

Article

Estimation of Groundwater Recharge in a Volcanic Aquifer System Using Soil Moisture Balance and Baseflow Separation Methods: The Case of Gilgel Gibe Catchment, Ethiopia

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Abstract: Understanding the recharge–discharge system of a catchment is key to the efficient use and effective management of groundwater resources. The present study focused on the estimation of groundwater recharge using Soil Moisture Balance (SMB) and Baseflow Separation (BFS) methods in the Gilgel Gibe catchment where water demand for irrigation, domestic, and industrial purposes is dramatically increasing. The demand for groundwater and the existing ambitious plans to respond to this demand will put a strain on the groundwater resource in the catchment unless prompt intervention is undertaken to ensure its sustainability. Ground-based hydrometeorological 36-years data (1985 to 2020) from 17 stations and satellite products from CHIRPS and NASA/POWER were used for the SMB method. Six BFS methods were applied through the Web-based Hydrograph Analysis Tool (WHAT), SepHydro, BFLOW, and Automated Computer Programming (PART) to sub-catchments and the main catchment to estimate the groundwater recharge. The streamflow data (discharge) obtained from the Ministry of Water and Energy were the main input data for the BFS methods. The average annual recharge of groundwater was estimated to be 313 mm using SMB for the years 1985 to 2020 and 314 mm using BFS for the years 1986 to 2003. The results from the SMB method revealed geographical heterogeneity in annual groundwater recharge, varying from 209 to 442 mm. Significant spatial variation is also observed in the estimated annual groundwater recharge using the BFS methods, which varies from 181 to 411 mm for sub-catchments. Hydrogeological conditions of the catchment were observed, and the yielding capacity of existing wells was assessed to evaluate the validity of the results. The recharge values estimated using SMB and BFS methods are comparable and hydrologically reasonable. The findings remarkably provide insightful information for decision-makers to develop effective groundwater management strategies and to prioritize the sub-catchments for immediate intervention to ensure the sustainability of groundwater.

Keywords: groundwater recharge; catchment hydrology; soil moisture balance; baseflow separation; sustainability assessment

1. Introduction

Groundwater, a crucial element of the hydrologic cycle, plays a pivotal role in regulating surface water flow, sustaining ecosystems, and providing life-sustaining water resources [1]. Approximately 2.5 billion people across the world rely exclusively on groundwater resources to meet their basic daily water needs [2]. Its historical use for domestic

water supply is long-standing, with increasing significance anticipated due to factors like population growth, surface water pollution, and unreliable surface water sources for irrigation [3–5]. Globally, groundwater allocation stands at 69% for agriculture, 22% for domestic use, and 9% for industrial purposes, with figures in Africa being 65%, 32%, and 2%, respectively [6]. In Ethiopia, groundwater plays a substantial role, providing 90% of domestic use, 95% of industrial need, and 1% of irrigation water supply, with an ambitious plan to develop large groundwater-based irrigated agriculture [7].

Despite its critical importance, groundwater constitutes less than 2% of the world's total water resources and often suffers from inadequate understanding, undervaluation, mismanagement, and over-exploitation [1]. Densely populated regions and established agricultural areas witness intensive groundwater development and depletion, underscoring the urgent need for responsible groundwater management [5]. The Gilgel Gibe catchment currently maintains extra inflows compared to outflows [8]. However, impending challenges like population growth, land cover changes, and increasing water demands raise concerns about potential future groundwater stress.

Takala's [9] analysis of land use and land cover (LULC) changes in the upper Gilgel Gibe catchment reveals an increase in agricultural land and a significant rise in urban areas between 1987 and 2010. A recent LULC map of the catchment extracted from the global Sentinel-2 LULC product with a 10 m resolution indicates that approximately 69% of the catchment is now classified as cropland. The catchment's population is projected to rise from 2.07 million in 2020 to 3.65 million by 2050 [10], leading to a dramatic surge in water demand. In 2020, average daily water demand, including both domestic and non-domestic usage, amounted to 70,244 m³/day, with projections indicating a three-fold increase by 2050.

To address the escalating water demands, several deep and shallow wells are under construction. This includes deep wells for the Jimma Industrial Park and Jimma University, along with additional wells in various stages of construction. Additionally, seven shallow wells are being built in the Kersa district to meet local domestic water needs.

Given these developments, proactive policies and management strategies are crucial to ensure effective groundwater utilization in the catchment. The accurate estimation of groundwater recharge and identification of potential sources play a central role in guiding policy decisions and determining sustainable extraction limits from the aquifer [11]. So far, a limited number of studies have been conducted in the Gilgel Gibe catchment regarding groundwater recharge. Mengistu [12] characterized the recharge potential area of the upper Gilgel Gibe catchment based on proxy data using GIS and analytical hierarchy processes (AHP). However, he did not quantify the groundwater recharge of the catchment. Abebe [8] evaluated the groundwater potential of the upper Gilgel Gibe catchment based on the limited recorded data using a water balance model (WTRBLN). The model was run on a monthly basis and the annual groundwater recharge and abstraction rates were estimated to be 298 and 3.5 mm, respectively. This study does not cover the whole Gilgel Gibe catchment, and the spatial and temporal distribution of groundwater recharge was not discussed. Shimelis [13] applied SMB and BFS methods to the Bulbul catchment to estimate the annual groundwater recharge and found them to be 351 and 406 mm, respectively.

In the present study, SMB and BFS methods were applied on daily time steps to the Gilgel Gibe catchment. The SMB method, relying on historical climatological data, serves as a valuable tool for estimating groundwater recharge [14]. Recent advancements in satellite-based climatic data, which can well represent spatial and temporal variations, expand its applicability and enable upscaling to watershed or regional scales. The SMB method has been commonly applied in Ethiopia, particularly in the Upper Blue Nile River Basin [15–18]. Previous studies have validated its effectiveness against alternative methodologies, further affirming its reliability in groundwater recharge estimation [16–18]. Baseflow separation methods, especially in regions with readily available streamflow data, play a pivotal role in estimating groundwater recharge [8,11,13,16,19–25]. The method is reportedly efficient in humid and sub-humid regions [11,23]. Various techniques, ranging from geochemical

to analytical and graphical approaches, have been developed and are applied globally, attesting to their versatility and applicability [26,27].

The graphical method, in particular, relies on specific assumptions to delineate baseflow from streamflow dynamics [28–30] and it is applicable in regions like the Gilgel Gibe basin where predefined catchment indices like alpha may be lacking. Noteworthy developments in this domain include the HYSEP computer program, which incorporates algorithms for graphical baseflow separation methods, enhancing efficiency [30]. Efforts have also been made to address user-friendliness concerns through integration with other software, such as BFI + 3.0, and web-based tools like WHAT [31]. The recent development of SepHydro, integrating 11 distinct baseflow separation methods including graphical methods, offers both user-friendliness and a platform for method intercomparison [28].

Several recursive digital filter methods are also available for baseflow separation including Chapman [32], Boughton [33], Chapman and Maxwell [34], Szilagyi and Parlange [35], BFLOW [11], Furey and Gupta [26], Eckhardt [36], and EWMA [37]. BFLOW is a computer program developed by Arnold and Allen [11] for a one-parameter recursive digital filter based on the Lyne and Hollick method. The method filters the high-frequency flow component (runoff) from the low-frequency flow component (baseflow) based on signal analysis and processing [38] and has been used by several scholars [11,23,39]. The method has no true physical bases but is shown to estimate a realistic value of baseflow when an appropriate filter parameter is used [11,23,31,39].

