in the winter /dry stress period (recharge; Figure 11b), the groundwater level varied from 2,051.41 to 3,061.92 m, and also from (Figure 11c), which shows the groundwater level due to the annual stress period (recharge) varied from 2,053.76 to 3,064.5 m. From the simulation result, there is a change in the hydraulic head of 0.89 m in the central and 1.14 m in the northern parts of the catchment in wet and dry stress periods, whereas the hydraulic head between the wet stress period and the annual stress period varied from 0.43 m in the central and 1.44 m in the northern parts of the subbasin, and the hydraulic head between the winter and annual stress periods varied

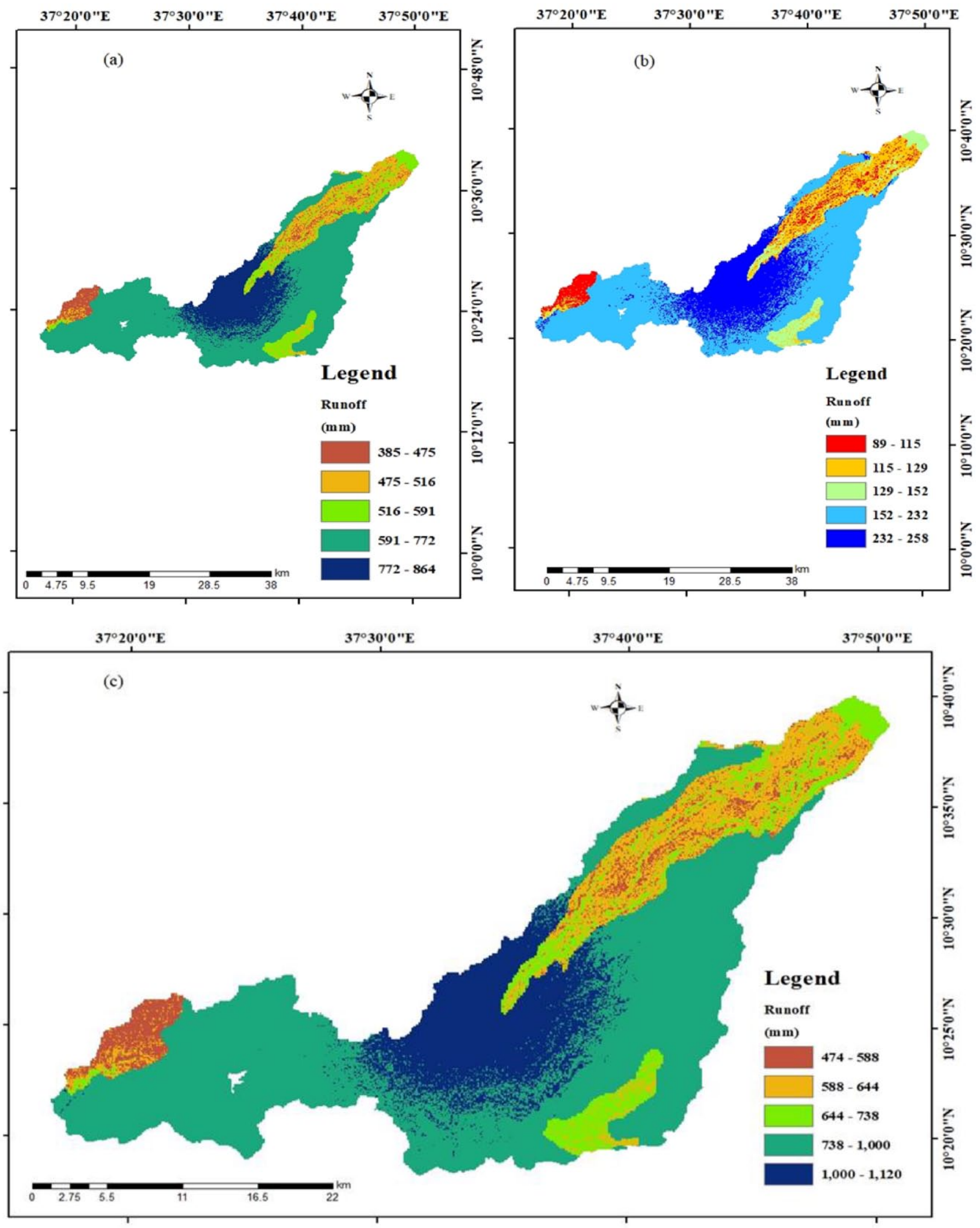

Figure 9. (a) Summer, (b) winter, and (c) annual simulated runoff of Jedeb watershed.

from 1.35 m in the central and 2.58 m in the northern parts of the subbasin. Generally, the groundwater level from the central to the northern part of the subbasin increases in both stress periods. Which indicates the groundwater flow direction in the study area is the rise in elevation from the high point of Choke Mountain to the lowest flat plain of Senera and Yewla.

A model-generated scatter diagram showing the calibrated fit between the observed and simulated heads is shown in Figure 12. The scatter plots are usually examined to determine whether points in a plot show deviation from the straight line in a random distribution or have systematic deviation, where the systematic deviation of the plots can indicate systematic error in adjusting the parameter values. The scatter plot shows a correlation coefficient of .89 in the summer, winter, and yearly stress periods plotted together. Between measured heads and simulated heads, which is also a good indicator of calibration quality with a mean error of 0.63, 0.59, and 0.62 in the summer, winter, and yearly stress periods, respectively (Figure 12).

Conclusion

The groundwater recharge in the Jedeb subbasin was evaluated by applying the Coupled WetSpass-M and MODFLOW models, which are crucial for the management and planning of water resources for sustainable development. The WetSpass-M model

