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Evaluation of groundwater resource potential by using water balance model: A case of Upper Gilgel Gibe Watershed, Ethiopia

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Abstract: Groundwater resource potential is the nation's primary freshwater reserve and accounts for a large portion of potential future water supply. This study focused on quantifying the groundwater resource potential of the Upper Gilgel Gibe watershed using the water balance method. This study began by defining the project area's boundary, reviewing previous works, and collecting valuable primary and secondary data. The analysis and interpretation of data were supported by the application of different software like ArcGIS 10.4.1. Soil water characteristics of SPAW (Soil-plant-air-water) computer model, base flow index (BFI+3.0), and the water balance model. Estimation of the areal depth of precipitation and actual evapotranspiration was carried out through the use of the isohyetal method and the water balance model and found to be 1 664.5 mm/a and 911.6 mm/a, respectively. A total water volume of 875 829 800 m^3/a is estimated to recharge the aquifer system. The present annual groundwater abstraction is estimated as 10 150 000 m^3/a. The estimated specific yield, exploitable groundwater reserve, and safe yield of the catchment are 5.9%, 520 557 000 m^3/a, and 522 768 349 m^3/a respectively. The total groundwater abstraction is much less than the recharge and the safe yield of the aquifer. The results show that there is a sufficient amount of groundwater in the study area, and the groundwater resources of the area are considered underdeveloped.

Keywords: Groundwater balance model; Groundwater resource potential; Recharge; Sustainable

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Introduction

The demand for fresh water is increasing as the world's population continues to grow and expects higher standards of living. Water conservation, better systems' operation, higher end-use, and water allocation efficiencies have not been able to offset the growing demand. In both arid and semiarid areas, groundwater may represent 80% or more of the total water resources (Karamouz et al. 2011). According to the United Nations World Water Development Report (WWAP, 2015), approximately 2.5 billion people depend on groundwater for their daily needs, and at least 50% of the world's drinking water comes from groundwater. The World Meteorological Organization estimated that about 20% of global water withdrawals come from groundwater (Abu-zeid and Shiklomanov, 2003).

Groundwater plays a vital role in Ethiopia in providing drinking water, increasing food and agricultural production, and facilitating industrial improvements. The rural areas that account for more than 85% of the country's population come across a shortage of potable water supply, which can be solved by proper groundwater utilization (Awulachew et al. 2007). Ethiopia is believed to have a large groundwater resource potential (Kassahun and Mohamed, 2018). Studies show flawed results of 2.5×10^9 m^3 by Water and Power Consultancy Services (WAPCOS), and 185×10^9 m^3 by Tamiru and Tenalem (Moges, 2012; Bashe, 2017). Another study indicates that the groundwater resource potential of Ethiopia can be estimated at 2.6×10^9 m^3–6.5×10^9 m^3 (Awulachew et al. 2007). This can be taken as an indication of how much detailed study and survey are needed to estimate the country's groundwater resources poten-

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tial with better accuracy (Kassahun and Mohamed, 2018).

The rapid expansion of the agricultural sector and the rising population growth heavily relied on groundwater. Consequently, many boreholes have been drilled, and groundwater has been developed and exploited. This may inevitably lead to excessive extraction and depletion of the groundwater resource. Hence, it is crucial to regulate and maintain the groundwater reserve in a state of dynamic equilibrium over some time without disturbing the natural condition of the ecosystem (Adem, 2012). The public has a perception of groundwater as a reliable, clean, and nearly unlimited source of water supply. Even though there could be exceptions, it is a dependable source almost all over the world (Karamouz et al. 2011).

Overdependence on groundwater resources for many purposes has led to over-exploitation, and this has led to much concern for groundwater characterization, potential assessment, and management. Owing to increased demand and natural climate change, groundwater is often abstracted beyond its natural recharging capacity, causing depletion of the resource (Bedient et al. 2013). The amount of potable water that can be extracted from an aquifer without causing depletion is mainly dependent on the groundwater recharge. Thus, a quantitative evaluation of the resource is a prerequisite, especially in developing countries like Ethiopia, where most people rely on it as a source of drinking water and for domestic uses. An abstraction of groundwater has an associated impact on the water balance and hence on the availability of water resources in other parts of the water cycle (Villholth, 2006). Thus, understanding of the aquifer system and assessment of the water balance components of the river basin is crucial for the sustainability of the resource. The water balance of the aquifer system is the key to the identification of the aquifer resources and the consequences of deviations in exploitation. The water balance is based on the principle of the continuity of flow (Kovalevsky et al. 2004).

To ensure the wise use of groundwater, a systematic evaluation of groundwater is required. Sustainable development, use, and management of groundwater resources is a challenge under the current conditions of population growth, land degradation, and climate change. Thus, economic development requires proper quantification of groundwater recharge (Gintamo, 2015). Despite the existence of numerous hydro-geological studies in the country, a particular study on the Upper Gilgel Gibe watershed estimating the total groundwater resource (groundwater recharge, specific yield, exploitable groundwater reserve, and safe yield) of the watershed, however, is scanty. One of the issues in the study area is the lack of up-to-date data on the quantity and distribution of groundwater resources. As a result, this study can help to fill a knowledge gap about the study area's groundwater resource potential. In general, it can be concluded from this study that the water balance model can be successfully applied for groundwater resource potential evaluation across the river basin.

The water balance model was used in this study to estimate various water balance components of the study area based on long-term average monthly meteorological data, hydrological data, and spatial data. The isohyetal method and the water balance model were used to estimate the study area's areal depth of precipitation, and groundwater recharge. The BFI+ 3.0 software was also used to separate baseflow from total stream flow, and borehole data was used to calculate groundwater abstraction in the study area.

This study has the general objective of quantifying the groundwater resource potential of the Upper Gilgel Gibe watershed. The outcome of the study may shed light on effective groundwater abstraction and can be an important input to administrative managers, decision and policymakers, and researchers. The groundwater balance study of an area may serve as a check on whether all flow components involved in the system have been quantitatively accounted for and to know which components have the greatest behavior on the problem under study, to calculate the unknown component of the groundwater balance equation while all other components are quantitatively known with sufficient accuracy, and it can also be used for modeling of hydrological processes which is used to forecast changes within the groundwater system (Kumar, 2012).