As the observed data acquisition is difficult for cross-validation, the application of two or more methods is convenient for groundwater recharge estimation. This study aims to employ the SMB method and BFS techniques to accurately estimate groundwater recharge in the Gilgel Gibe catchment, providing critical insights for the formulation of policies and management strategies to ensure sustainable groundwater utilization, in light of escalating water demands and potential future stressors. The BFS techniques applied include graphical methods through SepHydro, Eckhardt through WHAT, BFLOW, and PART.

2. Materials and Methods

2.1. The Study Area

The study area encompasses the Gilgel Gibe catchment, which is a sub-basin within the larger Omo Gibe river basin, located in the southwestern region of Ethiopia. Its centroid is positioned approximately 260 km away from Addis Ababa City and 70 km from Jimma City (Figure 1). The total land area of the Gilgel Gibe catchment is about 5145 km², delineated at the confluence of the primary Omo-Gibe River. Predominantly, 95% of the catchment area is situated within the Oromia National Regional State, specifically in the Jimma zone, while the remaining 5% is located in the Central Ethiopia Regional State, specifically in the Gurage and Yem zones. The terrain of the catchment is characterized by undulating topography, comprising mountains, hills, plains, deep V-shaped valleys, and flat river terraces along the main river course. This geographical layout facilitates the natural processes of both groundwater recharge and discharge [40]. The catchment's drainage system displays characteristics of dendritic, parallel, and subparallel patterns. The elevation of the study area exhibits a range from 3329 to 1080 m above sea level.

The Gilgel Gibe catchment is situated within a humid tropical region, predominantly characterized by a monomodal pattern of rainfall distribution. However, specific areas within dissected gorges exhibit traits of a semi-arid climate [41]. The principal source of water within the catchment emanates from rainfall [12]. While rainfall is distributed across the year, the catchment experiences a peak in rainfall during July and August. From March through October, the region receives an average monthly rainfall ranging from 92 mm to over 259 mm, whereas from November to January, the average monthly rainfall ranges from 29 mm to 42 mm based the data from CHIRPS for the period from 1985 to 2020. The annual average rainfall varies between 1193 mm and 1716 mm. The average temperature within the catchment is 19 °C.

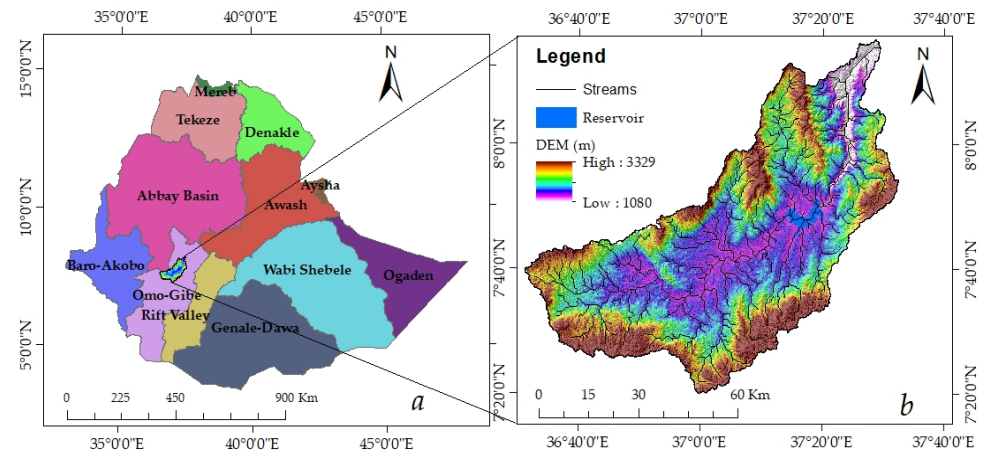


Figure 1. Location of Gilgel Gibe catchment: (a) Ethiopian river basins and (b) Gilgel Gibe catchment.

As delineated by the Land Use and Land Cover (LULC) map of 2018 derived from ESA Sentinel-2 imagery at 10 m resolution [42], cropland covers approximately 69% of the catchment area, while tree/forest occupies 13%, the built-up area covers 10%, rangeland encompasses 7%, and the remaining 1% is covered by water body, bare land, and regularly flooded vegetation. LULC stands as a pivotal determinant impacting groundwater recharge, surface runoff, and evapotranspiration processes.

The catchment is predominantly inhabited and cultivated by a substantial population of smallholding farmers, as noted by Teklu and Talema [43]. The natural vegetation in the region comprises dense, towering, broad-leaved trees, alongside evergreen trees, and expanses of open grassland [41]. Within the quaternary alluvial area, one can observe a transition from grassland to boggy terrain. In certain highland regions, bamboo forests are sporadically interspersed with trees, particularly along minor river courses. Additionally, apart from the indigenous vegetation, the cultivation of various tree species such as Eucalyptus, Coffee, and Inset is prevalent in specific localities [41].

It is important to note that the catchment area is subject to extensive cultivation, with LULC changes driven primarily by agricultural expansion, often at the expense of grassland, shrub-covered areas, and tree-dotted regions, as highlighted by Jillo [44]. The flatter, inadequately drained lowlands within the catchment typically remain uncultivated, instead serving as areas for dry season grazing and the establishment of Eucalyptus tree plantations. Figure 2a provides a detailed depiction of the LULC types and their distribution across the study area.

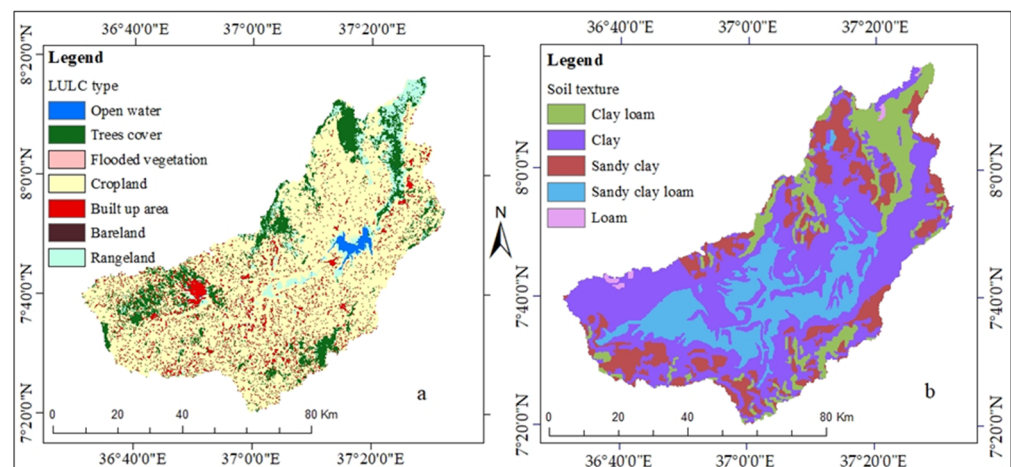


Figure 2. (a) LULC type and (b) Soil type of Gilgel Gibe catchment.

