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Catchment characterization for water resource monitoring and management, Upper Awash Basin, Ethiopia

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ABSTRACT

This study implements Digital Elevation Model (DEM) of Ethiopia to delineate the catchment, to develop the topographic map and slope map of the study area. Enhanced Thematic Mapper Plus (ETM+) satellite imagery was used to develop land use classification of the catchment; also the soil map of the study area was prepared from data-base of the Northeastern African countries. Finally the hydrologic characteristic of the catchment such as annual groundwater recharge, surface runoff and evapotranspiration was estimated through a grid-based physically distributed model, WetSpass. This method was tested in a 2,20200ha catchment with dominant agricultural lands where Settlement is actively increasing. The land cover classification has an overall accuracy of 96.8%. Agriculture 49.3%, grassland 16.5%, Tree & Shrub 15%, Water body 7% and Settlement 11% are the most dominant land cover within the catchment. The catchment is covered with four different soil textural classes, 54% of silty clay, 34% of silty loam, 8% of clay and 4% of loam soil. The hydrologic characteristic of the catchment in this study demonstrates spatial annual rainfall distribution as surface runoff (17.6%), evapotranspiration (73.5%), and groundwater recharge of (8.9%). The catchment characterization result in this study can be utilized by scientific community, policymakers, donors, non-governmental organizations, and other development practitioners to deliver the right policy and programs for water resource monitoring and management in the study area.

Keywords: Characterization; Catchment; Hydrologic; Evapotranspiration; Landuse; Recharge; Water Resource; Surface Runoff; DEM; ETM+.

1. Introduction

Knowledge of the hydrological conditions of an area are of great importance for decisions on water management. Catchment characteristics such as geometry, morphometry, land cover, and soil are important bases for the description of catchments and estimation of hydrological conditions using hydrological models. Catchment descriptors provide useful insights into similarity of catchment structure and are widely used to classify catchments into homogeneous groups (Sawicz et al., 2011; Merz et al., 2020b). Correspondingly, they are often instrumental in transferring information about the way catchments function, i.e., how they partition, store and release water (Wagener et al., 2007) from gauged to ungauged locations (Hrachowitz et al., 2013). Most importantly, catchment descriptors are key for generalization and transferability of local findings to other places and to larger spatial scales, and they facilitate the search for hydrological regularities (i.e., patterns that explain the variability of catchment response).

Remote sense is one technology that has been valuable in cleanup efforts and shows promise in providing an alternative to field sampling methods (Slonecker et al., 2010) and in identifying land use information (Singh et al., 2014). The temporal, spatial, and spectral advantage of remotely sense imageries can provide fast and repeated observations, which are the prerequisites in environmental monitoring. The most basic use of these remotely sensed (RS) data for environmental monitoring involves visual image interpretation (Slonecker et al., 2010), terrain modeling and analysis (Gorokhovich et al., 2006) and spectral analysis (Horta et al., 2015). Shuttle Radar Topographic Mission (SRTM), for example, has created an unparalleled data set of global elevations that are freely available for modeling and environmental applications (Gorokhovich et al., 2006). Catchment descriptors are typically obtained by aggregating Geo-spatial data-sets such as digital elevation models or land use maps into a scalar value. Hence, in this study, RS-derived products like digital elevation models (DEMs), Enhanced Thematic Mapper Plus (ETM+) and soil map are used for catchment modeling and characterization.

1.1. Study Objectives

- ✓ To articulate the classification of geometry, morphometry and land use of the catchment.
- ✓ To determine the Spatial characteristics of the catchment.
- ✓ To develop spatial and hydrologic map of the catchment.
- ✓ To describe the catchment using hydrological models.
- ✓ To determine the hydrologic characteristic of the catchment.

2. Material and Methods

2.1. Description of Study Area

This study was conducted at upper Awash Basin on the catchment area of 2,20200ha. The catchment is bounded within 8°75'N-9°05'N latitude and 38°56'E -39°17'E longitude. Elevation for the catchment ranges from 1594 to 3068 meter above mean sea level. The area has a bi-modal rainfall with a short rainy season. The mean annual temperature of the catchment is 19°C and the average annual rainfall is 936 mm. The relief of the study area is generally flat land with an undulation of some ridges and mountains and the catchment generally shows an eastward decrease in elevation. Regarding geological setup, the area belongs to the Quaternary rocks of Pleistocene and Holocene which is 70% quaternary volcanic rock and 30% unconsolidated sediment.

