International Journal of Weather, Climate Change and Conservation Research, 11(1),35-45, 2025
Print ISSN: ISSN 2059-2396 (Print)
Online ISSN: ISSN 2059-240X (Online)
Website: https://www.eajournals.org/
Publication of the European Centre for Research Training and Development -UK

Modeling the Groundwater Recharge of Hormat-Golina sub-basin by Wetspass and MODFLOW coupling, Northern Ethiopia

Seyoum Bezabih
Department of Water Resource Engineering and Management, Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia

doi: https://doi.org/10.37745/ijwcccr.15/vol11n13545 Published December 31, 2025

Citation: Bezabih S. (2025) Modeling the Groundwater Recharge of Hormat-Golina sub-basin by Wetspass and MODFLOW coupling, Northern Ethiopia, *International Journal of Weather, Climate Change and Conservation Research*, 11(1),35-45

Abstract: *The search for new groundwater resources in northern Ethiopia and the development of groundwater models to control and manage the resource are rooted in the water scarcity and the socio-economic importance of the water demand for agriculture and domestic use. In this paper, WetSpass-MODFLOW coupling was used to assess groundwater recharge of the Hormat-Golina sub-basin. This paper aims at determining the groundwater recharge in the Hormat-Golina sub-basin, which will be followed by simulating the hydraulic head distribution using the MODFLOW groundwater flow simulation model. The steady state groundwater flow calibration was achieved by comparing measured and simulated hydraulic heads. WetSpass also calculated the mean annual evapotranspiration, surface runoff, and groundwater recharge to be 516.6, 204.9, and 35.6 mm, respectively. Groundwater recharge represented 4.7% of precipitation, whereas actual evapotranspiration and surface runoff represented 27% and 68% of precipitation, respectively. For this type of seasonal variation, the range of groundwater head distribution is 9.37 to 29.86 m during the winter (dry season), 9.53 to 29.89 m during the summer (wet season), and 9.58 to 30.17 m during the annual stress periods (recharges). The predicted hydraulic heads in steady state match the measured heads well for all stress periods (summer, winter, and annual recharge) with a correlation coefficient of 0.86. Future groundwater resource development plans for the valley must be balanced with groundwater recharge rates and projected abstraction rates for agriculture and domestic water supply to ensure the long-term viability of this resource.*

Keywords: Ethiopia, groundwater recharge, Hormat-Golina, MODFLOW, WetSpass

INTRODUCTION

Water is a resource that has always been valuable to humans, as we use it nearly every day and will need it to measure everything physical. Although water is a naturally occurring resource, the supply of clean water is dwindling, and there is a persistent problem of water scarcity in many parts of the world [1] due to increased global demand for potable water. The determination of groundwater recharge has become a fundamental problem in hydrogeologic research for sustainable groundwater development, and many methods for estimating groundwater recharge are available [2]. Note that the majority of these methods estimate groundwater recharge over a small area (point or small basin scale) and over short periods of time [3].

The recharge and evapotranspiration rates are the most challenging and uncertain components to estimate in the groundwater budget because they change often in space and time, especially in arid and semi-arid areas [4, 5]. With the advent of Geographic Information Systems (GIS) [6], physically based hydrologic modeling has become an important, affordable tool to assess the water balance in space. Recharge, for example, is spatially variable because of variable land use and land cover, soil texture, topography, and meteorological conditions [7, 8].

One of the most important parameters for evaluating a resource is the rate of groundwater recharge. In the Hormat-Golina Sub-basin, scientific research was not conducted to quantify the area of groundwater recharge, define the components of the water balance, model the hydraulic head distribution in relation to stress, and understand the nature of groundwater recharge, which was a major concern for sound and suitable groundwater management in the sub-basin due to the high rate of population growth and increased dependence on groundwater.