The study area predominantly features soils formed from tertiary and quaternary volcanic rocks [45–47]. In 2013, the Ministry of Water and Energy (MoWE) of Ethiopia undertook comprehensive field soil surveys and laboratory analyses, leading to the development of a soil map at a scale of 1:250,000. This initiative aimed to formulate a strategic plan for irrigation development across major river basins, notably the Omo-Gibe region [45]. Attempts have also been made by researchers to develop more detailed soil maps of specific localities in the catchment [46]. For this study, the MoWE's map was employed because the map covers the whole study area, despite the existence of other specific soil types in certain areas of the study region.

According to the MoWE's soil map, eight distinct soil types are identified within the catchment. However, we grouped them into five classes (Figure 2b) based on their textural type, which determines soil water-holding capacity and infiltration for recharge estimation. Notably, clay soil predominates, encompassing 50% of the study area. It is primarily concentrated in the central, northern upstream, and southern downstream segments of the catchment (Figure 2b). Sandy clay and sandy clay loam soils cover 35% of the total area. Sandy clay occupies the northern and southern extremities of the catchment, while sandy clay loam soils are predominantly situated in the middle section (Figure 2b). In addition, clay loam and loam soils collectively account for 15% of the catchment area. These soils are primarily located downstream, aligning with the main river valley, and extend to higher elevations in the northern and southern catchment regions along the ridges (Figure 2b).

2.2. Geology and Hydrogeology

Over time, various regional geological investigations have been conducted in and around the study area, as documented by Alemu [40], Basalfew [48], Davidson [49], Haro [41], Merla et al. [50], and Tefera et al. [51]. However, mapping specifically focused on the geology of the Gilgel Gibe catchment has been comparatively limited, with studies by Regassa et al. [52], Tadesse [53], and Van Daele [54] providing notable contributions.

Merla et al. [50] initially mapped the geology of Ethiopia, representing the Gilgel Gibe catchment with Jimma volcanic flows that erupted during the Oligocene to Miocene periods. Subsequently, Tefera [51] provided a more detailed geological classification, incorporating Jimma volcanic formations (ranging from the late Eocene to late Oligocene), Makonnen Basalts (Oligocene to Miocene in age), and Nazret Series (Miocene to Pliocene in age). Recent geological surveys conducted by the Ethiopian Geological Survey have further refined our understanding of the country's geological formations [40].

The predominant rock types within the catchment encompass basalt flows, trachyte flows, rhyolite flow, pyroclastic flows, welded ignimbrite, alluvial deposits, and stratified tuffs (Figure 3). This comprehensive geological framework provides a critical foundation for understanding the hydrogeological characteristics of the Gilgel Gibe catchment.

The geological formation of the Gilgel Gibe catchment can be categorized into four main units. At the base lies lower-tertiary volcanic flow, dating back to pre-Oligocene times, comprising lower basalt flows overlain by lower pyroclastic flow. Above this, upper-tertiary volcanic flows from the Oligocene era are characterized by middle basalt flows topped by Trachyte flows. Further up, upper-tertiary volcanic formations from the Miocene to Pliocene epochs include upper basaltic flows, rhyolites, upper pyroclastic material, and Setema basalt. Lastly, there are quaternary stratified tuff and alluvial deposits [41].

Lower basalt flows, covering the downstream of the Gilgel Gibe River valley and extending from the reservoir to the main outlet, are characterized by aphanitic and slightly weathered basalt, containing plagioclase and pyroclastics with trachyte plugs [40,41]. These lower basalt flows are underlain by Omo trachyte flow and overlain by a fine-grained basalt layer. Lower pyroclastic deposits extend around the Gilgel Gibe dam, encompassing areas from Asendabo to Dimtu and from Bore to Serbo, with ignimbrite, tuffs, and lithic tuffs containing trachytic obsidian lenses. Middle basalt flows, found in the northwest of Jimma and northern Dimtu, comprise fine-grained dark gray basalt, interspersed with paleo soils and, in some places, basaltic pyroclasts with varying sizes of particles cemented by

fine-grained materials and scoriaceous basalt. Trachyte flows dominate the upstream area of the catchment, spanning Dedo, Jimma, and Sarbo, with mostly massive rock formations occasionally displaying fractures and intercalations of ignimbrite, basalt, and paleo soil. Downstream, upper basalt flows with minor trachyte and tuff layers overlay the trachyte flows and directly underlie the lower basalt along the Gilgel Gibe gorge, also extending into the southwestern catchment area south of Dedo. Quaternary alluvial deposits are prevalent along the main rivers in plateau regions, where streams flow and drain Tertiary to Pliocene volcanic flows [41]. Around the Gilgel Gibe dam reservoir, the Asendabo area is flat, with small hills and depressed areas that are filled with younger quaternary tuffs and alluvium. The depression extends to Jimma Town [55].

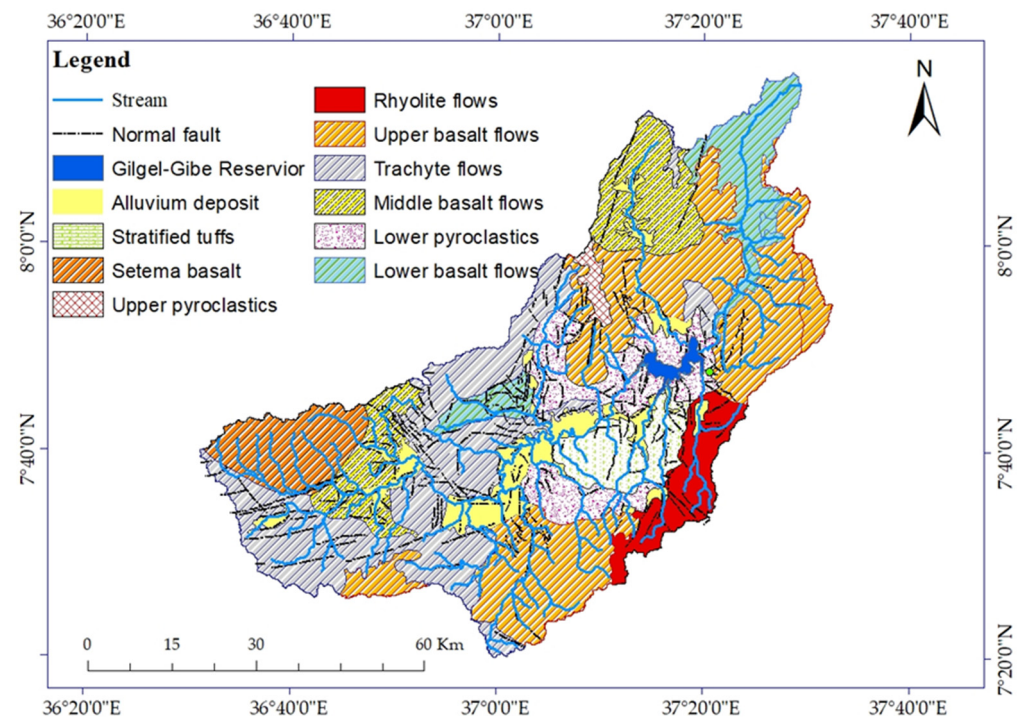


Figure 3. Geological map of Gilgel Gibe catchment.