2.2. Data Preparation

The foremost important activity in the hydrological catchment characterization task is the delineation of the catchment boundary. Longitude and latitude were the bases to limit the area of interest during acquiring the DEM files from SRTM and delineate of the catchment was carried out using ArcGIS10.2 tool. The data required to do catchment simulation with WetSpass are, the climatic data (precipitation, reference evapotranspiration, temperature and wind speed), the catchment configuration data (groundwater depth, slope, elevation, and land use), soil data and boundary conditions (extent of area to be modeled). Thus as a first step, a mask map should be prepared from the delineated catchment based on the DEM.

2.2.1. Catchment Spatial Data

Digital Elevation Model (DEM) of Ethiopia was obtained from the Shuttle Radar Topography Mission (SRTM), to delineate the catchment, develop the topographic map and slope map of the study area, Enhanced Thematic Mapper Plus (ETM+) satellite imagery from the Landsat Organization home page was downloaded to develop land use classification of the study area; and soil map data-base of the Northeastern African countries that is prepared by the Food and Agricultural Organization (FAO) of the United Nations to prepare the soil map of the study area.

2.2.2. Hydrologic Data

A. Precipitation

Among eight rainfall stations in the catchment; six stations which have sufficient data were selected and used for this study. Long year records of daily rainfall values were computed and average precipitation of each station data were interpolated and prepared to use in the catchment characterization (see table 1).

Table 1. Mean annual precipitation [mm] from rain gauge stations

	Cefedonsa	D/zeyit	Modjo	Hombole	Koka	Ejere
Rfall (mm)	1145	937	922	762	849	985

B. Temperature

The mean monthly temperature of twenty-eight years (1989-2016) was taken from National Meteorological Agency for six selected stations within the study area; average temperatures of each station were computed as shown on the (Table 2).

Table 2. Mean temperature [^{o}C] for six stations within the catchment

S.No	Station	Elevation (m)	Mean T[^{o}C]
1	Cefedonsa	2400	16
2	D/zeyit	1943	18
3	Modjo	1783	19
4	Hombole	1670	19
5	Koka	1597	17
6	Ejere	2233	20

C. Evapotranspiration

In this study, Instat version 3.1 software has been used to compute the reference evapotranspiration (Eto); using the daily maximum and minimum temperatures, daily precipitation, relative humidity, wind speed and solar radiation by applying FAO-Penman-Monteith equation. Finally, average evapotranspiration was taken from each station.

Table 3. Average ETo (mm/day) for each station in the catchment

Station	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Cefadonsa	4.8	5.4	5.7	5.9	6.0	5.8	5.2	5.1	5.2	5.4	5.1	4.8
D/zeyit	5.3	5.8	6.1	6.5	6.3	5.7	5.1	5.0	5.3	5.8	5.5	5.2
Modjo	5.2	5.7	6.0	6.5	6.5	6.4	6.0	5.7	5.7	5.8	5.5	5.1
Ombole	5.4	6.0	6.1	6.6	6.5	6.4	6.0	5.6	5.3	5.8	5.4	5.3
Koka	5.1	5.7	5.8	6.2	6.3	6.2	5.6	5.2	5.0	5.4	5.3	5.0
Ejere	4.9	5.2	6.0	6.5	6.7	6.9	6.7	6.2	6.0	5.7	5.3	4.9

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3. Result and Discussion

3.1. Spatial characteristics of the catchment

3.1.1. Soil type

The sub-basin is covered with four different soil textural classes, 54% of silty clay, 34% of silty loam, 8% of clay and 4% of loam soil. The soil map of the catchment used in the characterization is shown in Figure 1 as below.