1 Study area

The Upper Gilgel Gibe watershed is located on the upper reach of the Omo Gibe basin, contributing flow to the larger Omo Gibe basin. The watershed is located upstream of the Gibe Dam in Ethiopia's Oromia regional state, in the south-western part of the country. Upper Gilgel Gibe has a catchment area of 2 941 km^2 and is located between 7°20′4.9″ and 7°59′16″ North Latitudes and 36°31′49″ and 37°13′40″ East Longitudes (Fig. 1). Air temperature in the watershed shows small variations throughout the year. The long-term

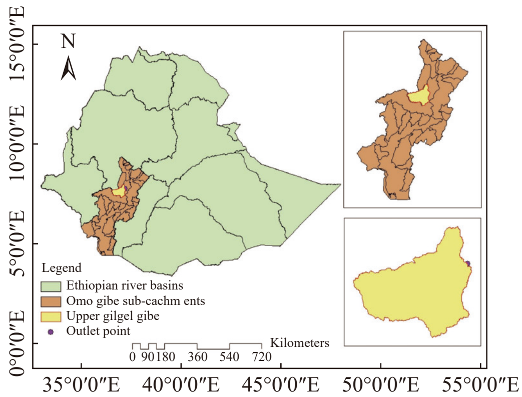

Fig. 1 Location map of the study area

monthly mean temperature varies between 19.38°C and 16.9°C, while the annual average temperature is 18.08°C. The long term mean monthly relative humidity varies between 83.9% and 54.6%, with an annual average of 69.4%. The seasonal variation in relative humidity follows a similar pattern to the rainfall. The general wind condition of the watershed can be grouped as light air wind throughout the year. The average monthly wind speed for a period of thirty-three as varies between 0.80 m/s and 0.99 m/s, with an average value of 0.90 m/s. The average monthly sunshine hour for a period of thirty-three as fluctuates between 3.84 hrs./d and 7.67 hrs./d with a mean value of 6.27 hrs./d.

The watershed is also characterized by numerous intermittent rivers. The main source of water for the rivers is the rainfall from the northern highlands. The Gilgel Gibe River is the main perennial river in the study area, and the Seka River is the tributary to this river. The highland areas reach elevations of up to 3 312 meters above mean sea level (masl). while the lowland areas reach elevations up to 1 677 masl (Fig. 2a). Steep

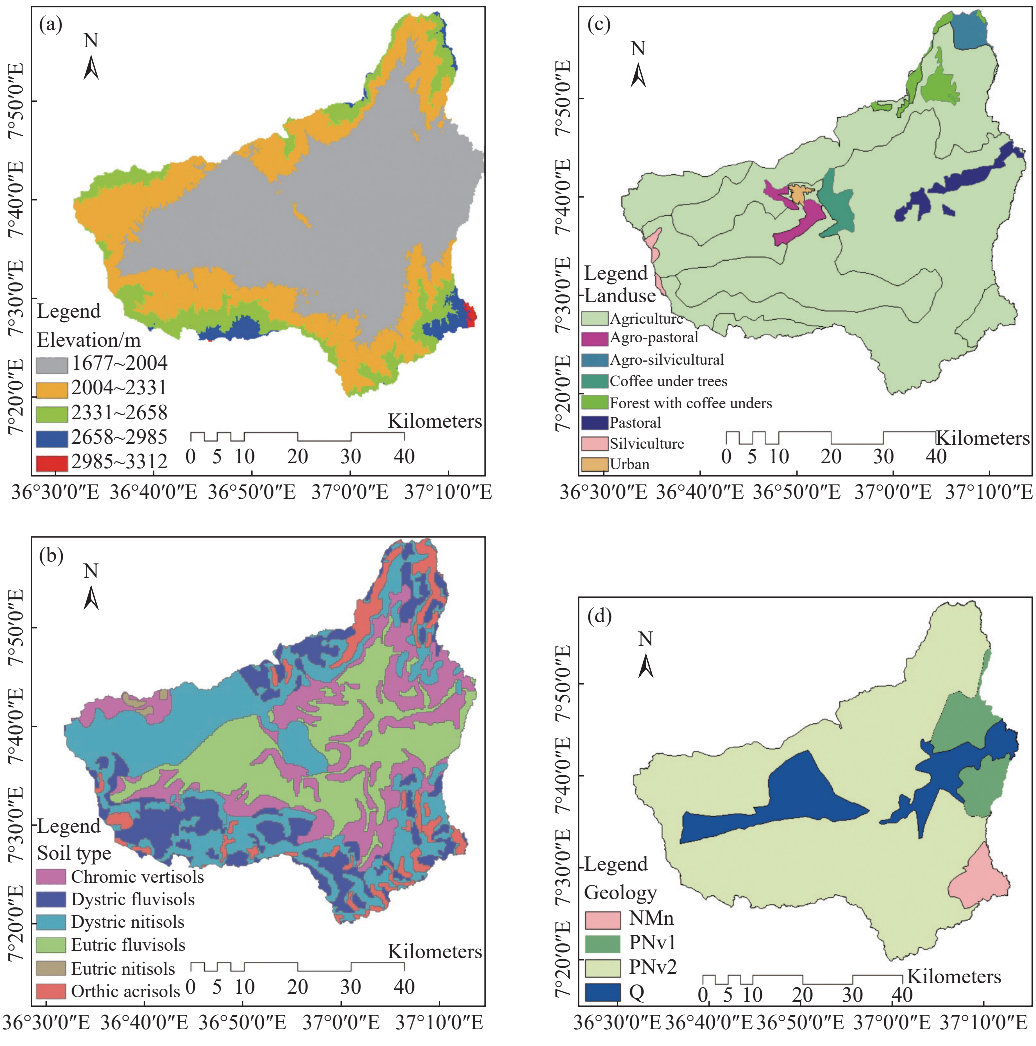

Fig. 2 Elevation (a), soil map (b), land use and land cover map (c) and geology (d) of the study area

(NMn = Very highly permeable volcanic sand; PNv1 = Lower felsic, volcanic, and sedimentary formation; PNv2 = Upper felsic volcanic; Q = Quaternary sediments) slopes with dissected hills characterize the highlands, while the lowlands are characterized by relatively gentle and undulating slopes. The soils in the watershed are, for the most part, permeable and well-drained (Fig. 2b). The watershed is under extensive cultivation, with an ever-increasing pressure on land as a result of the expansion of the area under agriculture. Forest areas are confined to areas that are very steep and inaccessible by farmers, and often have an understory of coffee (Fig. 2c). The region's base is made up of heavily folded and faulted Precambrian rocks, which are overlain by Mesozoic marine strata and tertiary basalt traps. The geology of the study area is dominated by basaltic lava flows, rhyolites, trachytes, and trap series ash flows. The geology of the watershed delivers serviceable groundwater resource potential and delivers upright diffusion of rainfall to recharge aquifers, which produce springs and feed perennial rivers (Fig. 2d).

