



Aquifer characterization and groundwater budget estimation of the Upper Mille River catchment, Lower Awash Basin, Ethiopia; an integrated approach for groundwater potential evaluation

Amanuel Godie Gigar^{1,2} · Dessie Nedaw² · Belay Molla Sisay^{2,3}

Received: 21 March 2023 / Accepted: 24 January 2024 / Published online: 17 February 2024
© Saudi Society for Geosciences and Springer Nature Switzerland AG 2024

Abstract

The present study is conducted in the Upper Mille River catchment of the Lower Awash Basin in Ethiopia. The main aim of the study is to investigate the groundwater potential of a complex fractured volcanic and unconsolidated Quaternary sediment aquifer system using integrated hydrogeological approaches. To estimate the hydrological components of the catchment, the soil water balance (SWB) method and Soil and Water Assessment Tool (SWAT) modeling techniques are employed. The SWB method and the SWAT model indicate that the long-term average annual groundwater recharge of the catchment is 105 mm and 150 mm, respectively, which accounts for 9.3% and 13.8% of the mean annual precipitation. Conventional hydrogeological investigation techniques are used to evaluate the spatial variability and flow dynamics of the groundwater system, as well as the various natures of the aquifers. Based on aquifer productivity, hydraulic conductivity, transmissivity, and discharge values, the aquifer system is classified into three different hydrogeological units: a highly productive intergranular aquifer, a medium productive fractured aquifer, and a low-productive aquifer. Lithological logs of deep boreholes, pumping test results, stratigraphic settings, water balance components, and the topographic position of each unit are also used to classify the aquifers. Schematic hydrogeological cross-sections, total dissolved solid (TDS) and electrical conductivity (EC) distribution maps, and groundwater head distribution contour maps are produced using lithological logs of drilled deep boreholes, field-measured inventory water points, and water level measurements, respectively. Based on converging evidence from geological, hydrogeological, and topographic settings, a conceptual model that approximates the groundwater system of the Upper Mille River catchment is developed, and the groundwater potential of the catchment is evaluated.

Keywords Aquifer characterization · Groundwater potential · Upper Mille River · SWAT · Soil water balance

Introduction

Ethiopia is believed to possess a significant amount of groundwater resources that can be utilized for domestic, industrial, and agricultural purposes, but its distribution is not uniform across the country mainly because of the geological conditions (Ayenew et al. 2008, Mengistu et al. 2019). The availability of high rainfall, as well as favorable environmental conditions such as topography and climate, might be contributing factors to the abundance of groundwater resources in Ethiopia. According to Kebede (2012), Ethiopian aquifers can be classified into four major types: sedimentary, volcanic, metamorphic, and unconsolidated sedimentary aquifers. The volcanic aquifer is the most prevalent type, covering most of Ethiopia's

Responsible Editor: Amjad Kallel

✉ Amanuel Godie Gigar
amanuelyd2010@gmail.com

Dessie Nedaw
dessie.nedaw@aau.edu.et

Belay Molla Sisay
belaymolla2009@gmail.com

¹ Department of Geology, Wollo University, Dessie, Ethiopia

² School of Earth Sciences, Addis Ababa University, Addis Ababa, Ethiopia

³ Department of Geology, Debre Berhan University, Debre Berhan, Ethiopia

landmass, with a highly diverse composition and stratigraphic structure due to geological processes (Ayenew et al. 2008, Yitbarek 2009).

Fresh groundwater is a critical resource that is highly valued for its quality, year-round availability, and location near areas of demand. Unfortunately, many regions are experiencing depletion or contamination of groundwater due to over-pumping and other anthropogenic activities (Gorelick and Zheng 2015). In Ethiopia, despite having abundant groundwater resources, freshwater scarcity is a significant problem in many regions, and it is expected to worsen in the future due to population growth and economic development (Abraha et al. 2022). Additionally, climate change may exacerbate water scarcity by altering precipitation patterns and increasing evapotranspiration.

Some parts of the Upper Mille River catchment were studied by Demlie (2002) which focused on the hydrology and hydrochemistry of the Hayk-Hardibo lakes system. The study identified two major hydrostratigraphic units – Quaternary unconsolidated sediments and fractured volcanic rocks – both with good permeability and transmissivity. However, the volcanic units are considered poor aquifers due to their morphological setting but serve as good recharge zones for the Quaternary unconsolidated sediments that occupy low-lying flat areas in the studied catchment (Saele 2001).

The Ethiopian Rift's volcanic aquifers have complex groundwater flow, recharge, and geochemical evolution. The geological architecture of the interface zone between the high rainfall region in the plateau and the rift floor aquifers is the single most important factor that controls groundwater flow continuity (Kebede et al. 2008).

The Upper Mille River catchment has a diversified geology, geomorphology, structure, and climatic conditions, making it a complex hydrogeological system. Despite its complexity, no detailed study on the characterization of the hydrogeological behavior of the catchment is available. The mechanism of groundwater flow, productivity level of aquifers, and groundwater head distribution remain unknown. It is also extremely important to know the extraction rate for the sustainable use of groundwater resources. The occurrence, distribution, and movement of water vary greatly depending on the nature of surface and subsurface materials, and the existing geological structures.

As a result, the main aim of this study is to address and improve the hydrogeological understanding of the study area by paying special attention to the estimation of groundwater recharge, characterization of the aquifer system, and groundwater flow mechanism. Generally, converging evidences are used to evaluate and assess the groundwater potential of the catchment.

In this study, the groundwater recharge and other components of the water balance were properly quantified using two techniques – Soil Water Balance (SWB) method and

Soil and Water Assessment Tool (SWAT). The SWB method provided an average estimate of groundwater recharge for the catchment, whereas the SWAT model (Arnold et al. 2012) was used to evaluate the surface water resources of the catchment and estimate the semi-distributed groundwater recharge to the aquifer.

On the other hand, a field inventory of different groundwater and surface water points, along with secondary pumping test data and previous hydrogeological reports, is utilized to effectively classify the aquifers into distinct hydrostratigraphic zones. This process also serves to characterize the hydraulic properties of the aquifer system, develop a conceptual hydrogeological model, and determine the groundwater flow condition of the catchment.

Study area description

Location and biophysical characteristics

The Upper Mille River catchment is situated on the western margin of the Main Ethiopian Rift (MER) and is part of the lower Awash basin. It lies at the border between the Amhara and Afar regional states, as shown in Fig. 1. In absolute terms, it is entirely enclosed in Universal Transverse Mercator (UTM) Zone 37P, between 0557969 and 0595777 east and 1236452–1300230 north, comprising a total area of 1360 km².

The topography of the catchment area, as shown in Fig. 2, is highly variable, with elevations ranging from 1120 to 3640 m above sea level. It is characterized by flat-topped plateaus and undulating terrain, with large volcanic mountains forming water divides and acting as regional groundwater recharge zones. The major rivers and their tributaries have carved deep canyons and gorges into the highlands, creating steep and narrow river valleys.

The slopes of the study area were classified into five classes: 0–5, 5–15, 15–25, 25–35, and 35–76 degrees (Table 1). The slope classification map (Fig. 3, left) indicates that the majority of the area falls between 15 and 25 degrees. The drainage pattern of the river networks is generally dendritic to sub-parallel (Fig. 3, right), with two well-known natural lakes, Lake Hayk and Lake Hardibo, covering 21 km² and 16 km², respectively. Swampy or wetland areas are also common, particularly near rivers and the two lakes.

Based on the FAO soil group classification, there are four main classes of soil groups (Fig. 4, left): Eutric Cambisols (CMe), Eutric Leptosols (LPe), Eutric Vertisols (VRe), and Lithic Leptosols (LPq). One of the most significant factors affecting a catchment's water resource potential is its land use/land cover (LULC). The watershed's water balance component is extremely sensitive to LULC. It is one of the parameters in the SWAT model that influences the amount

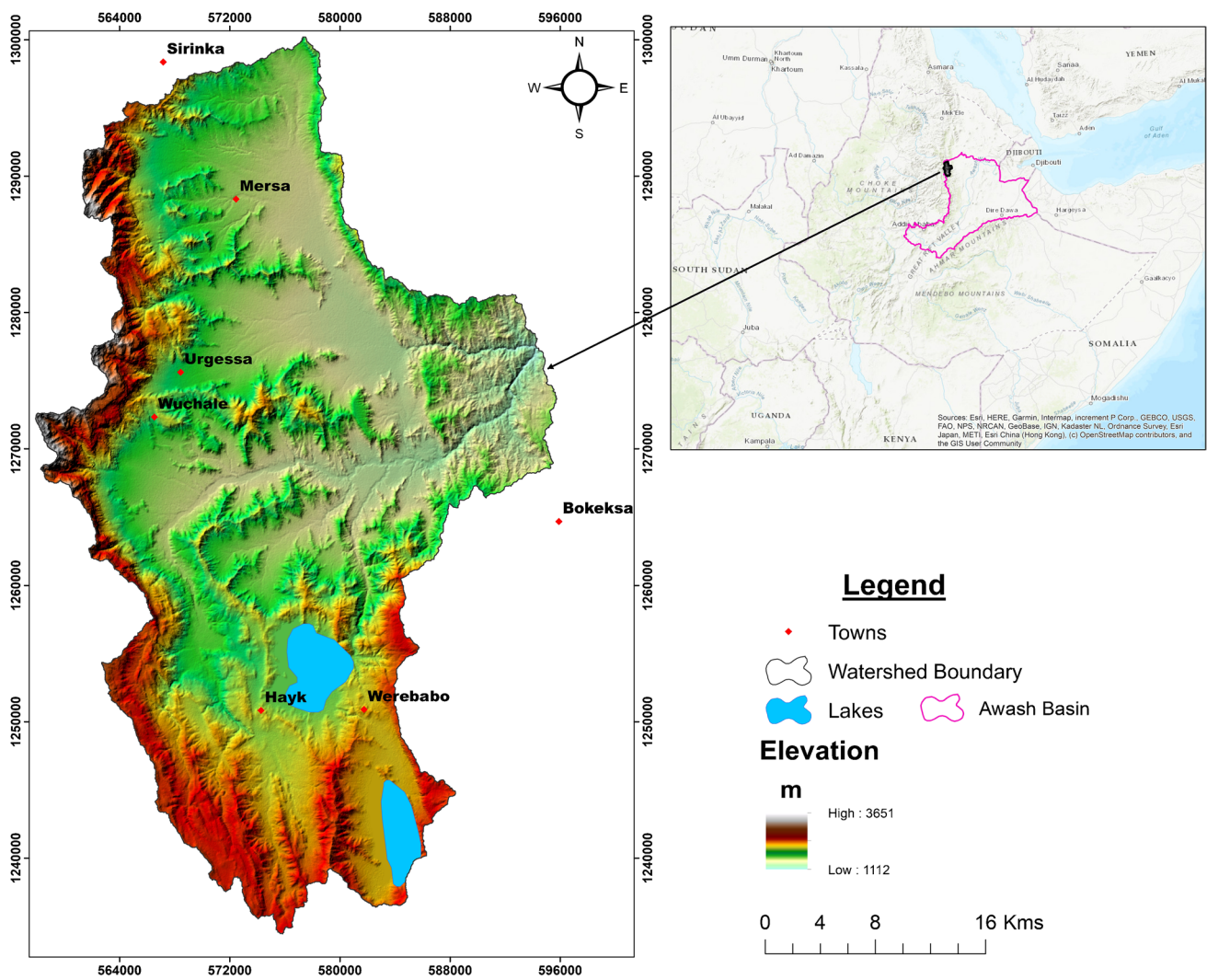


Fig. 1 Location map of the Upper Mille River catchment (DEM is added to show the physiography of the area)

and area of groundwater recharge and runoff generation. The LULC data for the area were obtained from the Sentinel-2 LULC map of Ethiopia with a resolution of 20 m. According to the LULC map (Fig. 4, right), eight land cover classes cover the watershed: cropland, shrub cover areas, grassland, tree cover areas, aquatic or regularly flooded vegetation, built-up areas, bare areas, and open water bodies with different proportions (Table 2).