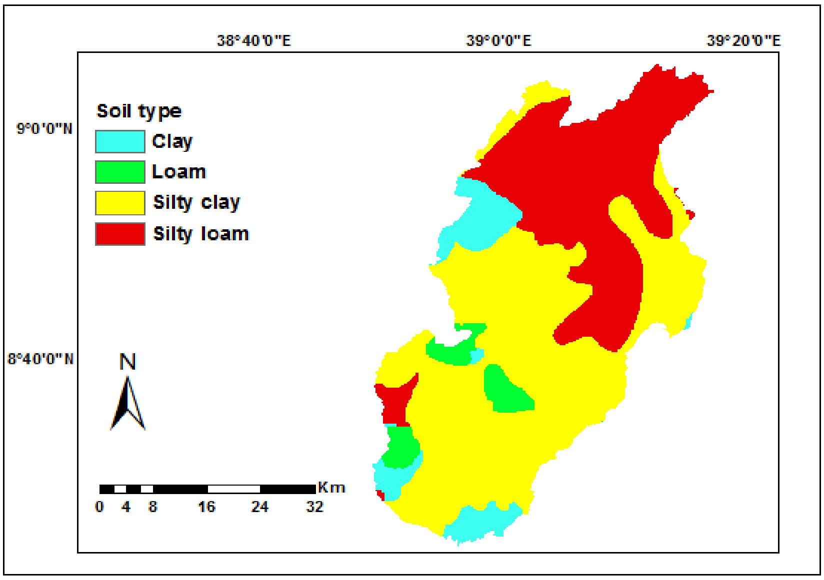

Figure 1. Dominant soil textural class of the catchment

3.1.2. Topography

Altitude in the basin increases from south to north and from west to east. The lowest point in the basin located in the western edge and the highest in the north. The mean elevation of the basin is 2030 m with a standard deviation of about 273 m. This considerably large standard deviation explains the fact that the topography is rugged. Figure 2 is the topographic grid map of the study area used in the catchment characterization.

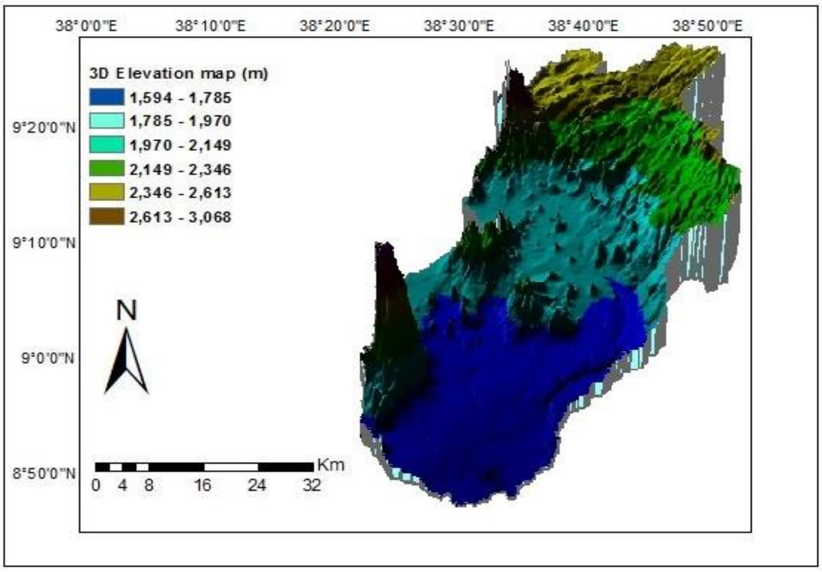

Figure 2. Topographic map of the catchment

3.1.3. Slope

The slope ranges from 0 to 52%, with 3% mean, 3% and 4% standard deviation respectively. Most of the agricultural area lies within the slope of 3-10%.