2 Material and methods

2.1 Data collection

Evaluation of groundwater resources potential mainly requires meteorological data, hydrological data, spatial data, and borehole data over a given period as indicated in Table 1 below.

Before use, meteorological data was checked for homogeneity of stations and consistency of data. Missing data was filled in using appropriate methods for each of the meteorological data. The most important time-series data necessary for this study was rainfall data.

2.1.1 Rainfall

Rainfall data is the most important data for the evaluation of groundwater resource potential. To examine the patterns of rainfall distribution in the watershed, 33 as of daily rainfall data from five meteorological stations (Jimma, Dedo, Assendabo, Shebe, and near Omo-Nada) were used. The study area has rainfall for about seven months, from March to September, with a range of 1 200–2 000 mm per year. The minor rains fall from October to March, and the major rains fall from April to September, with a significant increase in July and August. The northern (including Serbo and Kersa) and north-eastern parts of the study area receive 1 200–1 600 mm of rain per year. The rainfall in the southern part (around Dedo), western (around Seka Chekorsa), and central parts, including Jimma, ranges between 1 500 mm and 2 000 mm per year. The study area has a more even distribution of rainfall over March to September without any peaks in July and August, around Jimma.

2.1.2 Evaporation

Global warming, as a general trend, increases evaporation, which reduces runoff (Chaemiso et al. 2016). Changes in precipitation and temperature patterns can have a significant impact on the hydrology process and the availability of water resources in the study area. The warmer temperature in the study area may increase the air's water-holding capacity, increasing potential evapo-

Table 1 Data collected, source and purpose

No.	Data collected	Sources of data	Purpose
1	Long term meteorological data (1985-2017)	National meteorological service agency (NMSA) of Ethiopia	To determine aerial depth of precipitation and potential evapotranspiration
2	Hydrological data (1990-2013)	Ministry of water, irrigation and energy office (MoWIE)	For baseflow separation and to determine Runoff
3	Digital elevation model (DEM) 30 m × 30 m resolution	ftp://ftp.glcf.umd.edu/glcf/Landsat/WRS2/ server	To yield essential derivative products such as slope, flow accumulation and flow direction in the process of watershed delineation
4	Soil data	Ministry of water, irrigation and energy office (MoWIE) and also food and agricultural organization (FAO) soil classification map was used in combination	To determine available water capacity for different soil types and to determine actual evapotranspiration
5	Land use land cover data	Ministry of water, irrigation and energy office (MoWIE)	
6	Geology and hydrogeology		
7	Existing borehole data	Jimma zone water, mineral, and energy office, well completion reports of Jimma University and Jimma airport, from previous study around the watershed and Jimma zone water, sanitation and hygiene (WASH) report	To locate existing boreholes in the watershed and to determine groundwater abstraction

transpiration (PET), reducing soil moisture, and decreasing groundwater reserves, all of which affect river flows and water availability. Changes in precipitation and evaporation have a direct impact on groundwater recharge.

2.2 Methods

A water balance approach was used to evaluate the groundwater resource potential of the study area. A water balance model was used to estimate different water balance components, mainly actual evapotranspiration (AET). Estimation of available capacity of the root zone (AWC) and separation of base flow were carried out by using soil-water characteristics of the soil-plant-air-water (SPAW) computer model and the Base Flow Index (BFI+ 3.0) software, respectively.

2.2.1 Recharge estimation

The basic hydrological principles state that a balance must exist between the quantity of water supplied to the basin (inputs) and the amount leaving the basin (outputs) and the change in groundwater storage. Water balance is a quantitative evaluation of the total amount of water gained or lost from a given hydrological system during a specific period (Moges, 2012). Estimating a region's groundwater balance necessitates quantifying all individual inflows and outflows from a groundwater system, as well as changes in groundwater storage over a given time period. The general form of the groundwater balance equation for any natural area such as a river basin or water body indicates the relative values of inflow, outflow, and change in water storage for the area or water body under consideration, which can be given by:

$$\text{Inflow} - \text{Outflow} = \text{Change in storage}(\Delta S) \quad (1)$$

Groundwater recharge can be estimated using the various inflow and outflow components in a given study area as follows:

$$G_r = P - AET + \Delta S_m - R_o \quad (2)$$

Where: Gr = Groundwater recharge; P = Precipitation; AET = Actual Evapotranspiration; ΔS_m = Change in soil moisture; R_o = Runoff. The advantage of the water balance method is that recharge can usually be estimated from easily available data (rainfall, runoff, water levels) and is rapid to apply (Shimelis et al. 2014).

2.2.2 Water balance model

Water balance is a computer program that calculates water balance based on the long-term average monthly precipitation, PET, soil and vegetation characteristics (combined in the water capacity of the root-zone), and surface runoff, according to the method proposed by Thornthwaite and Mather (Ghandhari and Alavi Moghaddam, 2011; Hendrayana et al. 2021). The model assumes that a certain fixed percentage of rainfall leaves the area as direct runoff (DRo). This percent is used to obtain the direct runoff coefficient (K), where the remaining coefficient of rainfall is called the effective rainfall (P_{eff}) (Rwebugisa, 2008).

$$DR_O = KP_i \quad (3)$$

$$P_{eff} = P - DR_O \quad (4)$$

Where: DR_O = direct runoff, K = fixed percent of rainfall leaves the area as direct runoff, and P_i = the amount of rainfall received in a particular month.