Geological and hydrogeological settings

The East African rift system comprises two major segments: the Kenyan or Gregory Rift and the Main Ethiopian Rift (MER) (Feyisa 2018). Within the last 200 Ma, the initiation of continental flood basalt (CFB) magmatism is spatially and temporally related to the continental break-up, which results in the oceanic crust formation.

The Oligocene-Miocene felsic volcanic strata (rhyolites and minor trachytes) that cap the flood basalt sequences are well exposed along Ethiopia’s western margin of the southern Red Sea and the northernmost Main Ethiopian Rift (MER). Currently, traps in Ethiopia form high plateaus covering an area of approximately 600,000 km² and resting on either Precambrian bedrock or flat-lying Mesozoic sedimentary rocks (Zwaan et al. 2020).

In order from the oldest to the youngest lithologic unit, plateau basalt, plateau silicic, and shield volcanic have been identified based on the research of many researchers. Older volcanic and unconsolidated Quaternary sediments are the two main types of rock units in the study area (P. Mohr & Zanettin 1988; Williams 2016). From the oldest (Ashange basalt) to the youngest (Tarmaber basalt), the volcanic rocks in the region are lower basalt (Ashange), middle basalt (Aiba), Kemise Rhyolite (Alaji), and upper

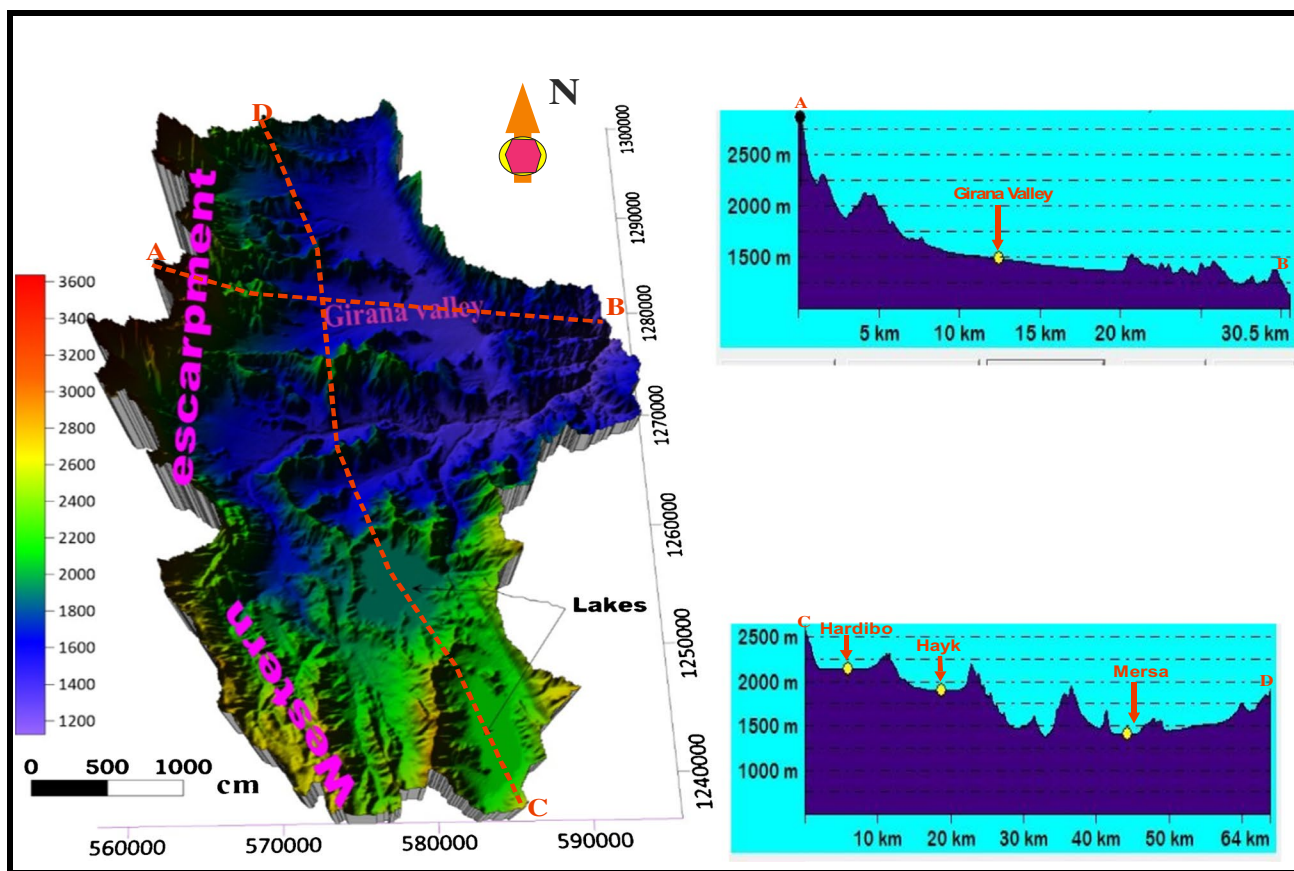


Fig. 2 Physiographic (left) and profile section maps (right) along the lines A-B and C-D of the study area

Table 1 Areal coverage and percentage of slope classification

Number	Slope class (^o)	Area (km ²)	Percentage of area (%)
1	0–5	326.7	24.9%
2	5–15	437.0	33.3%
3	15–25	285.1	21.7%
4	25–35	178.9	13.6%
5	35–76.8	85.8	6.5%

basalt (Tarmaber) (Hagos M. et al. 2016). The top of the volcanic sequences is covered with unconsolidated Quaternary material (Fig. 5).

Litho-hydrostratigraphy

Evaluating an area’s hydrodynamics requires an understanding of the hydraulic properties of rock units and their geometric relationship to adjacent aquifer systems. The hydraulic properties of the basin are highly dependent on the nature and types of rock units and associated primary and secondary geological structures. Volcanic rocks, in

particular, have a complex nature of lava flow that results in aquifers with highly variable primary porosity. After the formation of these rock units, the area has been subjected to weathering and fracturing related to tectonics since it is found on the western escarpment of the Main Ethiopian Rift (MER), which gives rise to secondary porosity. The flow and storage of these volcanic aquifer groundwater systems is the result of double porosity, where both the matrix and the fracture porosity control the productivity of the catchment.

The aquifers in Lower Awash can be broadly divided into two categories: primary porosity aquifers and double porosity aquifers. The first category includes aquifers related to Quaternary alluvial and lacustrine deposits. The second category comprises aquifers related to basaltic volcanics, which are further subdivided into upper and lower basaltic aquifers. These two subcategories are separated by less permeable, along fractured and weathered zones that are otherwise impermeable, acidic volcanic. The alluvial and lacustrine aquifers are found predominantly in the south-east around Girana and Tisabalima towns and locally in the northwestern part of the plain and along the main perennial river courses. The alluvial and lacustrine deposits around