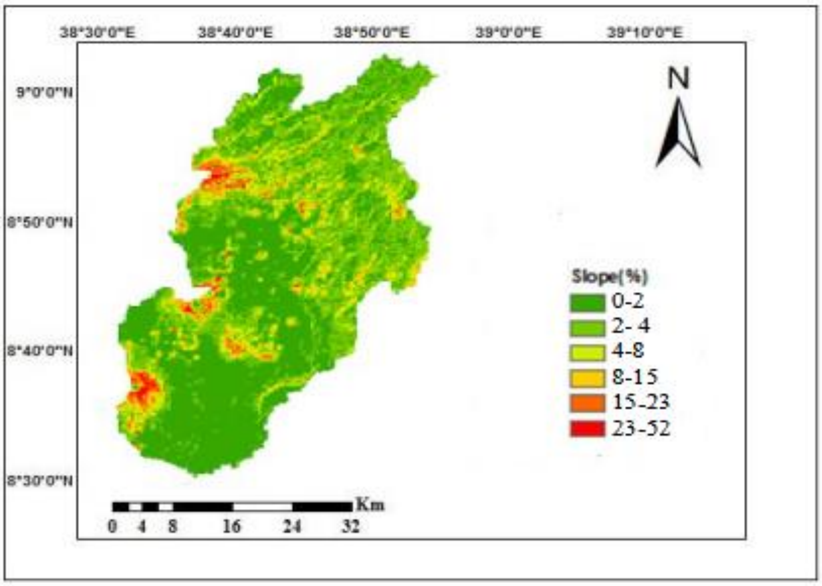

Figure 3. Slope map of the catchment

3.1.4. Land use/land cover

Enhanced Thematic Mapper Plus (ETM+) satellite imagery was used to develop land use classification of the catchment. Images for the study area were downloaded at *path68 rows 53 and 54* acquired on the 27th of January land use. ArcGIS10.2 were used to process the satellite image and the identity of each class is determined by the combination of experience and ground truth. The land cover classification has an overall accuracy of 96.8%. Agriculture 49.3%, grassland 16.5%, Tree & Shrub 15%, Water body 7% and Settlement 11% are the most dominant land cover within the catchment.

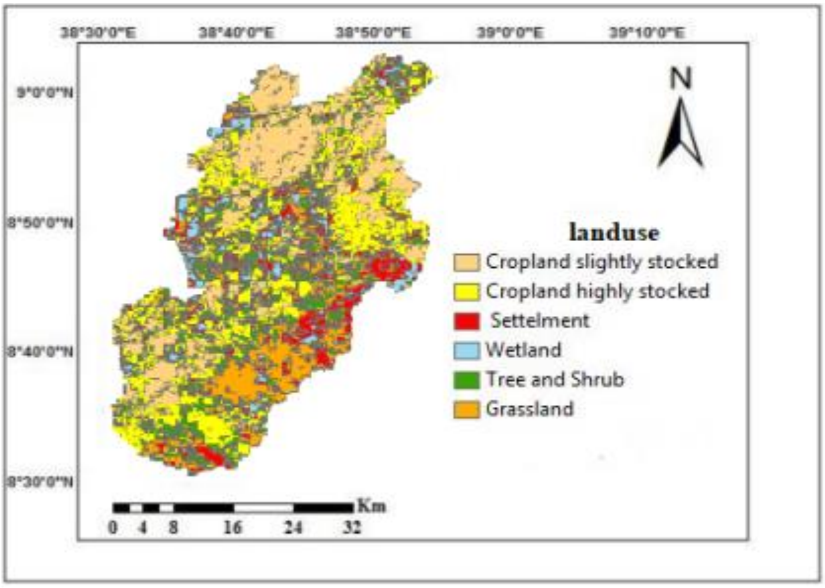

Figure 4. Land use/land cover map of the catchment

3.2. Hydrologic characteristic of the catchment

3.2.1. Areal rainfall distribution

For computation of areal rainfall, Theissen polygon method was used in ArcGIS environments and the weights developed for the catchments are presented in Table 4.