The runoff coefficient was calculated using the area's land use and land coverage. The value of K has been calculated as an area-weighted composite of the catchment's various land uses. The model calculates the soil moisture status for each month using an Equation (5) in which evapotranspiration exceeds precipitation.

$$SM = W.\exp\left(-\frac{A_{cc}PWL}{W}\right) \quad (5)$$

$$\Delta SM = SM_{current\ month} - SM_{previous\ month} \quad (6)$$

Where: SM = soil moisture (mm); $A_{cc}PWL$ = accumulated potential water loss (mm); W = water capacity (mm); ΔSM= Change in soil moisture.

The use of this Equation, however, assumes that the root zone of the soil is at field capacity at least for the last month (m) of the period with precipitation in excess of PET. A problem arises when the climate is so dry that the root zone's water capacity is never filled. The successive approximation method must be used to calculate the water balance in this case. This procedure creates an accumulated potential water loss for month. There are now two methods for calculating the soil moisture of month: (1) Add the last month's soil moisture to the sum of the subsequent monthly positive (P_{eff} – PET) values; (2) Use Equation (5) to calculate the accumulated potential water loss of month. When the results of these two methods match, the successive approximation is terminated. Calculation of AET considers the following situations:

$$\text{If}, P_{eff} - PET > 0, AET = PET,$$
$$\text{Otherwise}, AET = (P_{eff} - \Delta SM) \quad (7)$$

As previously stated, Equation (6) can be used to calculate changes in soil moisture.

Soil moisture deficit (SMD) is calculated by:

$$SMD = PET - AET \tag{8}$$

Moisture surplus (*S*):

$$S = P_{eff} - (\Delta SM + AET) \tag{9}$$

Total water available for runoff (*TARO*):

$$TARO_i = S_i, i = first\ month$$
$$TARO_{i+1} = S_{i+1} + DET_i \ldots$$
$$TARO_j = S_j + DET_{j-1}, j = last\ month \tag{10}$$

Equation (9) can be used to calculate the moisture surplus (*Si*) for each month.

Runoff (*RO*) and Detention (*DET*) can be calculated as:

$$RO_i = \%\ of\ runoff * TARO_i \tag{11}$$

$$DET_i = TARO_i - RO_i \tag{12}$$

Average monthly runoff expressed as a percentage of water available for runoff (% of runoff) is obtained by considering land use and land cover of the study area. Finally, runoff including direct runoff (*ROTL*) is calculated as:

$$ROTL = DR_O + RO \tag{13}$$

The important input parameters for the model are 12 long-term average monthly precipitation values, direct runoff values, reference potential evapotranspiration values, runoff expressed as a percentage of water available for runoff (a value of 50% is recommended), and the available water capacity of the root zone in millimeter. Values for precipitation, direct runoff, and potential evapotranspiration are in millimeter and integer form. The month will start in January. The values of the available water capacity of the root zone are estimated based on the soil texture of the different soil types in the catchment.

2.2.3 Soil water characteristics

Experience has shown that soil texture predominately determines the water-holding characteristics of most agricultural soils and serves as the primary input for estimating soil-water characteristic relationships (Saxton and Rawls, 2006). To get a more realistic value of available water capacity for different soil types, the soil water characteristics of the SPAW (Soil-Plant-Air-Water) computer model were used in combination with CROPWAT 8.0. Soil water characteristics are a graphical and interactive method of relating soil texture to soil water holding characteristics that are included with the SPAW model. It can also be obtained as a "stand-alone" program from a web site: http://www.bsyse.wsu.edu/saxton/soilwater.

2.2.4 Base flow index (BFI+ 3.0)

The base flow index (BFI+ 3.0) helps with the analysis and separation of baseflow for total catchment discharge. A time-series of baseflow has been seen as useful as a measure of the dynamic behavior of groundwater in a catchment, whereas the baseflow proportion of the total flow has been seen as an index of the catchment's capability to store and release water during dry weather (Gregor, 2010).

2.2.5 Specific yield, exploitable groundwater reserve and safe yield

Generally, "specific yield" can be defined as the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table (Chinnasamy et al. 2018). The values of the specific yield vary from 0.01 to 0.30 and are much higher than the storativity of confined aquifers. It can be estimated using the Equation.

$$G_r = (S_y * A * Dl_w) + Q_b + Ls_o \tag{14}$$

Where: *Gr* = Groundwater recharge (from Equation 2); *Sy* = Specific yield; *A* = effective area for groundwater recharge (area of the watershed); Dl_w = average water level rise in wet period; Q_b = groundwater abstraction (Field measurement and borehole data are used to determine Dl_w and Q_b); Ls_o = Lateral subsurface outflow.

The exploitable groundwater reserve is the volume of groundwater that can be abstracted annually from a given aquifer under prevailing economic, technological, and institutional constraints and environmental conditions. It represents the long-term average annual recharge under the condition of maximum groundwater use (Voudouris, 2006). Estimation of the exploitable groundwater reserve (Q_{ed}) requires defining the effective area for groundwater recharge (*A*), specific yield (S_y) (from Equation 14), and average water-level decline in the dry period (D_L) (determined from field measurements and borehole data). It can be calculated using the Equation:

$$Q_{ed} = A * S_y * D_L \tag{15}$$

In groundwater management, the safe yield is defined as the rate at which groundwater can be withdrawn annually without producing an undesirable adverse effect. In other words, the safe yield is the limit to the quantity of water that can be regulatorily withdrawn without depletion of the aquifer storage reserve (Tizro et al. 2007). Safe yield can be estimated by the following formula:

$$\text{Safe yield} = Q_{ed} + Q_b + Q_{ri} + Q_{si} \tag{16}$$

Where: Q_{ed} = Exploitable groundwater reserve (from equation 15); Q_b = groundwater abstraction during the recharge period; Q_{ri} = Recharge due to irrigation returns; Q_{si} = Sewage infiltration. In the study area, recharge from irrigation returns and sewage infiltration are negligible.

3 Results and discussions

3.1 Results

3.1.1 Recharge

The quantification of the natural groundwater recharge is a basic pre-requisite for efficient groundwater resource management. To calculate the groundwater recharge of the study area, the water balance components in Equation (2) must be calculated first.