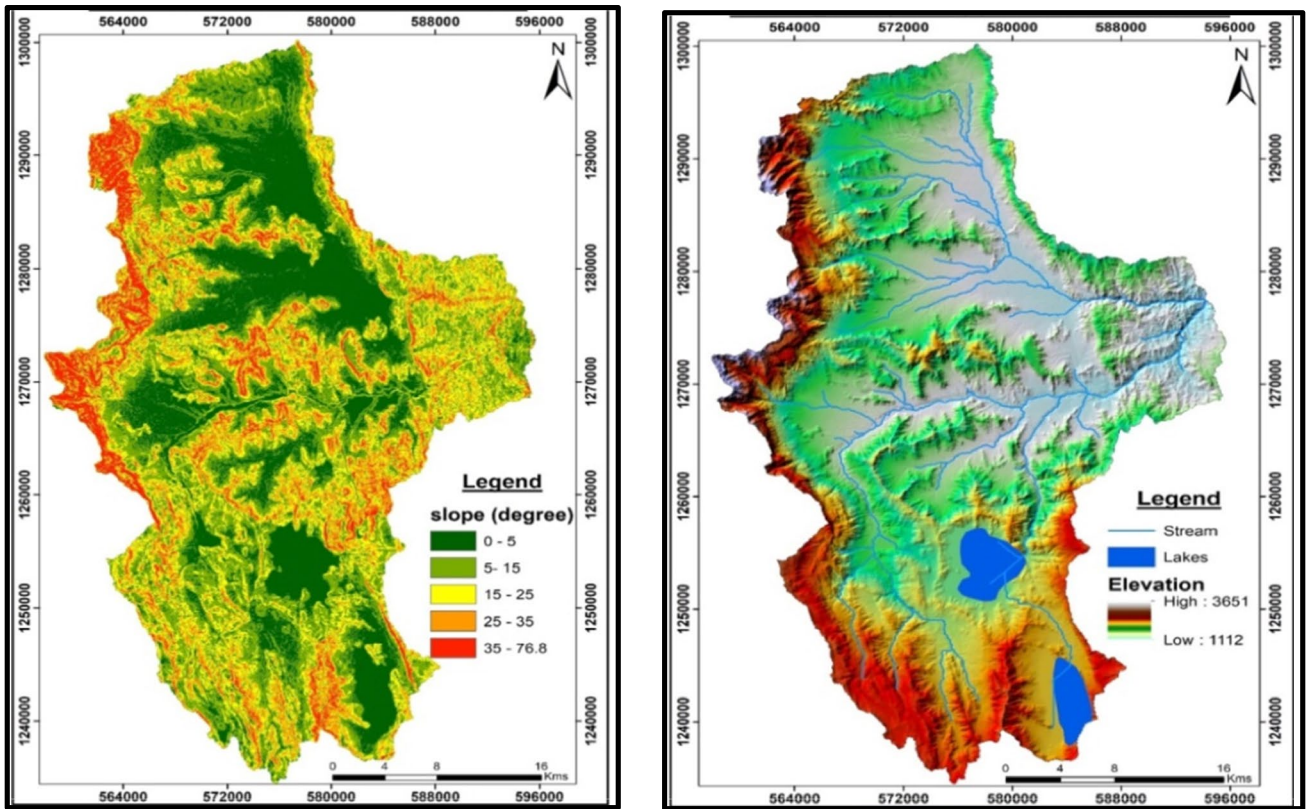


Fig. 3 Slope classification (left) and drainage (right) map of the study area

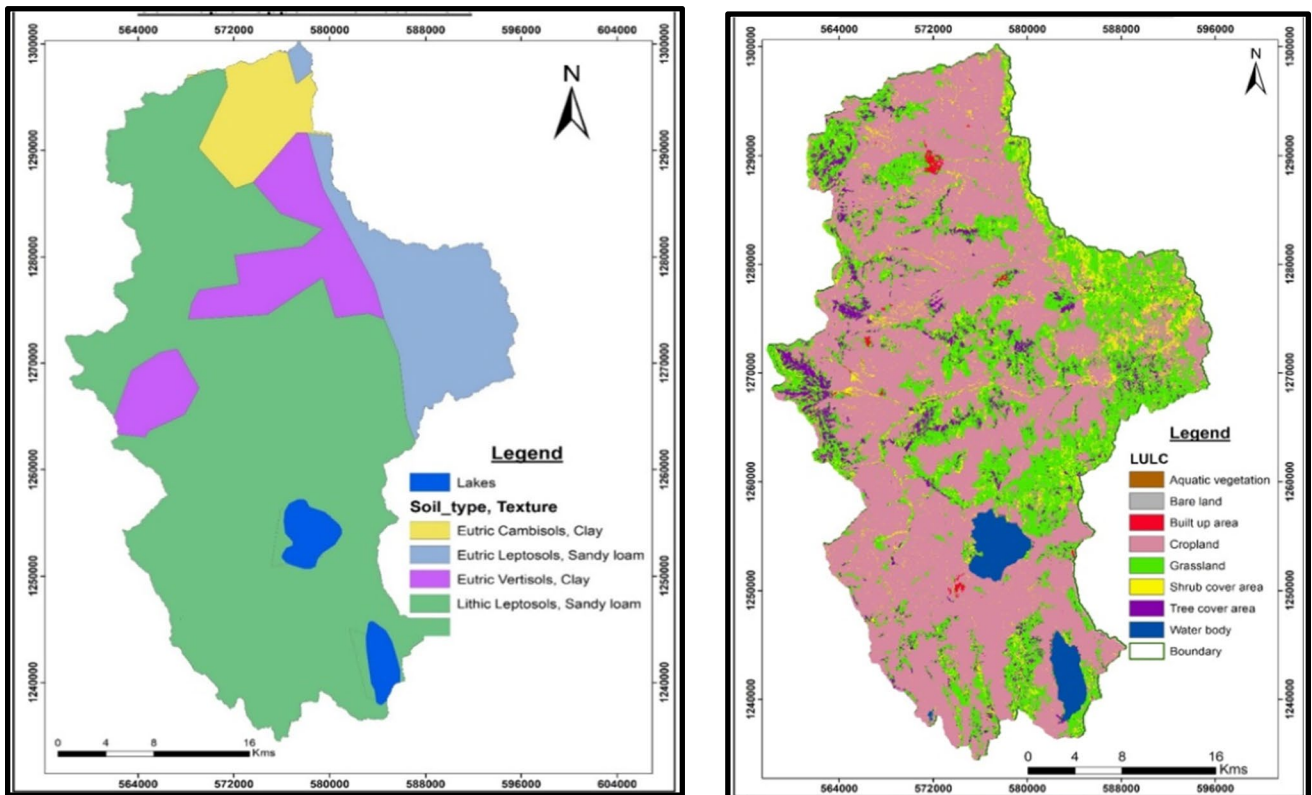


Fig. 4 FAO soil (left) and LULC (right) classification map of the study area

Table 2 Areal coverage and percentage of LULC classification

No.	LULC types	Area (km ²)	%
1	Cropland areas	834.3	61
2	Grassland areas	347	26
3	Shrubs cover areas	75.2	6
4	Tree cover areas	65	5
5	Open Water	34.4	2.5
6	Aquatic/flooded	0.92	0.8
7	Built-up areas	3.82	0.3
8	Bare land areas	0.04	0.003

Girana have a thickness of up to 80 m and are composed of coarse sediments (WWDSE, 2011). Depth to static water level varies from 3 to 45 m. The alluvial aquifers in the southern part have a direct hydraulic connection with the underlying basaltic main aquifer.

Materials and methods

Soil water balance (SWB) method

This study utilized data from seven meteorological stations to analyze the water balance components of the catchment (Table 3). Daily data from the National Meteorological Agency (NMA) for 19 successive years (2000–2018) were used for each parameter. The stations used were Bokeksa, Hayk, Mersa, Sirinka, Urgessa, Werebabo, and Wuchale, all located within and near the area.

Precipitation

To analyze the precipitation conditions of the watershed, daily data from the seven stations were collected. Thiessen polygon maps were constructed, and the precipitation of each station was calculated for that area. Finally, each

Fig. 5 Geological map of Upper Mille River catchment (adopted from GSE, 2015)

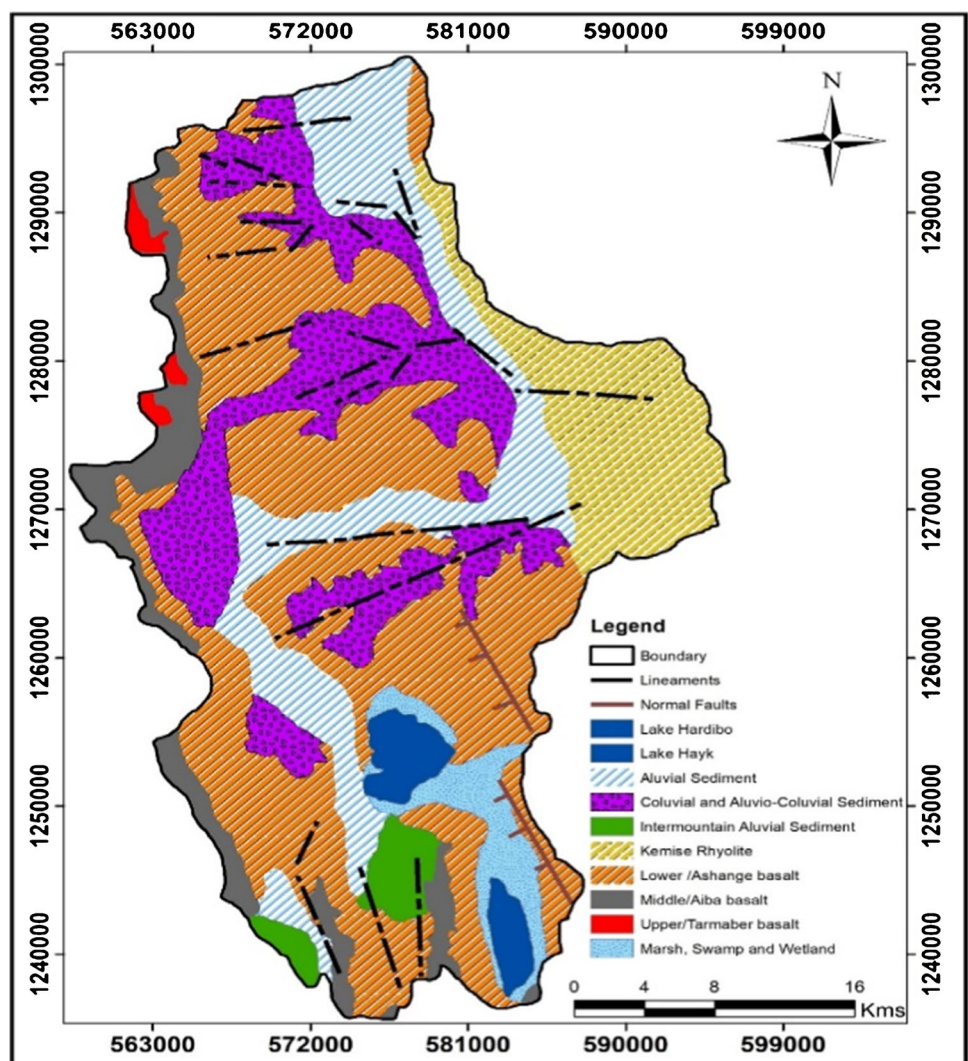


Table 3 Estimation of mean annual precipitation using the Thiessen polygon method

Station	Prec (Pi)	Area (Ai)	Area (At)	Ai/At	Pi*(Ai/At)
Bokeksa	1090.4	184.9	1363.8	0.13563	147.9
Hayk	1193.9	285.3	1363.8	0.20922	249.8
Mersa	988.2	253.6	1363.8	0.18595	183.8
Sirinka	1065.6	44.5	1363.8	0.03264	34.8
Urgessa	1155.8	193.9	1363.8	0.14219	164.3
Werebabo	1172.9	203.1	1363.8	0.14893	174.7
Wuchale	1219.3	198.4	1363.8	0.14545	177.3
Total					1132.6

weighted precipitation was summed to estimate the total average annual and the mean monthly (Table 4) precipitation of the area. As shown below (Fig. 6), a high amount of precipitation is recorded in August.

Temperature

The mean monthly temperature of the area reaches its lowest value in November (16.34 °C) and increases until June (20.41 °C). June is the hottest month, and the area has a mean annual temperature of 18.20 °C (Fig. 6).

SWAT model setup

The SWAT model is a time-continuous, semi-distributed watershed simulator that uses a daily time step (Arnold et al. 2012). The model uses inputs such as DEM, LULC, slope, meteorological data, river flow, and soil data. The watershed is divided into sub-watersheds, which are divided into hydrologic response units (HRUs). The overlapping maps for soil, LULC, and slope serve as the foundation for the semi-distributed SWAT model. Each HRU is made up of particular classes of soil, slope, and land use, and these classes share comparable hydrologic properties. This assumption of homogeneity varies depending on the size of the watershed’s sub-basin. Thus, a threshold region is chosen to identify streams and establish watershed and sub-basin boundaries (Megersa et al. 2019). To simulate the SWAT model, a 30-m-resolution DEM was projected correctly and fed into the Arc SWAT interface. The DEM was masked, and stream networks were built using the supplied DEM. The streams that join the Megenagna and Paso Mille, the two major rivers, were considered when choosing the watershed outlet.