Hydrogeologically, the aquifer/aquitard systems encompass quaternary alluvial deposits, stratified tuffs, basalts, trachyte, sedimentary, and pyroclastic rocks [55]. Different hydrogeological units are identified: (1) porous permeable aquifers, primarily consisting of alluvial sediments, which are concentrated along major rivers and the Asendabo area; (2) fissured permeable aquifers, located in the eastern part of Jimma, are predominantly composed of basalts with trachyte and rhyolites, featuring open faults and fault systems that serve as significant groundwater flow pathways; (3) mixed fissured and porous permeable aquifers, consisting of trachyte lava flows, ignimbrites, and rhyolite intercalated with porous tuffs and pumice. These aquifers can be both unconfined and confined, with varying thickness. The topographic configuration plays a pivotal role in defining potential recharge and discharge areas within the aquifers system.

2.3. Data Collection and Analysis

A 30 m resolution Digital Elevation Model (DEM) from the Shuttle Radar Topographic Mission (SRTM) "<https://earthexplorer.usgs.gov> (accessed on 15 February 2022)" was employed in conjunction with ArcGIS to analyze the catchment and its sub-catchments. Utilizing LULC and soil maps (Figure 2a,b), surface runoff was estimated using a modified SCS-CN method. Additionally, a geological map (Figure 3) was referenced to gain a comprehensive understanding of the aquifer system within the catchment.

The availability and reliability of hydrometeorological data are the key for groundwater recharge estimation and runoff assessment through the SMB method. In many African regions, traditional ground-based observations have been the primary source of such data [56]. Nevertheless, these methods are prone to uncertainties and offer limited spatial coverage. Even in well-monitored areas, temporal inconsistencies and prolonged periods of missing data are common [44,57]. Within the Gilgel Gibe catchment, there are 15 meteorological stations along with 2 neighboring stations (Figure 4), each exhibiting varying temporal coverage and substantial data gaps, particularly in rainfall records. Only the Jimma station consistently maintained reliable hydrometeorological data, with a mere 1% data deficit from 1985 to 2020. This underscores the inadequacy of relying solely on ground-based measurements for groundwater recharge estimation in this catchment.

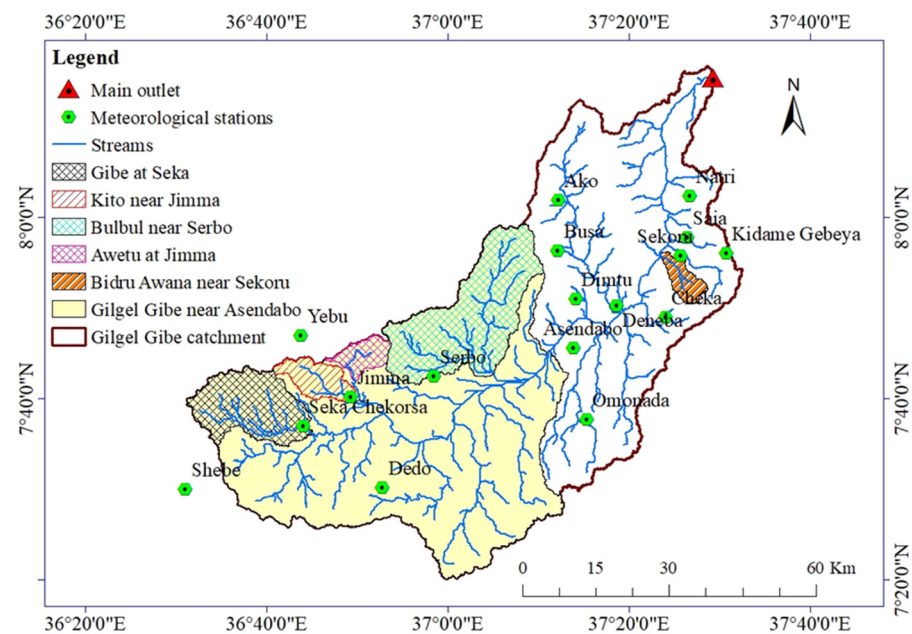


Figure 4. Map of gauged sub-basins and locations of meteorological stations.

To mitigate these challenges, satellite-based data, exhibiting good correlation with the available ground-based measurements in Ethiopian basins in general and the Gilgel Gibe basin in particular, were reviewed [16,56,58]. Accordingly, Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) with $0.05^\circ \times 0.05^\circ$ spatial resolution demonstrated a robust correlation with observed data in the catchment. While CHIRPS provides rainfall data from 1981 to the present at daily, monthly, and annual temporal scales [59], additional sources were needed for temperature, relative humidity, wind speed, and solar radiation. The National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources (NASA/POWER), which emerged as a valuable data source offering satellite and model-based solar and meteorological data [60–62], was used. These parameters have demonstrated sufficient accuracy in providing reliable data [62]. NASA/POWER supplies daily meteorological data on a global grid with varying spatial resolutions, ranging from 1° latitude by 1° longitude for radiation datasets to 0.5° latitude by 0.625° longitude for meteorological datasets. These data are accessible from 1981 to near real-time. The rainfall data obtained from both CHIRPS and NASA/POWER were corroborated with available ground-based measurements (Table 1), revealing a strong agreement. However, the available ground-based measurements are insufficient and inconsistent to evaluate the correlation of other weather parameters. This combined dataset, encompassing rainfall from CHIRPS and comprehensive hydrometeorological data from NASA/POWER, was then utilized for groundwater recharge estimation.

Table 1. Correlation of CHIRPS and NASA/POWER with ground-based measured monthly rainfall.

Stations	Year	Number of Years	Correlation Coefficient	
			CHIRPS	NASA/POWER
Ako	2019	1	0.82	0.76
Asendabo	1995–2003	9	0.97	0.93
Busa	1994–2002	9	1.00	1.00
Cheka	1998–2005	8	0.97	0.93
Chekorsa	2000–2005	6	0.95	0.90
Dedo	1985–1990	6	0.95	0.90
Deneba	1994–2000	7	0.78	0.66
Dimtu	2004–2007	9	0.96	0.94
Jimma	1985–2017	33	0.98	0.92
Kidame Gebeya	1988–1993	6	0.96	0.93
Natri	1989–1990	2	0.85	0.76
Omonada	1999–2005	7	0.93	0.78
Saja	1985–1995	11	1.00	0.98
Sekoru	1985–1991	7	0.99	0.95
Serbo	1999–2005	7	0.98	0.84
Shebe	1985–1993	9	0.98	0.97
Yebu	1985–1992	8	0.95	0.96

Stream flow data from six gauging stations of different duration were collected from the Ministry of Water and Energy (Table 2). However, there is no gauging station at the main outlet of the catchment (Gilgel Gibe station). Stream flow for the Gilgel Gibe station was obtained by using an appropriate regionalization method. The modified linear interpolation [63] is an appropriate method for regionalization if the ungauged catchment is located either upstream or downstream of the gauged catchment. Asendabo, a gauged station that drains about 60% of the Gilgel Gibe catchment, is located upstream of the Gilgel Gibe outlet. The location of gauged sub-catchments and meteorological stations is depicted in Figure 4.

Table 2. Streamflow gauging stations.