3.1.1.1 Determination of aerial depth of precipitation

A precipitation event recorded by a rain gauge is a point observation at a specific location and may not be used as a representative value for the entire watershed under consideration. Hence, the recorded point precipitation has to be averaged over the watershed. Different methodological approaches exist for the estimation of the aerial depth of precipitation over a given basin. The most frequently applied methods are the simple arithmetic mean, the Thiessen polygon, and the isohyetal methods. The criteria for selecting the best method include the densification of meteorological networks, the characteristics of the relief within the catchment, and the size of the watershed. For this study, the isohyetal method was used because it takes into account the influence of physiographic parameters, which include elevation, slope, distance from the coast, and exposure to rain-bearing winds (Shaw et al. 2010). Since the study area has non-uniform land and varies in topography, the method is preferred. Accordingly, the isohyetal method has been used for the estimation of the aerial depth of precipitation in the watershed. Moreover, the isohyetal method is the most accurate approach for determining the average rainfall over an area (Bedient et al. 2013). It is employed by drawing contours of the equal aerial depth of precipitation (Fig. 3), and the calculated value of the monthly aerial depth of precipitation by the isohyetal method is presented in Table 2.

The general formula which has been used for estimation of the average aerial depth of rainfall by the isohyetal method is given by (Raghunath, 2006).

$$P_{av} = \frac{\sum (P_{1-2} * A_{1-2})}{\sum A_{1-2}} \quad (17)$$

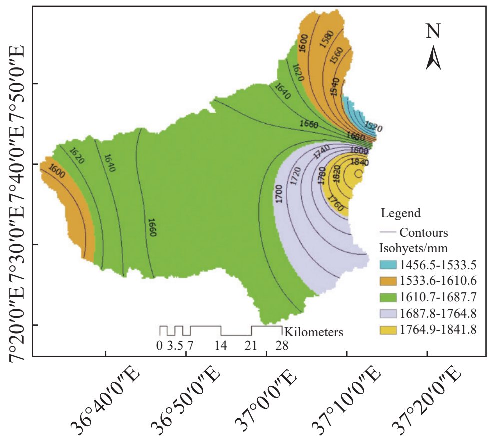

Fig. 3 Isohyetal map of the study area

Where: P_{av} = Annual average aerial depth of precipitation; P_{1-2} = Mean isohyetal value; A_{1-2} = Area between the two successive isohyets.

3.1.1.2 Actual evapotranspiration

A value of the actual evapotranspiration (AET) over a watershed is more often obtained by first calculating the potential evapotranspiration (PET). Several methods have been developed to estimate the PET. For this study, the modified Penman method was used to compute the PET. Penman have produced a formula to describe the conditions under which evaporation plus transpiration takes place on a vegetated surface, which is given by (Shaw et al. 2010).

$$PET = \frac{(\Delta/\gamma)H_T + E_{at}}{(\Delta/\gamma)+1} \quad (18)$$

Where: PET is Potential Evapotranspiration; Δ represents the slope of the curve of saturated vapor pressure plotted against temperature; γ is the hygrometric constant (0.27 mm of mercury/°F) = (0.5 mmHg/°K); H_T is the available heat often calculated from incoming (R_I) and outgoing (R_o) radiation determined from sunshine records, temperature, and humidity and E_{at} is the parameter including wind velocity and saturation deficit.

Based on the above basic formula given for PET, the calculated annual PET of the study area according to the modified Penman method is obtained as 1 019.89 mm/a as shown in Table 3.

Based on the aerial coverage of each soil type in the catchment (Table 4), the water balance model was executed for different soil types in the study area individually, and the computed AET values for the chromic vertisols and dystric nitosols, dystric fluvisols, eutric fluvisols, eutric nitosols, and orthic arcisols were 921.3 mm/a, 885.69 mm/a, 906.02 mm/a, 896.61 mm/a, and 914.18 mm/a, respectively.

Table 2 Mean monthly aerial depth of precipitation by isohyetal method

1	2	3	4	5
No.	**Isohyets interval**	**Mean isohyetal value, $P_{1\text{-}2}$ (mm)**	**The area between isohyets, $A_{1\text{-}2}$ (km^2)**	**Col. 3 * Col. 4**
1	1 460-1 480	1 470	4.41	6 479.5
2	1 480-1 500	1 490	5.67	8 453.5
3	1 500-1 520	1 510	7.79	11 763.0
4	1 520-1 540	1 530	14.73	22 531.2
5	1 540-1 560	1 550	33.29	51 597.8
6	1 560-1 580	1 570	60.56	95 078.1
7	1 580-1 600	1 590	90.92	144 558.6
8	1 600-1 620	1 610	206.30	332 137.0
9	1 620-1 640	1 630	222.33	362 394.6
10	1 640-1 660	1 650	349.81	577 190.4
11	1 660-1 680	1 670	1 231.83	2 057 152.1
12	1 680-1 700	1 690	313.83	530 367.9
13	1 700-1 720	1 710	152.26	260 371.2
14	1 720-1 740	1 730	92.11	159 358.8
15	1 740-1 760	1 750	53.23	93 146.3
16	1 760-1 780	1 770	36.02	63 758.3
17	1 780-1 800	1 790	26.25	46 988.9
18	1 800-1 820	1 810	20.40	36 928.8
19	1 820-1 840	1 830	18.37	33 610.1
Annual aerial depth of precipitation				1 664.5 mm/a