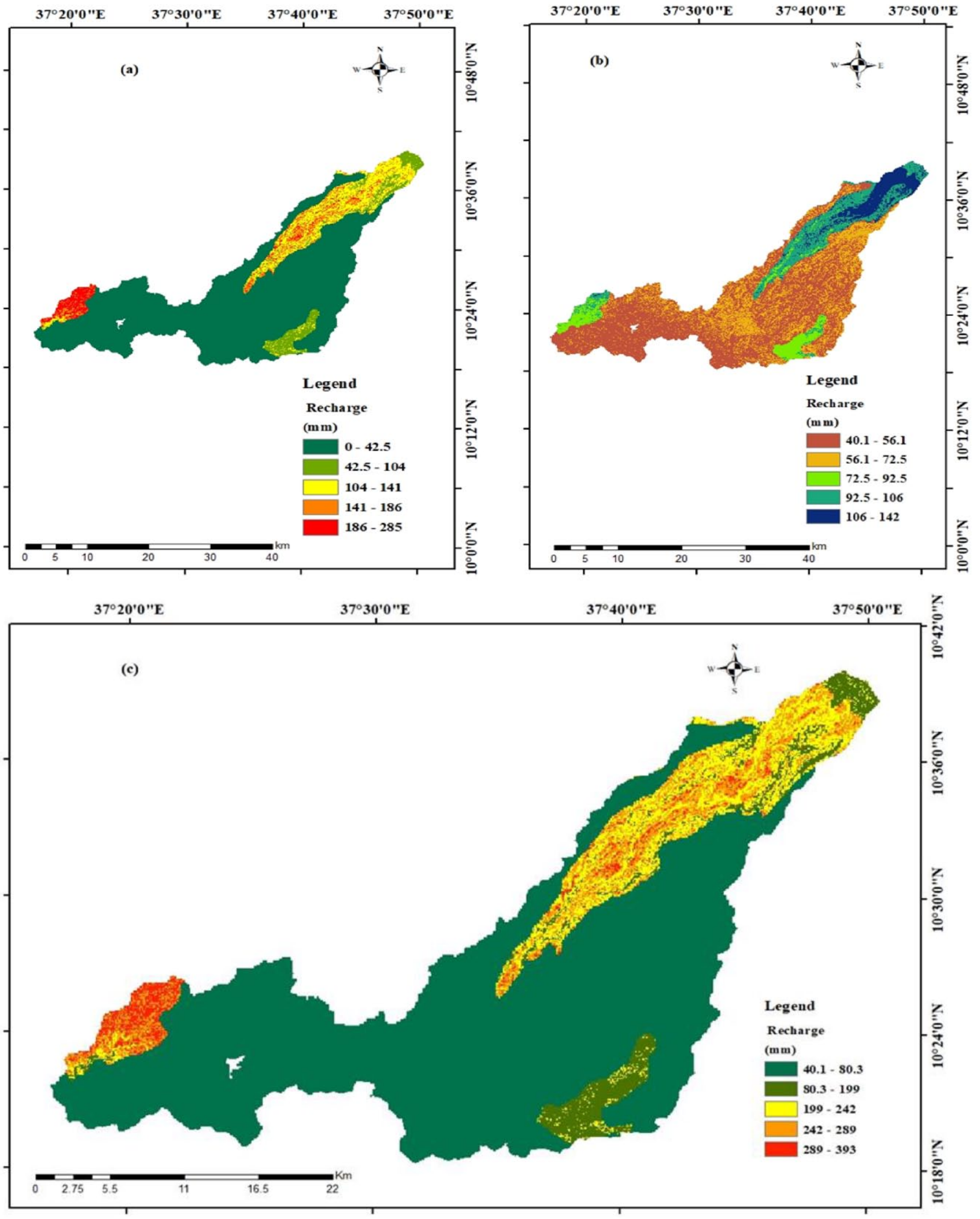

Figure 10. (a) Summer, (b) winter, and (c) annual simulated recharge of Jedeb watershed.

estimates the annual actual evapotranspiration of the basin for the period from 1990 to 2021 at 463 and 638 mm as minimum and maximum values, respectively. This represents 36.4% of the annual average precipitation. The minimum and maximum values of annual runoff in the Jedeb subbasin are 474 and 1,120 mm, with a mean value of 898 mm, which accounts for 57% of total rainfall (1,578 mm). Annually, simulated groundwater recharge ranges from 40 to 393 mm, with a mean of 99 mm, which represents 6.3% of the annual precipitation (1,578 mm).

The groundwater level in the Jedeb Sub-basin was studied under various stress conditions (dry season, wet season, and annually). The groundwater level distribution varied from 2,052.3 to 3,063.06 m in the summer stress period (recharge). While in the winter stress period (recharge), the groundwater level varied from 2,051.41 to 3,061.92 m, and the groundwater level due to the annual stress period (recharge) varied from 2,053.76 to 3,064.5 m. With a correlation coefficient of .89, which is an acceptable fit between the simulated and observed heads in steady state for all stress periods (summer, winter, and annual recharge). To preserve the groundwater resource's long-term viability, it is critical to consider the balance between groundwater recharge and projected abstraction rates for agriculture and domestic water supply in future groundwater resource development plans in the valley.