Gauging Station	Longitude	Latitude	Area (km ²)	Year
Awetu at Jimma (Awetu)	36.83	7.68	72	1985–2007
Bidru Awana near Sekoru (Bidru Awana)	37.40	7.92	41	1985–2014
Gibe Near Seka (Seka)	36.75	7.60	280.4	1985–2014
Gilgel Gibe Near Asendabo (Asendabo)	37.18	7.75	2966	1985–2019
Kito Near Jimma (Kito)	36.83	7.70	85	1985–2005
Bulbul Near Serbo (Bulbul)	37.08	7.57	526	1986–2018
Gilgel Gibe at main outlet (Gilge Gibe)	37.49	8.26	5145.41	1985–2003

Asendabo station was selected for the regionalization method because it drains a larger area compared to other sub-catchments. The stream flow at the main outlet was determined from stream flow measured at the Asendabo station using the modified linear interpolation equation (Equation (1)).

$$Q_u = \frac{A_u * P_u}{A_g * P_g} * Q_g \quad (1)$$

where Q_u and Q_g are the stream flow of ungauged and gauged catchment, respectively (m³/s);

A_u and A_g are the area of gauged and ungauged catchment, respectively (km²);

P_u and P_g are the mean annual rainfall in the drainage area of the ungauged and gauged catchments, respectively (mm).

The stream flow data observed at sub-catchments and determined at the main outlet using Equation (1) were used to estimate the recharge using BFS methods for the respective sub-catchments. The catchments and sub-catchments area with the duration of recorded data are described in Table 2.

2.4. Recharge Estimation Methods

2.4.1. Soil Moisture Balance Method

The SMB method (Equation (2)) was developed by Thornthwaite [64], further revised in 1955 [65], and edited in 1957 by Thornthwaite and Mather [14]. The method estimates the groundwater recharge indirectly as a residual of water balance components of the soil layer. The method allows us to compute the groundwater recharge on hourly, daily, monthly, or annual timesteps using available climate data [66]. It estimates the diffuse recharge from rainfall and does not take into account the recharge from preferential flows. The required input data for the SMB method are rainfall, PET, runoff coefficient, PAW, and initial soil moisture content [67], allowing us to estimate the soil water balance components:

$$R = P - Ea + \Delta S - Ro \quad (2)$$

where R = recharge; P = precipitation; Ea = actual evapotranspiration; ΔS = change in soil water storage; and Ro = runoff.

The SMB method estimates groundwater recharge using a point scale. However, runoff is usually estimated for land areas of varying scales. The USDA Natural Resources Conservation Service, previously called the Soil Conservation Service (SCS-CN), curve number method [68] which was developed for small catchments [33,69–72], was applied in this study, creating a Thiessen polygon for 17 hydrometeorological stations. The area represented by each station and the estimated runoff coefficient are described in Table 3.

Table 3. Meteorological stations and respective PAW and runoff coefficients.

No	Stations	Area (km ²)	Average RD (cm)	(FC-PWP) (mm)	PAW (mm)	Runoff Coefficient (%)
1	Ako	365	156	216	338	23
2	Asendabo	303	77	209	161	35
3	Busa	319	114	203	231	26
4	Cheka	193	74	186	138	18
5	Seka Chekorsa	486	122	208	254	20
6	Dedo	704	79	211	167	26
7	Deneba	162	74	204	151	27
8	Dimtu	169	81	205	166	33
9	Jimma	264	140	212	297	18
10	Kidame Gebeya	81	94	204	192	10
11	Natri	392	160	192	307	12
12	Omonada	635	88	211	186	20
13	Saja	88	124	199	247	14
14	Sekoru	141	110	200	220	16
15	Serbo	646	92	216	199	25
16	Shebe	130	117	204	238	19
17	Yebu	67	118	186	220	32

The SCS-CN method is most widely used because of its ease of use and stability, and it considers the most important watershed characteristics such as soil, LULC, hydrologic condition, and antecedent moisture [69]. The depth of runoff is determined from rainfall using an empirical equation (Equation (3)) [69,73].

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \text{ for } P > 0.2S, \text{ else } Q = 0 \quad (3)$$

where Q —surface runoff (mm), S —potential maximum retention (mm) and P —precipitation (mm).

Potential maximum soil storage is given by

$$S = \frac{25,400}{CN} - 254; CN \text{ is the curve number.} \quad (4)$$

Rainfall-runoff processes are highly affected by soil, LULC, and Antecedent Moisture Conditions (AMC). AMC refers to the degree of soil saturation before rainfall events and is categorized into 3 types (AMCI, AMCII, and AMCIII) [69,70]. The associated curve numbers, CNI, CNII, and CNIII, are required to determine runoff from rainfall. The curve number for AMCII (CNII) for soil and LULC complex was adopted from the Ethiopian Road Authority's Drainage Design Manual [71]. The land surface slope is another important factor that significantly affects the rainfall-runoff process but was not considered in the original curve number method. The land slope correction factor developed by Huang and Gallichand [72] (Equation (5)) was applied to improve the accuracy of the method to estimate the surface runoff from the catchment.

$$CNII\alpha = \frac{322.79 + 15.63\alpha}{\alpha + 323.52} \quad (5)$$

The slope α was generated from DEM using ArcGIS and Zonal statistics in the ArcGIS environment; this was applied to calculate the average value of α for each Thiessen polygon corresponding to meteorological stations.

The curve number for dry and wet conditions, CNI and CNIII, were derived from modified CNII using Equations (6) and (7), respectively [69,70].

$$\text{For dry conditions : } CNI = \frac{4.2CNII}{10 - 0.058CNII} \quad (6)$$

$$\text{For wet condition : } CNIII = \frac{23CNII}{10 + 0.13CNII} \quad (7)$$

The most widely used approach, the 5-day antecedent precipitation index (API), was used to determine the daily runoff from daily rainfall data.

Evapotranspiration was estimated using the modified Penman–Monteith method [74,75]. This method is widely accepted and has the advantage of considering the effect of standard climatological parameters including temperature, relative humidity, solar radiation, and wind speed [75]. Moreover, the method has the advantage of adapting local parameters of specific locations.

To estimate the plant's available water (PAW), the essential parameters including field capacity (FC), permanent wilting point (PWP), bulk density (BD), and rooting depth (RD) of the plants were obtained from both laboratory analyses and the literature. The FC was estimated in the soil laboratory of the Jimma Institute of Technology, Jimma University, using the gravimetric and oven drying techniques. A purposive sampling technique was used at seven points near the weather stations (Seka, Dedo, Jimma, Dedo, Asendabo, Dimtu, and Serbo and Matoria near Yebu), representing major soil types including clay, loam, and sandy clay loam, which were the selected types. Two samples for each station at depths of both 0–30 cm and 30–60 cm were taken for the analysis. The samples were taken using an auger and transported to the laboratory using plastic bags. Then, they were saturated in the laboratory and subjected to gravity for 24 h to drain the excess water and consequently maintain the soil water content at FC. The weight of the sample was measured and oven-dried at 105 °C for 24 h. The oven-dried sample was reweighed, and the difference was calculated to obtain the gravimetric water content at FC. For the determination of BD, undisturbed samples were collected using core samplers of 38 mm in diameter. The samples were taken to the laboratory and extruded from the samplers using a hydraulic extruder. The volume of the sample was determined and oven-dried to

obtain the dry mass of the sample. Then, the BD was determined by dividing the dry mass of the sample by the volume. The estimated gravimetric soil water content was converted to volumetric soil water content by multiplying it with the BD [76]. The PWP and FC of loam, clay loam, and sandy clay were adopted from previous studies [77–80].