Table 4. Theissen gauge weights for the catchment

S. No.	Rainfall stations	Area weight (km^2)	weight
1	Chefedonsa	450	0.20
2	Debrazeyit	694	0.32
3	Modjo	510	0.23
4	Koka	173	0.08
5	Hombole	142	0.06
6	Ejere	233	0.11

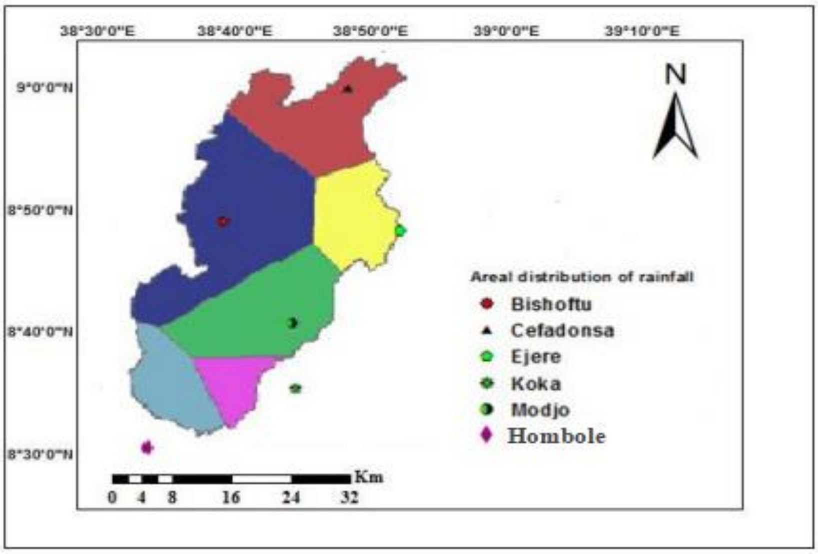

Figure 5. Theissen polygon developed for the catchment

3.3. Water Balance Analysis

Water balance represents the hydrological gains and losses of a given system. In this study, WetSpass model was applied and the total water balance of a raster cell was calculated. The total water balance for a raster cell in WetSpass model is split into independent water balances for the vegetated, bare-soil, open-water and impervious parts of each cell. The processes in each part of a cell are set in a cascading way, that an order of occurrence of the processes, after the precipitation event, is assumed.

$$Rv = P-Sv-ETv-Es-I \qquad (1)$$

Where: (Rv) recharge, (P) precipitation, (Sv) surface runoff (ETv) Evapotranspiration, of a raster cell.

3.3.1. Evapotranspiration

The WetSpass model calculates the total actual evapotranspiration as a sum of the evaporation of water intercepted by vegetation, the transpiration of the vegetative cover and the evaporation from the bare soil between the vegetation. The simulated average minimum and maximum annual evapotranspiration of the catchment were 359 mm and 952 mm, respectively with 686 mm mean and standard deviation of 141 mm.

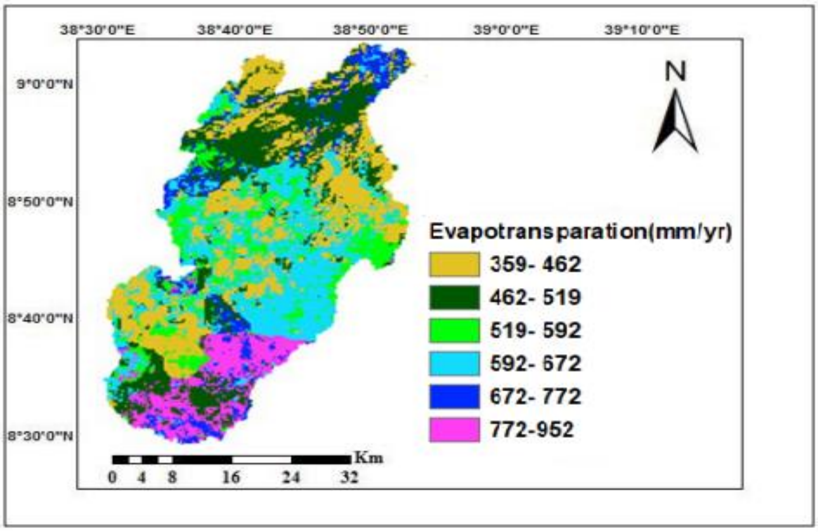

Figure 6. Simulated annual evapotranspiration for the catchment

The average evapotranspiration accounts for 73.5% of the total annual rainfall. This shows that evapotranspiration is the main processes by which water lost in the catchment. This is attributed to the high rates of radiation and the persistence of strong dry westerly winds coming from the Awash depression. The evapotranspiration is largely determined by solar radiation, which is fairly constant for different years. According to Behailu (2007), the annual potential evapotranspiration of upper Awash catchment is about 650.33 and 789.47 mm with Thornthwaite and Turc method respectively. Thus 952 mm maximum and 686 mm average annual potential evapotranspiration, simulated by for the catchment, is reasonable.