Table 3 PET of the study area according to modified Penman method

Parameters	**Months**											
	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
T (°C)	18.43	19.02	19.38	18.99	18.65	17.81	16.91	17.20	17.60	17.62	17.73	17.67
T (°F)	65.17	66.24	66.88	66.17	65.58	64.06	62.44	62.96	63.69	63.71	63.91	63.80
e_a (mm/d)	15.9	16.4	16.9	16.4	16.1	15.3	14.4	14.7	15.1	15.1	15.2	15.1
RH (%)	56.7	54.6	60.5	69.0	74.9	80.7	83.9	82.7	79.6	69.8	62.0	58.3
e_d (mm/d)	9.01	8.95	10.23	11.32	12.06	12.35	12.09	12.16	12.03	10.54	9.42	8.81
U_2 (m/s)	0.93	0.97	0.99	0.96	0.94	0.83	0.80	0.80	0.83	0.92	0.92	0.92
n (hrs./d)	7.14	7.22	6.91	6.34	6.51	5.59	3.84	4.21	5.52	6.85	7.51	7.67
N (hrs./d)	11.7	11.9	12.0	12.2	12.4	12.5	12.4	12.3	12.1	11.9	11.5	11.7
n/N	0.61	0.61	0.58	0.52	0.53	0.45	0.31	0.34	0.46	0.58	0.65	0.66
f_a(n/N)	0.54	0.54	0.52	0.48	0.49	0.44	0.35	0.37	0.44	0.52	0.56	0.57
R_a (mm/d)	13.25	14.16	14.90	15.08	14.73	14.45	14.57	14.83	14.82	14.40	13.47	12.95
R_I(1-r) (mm/d)	5.49	5.85	5.93	5.60	5.51	4.86	3.95	4.25	5.05	5.73	5.86	5.65
αT_a^4 (mm/d)	14.52	14.62	14.69	14.62	14.55	14.40	12.24	14.30	14.37	14.37	14.39	14.38
R_o (mm/d)	2.40	2.42	2.19	1.91	1.85	1.61	1.09	1.35	1.66	2.11	2.46	2.54
H_T	3.09	3.43	3.74	3.69	3.66	3.26	2.86	2.90	3.40	3.62	3.40	3.11
Δ/γ	2.04	2.12	2.15	2.12	2.07	1.97	1.88	1.91	1.95	1.95	1.97	1.96
E_{at}	2.43	2.63	2.36	1.80	1.43	1.04	0.82	0.89	1.08	1.61	2.04	2.22
PET (mm/d)	2.87	3.17	3.30	3.08	2.93	2.51	2.15	2.21	2.61	2.94	2.94	2.81
PET (mm/month)	89.01	89.78	102.38	92.42	90.94	75.31	66.58	68.47	78.44	91.15	88.32	87.08
PET (mm/a)						1 019.89						

Table 4 Available water capacity of root zone and area coverage of soil types

Soil type	Aerial coverage (km^2)	The area in (%)
Chromic vertisols and dystric nitosols	1 571	53.4
Dystric fluvisols	445	15.1
Eutric Fluvisols	700	23.8
Eutric nitosols	13	0.5
Orthic arcisols	212	7.2
Total	2 941	100

Based on the aerial coverage of each soil type in the catchment, the AET and other water balance parameters have been weighted. Accordingly, the adjusted AET of the catchment is found to be 911.65 mm/a (Table 5).

3.1.2 Runoff

The Gilgel Gibe river in the study area has a gauging station at Assendabo at a location of 7.45°N latitude and 37.11°E longitude with a drainage area of 2 966 km^2. A total of twenty-four as (1990-2013) of daily river flow data from the Gilgel Gibe river recorded near Assendabo was used for runoff analysis (Table 6). The mouth, or outlet point, of the Upper Gilgel Gibe watershed is near to the Assendabo gauging station, and the discharge at the outlet of the watershed is calculated by the drainage-area ratio. Extrapolation of the discharge rate to the outlet of the watershed is made because of having a similar climate, topography, and land use land cover. Drainage-area ratio can be computed as (Emerson, et al. 2005).

$$Q_C = (A_C/A_G)\,Q_G \tag{19}$$

Where: Q_C = Discharge from the catchment; A_C = Drainage area of the catchment; A_G = Drainage

Table 5 Adjusted WTRBLN for the whole study area

Parameters	Months												Annual (mm/a)
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	
P	30.5	36.9	90.6	164.8	207.7	246.5	271.8	264.8	181.4	97.1	43.9	28.6	1 664.5
DR_O	1.5	1.8	4.5	8.2	10.4	12.3	13.6	13.2	9.1	4.9	2.2	1.4	83.2
P_{eff}	29.0	35.1	86.1	156.6	197.3	234.2	258.2	251.6	172.3	92.2	41.7	27.1	1 581.3
PET	89.0	89.8	102.4	92.4	90.9	75.3	66.6	68.5	78.4	91.2	88.3	87.1	1 019.9
P_{eff} - PET	−60.0	−54.7	−16.3	64.2	106.4	158.9	191.6	183.1	93.9	1.1	−46.6	−59.9	561.4
$A_{cc}PWL$	−166.6	−221.4	−237.6	-	-	-	-	-	-	-	−46.6	−106.6	
S_m	69.7	51.7	47.3	111.4	176.7	176.7	176.7	176.7	176.7	176.7	135.8	97.2	1 573.0
ΔS_m	−27.5	−18.1	−4.4	64.2	65.2	0.0	0.0	0.0	0.0	0.0	−40.8	−38.6	0.0
AET	56.4	53.1	90.5	92.4	90.9	75.3	66.6	68.5	78.4	91.2	82.5	65.8	911.6
SMD	32.6	36.6	11.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.8	21.3	108.2
S	0.0	0.0	0.0	0.0	41.1	158.9	191.6	183.1	93.9	1.1	0.0	0.0	669.6
TAR_O	0.0	0.0	0.0	0.0	41.1	179.4	281.3	323.7	255.7	129.0	64.5	32.2	1 307.0
R_O	0.0	0.0	0.0	0.0	20.6	89.7	140.7	161.9	127.9	64.5	32.2	16.1	653.5
DET	0.0	0.0	0.0	0.0	20.6	89.7	140.7	161.9	127.9	64.5	32.2	16.1	653.5
R_OTL	1.5	1.8	4.5	8.2	31.0	102.0	154.2	175.1	136.9	69.3	34.4	17.5	736.7

Notes: P = Mean monthly aerial depth of precipitation, DR_O = Direct runoff, P_{eff} = Effective rainfall, PET = Potential evapotranspiration, $A_{cc}PWL$ = Accumulated potential water loss, S_m = Soil moisture, ΔS_m = change in soil moisture, AET = Actual evapotranspiration, SMD = Soil moisture deficit, S = Surplus, TAR_O = Total available water for runoff, R_O = Runoff without direct runoff, DET = Detention, and R_OTL = Runoff including direct runoff. All values are in mm.

Table 6 Mean monthly discharge of Gilgel Gibe near Assendabo river

Discharge	Recording period (1990-2013)												
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
($\times10^6$ m^3)	24.57	18.56	19.31	25.58	54.96	117.1	223.7	311.3	267.2	159.6	77.38	39.12	1 338.44
mm/a	8.35	6.31	6.57	8.70	18.69	39.80	76.07	105.8	90.87	54.27	26.31	13.30	455.10

area of gauging station and Q_G = Discharge at the gauging station.