Table 4 Mean monthly precipitation of Upper Mille River catchment

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	39.2	31.1	77.5	99.6	71.7	44.3	253	291.6	116.2	49.6	28.5	24.4

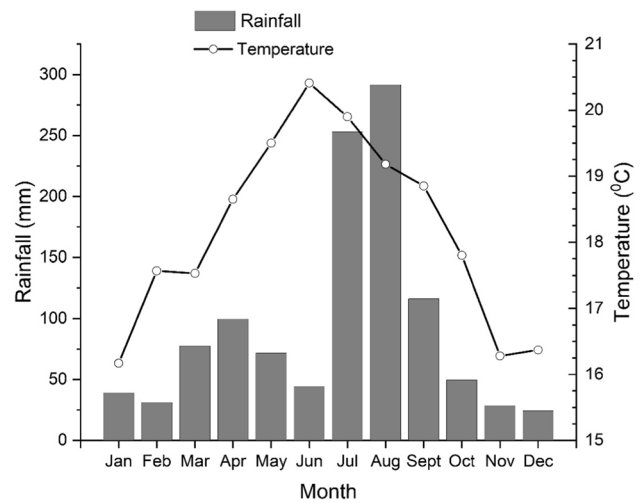


Fig. 6 Mean monthly precipitation and mean monthly air temperature of the catchment

The sub-watersheds and the watershed boundary were then established based on the earlier identified outlet point. The land use/soil/slope definition menu was used to load the LULC map, slope, and soil to define the HRUs. Using proper look-up tables, the slope map was reclassified into 5 classes with various slope value ranges. The soil and LULC maps were also reclassified. By collecting numerous HRUs from each sub-watershed, the HRUs were defined. A threshold of 0% for land use, soil, and slope was chosen in order to maximize the number of HRUs (for higher accuracy). The daily weather dataset was used to write the weather input file. The watershed is divided into 160 sub-watersheds based on each stream, which is further subdivided into 3329 HRUs. Finally, the model run daily from January 1, 2000, to December 31, 2018, and the results were printed on a monthly scale. The water balance component of the watershed is calculated and presented as graphs, tables, and figures.

In general, the study follows the following major activities and approaches (Fig. 7).

Result and discussion

Soil water balance method

Evapotranspiration

To calculate potential evapotranspiration (PET), we used the Thornthwaite, C.W. (1948) method, which involves the following formula.

$$Et = 1.6b \left[\frac{10T_a}{I} \right]^a$$

where Et is the potential evapotranspiration in cm/month, T_a is the mean monthly air temperature in ($^{\circ}C$), b is the latitude correction, and I is the annual heat index.

The mean annual PET (Fig. 8) is calculated to be 821.15 mm/year, with the maximum values occurring in June (87.8 mm/month) and July (83.5 mm/month). Actual evapotranspiration is calculated from PET, and the mean annual AET (Table 5) is 775 mm/year. The lowest average monthly actual evapotranspiration occurs in December and January (Fig. 8) due to a soil moisture deficit.

Surface runoff

Estimation of direct runoff was carried out using the soil conservation services (SCS) curve number method (Ponce and Hawkins, 1996) using the following formula:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

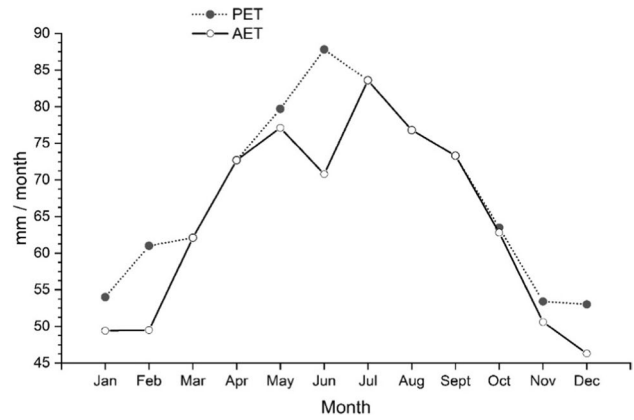


Fig. 8 Mean monthly AET and PET calculated using the SWB technique

where S is the potential maximum retention after runoff begins; Q is the volume of runoff in inches; P is the rainfall depth in inches; thus, the mean annual total runoff of the catchment is 251.5 mm/year.

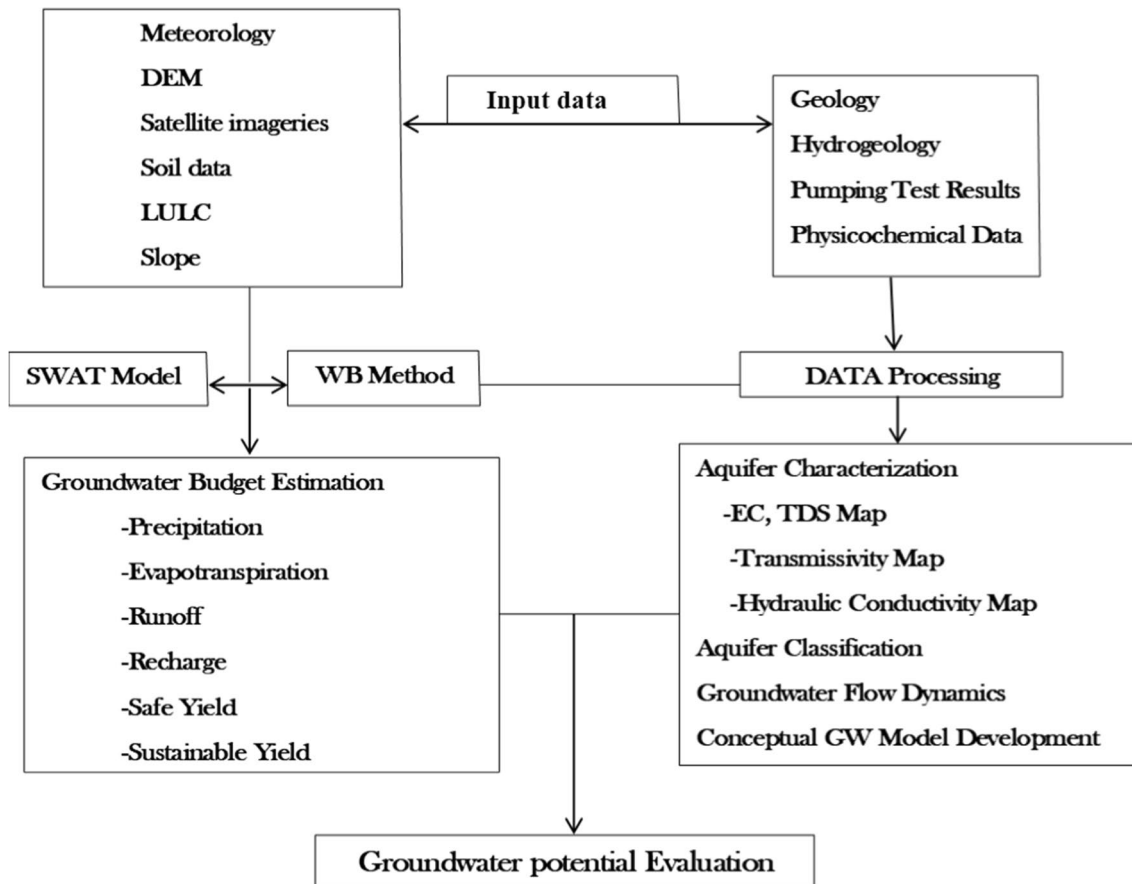


Fig. 7 Flowchart of the methodology adopted for the present study

Table 5 Mean monthly PET and AET of Upper Mille River catchment

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
PET	54	61	62.1	72.7	79.7	87.8	83.6	76.8	73.3	63.5	53.4	53	821.15
AET	49.4	49.5	62.1	72.7	77.1	70.8	83.6	76.8	73.3	62.8	50.6	46.3	775 mm

Groundwater recharge estimation

Using the SWB method, the groundwater recharge was calculated based on the following formula (Sophocleous, 1991):

$$\text{Groundwater recharge} = \text{Precipitation} - (\text{Actual evapotranspiration} + \text{Surface runoff})$$

Thus, the mean annual groundwater recharge of the area is determined to be 106.5 mm/year. This means that only 9% of the total mean annual precipitation (1132 mm) percolates through the subsurface and joins the groundwater system.

SWAT model results

The results of the SWAT hydrologic model (Table 6) were generated based on the input dataset as explained above. The mean monthly precipitation, surface runoff, potential evapotranspiration, and actual evapotranspiration of the area follow a similar pattern as they are all dependent on the volume of precipitation received by the catchment (Fig. 9).

According to the SWAT model, the average annual groundwater recharge in the area is 150.6mm, as shown in Fig. 10. However, this estimate is rather inflated compared to the recharge calculated using the soil water balance method. The reason for this discrepancy could be the fact that the result has not been calibrated, as there are no operational river gauge stations within or in the vicinity of the Upper Mille catchment.

Comparison of SWB and SWAT model results

The annual estimation of groundwater recharge for the watershed has been calculated using the two methods,

and the results are explained above. A comparison of the values calculated using the two methods is presented in Table 7.

Aquifer characterization

Aquifer characterization is an essential step in the development and efficient management of groundwater resources. During fieldwork, different groundwater and surface water points are inventoried to characterize the hydraulic properties of the aquifer system. The field parameter measurement inventorying is performed by taking the location of water points using GPS. PH, electrical conductivity (EC), total dissolved solids (TDS), and temperature were measured and recorded from deep boreholes, shallow hand-dug wells, springs, lakes, and rivers (Table 8). Hydraulic properties are investigated, and the aquifer is characterized based on the hydrogeological data obtained from those inventory points in conjunction with literature reviews.