3.3.2. Surface runoff

According to Batelaan (2007), surface runoff is dependent on the availability of vegetation, soil type and slope of the sub-basin. Hence the surface runoff of the catchment varies spatially with topography and other catchment characteristics. Rugged topography and dominance of silty clay, silty loam soil type produced the high runoff in the catchment (Figure 7). This is due to a lower concentration-time of overland flow for rugged topographic surface and the lesser infiltration capacity of the soil type. The simulated annual runoff varies from 83 mm to a maximum of 341 mm with a mean and standard deviation of 164 mm and 66.89 mm, respectively. This accounts for about 17.6% of the total annual precipitation. Average annual surface runoff for the catchment has been calculated (361Mm^3). The rainfall exceeds the infiltration capacity of the soil during the wet season, this leads to high surface runoff. Behailu (2007), applied runoff coefficient method and revealed that the annual surface runoff of Upper Awash catchment of an area of 2202 km^2 is 130 mm. Thus 83 mm minimum and 341 mm maximum annual surface runoff, simulated by WetSpass for catchment, seems reasonable.

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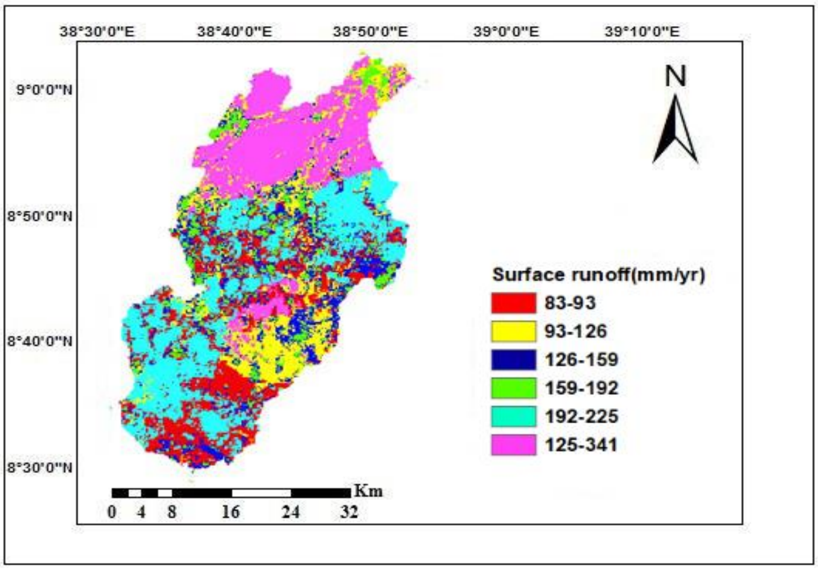

Figure 7. Simulated annual surface runoff for the catchment

3.3.3. Groundwater recharge

Recharge is promoted by natural vegetation cover, flat topography, permeable soils, a deep water table and the absence of confining beds. The WetSpass model determines the long term average spatially distributed recharge as a spatial variable dependent on the soil texture, land use, slope and meteorological conditions. The resulting groundwater recharge from WetSpass for the present land use classes ranges from 274 mm/yr to 0 mm/yr as indicated in Figure 8, with an average value of 83 mm/yr, which is about 8.9% of the mean annual precipitation.