Therefore, it is necessary to estimate groundwater recharge in the region to ensure that the water resources are sustainable and protected from pollution and depletion. This study could initiate to estimate groundwater recharge, runoff, evapotranspiration, and groundwater head /hydraulic head/ in the study area. The objective is to determine the groundwater recharge of the Hormat-Golina sub basin using Wetspass and MODFLOW coupling with some spatial and hydrological information. Using the groundwater recharge distributions from WetSpass, the hydraulic head distribution was simulated using MODFLOW.

MATERIALS AND METHODS

Description of the Study Area

The study was carried out in the northern Ethiopian region with latitudes of 11°55'35\" to 12°13'10\" north and longitudes of 39.525°to 39.90556° east (figure 1) which is known as the Hormat–Golina sub-basin, with a surface area of 689.25 km2. It is surrounded by the Lasta Mountains in the west, the Zobel Mountains in the east, the Raya Valley in the north, and volcanic ridges in the south. It is considered part of the Ethiopian rift system that connects the valleys.

The Hormat-Golina sub-basin has an open surface water drainage system that empties into the Afar area at the Golina outlet and lies within the Denakil dry basin. The basin is drained by three major streams that rise in the western highlands: the Golina, Hormat, and Kelkelit (figure 1). In the rainy season, large amounts of sediment are washed from the mountains and deposited on the valley plain by all streams and ravines. The climate of the HormatGolina sub-basin is semi-arid in the valley plain and subhumid in the hills with an average annual temperature of 21.6 °C and an average yearly temperature range of 17.5 to 26 °C. Estimated annual rainfall of 756.85 mm with potential evapotranspiration of 1669.6 mm during the period 2000-2019

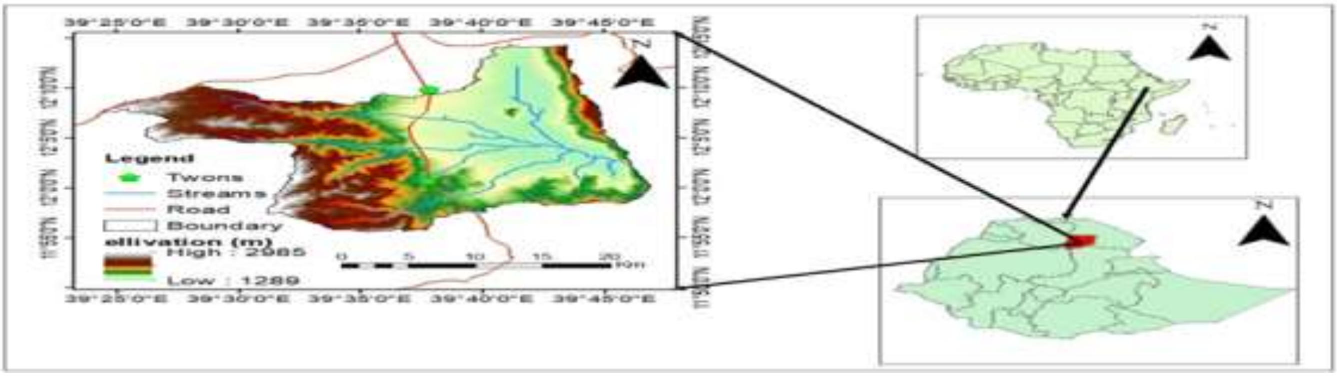

Figure 1. Location map and Drainage of the study area.

Recharge Modeling Approach

A coupling of WetSpass and MODFLOW was used to assess the groundwater recharge of the Hormat-Golina subbasin. Data exchange between MODFLOW and WetSpass is ensured until recharge rates and hydraulic heads become stable. Using a variety of input data, the WetSpass model was run first and groundwater head was simulated using MODFLOW with the calculated groundwater recharge. WetSpass solves the water balance equation [9] cell by cell for the vegetated area, bare soil, open water, and impermeable surfaces, and can compute surface runoff, actual evapotranspiration, and groundwater recharge for seasonal periods [10]. For a vegetated area, the water balance is estimated with the following equation [10];

$$P = I + S_V + T_V + R_V \qquad (1)$$

where P is the mean seasonal precipitation, I is the fraction of precipitation lost to interception, Sv is the surface runoff, Tv is the actual transpiration, and Rv is the groundwater recharge, all in [LT-1].