The development and efficient management of groundwater resources requires a good understanding of the hydrogeological properties of the rocks that form the major aquifer systems (Leap 1999). Aquifers in the Upper Mille River

Table 6 Average hydrologic parameters derived from the SWAT model

Hydro-logic parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
PET	54.9	57.9	105.4	123.8	140.1	138.7	154.99	149.8	131.4	109.9	82.5	66.36	1316.2
AET	18.6	20.9	36.76	41.2	53.54	83.97	100.8	86.3	42.03	31.79	23.4	18.37	557.8
Surface runoff	8.5	16.1	33.2	16.25	24.68	51.55	55.28	45.4	40.29	29.65	4.95	9.44	335.3
Inter flow	1.07	1.48	2.98	2.27	2.23	3.76	6.07	6.05	5.37	4.13	2.13	1.2	38.7
Total													1083.2

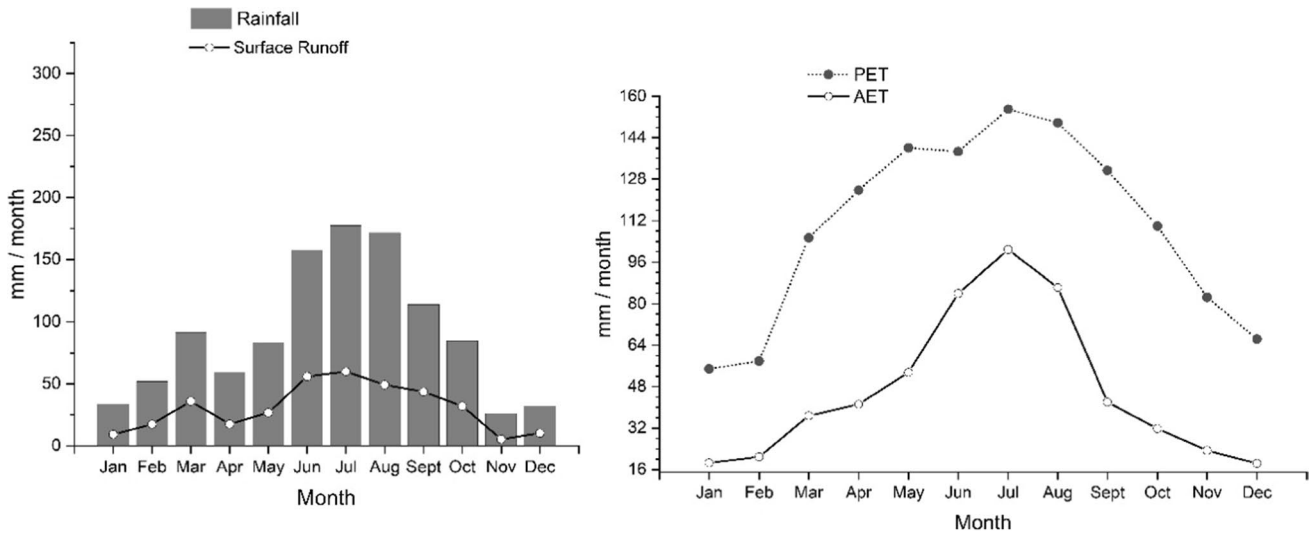
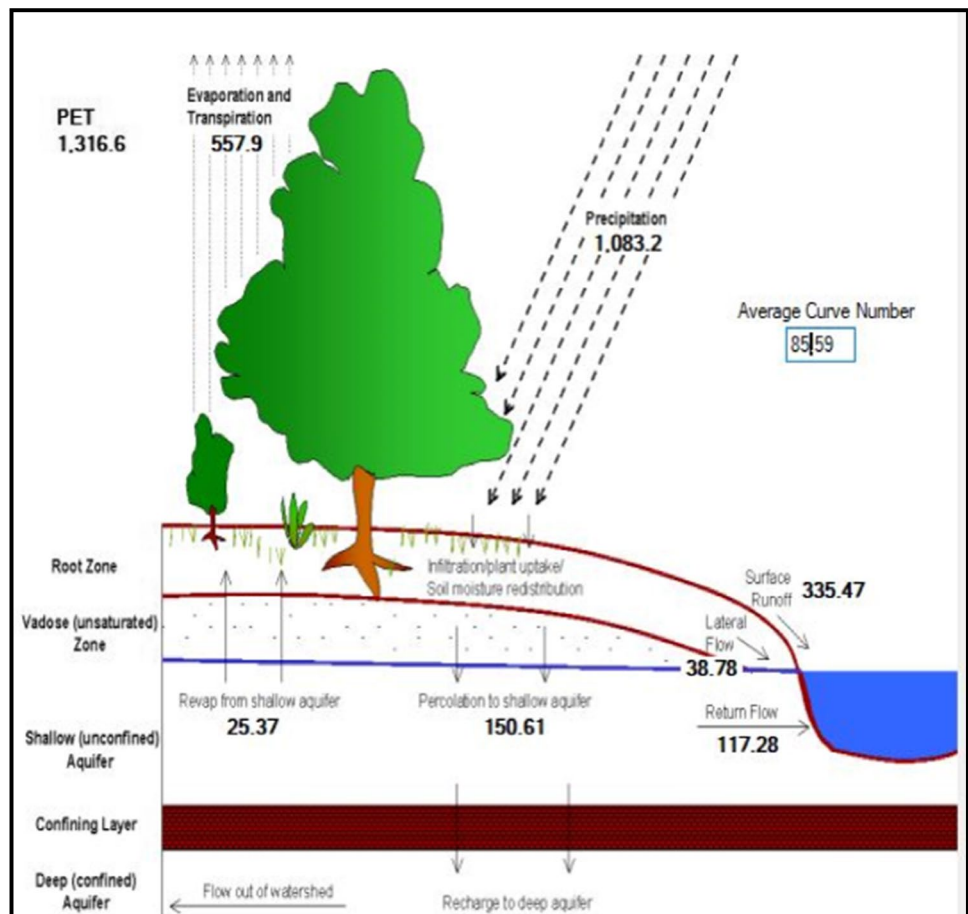


Fig. 9 Mean monthly precipitation, runoff (left), and PET, AET (right) by SWAT model

Fig. 10 Average annual hydrologic components obtained from the SWAT model



catchment are broadly divided into two categories based on the nature of porosity: aquifers that contain primary porosity, and those that contain double porosity. The first comprises unconsolidated alluvial, colluvium, and intermountain

Quaternary sediments in which the porosities were formed during deposition of sediments. The second category of aquifer includes volcanic rocks which contain primary porosities such as columnar jointing, bedding plane, and

Table 7 Comparison of water balance components computed using SWB and SWAT model methods

SWB components						
Methods	Prec.	PET	AET	Runoff	Inter flow	GW recharge
SWB	1132	821.15	775	251.1	0.00	106.5 mm
	% of precipitation	72.5%	68.5%	22.2%	0%	9.4%
SWAT model	1083.2	-	557.9	335.47	38.78	150 mm
	% of precipitation	-	51.5%	31%	3.6%	13.8%

Table 8 Fieldwork inventory points and the parameters measured for each point

Inventory types	Number of points	Measured parameters
Springs	60	T, pH, TDS, yield(l/s), and elevation
Hand-dug wells	6	T, SWL, pH, yield, and TDS
Deep boreholes	30	T, SWL, pH, yield, and TDS
Lakes	2	T, pH, and TDS, elevation

vesicles formed during the time of rock formation, and later on through time, these volcanic rocks have been subjected to weathering and fracturing related to tectonics, giving rise to secondary porosities.

Physico-chemical parameters

Physico-chemical parameters are of special emphasis for this research work, including EC, TDS, and PH. These parameters are measured at the inventory points (boreholes, springs, lakes, and rivers), and a spatially distributed map was produced from point measurements. The EC (Fig. 11, left) and the TDS (Fig. 11, right) values of the watershed range from 310 to 200 $\mu\text{s}/\text{cm}$ and 200 to 1145 mg/l, respectively.

The pH of most water point measurements in the watershed ranges from 6.5 to 8.5. Lower pH values are measured on the highlands of the watershed, which indicates the recharge area, whereas high pH was observed at the outlet of the watershed. Generally, TDS, EC, pH, and temperature values are higher in deep boreholes than in shallow hand-dug wells and springs. Moreover, an increasing trend was observed along the flow path.

Hydraulic properties of aquifers

To characterize and classify the aquifer system into different hydrogeological groups, existing pumping test data, geologic and hydrogeological maps, lithology obtained from borehole logs, aquifer thickness, transmissivity, hydraulic conductivity, water table depth, geological structures, and surface water features are synthesized. Hydraulic conductivity is a measure of how easily water can pass through soils or rocks.

High values of hydraulic conductivity indicate a permeable material through which water can pass easily; low values of hydraulic conductivity indicate that the material is less permeable. Various factors, such as rock type, primary and secondary structures, degree of weathering, and stratigraphic setting, can influence hydraulic conductivity. As observed in (Fig. 12, left), a wide range of hydraulic conductivity values (0.06–17 m/day) were observed. Transmissivity is a measure of the amount of water that can be transmitted horizontally through a unit width by the full saturation thickness of the aquifer under a unit hydraulic gradient (C.W. Fetter 2001). The spatially distributed transmissivity map (Fig. 12, right) was constructed by interpolating point values from borehole data, which ranged from 2.44 to 1406 m^2/day .

The hydraulic conductivity and transmissivity maps show a similar pattern, in which unconsolidated sediments have higher transmissivity and hydraulic conductivity values. The wide range of values in hydraulic conductivity and transmissivity indicated the heterogeneity of the catchment in terms of geology and hydrogeology.

Hydrogeological units

After integrating and synthesizing geological and hydrogeological data with general background knowledge, lithological units that share similar hydrogeological characteristics are grouped together as the same aquifer based on their productivity. Thus, the aquifer types in the area are classified and mapped into three hydrogeologic units: high productive intergranular porosity aquifer, medium productive double porosity aquifer, and slightly weathered and fractured low-productive aquifer.