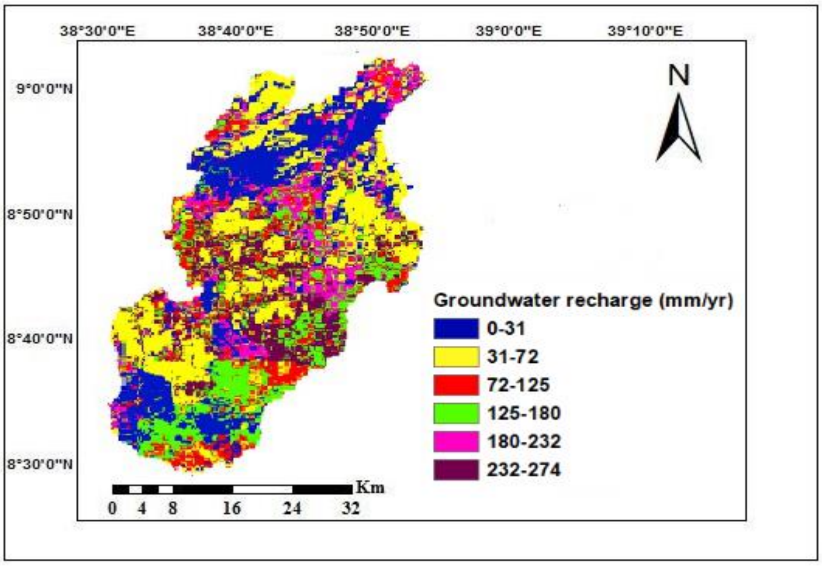

Figure 8. Simulated annual groundwater recharge for the catchment

An average of 183 Mm^3 of groundwater will be recharged per year or 5,802 l/s for entire catchment. For the study conducted on groundwater potential of Ada'a Becho plain using water balance method, annual groundwater recharge contributed from Modjo River to Ada'a Becho plain is 85 mm and 153 Mm^3 (Semu, 2012), which is almost comparable with WetSpass result. Therefore, the result simulated by WetSpass for the catchment is within the previous study range and was found reasonable. WetSpass simulation result gives additional information through mapping and indicating the spatial distribution of groundwater recharge, whereas other method mentioned above gives only total recharge of the catchment.

4. Conclusion and Recommendations

Knowledge of the hydrological conditions of an area are of great importance for decisions on water management. Catchment characteristics such as geometry, morphometry, land cover, and soil are important bases for the description of catchments and estimation of hydrological conditions using hydrological models. This study implements Digital Elevation Model (DEM) of Ethiopia to delineate the catchment, to develop the topographic map and slope map of the study area. Enhanced Thematic Mapper Plus (ETM+) satellite imagery was used to develop land use classification of the catchment; also the soil map of the study area was prepared from data-base of the Northeastern African countries. Finally the hydrologic characteristic of the catchment such as annual groundwater recharge, surface runoff and evapotranspiration was estimated through a grid-based physically distributed model, WetSpass. This method was tested in a 2,20200ha catchment with dominant agricultural lands where Settlement is actively increasing. The land cover classification has an overall accuracy of 96.8%. Agriculture 49.3%, grassland 16.5%, Tree & Shrub 15%, Water body 7% and Settlement 11% are the most dominant land cover within the catchment. The catchment is covered with four different soil textural classes, 54% of silty clay, 34% of silty loam, 8% of clay and 4% of loam soil. The hydrologic characteristic of the catchment in this study demonstrates spatial annual rainfall distribution as surface runoff (17.6%), evapotranspiration (73.5%), and groundwater recharge of (8.9%).

From the results of this study, the following recommendations are made:

- Both hydrologic and spatial catchment characteristics results obtained from this study can be used as a base for future water resources development and improvement for catchment in particular, for soil and water conservation works in general.
- To harvest the simulated annual surface runoff (i.e. 361Mm^3) excess water, it could be advantageous to practice bunds and terraces of soil and water conservation structures (artificial recharge), which is helpful to reduce soil erosion and enhancing more recharge to groundwater.

Declarations

Source of Funding

This research work was funded by the Oromia Agricultural Research Institute, Ethiopia.

Competing Interests Statement

The author declares no competing financial, professional, or personal interests.

Consent for publication

The author declares that he consented to the publication of this study.

Authors' contributions

The author has contributed from proposal development then data collection, data analysis to full write up of the manuscript.

Availability of data and material

All data used for this research are at the hand of the author and can be submitted for the publishing journal editors if necessary.

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