The fraction of precipitation lost to interception (I) is calculated first; it is a constant fraction of the annual precipitation and is primarily a function of the type of plant. Surface runoff (S) is calculated in two stages: first, the relationship between precipitation amount, precipitation intensity, interception, and soil infiltration capacity are used to determine surface runoff.

$$S_{V-pot} = C_{sv}(P - I) \qquad (2)$$

where Csv is the surface runoff coefficient for vegetated regions, which depends on vegetation, soil type, slope, and areas of groundwater saturated soils; P is the mean seasonal precipitation [LT−1], and I is the interception fraction [LT−1]. S is then calculated using seasonal precipitation intensities relative to soil infiltration capacity [10].

$$S = C_{HOR} S_{V-pot} \qquad (3)$$

Where CHOR is a coefficient that parameterizes seasonal precipitation [11] (considering effective precipitation contributing to runoff) and the evapotranspiration is computed as open-water evaporation multiplied by the vegetation coefficient, defined as the ratio of reference vegetation transpiration to the potential open water evaporation [10], which is calculated first by calculating the reference transpiration as a fraction of the open-water evaporation:

$$T_{rv} = cE_0 \qquad (4)$$

where Trv is the reference transpiration of a vegetated surface [LT–1], E0 is the potential open-water evaporation [LT–1], and c is the vegetation coefficient, calculated as the ratio of reference vegetation transpiration to potential open-water evaporation [10]. WetSpass calculates evapotranspiration in a vegetated area by considering the root depth and the tension saturation height when the groundwater is above the root depth, and by considering water content otherwise; the resulting water balance is used to compute the groundwater recharge for the vegetated area.

$$R_v = P - S_v - ET_v - E_s - I \quad (5)$$

where R is groundwater recharge, P is precipitation, Sv is surface runoff, ETv is actual evapotranspiration, and I indicate interception fraction, all in units of [LT–1]. In contrast, for bare soil, open water, and impervious surfaces, there is no interception and no transpiration term, because there is no vegetation, so ETv becomes Es. The total water balance is then calculated from the water balance components of each area using the following equations [10]:

$$\mathrm{ET}a = avETv + asEs + aoE0 + aiEi \quad (6)$$

$$Sa = vSv + asSs + aoRo + aiRi \quad (7)$$

$$R\ a = vRv + asRs + aoRo + aiRi \quad (8)$$

Where Eta, Sa, and Ra are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell respectively, each having vegetated, bare soil, open water and impervious area fractions denoted by av, as, ao and ai respectively, E is evaporation.

WetSpass Input Data

The model inputs are topography, slope, and soil texture grids, seasonal grids of groundwater level, land use, and meteorological data (precipitation, wind speed, temperature, and potential evapotranspiration), with attribute tables for land use and soil [12]. All inputs are prepared using Geographic Information Systems (ArcGIS 10.8, and the cell size is 30 m × 30 m with 1356 columns and 1149 rows.

Because the calculated recharge by WetSpass will be used for the groundwater flow model MODFLOW, the input and output grids are then set to have the same coordinate projections and lateral extents using the resample tool of ArcGIS. The period 2000–2019 is used for meteorological data (precipitation, evapotranspiration, temperature, and wind speed) with an average value for each seasonal time step (the winter /dry/ and summer /wet/ seasons, October to May and June to September, respectively), which coincides with the groundwater flow model calibration period during steady state.

Table 1. WetSpass input parameters.