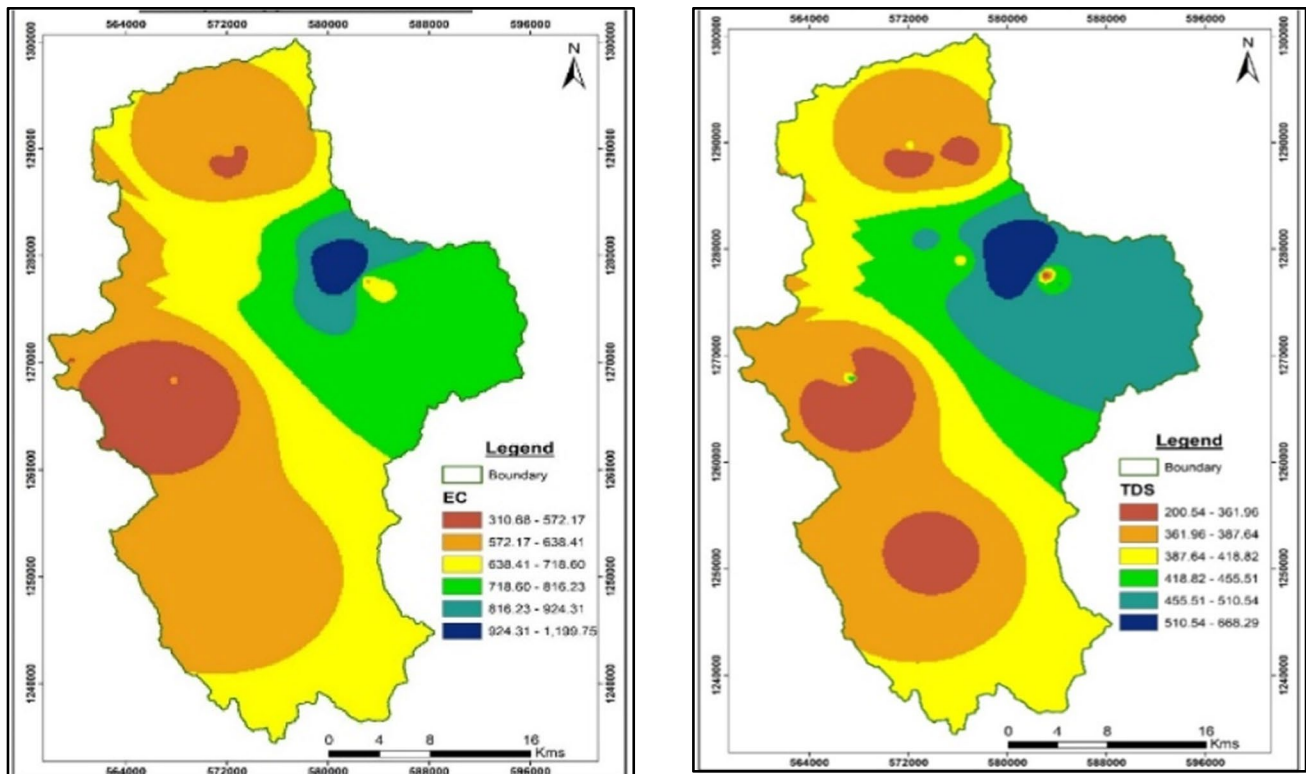


Fig. 11 Spatially distributed EC (left) and TDS (right) map of the study area

The highly productive intergranular porosity aquifer is composed mainly of unconsolidated lithological units of alluvial, fluvial, and intermountain Quaternary sediments with high hydraulic conductivity, transmissivity, and specific yield. These sediment units are found in valley and graben fill areas, occupying the flat parts of the study area, through which major rivers drain. The primary porosity of these units is responsible for their high permeability, as they are composed of coarse-grained sandstone to gravel-sized sediments. As previously mentioned, due to the topographic nature of this unit being in the flat and discharge area of the catchment, it is highly advisable and recommended to drill boreholes to obtain high amounts of discharge.

Based on borehole and spring discharge, conductivity, and transmissivity values obtained from different drilling companies and water offices, the lower (Ashange) basalt is grouped and mapped into a medium productive double porosity volcanic aquifer. The lower basalt is mainly found in the central part of the study area, where its hydraulic conductivity and transmissivity vary significantly. The unit is highly affected by major NE-SW faults, which result in intense fracturing and high permeability (Abebe B et al. 2007).

Some of the lithological units in the area are not productive due to the lack of effective primary and secondary porosity, which limits the permeability and conductivity of the aquifer system. For instance, Tarmaber basalt, Aiba basalt, Kemise

rhyolite, and swampy areas are grouped under low-productive aquifers. The former two units (Tarmaber basalt and Aiba basalt) are not productive as a result of their topographic setting, although they are considerably fractured and weathered, hence believed to be good potential aquifers. However, they are used as groundwater recharge zones, especially along the rift escarpment. Kemise rhyolite, on the other hand, is not productive due to the lack of effective primary and secondary porosity. Swampy and wetland areas lack effective porosity because of the presence of a high percentage of clay and silt. The area around the lakes is also not a productive aquifer. As shown on the map below (Fig. 13), the western corridor (recharge area) and the eastern corridor (outlet of the Upper Mille River) of the study area are predominantly covered by low porosity and low permeability lithological units. As a result, it is not recommended to expect and drill high-discharge boreholes in these localities.

Groundwater flow system of the watershed

Several parameters are considered to determine the groundwater flow directions and to identify the recharge and discharge areas in the catchment. These parameters include slope/gradient and geomorphology, geological structures, groundwater level, and physico-chemical parameters such as EC and TDS. Groundwater head data is collected and used to create a map

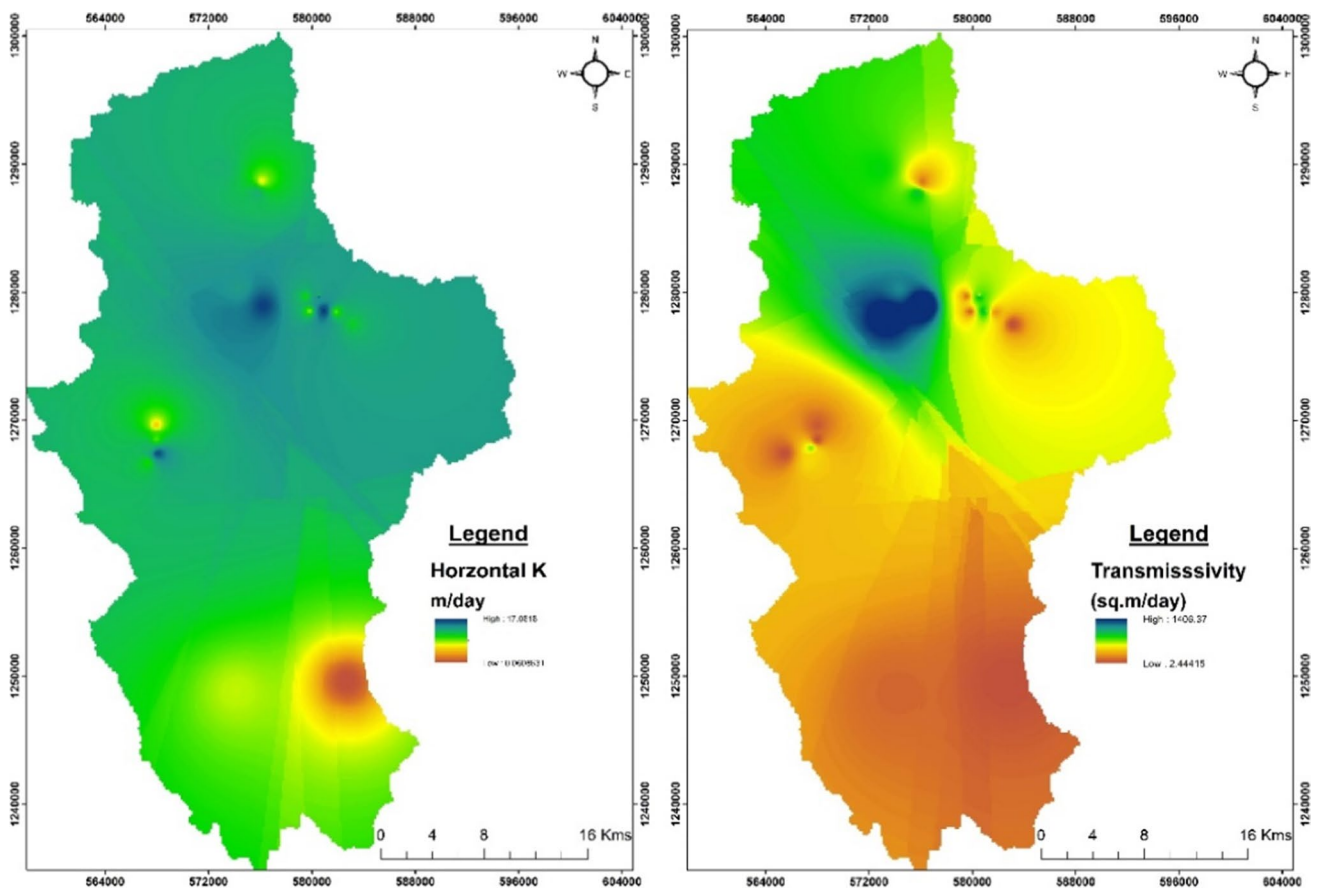


Fig. 12 Spatially distributed hydraulic conductivity (left) and transmissivity (right) map

that shows points having equal hydraulic heads. Perpendicular lines are then constructed based on these contour lines, which indicate the direction of groundwater flow in the aquifer system.

The ultimate source of recharge to the regional aquifer is highland rainfall, which infiltrates into the fractured and weathered volcanic rocks. Groundwater flows from the southern and western corridors of the catchment area to the central-eastern part of the watershed, following faults and lineaments (Fig. 14). Based on this, it can be concluded that the western and southern weathered and fractured highlands act as recharge areas, whereas the central-eastern lowlands are the discharge zones of the catchment.

Conceptual hydrogeological model

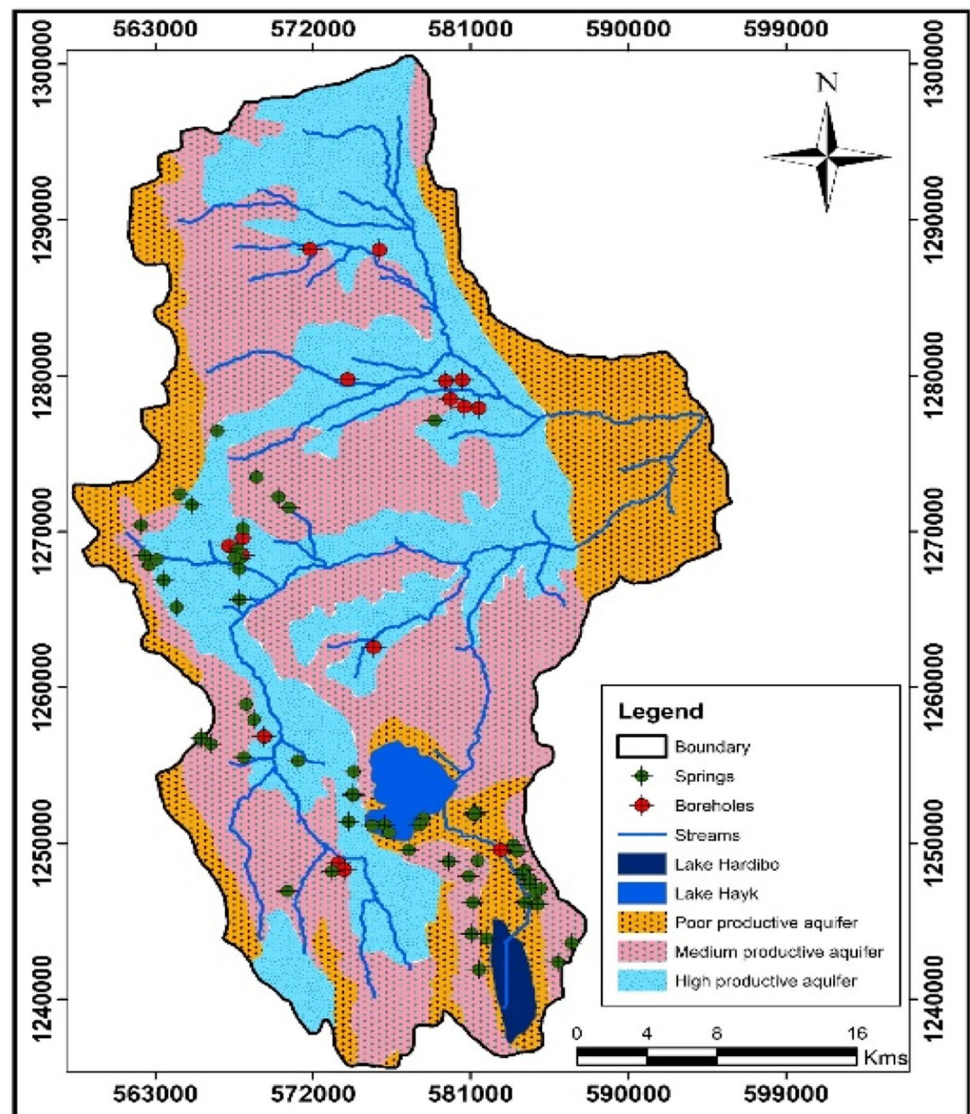
A conceptual model is a simplified diagram or hydrogeological cross-section that visually represents the groundwater flow system. It results from the combination of static factors (such as lithology and geological structures) and dynamic factors (such as hydrology) (Anderson and Woessener, 1992). Hence, the construction of groundwater models relies on the comprehension of the conceptual hydrostratigraphic model, and the development of such a