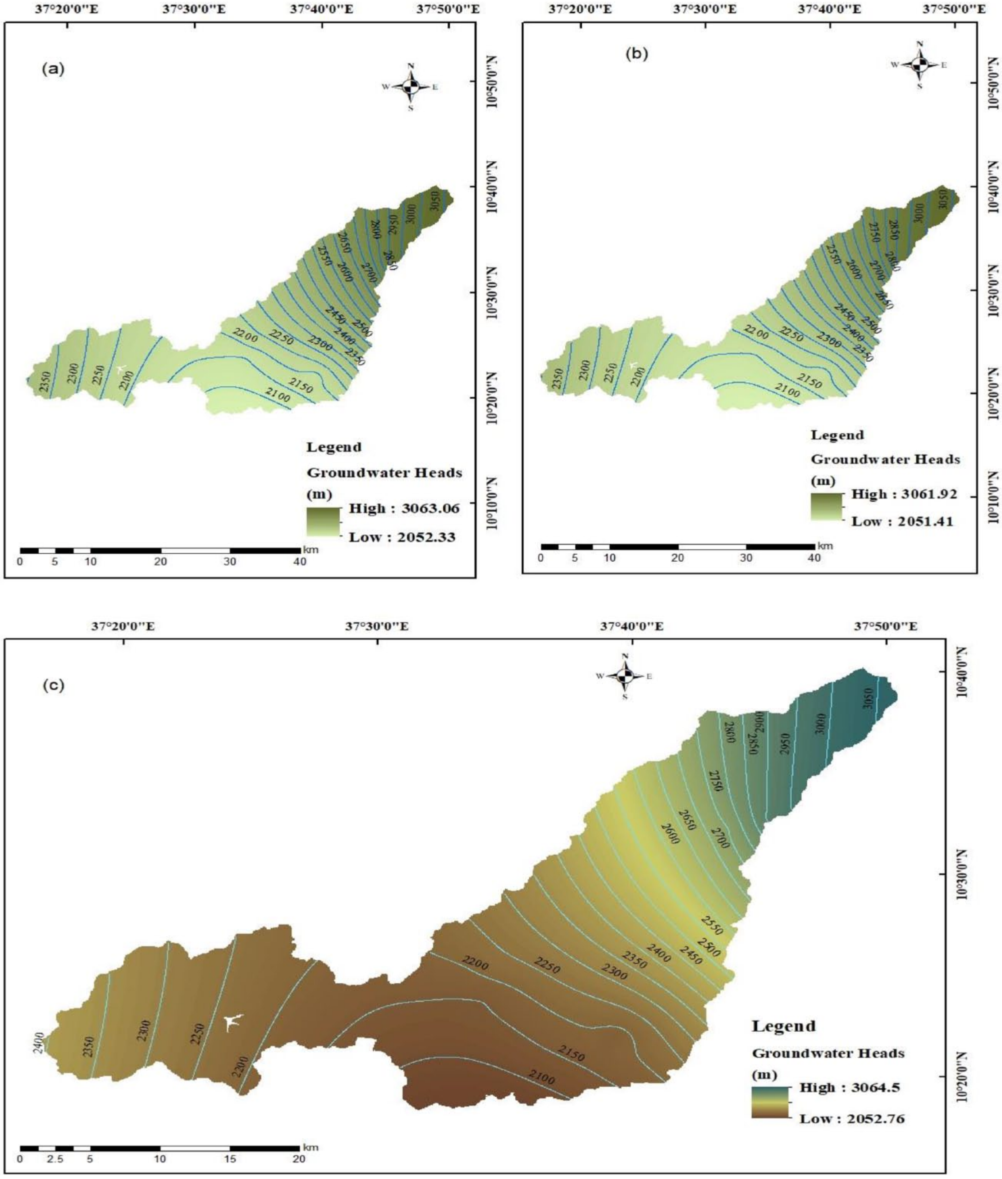

Figure 11. Groundwater level with respect to stress (recharge): (a) wet season, (b) dry season, and (c) yearly.

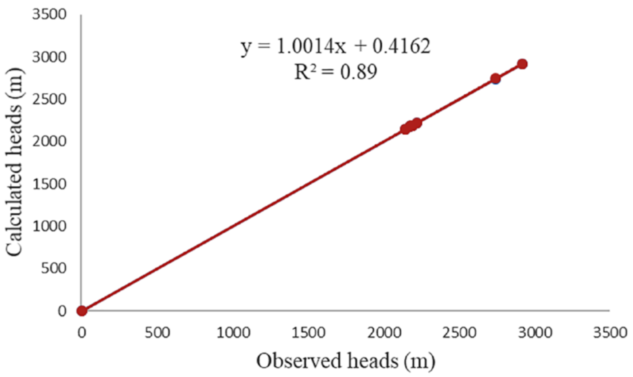

Figure 12. The scatter plots of simulated versus observed heads.

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