The major LULC types of the catchment are cropland, tree covers, grassland, and shrubs (Figure 2a). The major crops grown in the area include teff, wheat, barley, beans, sorghum, and maize [81]. The average rooting depth of these crops is 70 cm [82]. The major vegetation in the catchment is evergreen trees [40,41] and the average rooting depth is 336 cm. The average rooting depths of shrubs and grassland are 350 and 140 cm, respectively [83].

To determine the plant available water (PAW), a Thiessen polygon was created for 17 meteorological stations and overlaid with soil and LULC maps to determine the weighted average of the root depth and water-holding capacity (FC-PWP) of the soil in the polygons. The initial soil moisture content is another input parameter required for the SMB method. Since the initial time step was set to the first day of January, the average soil moisture content measured at the Jimma and Sekoru stations on that day was used for the stations located upstream and downstream, respectively.

2.4.2. Baseflow Separation Methods

Baseflow separation techniques can provide valuable insight into the contribution of groundwater to rivers [27,84] as a proxy of groundwater recharge in areas where groundwater withdrawal is negligible. To estimate the groundwater recharge in the Gilgel Gibe catchment, algorithms from SepHydro, BFLOW, and WHAT were utilized.

1. SepHydro

Among eleven baseflow separation algorithms incorporated in SepHydro [28], fixed interval, sliding interval, and local minimum methods were used in the present study. The methods conceptually consider the line connecting the low points of the hydrograph to define the baseflow hydrograph [30]. The baseflow hydrograph is drawn for consecutive specified widths or windows. The length of the width is equal to $2N$ but the nearest integer is between 3 and 11. N can be determined from the catchment area using an empirical equation suggested by Pettyjohn and Henning [28] (Equation (8)). These methods are simple to use and are able to reproduce consistent results that can replace manual separation.

$$N = A^{0.2} \quad (8)$$

N is the number of days after which runoff ceases;

A is drainage area (km^2).

a. Fixed interval method

All baseflow values in a given interval or window are set to a minimum stream flow value in that interval. The first interval starts with the first day of the streamflow record. The method can be visualized as a moving window of $2N$ days, considering the width or window. The window moves horizontally by $2N$ days and the process is repeated until the last interval to complete the baseflow separation for the entire streamflow data is recorded [28].

b. Sliding interval method

The value of baseflow at the middle of each interval or window is set to the minimum streamflow value in the respective interval. The window moves vertically upward until it intersects with the lowest point of the stream flow hydrograph in the respective interval and the window then slides to the next day. The process is repeated until the last interval to complete the complete baseflow separation for the entire streamflow data is recorded [28].

c. Local minimum method

The streamflow value of each day in a given interval is checked whether it is the lowest value in that interval or not. If it is, then it is considered a local minimum and is joined with adjacent local minimums using a straight line. The resulting line, across the whole dataset, represents the baseflow hydrograph [28].

2. BFLOW

The algorithm of BFLOW [11] was developed based on the one-parameter recursive digital filter developed by Lyne and Hollick [38] and used by Nathan and McMahon [23] and Arnold, Allen [11]. The separation process is based on the wave of the hydrograph [31] and the filter passes over the entire stream flow three times (forward, backward, and forward) [11,39]. BFLOW algorithm uses the filter equation described in Equation (9).

$$qt = \beta q(t-1) + \frac{(1+\beta)}{2} * (Qt - Q(t-1)) \quad (9)$$

qt —filtered surface runoff (m^3/s) at the t time step (day);

Q —original streamflow (m^3/s);

β —filter parameter.

Once the runoff component (quick response) is determined using Equation (9), the baseflow component (bt) can be computed using Equation (10).

$$bt = Qt - qt \quad (10)$$

The value of the filter parameter was determined by Nathan and McMahon [23]. According to Nathan and McMahon [23], based on visual inspection, the baseflow index falls in an acceptable range when the value of the filter parameter is between 0.9 and 0.95. Nathan and McMahon [23] applied three values (0.9, 0.925, and 0.95) to the whole datasets of 186 catchments and identified the most appropriate value filter value, which was 0.925. The results from the digital filter were compared with those of smoothed minima and manual methods for all catchments. The digital filter provided a more stable baseflow index (BFI) than that of smoothed minima method with a 0.97 coefficient of determination. The filter parameter determined by Nathan and McMahon [23], 0.925, was used in this study.

3. WHAT

WHAT is a web-based hydrograph analysis tool developed by Lim [31] and is currently integrated with three baseflow separation methods including a two-parameter recursive digital filter, the Eckhardt method [36]. Eckhardt [36] developed the two-parameter recursive digital filter based on a one-parameter recursive digital filter [38], introducing an additional parameter called the Maximum Baseflow Index (BFI_{max}) (Equation (11)). The filter separates the direct runoff from baseflow based on the frequency signals. Low-frequency signals are associated with baseflow, and high-frequency signals are associated with runoff [31].

$$bk = \frac{[(1 - BFI_{max}) * \alpha b_{k-1} + (1 - \alpha) * BFI_{max} * yk]}{1 - \alpha * BFI_{max}} \quad (11)$$

where

bk : baseflow at time step k ;

b_{k-1} : baseflow at time step $k - 1$;

yk : total streamflow at time step k ;

BFI_{max} : Maximum Baseflow Index;

α : filter parameter.

The accuracy of the method depends on the quality of stream flow data and filter parameter used [85]. BFI_{max} is the maximum value of a long-term ratio of baseflow total

stream flow. Eckhardt [36] estimated the value of BF_{Imax} for different hydrological and hydrogeological conditions. According to Eckhardt [36], the BF_{Imax} for perennial streams with porous aquifers is 0.8, for ephemeral streams with porous aquifers it is 0.50, and it is 0.25 for perennial streams with hard rock aquifers. The values were validated by comparing them with the values obtained from other research under similar conditions. Lim, Park [31] applied the Eckhardt method in a small catchment with Eckhardt's filter value ($BF_{Imax} = 0.8$ and $\alpha = 0.98$) to filter the direct runoff components from streamflow. The result was highly correlated with that of BFLOW with a unit coefficient of determination. Eckhardt's filter parameter values were applied in the Gilgel Gibe catchment.

4. PART

PART uses streamflow partitioning to estimate baseflow from a daily streamflow record. The program scans the streamflow data series for days that fit a requirement of antecedent recession and designates baseflow to be equal to streamflow on these days, then linearly interpolates on the days that do not fit the requirement of antecedent recession [86]. Although the program uses daily streamflow data, Rutledge [87] recommended that results should be reported at a larger time scale, at least monthly. The program is recommended for the estimation of baseflow in aquifers characterized by diffuse areal recharge to the groundwater table and groundwater discharge to the stream [86]. The program is appropriate for the basin in which natural groundwater flow is maintained and gauging stations located downstream at the end of the basin that capture the most outflow. The only groundwater recharge source in the Gilgel Gibe catchment has been rainfall.