model involves synchronizing data obtained from different approaches such as field investigations (i.e., drilling activities and/or geophysical surveys). By integrating evidence from deep drilled boreholes, lithostratigraphic relationships, and physico-chemical parameters (pH, EC, and TDS), the groundwater occurrence and flow in the Upper Mille watershed can be conceptualized and represented in a hydrogeological cross-section.

The first section (B-B') (Fig. 15) is constructed from east to west, crossing the Tisabalima and Girana Quaternary sediment deposits, where many boreholes are drilled. These units are grouped under high porosity productive aquifers in this study. As shown in the map below, the water flows from the recharge to the discharge area, and the water level follows the surface topography of the catchment.

The second section (A-A') (Fig. 16) is constructed from north to east only along the Quaternary unconsolidated sediment deposits. In the area, boreholes are drilled up to the fractured basalt since they are the source of groundwater for drinking and irrigation purposes. As observed on the map below, the water level confirms that the groundwater flows from north to east, as previously indicated by the constructed groundwater flow map.

Fig. 13 Aquifer productivity classification map of the study area, modified after Sima (2017)



Conclusion

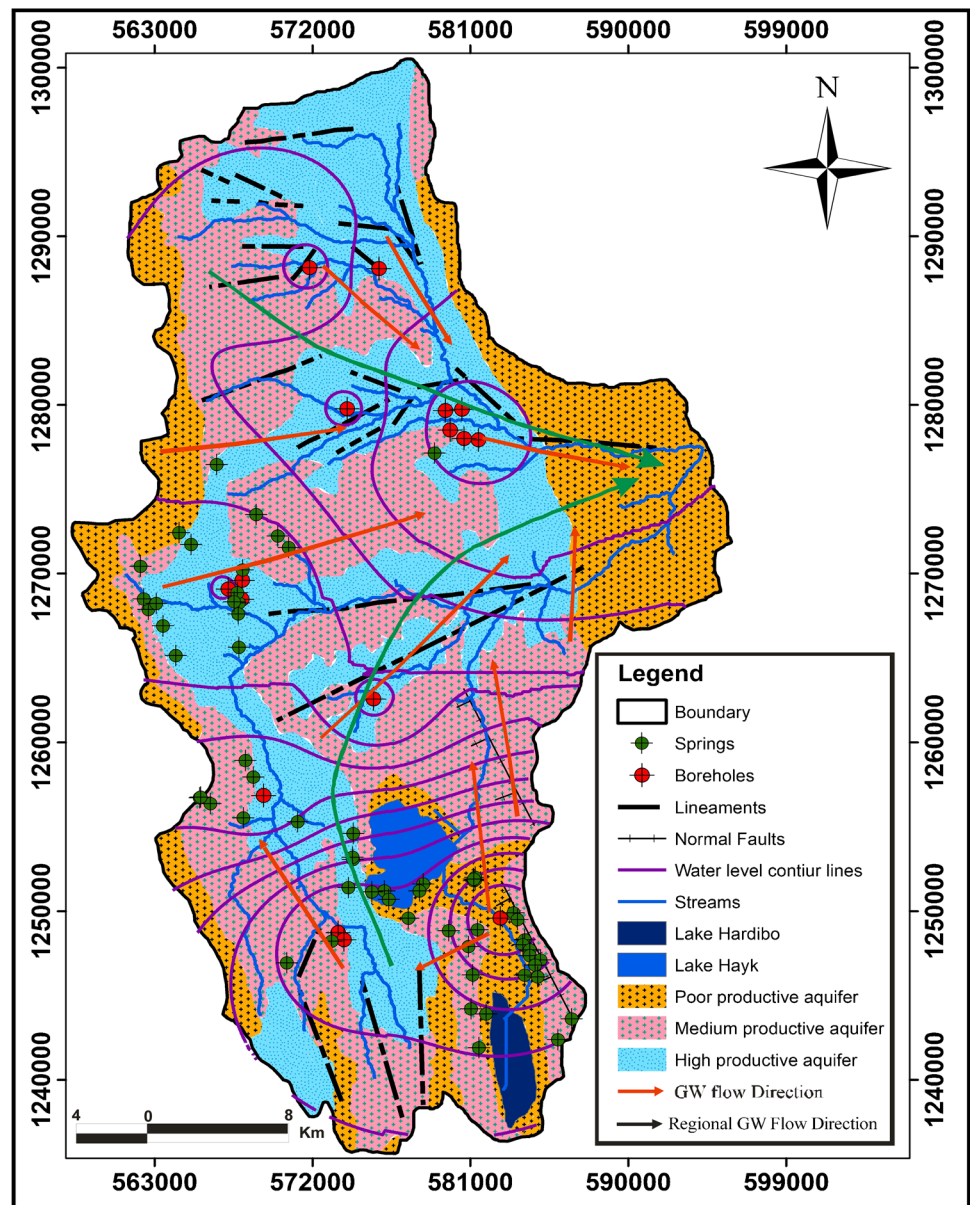
The groundwater resource potential of the Upper Mille River catchment was evaluated using various approaches and methodologies, as discussed in each section of this research. The region boasts a diverse and intricate topography, with flatlands, ridges, mountains, and escarpments, all prevalent in different parts of the study area.

The annual groundwater recharge of the area was estimated using SWB and SWAT model techniques. Each water balance component of the watershed was properly estimated and quantified. According to the SWB method, the mean annual precipitation, AET, and surface runoff are 1132.5 mm, 775 mm (69% of the total mean annual precipitation), and 251.1 mm (22% of the total mean annual precipitation), respectively. Additionally, the SWB method indicates that the groundwater recharge of the watershed is 106.5 mm

(9% of the total mean annual precipitation). Meanwhile, the SWAT model output indicates that the mean annual precipitation, AET, surface runoff, and groundwater recharge of the watershed are 1083.2 mm, 558 mm (51.5% of the precipitation), 335.5 mm (31% of the precipitation), and 150 mm (13.8% of the precipitation), respectively.

The local lithostratigraphic units in the study have been generally grouped into two rock types: older volcanic (Ashange basalt, Aiba basalt, Kemise rhyolite, and Tarmaber basalt) and younger unconsolidated Quaternary sediments (alluvial, colluvium, aluvio-colluvial, and intermountain sediments). The hydraulic properties and physico-chemical parameters of the area were investigated. The transmissivity and hydraulic conductivity of the area range from 2.4 to 1407 m²/day and 0.06 to 17 m/day, respectively. In addition, the EC (310–1200 µs/cm) and TDS (200–669 mg/l) values of the watershed generally exhibit an increasing trend from

Fig. 14 Groundwater flow contour line and flow direction map of the catchment, modified after Sima (2017)



the western parts (recharge area) to the eastern parts (discharge area) of the catchment.

The lithostratigraphic units were transformed into hydrostratigraphic units, using data from field observations, borehole lithological logs, pumping test results, and measured physico-chemical parameters. Similar hydrogeological characteristics were used to group the lithostratigraphic units together. Aquifer types are then qualitatively classified and mapped into three hydrogeologic units: high productive intergranular aquifer, medium productive double porosity aquifer, and low-productive aquifer. Unconsolidated Quaternary sediments are grouped under high productive aquifers, while Ashange basalt is classified as a medium productive aquifer, and Aiba basalt, Tarmaber basalts, Kemise rhyolite,

and swampy areas are grouped under low productive aquifers. However, it is important to note that the different aquifer groups are hydraulically interconnected.

On the other hand, the conceptual groundwater flow model of the catchment reveals that groundwater flows from the eastern regions of the catchment, where there is more annual rainfall and rugged terrain, to the discharge areas in the western regions (like the Girana and Tis Aba Lima valleys). The groundwater resource in the Upper Mille catchment is replenished by streams, runoff during the rainy season, groundwater inflow from the highlands of the western margins, and direct rainfall. The groundwater from the catchment is discharged through base flow (groundwater outflow), springs and boreholes for irrigation and water supply purposes.