Separation of baseflow (Fig. 4) has been made using a software known as base flow indices (BFI+ 3.0). The amount of base flow separated by this software was 993.14×10^6 m^3, or 337.69 mm/a. The method shows that about 74.2% of the flow is contributed by baseflow and 25.8% by surface runoff out of the total mean annual flow.

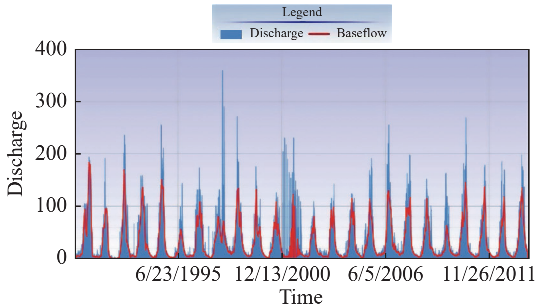

Fig. 4 Long term hydrograph of the Gilgel Gibe River with separated base flow

3.1.3 Groundwater balance and groundwater resource potential evaluation

The previously calculated values of the aerial depth of precipitation and actual evapotranspiration of the catchment are 1 664.5 mm/a and 911.6 mm/a. The adjusted value of the change in soil moisture was found to be zero, and the runoff from the catchment was 455.10 mm/a. Substituting the values in the water balance equation (Equation 2), the total recharge of the study area was 297.8 mm/a. Considering the total area of the catchment at 2 941 km^2, the annual groundwater recharge of the Upper Gilgel Gibe catchment was estimated at 875 829 800 m^3/a.

Specific yield can be estimated using the formula given in Equation (14). Groundwater abstraction during the recharge period is assumed to be equal to the volume of water used for domestic use. This is due to the study area's insignificant industrial or agricultural water consumption from groundwater. For these purposes, there is an adequate amount of surface water available in the study area. In developing countries, the average per capita water consumption was estimated to be 5–15 L/d/person (WHO, 2006). According to a report by the Central Statistics Agency, the study area was populated with 159.69 people per square kilometer (CSA, 2007). The Upper Gilgel Gibe watershed covers an area of 2 941 km^2 of which the population size was estimated to be 469 650. By considering the population growth rate of the Oromia region (2.9%), the projected population number of the study area was found to be 605 849. Hence, the amount of water abstracted for domestic consumption was estimated at an average rate of 10 L/d/person, and the abstraction was found to be in the order of 2 211 349 m^3/a. Field measurements and borehole data are used to calculate the average water level rise and decline during the wet and dry seasons, which is 5 m and 3 m, respectively. The values were also validated after an oral discussion with farmers and field visits. The lateral subsurface outflow (*Lso*) from the watershed is assumed to be equal to the lateral subsurface inflow (*Lsi*) into the watershed and they are considered to balance each other (zero). Using the above-mentioned parameters, the specific yield was estimated to be 0.059, or 5.9%. By using Equation (15), the exploitable groundwater reserve of the watershed was estimated as 520 557 000 m^3/a.

In this study, safe yield is used as a management concept and is estimated by using Equation (16). The exploitable groundwater reserve of the watershed and the volume of water used for domestic use in the rainy season of the area from the previous estimation are 520 557 000 m^3/a and 2 211 349 m^3/a. Since the values of recharge due to irrigation returns and sewage infiltration are insignificant and taken as zero. Thus, the annual safe yield of the watershed was estimated at 522 768 349 m^3/a.

Pumping from both hand-dug wells and boreholes is the major way in which groundwater is abstracted from the system. The shallow boreholes and hand-dug wells fitted with submersible and hand pumps have been serving as domestic water supplies for both the urban and rural communities. According to the Jimma Zone water, mineral, and energy office and the Water Sanitation and Hygiene (WASH) report of Jimma Zone, there are about 98 hand-dug wells within the study area (Fig. 5). The hand-dug wells yield on average 0.5 L/s when pumping for 8 hours per day. Therefore, groundwater abstraction from these wells was found to be 515 088 m^3/a. The collected data indicates that the groundwater of the study area was also abstracted through 56 shallow and deep wells, with a total yield of 7 131 170 m^3/a. The report by water, sanitation, and hygiene also indicates that there are an additional 10 deep wells and 16 shallow wells. By assuming an average yield of 21.15 L/s and 5 L/s and average pumping hours of 6 hours and 8 hours for deep wells and shallow wells, respectively, the groundwater abstraction from these wells was found to be 2 508 426 m^3/a. The total groundwater abstraction from the study area was found to be in the order of 10 154 684 m^3/a.

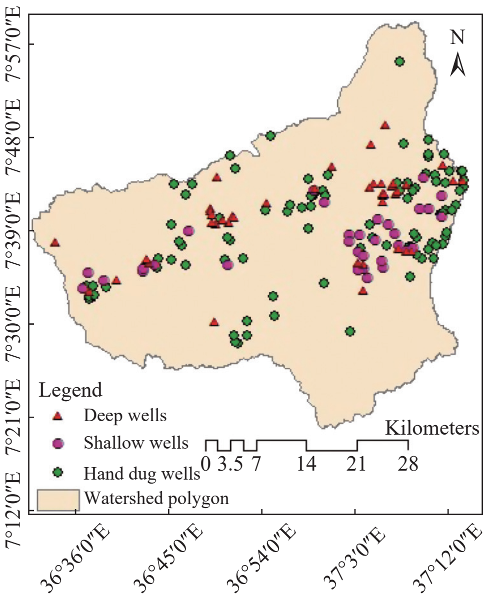

Fig. 5 Location and types of wells collected

Based on the previous estimation, the groundwater recharge, the safe yield of the watershed, and the total groundwater abstraction or withdrawal were 875 829 800 m^3/a, 522 768 349 m^3/a, and 10 154 684 m^3/a, respectively (Table 7). The total annual inflow of the watershed was greater than the total outflow of the watershed. Thus, the current groundwater abstraction is lower than the safe yield of the aquifers and the annual groundwater recharge of the watershed.