3. Results and Discussions

3.1. Soil Moisture Balance Method

Meteorological data highly influence groundwater recharge estimated using the SMB method. Rainfall and potential evapotranspiration play a major role. Rainfall is a primary source of groundwater recharge while PET adversely affects the recharge. Figure 5 describes the spatial distribution of rainfall and potential evapotranspiration in the catchment. The spatial distribution of annual rainfall shown in Figure 5a shows that rainfall decreases from west to east. The potential evapotranspiration was estimated using the Penman–Monteith method at each meteorological station and interpolated using the Inverse Distance Weighted (IDW) method in the GIS environment, as shown in Figure 5b. The map shows PET is increasing in the downstream direction, from a southwest to northeast direction. PET varies from 1171 to 1434 mm with a mean value of 1285 mm, whereas rainfall varies from 1193 to 1716 mm with a mean value of 1539 mm based on CHIRPS data. To develop the groundwater management strategies in the catchment, the spatial distribution of rainfall and PET along with the estimated groundwater recharge, offer valuable insights.

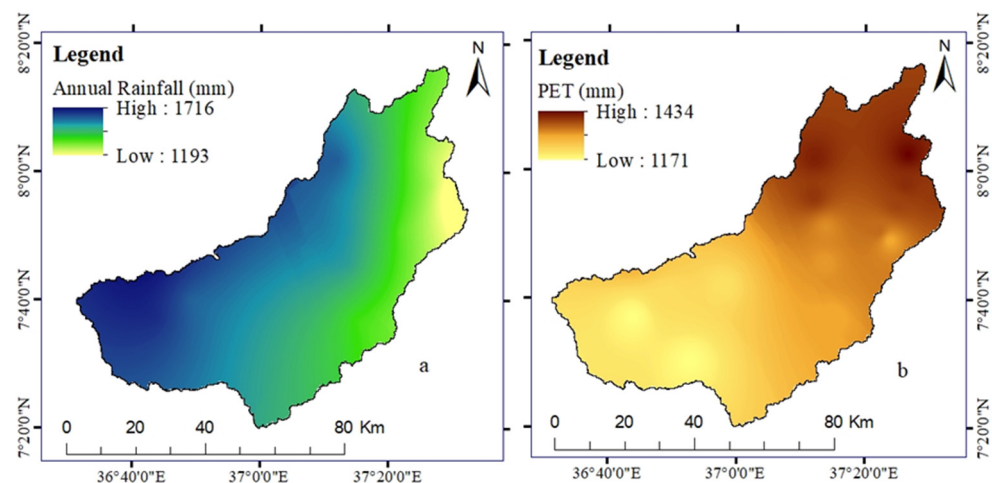


Figure 5. The map of (a) rainfall and (b) potential evapotranspiration (PET).

In addition to the daily rainfall and PET data, PAW, runoff coefficient, and initial soil moisture content are required in the SMB method. The method needs a single value for each parameter for each station representing the Thiessen polygon. The SMB method uses the initial soil moisture content to start the simulation and the parameter influences only the initial time steps. The model iteratively calculates the soil moisture content for the entire time steps and the influence of this parameter on the annual recharge is insignificant (Figure 6). The PAW, rooting depth, and runoff coefficient values determined at each meteorological station are described in Table 3, with respective area coverage as delineated by Thiessen polygons based on the soil and LULC matrix.

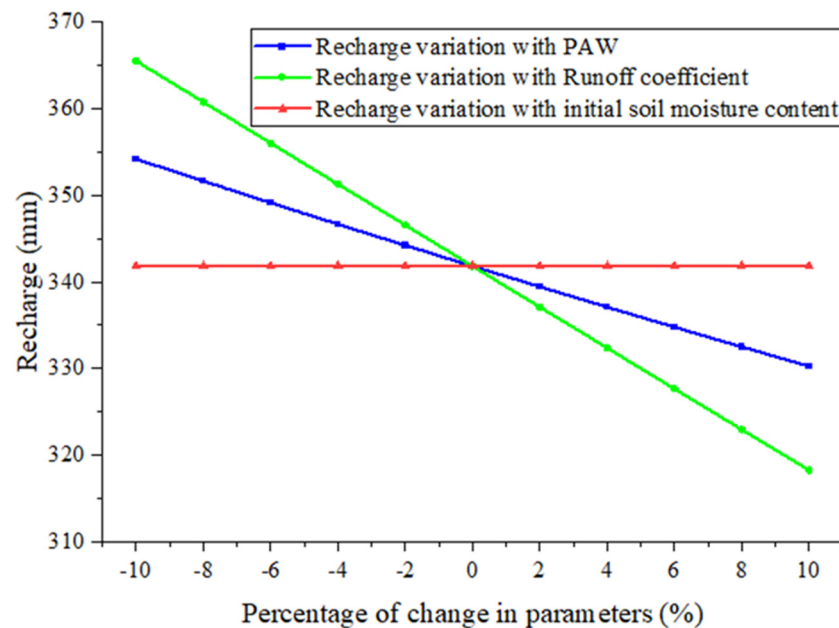


Figure 6. The effect of PAW, runoff coefficient, and initial soil moisture on the annual recharge.

A sensitivity analysis was carried out to identify the sensitivity of the lumped input parameters (PAW, runoff coefficient, and initial soil moisture content). The sensitivity analysis was conducted for the Jimma area to provide insight into the potential errors that might be incorporated, due to parameter value estimations. The meteorological station located in the area, Jimma station, provides better recorded data compared to the others. The analysis was carried out by changing a parameter at a certain time, keeping the remaining parameters constant (Figure 6).

The estimated value of PAW, runoff coefficient, and initial soil moisture content at Jimma station are 297 mm, 18%, and 144 mm, respectively, and the corresponding estimated annual recharge is 342 mm.

Figure 6 illustrates that the annual recharge does not vary with the initial soil moisture content, indicating that initial soil moisture is an insensitive parameter to the recharge. The increment of PAW by 2% decreases the annual recharge by 2.39 mm, while the increment of runoff coefficient by 2% decreases the recharge by 4.72 mm (Figure 6). The sensitivity analysis shows that the runoff coefficient is more sensitive than PAW, and the initial soil moisture is an insensitive parameter to the annual recharge. Among the lumped input parameters used in SMB method, the annual recharge is highly influenced by the runoff coefficient. This implies that to improve the groundwater recharge in the catchment, for instance, one can apply water management practices that reduce the surface runoff to be more efficient and effective.

The daily groundwater recharge was estimated for Thiessen polygons corresponding to each meteorological station, but the result is reported on a monthly, seasonal, and annual basis. Table 4 shows the annual rainfall (RF), potential evapotranspiration (PET), actual evapotranspiration (AET), and groundwater recharge estimated at each meteorological

station corresponding to each Thiessen polygon. Based on the data obtained from CHIRPS, the catchment gains 1538 mm of water annually from rainfall and loses 862 mm through evapotranspiration, as estimated using the SMB method. The annual groundwater recharge estimated using the SMB method is 313 mm, which is 20% of the annual rainfall.

Table 4. Annual RF, PET, AET, and recharge.