Input variables		Sources
1	Topography	DEM (12.5*12.5m) resolution
2	Slope	DEM (12.5*12.5m) resolution
3	Land use land cover	Landsat 8 and own processing
4	Soil textural class	FAO web page
5	Temperature (summer & winter)	National meteorological agency
6	Precipitation (summer & winter)	National meteorological agency
7	PET (summer & winter)	Estimated by using R-programming
8	Wind speed (summer & winter)	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 mean seasonal precipitation was calculated for seven meteorological stations from daily precipitation data observed over the 20-year period of 2000 to 2019. The spatial precipitation is generated using the inverse distance weighting (IDW) method, which is the most common method due to its simplicity and generally good results [13]. This is particularly useful when the network of rainfall is distributed unevenly. The minimum and maximum values of the precipitation were 236.7mm and 334.6mm for the winter and 350.6 mm and 586.8 mm for the summer, with means of 297.03mm and 459.9mm, respectively. The maximum values are concentrated in the western parts of the Hormat-Golina sub basin. The annual mean precipitation for the Hormat-Golina sub basin was 756.85mm.

As there were no data, the PET was computed using the Hargreaves equation [14], which is recommended when only temperature is available as climatic data in semiarid regions. When meteorological data are insufficient to apply the Penman Monteith approach, the Hargreaves method [15] is suggested by the FAO as an alternative method for estimating PET. Average monthly PET was calculated using monthly average temperature values from 2000 to 2019 for seven (7) stations, with the highest value (1076.7 mm) during the dry season /winter/ season (October to May) having a mean value of 1048.8 mm and minimum and maximum values of 1020.7 mm and 1076.7 mm (figure 4a), and the summer/wet/season having a minimum and maximum of 590.4 mm and 620.6 mm, and a mean value of 620.6 mm.

Average temperature and wind speed were also rated from 18.6°C to 21.6°C (figure 5a) with a mean value of 20.4°C (computed from monthly values of the same weather station) and ranged from 20.1°C to 24°C and 22.5°C for the minimum and maximum temperatures of the summer /wet/ season and the maximum temperatures of the dry season /winter), respectively.

The average summer wind average winter wind speed was approximately 1.66 m/s with a minimum and maximum values ranged from 1.58 m/s to 1.67 m/s and 1.99 m/s to 2.1 m/s, while the average winter wind speed was 1.89 m/s in the Hormat-Golina sub-basin.An elevation and slope map of the study area was created using the Alaska satellite facility (ASF) data set which includes a digital elevation model with a resolution of 12.5*12.5m (DEM). The highest point within the sub-basin (2988 meters) is located upstream on the western escarpment, and the lowest point (1289 meters) is located in the eastern/downstream section.

Slope is an attribute that affects the hydrological characteristics of the watershed and is classified based on the steepness of the slope from 0 (gentle/lowland) to 430 (steep/escarpment).

The land use grid was prepared from Landsat 8 products of the total area, followed by shrubs (37.3%), bare land by supervised land use classification using bands from 1 to 7 (9.3%), riverain vegetation 1.6%, trees/forest 1.4, and as shown in the figure, settlement 0.7%. of the sub basin was agriculture, which accounted for 49.7%.

We obtained the soil texture map of the Hormat-Golina sub basin from the FAO website (http://www.fao.org) and classified the soil texture of the research region into four classes (sandy loam, silty clay loam, loam, and clay loam) according to the USDA textural classification (Figure 10); the majority of the land is silty clay loam. Groundwater depth for the WetSpass model was directly measured from the Kobo Girana Valley Development project and interpolated with IDW interpolation and was between 11.8m and 27 m with a mean value of 21.3m.

RESULTS AND DISCUSSION

WetSpass Model Simulation

The WetSpass model was run for the sub-basin, and spatial average grid maps were simulated for winter, summer, and annual periods. During simulation, the model generates various types of grid maps. The model also generated water balance components, such as surface runoff, actual evapotranspiration, and recharge, for the sub-basin. The results of the Hormat- Golina sub basin were presented in table 3.
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Table 3. Long-term annual and seasonal averages of Wetspass simulated water balance parameters.