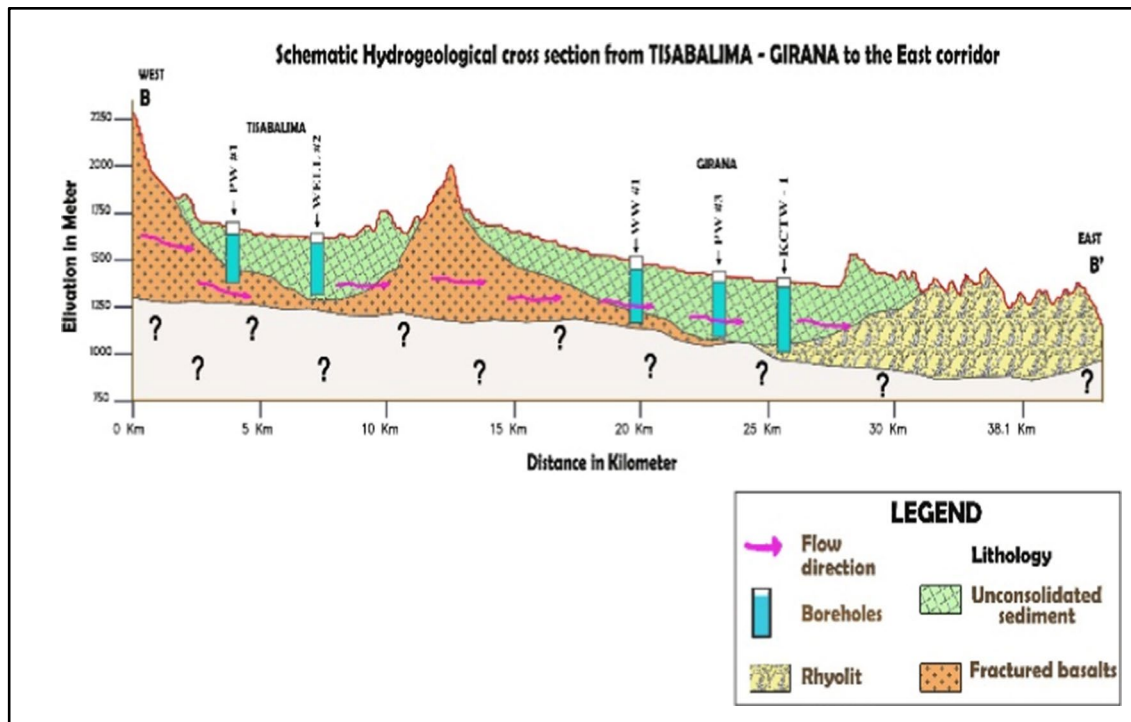


Fig. 15 Schematic hydrogeological cross-section and groundwater flow map from recharge (B) to discharge (B') area

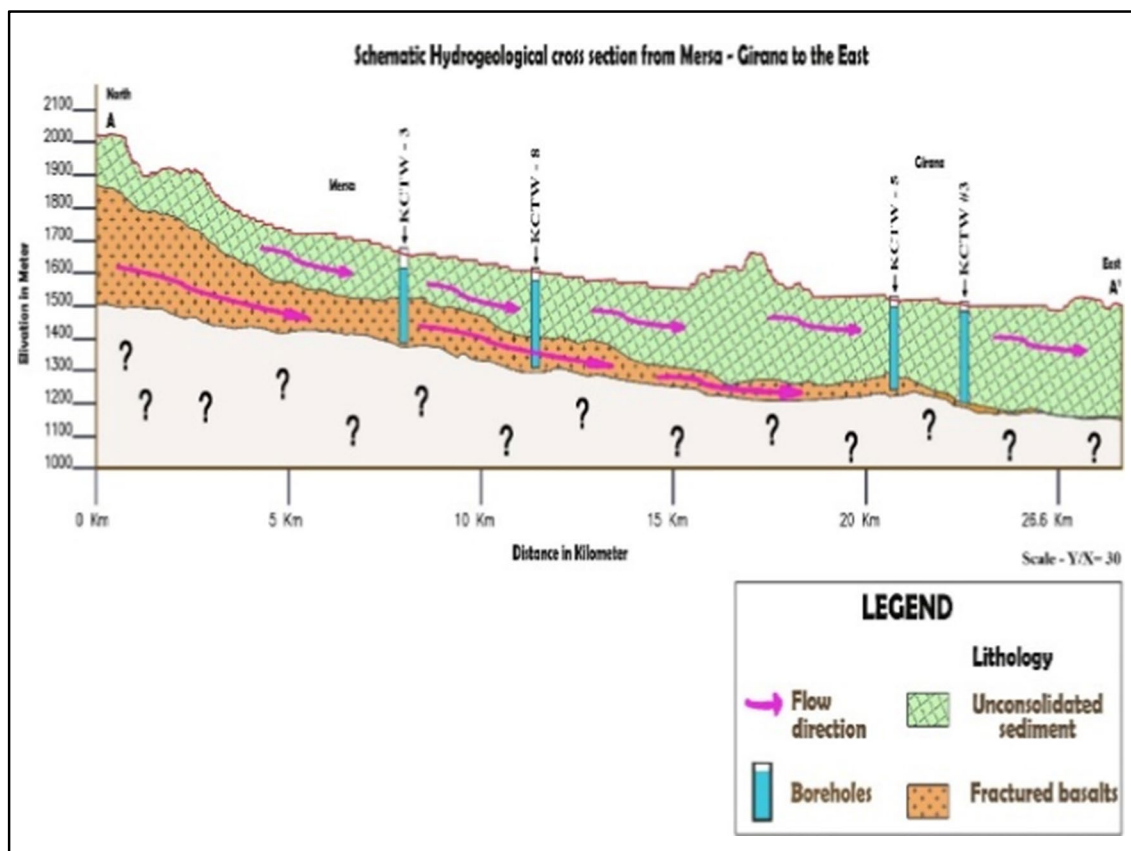


Fig. 16 Schematic hydrogeological cross-section and groundwater flow map from recharge (A) to discharge (A') area

Acknowledgements We greatly appreciate the National Meteorology Agency of Ethiopia, Amhara Water Works Construction Enterprise (AWWCE), and Woreda Water Bureaus for providing the necessary data for this study.

Funding This research work is partially funded by Addis Ababa University and self-sponsored by the authors.

Data Availability Data will be made available on request from the corresponding author.

Declarations

We, the authors, declare and confirm that this work is our own original work and is part of the MSc thesis of the principal author. We have followed all ethical and technical research principles in the preparation, data collection, data analysis, and compilation of the research.

Conflict of interest The authors declare that they have no competing interests.

References

- Abebe B, Acocella V, Korme T, Ayalew D (2007) Quaternary faulting and volcanism in the Main Ethiopian Rift. *J Afr Earth Sci* 48(2–3):115–124. <https://doi.org/10.1016/j.jafrearsci.2006.10.005>
- Abraha T, Tibebu A, Ephrem G (2022) Rapid urbanization and the growing water risk challenges in Ethiopia: the need for water sensitive thinking. *Front Water* 4:890229. <https://doi.org/10.3389/frwa.2022.890229>
- Anderson MP, Woessener W (1992) Applied groundwater modeling — simulation of flow and advective transport. *J Hydrol* 140:1–4. [https://doi.org/10.1016/0022-1694\(92\)90251](https://doi.org/10.1016/0022-1694(92)90251)
- Arnold JG, Moriassi DN, Gassman PW, Abbaspour KC, White MJ, Srinivasan R, Santhi C, Harmel RD, Van Griensven A, Van Liew MW, Kannan N, Jha MK (2012) SWAT: Model use, calibration, and validation. *Trans ASABE* 55(4):1491–508
- Ayeneu T, Demlie M, Wönllich S (2008) Hydrogeological framework and occurrence of groundwater in the Ethiopian aquifers. *J Afr Earth Sci* 52(3):97–113
- Demlie M (2002) Hydrology, hydrogeology and hydrochemistry of the lakes system Hayq-Ardibo, Northern Ethiopia. Unpublished MSc thesis, Addis Ababa University, Addis Ababa, Ethiopia
- Fetter CW (2001) Applied hydrogeology. Fourth Edition. Pearson New International Edition 598
- Feyisa D (2018) Petrologic and Geochemical evidence for diversity of magma compositions at the Ethiopian volcanic province: implications for thermo-chemical plume influence. PhD Thesis, Okayama University, p 259
- Geological survey of Ethiopia (GSE) (2015) Regional hydrogeological, hydro geophysical, hydrogeochemical and isotope hydrology of Chifra- Eliwuha area, Afar, Ethiopia. Unpublished technical report, GSE, Addis Ababa, Ethiopia, p 102
- Gorelick SM, Zheng C (2015) Global change and the groundwater management challenge. *Water Resour. Res.* 51:3031–3051. <https://doi.org/10.1002/2014WR016825>
- Hagos M, Konka B, Ahmed J (2016) A preliminary geological and generalized stratigraphy of western margin of northern afar. *Momona Ethiop J Sci* 8(1):1–22
- Kebede S (2012) Groundwater in Ethiopia: features, numbers and opportunities. Springer Science & Business Media
- Kebede S, Travi Y, Asrat A, Alemayehu T, Ayeneu T, Tessema Z (2008) Groundwater origin and flow along selected transects in Ethiopian rift volcanic aquifers. *Hydrogeol J* 16(1):55–73. <https://doi.org/10.1007/s10040-007-0210-0>
- Leap DI (1999) Geological occurrence of groundwater. In Delleur J. The Handbook of Groundwater Engineering, CRC Press LLC, pp 17–69
- Megersa T, Nedaw D, Argaw M (2019) Combined effect of land use/cover types and slope gradient in sediment and nutrient losses in Chancho and Sorga sub watersheds East Wollega Zone Oromia Ethiopia. *Environ Syst Res* 8(1). <https://doi.org/10.1186/s40068-019-0151-3>
- Mengistu HA, Demlie MB, Abiye TA (2019) Review: groundwater resource potential and status of groundwater resource development in Ethiopia. *Hydrogeol J* 27:1051–1065
- Mohr P, Zanettin B (1988) The Ethiopian flood basalt province. *Continental Flood Basalts* 63–110. https://doi.org/10.1007/978-94-015-7805-9_3
- Ponce VM, Hawkins RH (1996) Runoff curve number: has it reached maturity? *J Hydrol Eng* 1(1):11–19
- Sahele M (2001) Hydrogeological investigation of the upper and middle Borkena river catchment, northern Ethiopia, wollo., unpublished MSc Thesis. Addis Ababa University, Addis Ababa, Ethiopia
- Sima J (2017) Hydrogeological and hydrochemical maps of Des-sie NC 37-3 Map Sheet. Geological Survey of Ethiopia, Addis Ababa, Ethiopia
- Sophocleous MA (1991) Combining the soilwater balance and water-level fluctuation methods to estimate natural groundwater recharge: practical aspects. *J Hydrol* 124(3-4):229–241
- Thorntwaite CW (1948) An approach toward a rational classification of climate. *Geogr Rev* 38:55–94
- Water works design and supervision enterprise (WWDSE) (2011) Evaluation of the groundwater resources of the Teru area Groundwater basin. Unpublished technical report, WWDSE, Addis Ababa, Ethiopia, p 89
- Williams FM (2016) Understanding Ethiopia. Springer International Publishing, Australia, Wolfgang Eder AV. <https://doi.org/10.1007/978-3-319-02180-5>
- Yitbarek Baye A (2009) A hydrogeological and hydrochemical framework of complex volcanic system in the Upper Awash River basin, Central Ethiopia : with special emphasis on inter-basins groundwater transfer between the Blue Nile and Awash. Ph.D. Thesis, December, 185
- Zwaan F, Corti G, Sani F, Keir D, Muluneh AA, Illsley-Kemp F, Papini M (2020) Structural analysis of the Western Afar Margin, East Africa: evidence for multiphase rotational rifting. *Tectonics* 39(7):1–25. <https://doi.org/10.1029/2019TC006043>

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.