3.2 Discussions

The groundwater resource potential of the Omo Gibe river basin as a whole was estimated by different governmental and non-governmental organizations. Firstly, the baseflow separation approach was used to separate the streamflow of Omo Gibe main and tributary rivers, which originate from stored groundwater, and it is referred to as groundwater runoff or base flow. This approach is an indirect way to estimate groundwater resource potential. To study the total groundwater resource potential in the river basin, different researchers took this method as a basic tool and estimated the groundwater resource potential. The Report by the Water and Power Consultancy Service (WAPCOS)[①]* shows that using the streamflow data of twenty-one as, the total base flow volume of the Omo Gibe river basin is estimated at 2 785 million m^3 (Moges, 2012). The base flow obtained from this study (993.14 million m^3) contributes about 35.66% to the Omo Gibe river basin.

The subsurface drainage approach was the second method that the previous study used to estimate the groundwater resource potential of the Omo Gibe river basin. The method used generated groundwater runoff contour map of Ethiopia and the groundwater runoff contour map is superimposed onto the river basin, then the groundwater represents the replenishable recharge of the river basin. According to the report by WAPCOS, the groundwater runoff is obtained as 1.35 L/s/km^2 and, considering the total area of the river basin, the annual recharge of the Omo Gibe river basin is estimated at 3 329 million m^3. The groundwater recharge for the Upper Gilgel Gibe watershed obtained by the water balance method (875 million m^3) contributes about 26.28% to the Omo Gibe river basin.

The recharge area approach was the third method that the previous researchers used to estimate the groundwater resource potential of the Omo Gibe river basin. Groundwater recharges in the river basin come due to infiltration of precipitation and seepage from streams and other water bodies. Major groundwater replenishment in the river basin takes place through direct precipitation over the upland areas of the river basin. The seasonal fluctuations in water level in the river basin depend on the rate of replenishment of the saturated zone. This rate is a function of precipitation, surface run-off, the permeability of the soil, drainage network, and antecedent moisture content of the soil and the slope of the land surface. This approach is also used to identify the discharge and recharge zones of the study area. According to the WAPCOS report, the mean annual rainfall, the extent of recharge area, the percentage of rainfall recharging groundwater, and replenishable recharge are estimated at 1 469 mm, 35 811 km^2, 8%, and 4 208 million m^3 respectively. The groundwater resource potential of the river basin was estimated indirectly, and the previous studies does not consider the groundwater sources like springs,

Table 7 Estimated water balance components of the study area

Components	Recharge (m^3/a)	Specific yield (%)	Exploitable groundwater reserve (m^3/a)	Safe yield (m^3/a)	Abstraction (m^3/a)
Estimated values	875 829 800	5.9	520 557 000	522 768 349	10 154 684

* The report is available in Ethiopia's Ministry of Water Resources (MWR) library.

hand-dug wells, shallow and deep wells that have been developed for different purposes (generally, groundwater abstraction) in the river basin.

Another study by Birhanu Haile in the year 2015, characterized and assessed the groundwater resource potential and the groundwater aquifer system in the Omo Gibe river basin by using a three-dimensional (3D) steady-state finite element method based groundwater modeling code (TAGSAC) (Gedamu, 2015). This model needs the hydrogeologic, recharge, and boundary conditions as its input. According to this study, the groundwater resource potential of the Omo Gibe river basin is about 4.38 billion m^3. Of the studies conducted at the sub-basin level, a study on the Bulbul sub-basin uses a water mass balance method to estimate different water balance components. The study shows the following results: Precipitation (771 932 000 m^3); recharge due to irrigation practices (70 388 501 m^3); runoff (275 074 089 m^3); evapotranspiration (363 329 000 m^3); water abstraction for domestic use (560 184 m^3); change in soil water content (25 289 436 m^3); and groundwater recharge (178 067 792 m^3) (Shimelis et al. 2014). Therefore, the water balance method used for this study shows almost comparable results to those studies conducted at a river basin level. The findings of previous studies are summarized in Table 8 below.

4 Conclusions

The groundwater resource potential in the study area was estimated based on the water balance approach, which is a viable method of establishing the rainfall-recharge relationship and for quantification of groundwater recharge. A water balance study is necessary for proper assessment of potential, present use, and additional exploitability of water resources at an optimal level. In the study area, precipitation was identified as a major recharging component of the aquifer. Whereas evapotranspiration (the principal cause of water loss from precipitation), runoff, and household consumption discharge the system. However, net groundwater inflow and outflow from the watershed, effluent seepage to rivers and recharge from the irrigated field were not assumed as it is difficult to analyze those components and their effects may compensate for each other.

According to the findings of this study, a total water volume of 875 829 800 m^3/a is estimated to recharge the aquifer system. Annual groundwater abstraction is currently estimated to be 10 150 000 m^3/a. The catchment's estimated specific yield, exploitable groundwater reserve, and safe yield are 5.9 percent, 520 557 000 m^3/a, and 522 768 349 m^3/a, respectively. The current groundwater abstraction is much lower than the safe yield of the aquifers, the annual groundwater recharge of the watershed and the exploitable groundwater resources. This indicates underdeveloped groundwater resources in the study area. The available groundwater resources of the study area can support the total population as a domestic water supply. To utilize the existing groundwater resources, appropriate management and rules should be applied at large in different groundwater resource potential zones of the country. In the study area, there is enough groundwater resource potential for the planning and implementation of different groundwater resource development projects. Groundwater resource potential evaluation across the river basin plays a vital role in the case of groundwater quality control, occurrence, extraction, and management of the resources in the study area. In general, this study concludes that the water balance model can be successfully applied for evaluating groundwater resource potential across the river basin.

Data availability

All the relevant data is uploaded on GitHub and accessible via the following URL: https://github.

Table 8 Summary of methods used and results obtained by different studies

Study area	Method	Results	Reference
Omo Gibe	Baseflow separation	Baseflow volume = 2 785 million m^3	WAPCOS, (Moges, 2012)
Omo Gibe	Sub-surface drainage approach	Annual groundwater recharge = 3 329 million m^3	WAPCOS
Omo Gibe	Recharge area approach	Annual replenishable recharge = 4 208 million m^3	WAPCOS
Omo Gibe	3D steady-state Finite Element Method based groundwater modeling code (TAGSAC)	The groundwater resource potential = 4.38 billion m^3	(Gedamu, 2015)
Bulbul sub-basin	Water balance method	The groundwater recharge = 178 067 792 m^3	(Shimelis, Megerssa and Fantahun, 2014)

com/wondiye8/Groundwater.

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