Groundwater Recharge

Hydrological parameters	Seasonal average		
	Dry/winter/(mm)	**wet/summer/(mm)**	**Annual average (mm/yr)**
Precipitation	297.03	459.95	756.85
Runoff	100.6	104.3	204.9
AET	183.7	334.9	516.6
Groundwater recharge	12.8	22.8	35.6

The amount of infiltration-percolation into groundwater replenishment depends on slope, land use, soil texture, and groundwater level [16]. The simulated average recharge is 12.8, 22.8, and 35.6 mm for winter, summer, and yearly, respectively, with minimum and maximum values of 6.4 and 18.0 mm for dry /winter, -0.65 and 126.72 mm for wet /summer/ and 6.6 and 140.70 mm yearly. Therefore, the annual recharge water (35.6 mm) is added to the groundwater and replenishes the available groundwater each year. The average annual long-term groundwater recharge for the watershed is approximately 4.7% of the average annual precipitation (756.85 mm) (Figure 2). Using the area of the sub basin (698.25 km^2), the average annual recharge (35.6 mm) is equal to 2.5*107m^{3}year-1.

During the wet season (summer) approximately 64% of the annual groundwater recharge occurs, and the remaining 36% occurs during the dry season (winter) season. Areas with higher annual groundwater recharge (64.5 to 140.7 mmyr-1) are the southern and south eastern areas of the sub-basin where the rainfall is higher during the summer season (figure 2).

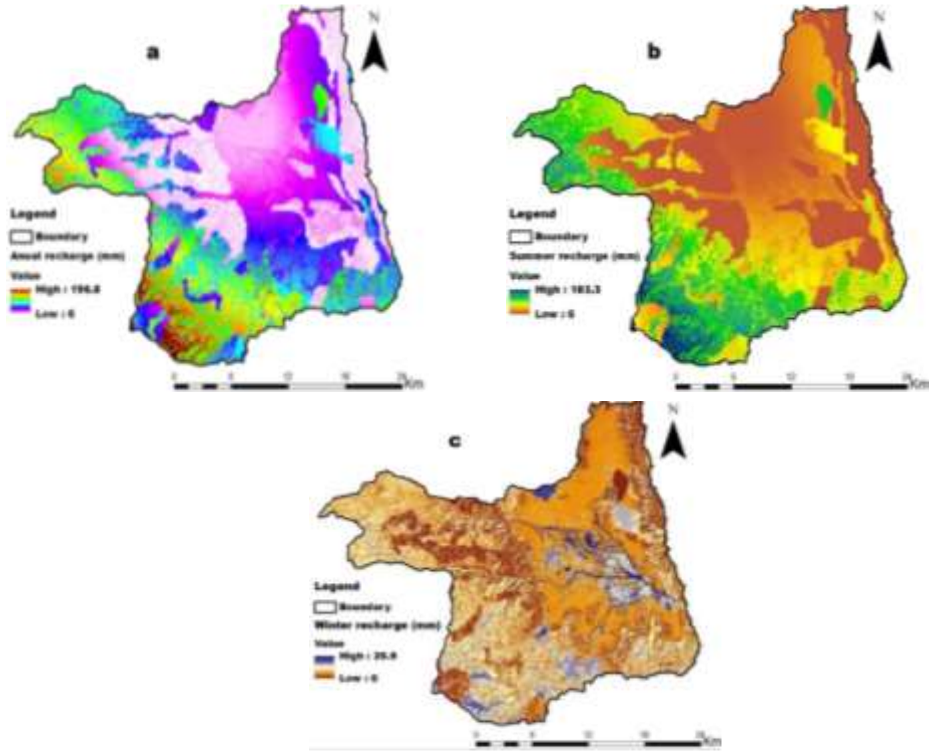

Figure 2. Ground water recharge map of Hormat-Golina sub basin.

Water Balance Components

The simulated results indicated that evapotranspiration is responsible for approximately 68% of precipitation loss, which is higher in water courses and shrub areas (sandy loam and silty loam soils) with values of evapotranspiration ranging from 342.1 to 758.9 mm/year (Figure 3c) with a mean value of 461 mm/year and the seasonal average evapotranspiration was estimated to be 183.7 and 334.9 mm for the winter/dry/ and summer/wet/ seasons, respectively.

For the dry season, the minimum and maximum values of evapotranspiration were 111.6mm and 284.6mm (Figure 3a), while for the wet season, the minimum and maximum value ranged from 210.8mm to 489.4mm (Figure 3b). Given the area of the sub basin (698.25 km^2), the average annual evapotranspiration (461 mm) is equivalent to 3.22*108 m^{3}year-1. Evapotranspiration losses are significant due to high radiation in the watershed, higher surface temperatures, and dry winds.

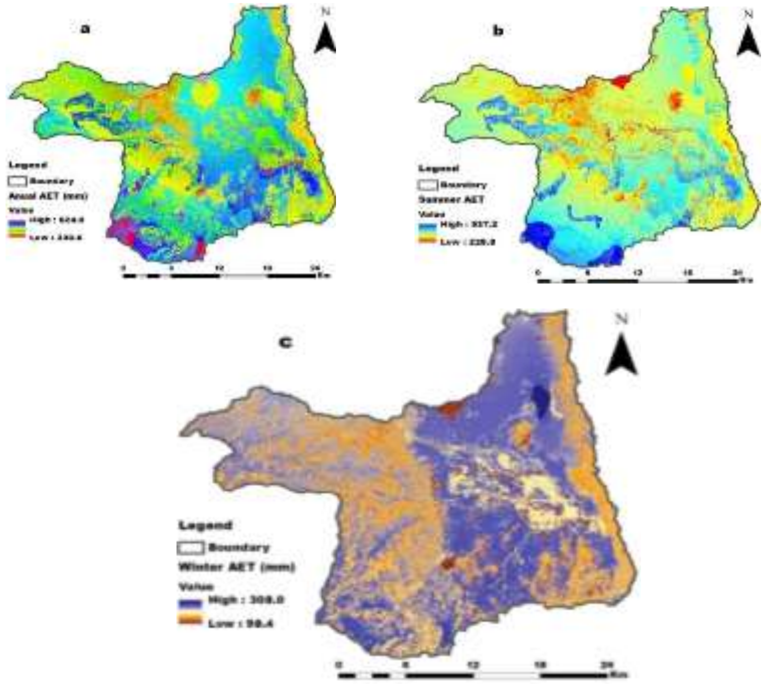

Figure 3. Actual evapotranspiration from Hormat-Golina sub basin.

The presence of vegetation, soil, and the slope of the watershed are the main factors that affect surface runoff [11]. Figures 4 (a–c) show spatially explicit annual and seasonal values of surface runoff simulated by the model and compared with annual precipitation shown in Figure 4. Seasonal and annual average values of surface runoff are also given in Table 3.

Table 3 also lists seasonal and annual average values of surface runoff. Surface runoff during the main rainy season from June to September is 33.7 to 164.0 mm, with a mean of 104.3 mm (Figure 4b), during the long dry season it is 28.8 to 160.7 mm, with a mean of 100.6 mm (Figure 4a), and for the year it is 62.5 to 343.1 mm, which is 27% of the long-term mean annual precipitation of 756.85 mm (Figure 4C). Since biophysical and hydro-meteorological parameters fluctuate with the season and are strongly coupled to rainfall amount, surface runoff is greater in summer than in winter. Based on the area of the watershed (698.25 km^2), the annual surface runoff (204.9 mm) is equal to 1.43*108 m^3 year-1

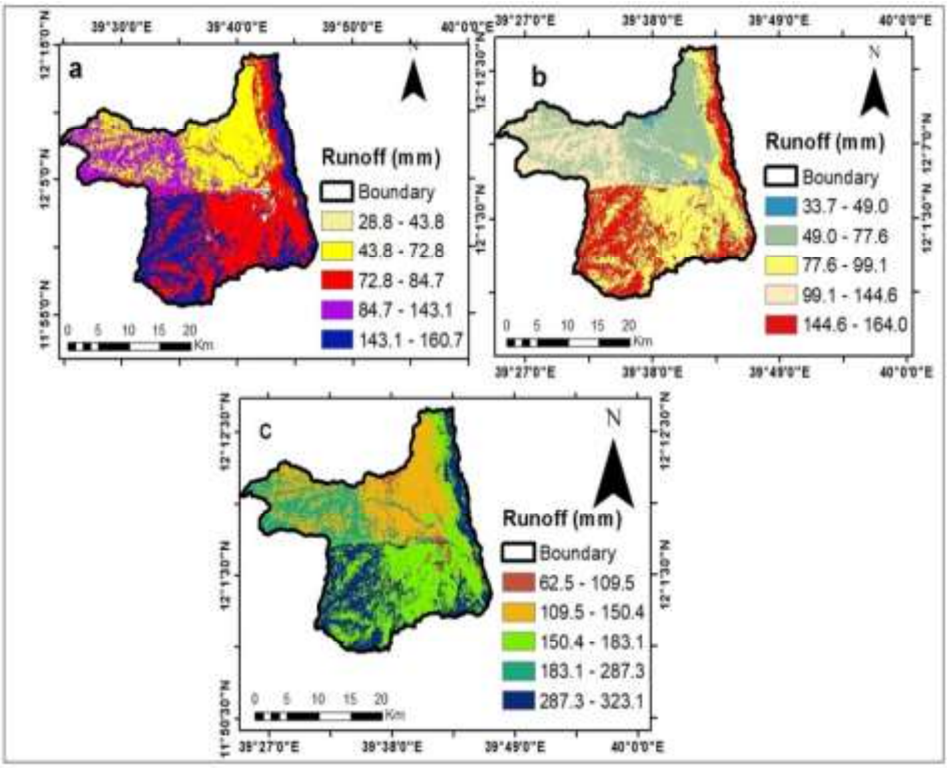

Figure 4. Surface runoff from Hormat-Golina sub basin.

CONCLUSION

Groundwater recharge of the Hormat-Golina sub basin was evaluated using Coupled WetSpass and MODFLOW, which takes into account all meteorological, hydrological, and biophysical factors in the area. Hydro-meteorology, land use, soil texture, topography, and slope of the area were analyzed in order to estimate groundwater recharge and other water balance components of the watershed. According to the model, the annual groundwater recharge for Hormat-Golina is 6.6 and 140.7 mm, with a mean of 35.6 mm, which accounts for 4.7% of the annual rainfall. The recharge was 64% (22.8mm) in summer (June to September) and the remaining 36% (12.8mm) in winter (October to May). The annual actual evapotranspiration in the Hormat-Golina sub basin varies between 342.1mm and 758.9mm, with an average value of 516.6mm, which is 68% of the total rain fall (756.85mm). 64% (334.mm) of the annual actual evapotranspiration falls during the wet season, while the remaining 36% (183.7 mm) falls during the dry season. The runoff from the model was 62.5 to 343.5 mm per year with an average of 204.9 mm per year, which is 27% of the total annual precipitation (756.85 mm), of which 51% (104.3 mm) was during the wet season and 49% (100.6 mm) was during the dry season. Groundwater management has found a range of acceptable pumping rates with a higher recharge rate, and excessive groundwater exploration from the unconfined aquifer has damaged future sustainability. Future groundwater resource development plans in the valley should take into account the recharge rate and the projected abstraction rates for both agriculture and domestic water supply to ensure the long-term viability of the groundwater resource.

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