Meteorological Stations	RF (mm)	PET (mm)	AET (mm)	Recharge (mm)
Ako	1657	1414	959	312
Asendabo	1569	1312	786	233
Busa	1573	1393	887	274
Cheka	1373	1300	775	350
Seka Chekorsa	1700	1171	914	442
Dedo	1585	1171	820	351
Deneba	1373	1349	774	228
Dimtu	1569	1321	797	253
Jimma	1588	1220	956	342
Kidame Gebeya	1129	1391	806	209
Natri	1304	1434	919	225
Omonada	1387	1300	827	282
Saia	1368	1402	892	282
Sekoru	1368	1382	884	264
Serbo	1582	1214	847	337
Shebe	1699	1190	926	446
Yebu	1758	1313	905	287
Weighted Average	1539	1285	862	313

Figure 7 shows the recharge distribution in the catchment as estimated using the SMB method per each Thiessen polygon. The Seka Chekorsa area, where the Gilgel Gibe rises, has the highest annual recharge of the catchment followed by the Dedo, Jimma, Serbo, Ako, and Cheka areas, which receive moderately high recharge. The annual recharge value estimated at these stations is greater than the average catchment recharge of 313 mm. High rainfall occurs with vegetated LULC characteristics favoring the recharge in these areas of the catchment. However, the Natri, Kidame Gebeya, Deneba, and Asendabo areas receive the relatively lowest annual recharge of the catchment. The annual recharge value estimated for these is less than the average recharge value of the catchment. The Omonada, Busa, Dimtu, Sekoru, and Saja areas cover the middle part of the catchment and receive relatively moderate annual recharge. Based on the SMB method, the annual recharge estimated at Kidame Gebeya is lower than that of the Seka Chekorsa station by 53%, where the discrepancy in the annual rainfall is 34%.

The temporal distribution of average annual rainfall and recharge for the Seka Chekorsa, located upstream, and the Sekoru station, located downstream, for the period from 1985 to 2020, is shown in Figure 8a,b, respectively. For both stations, the highest annual rainfall occurred in 2019, which is 2213 and 1739 mm at the Seka Chekorsa and Sekoru stations, respectively. The annual maximum groundwater recharge also occurred in 2019, which is 882 mm and 567 mm at the Seka Chekorsa and Sekoru stations, respectively. The minimum annual recharge values estimated at Seka Chekorsa and Sekoru were 210 and 64 mm, occurring in 2002 and 2000, respectively. The annual recharge percentage of rainfall varied from 14% in the year 1995 to 40% in 2019 at the Seka Chekorsa station and ranged from 5% (2000) to 33% (2019) at the Sekoru station. In general, groundwater recharge is highly varied with time, not only at the Seka Chekorsa and Sekoru stations (Figure 8a,b), but also for all the other stations. The recharge increases with rainfall but the trend is not a one-to-one correspondence (Figure 8). As a result of fluctuating annual rainfall, Figure 8a,b demonstrate that while PET varies little, recharge varies significantly. This indicates that the variation in recharge is more affected by the rainfall magnitude and intensity. The SMB estimates the recharge on a daily time step and the daily rainfall, and its frequency controls

the recharge temporal variability. Annual recharge is calculated as a percentage of annual rainfall, and does not take the temporal variability of rainfall and recharge into account.

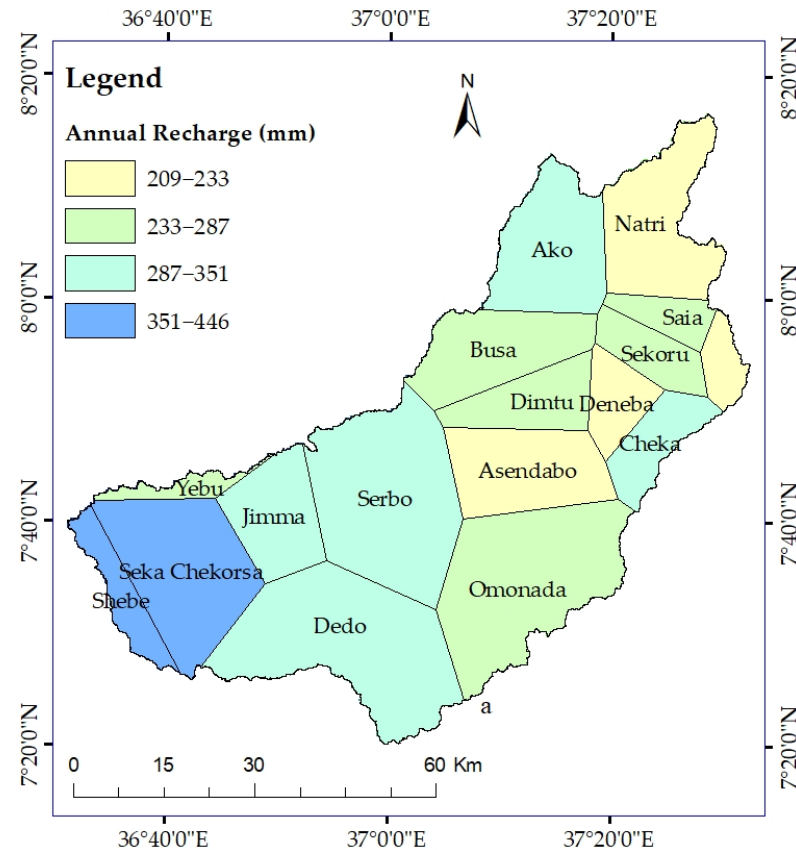


Figure 7. Annual recharge of the catchment estimated for each Thiessen polygon.

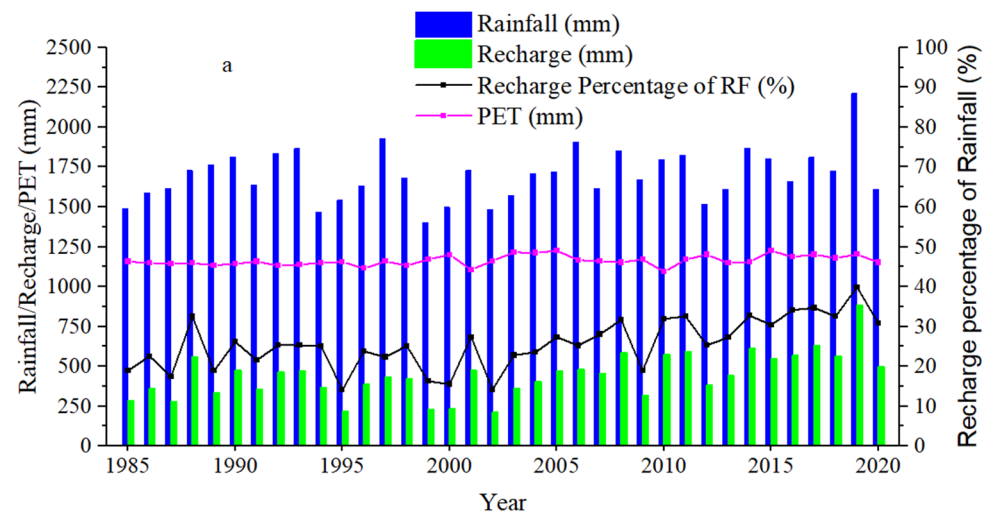


Figure 8. Cont.

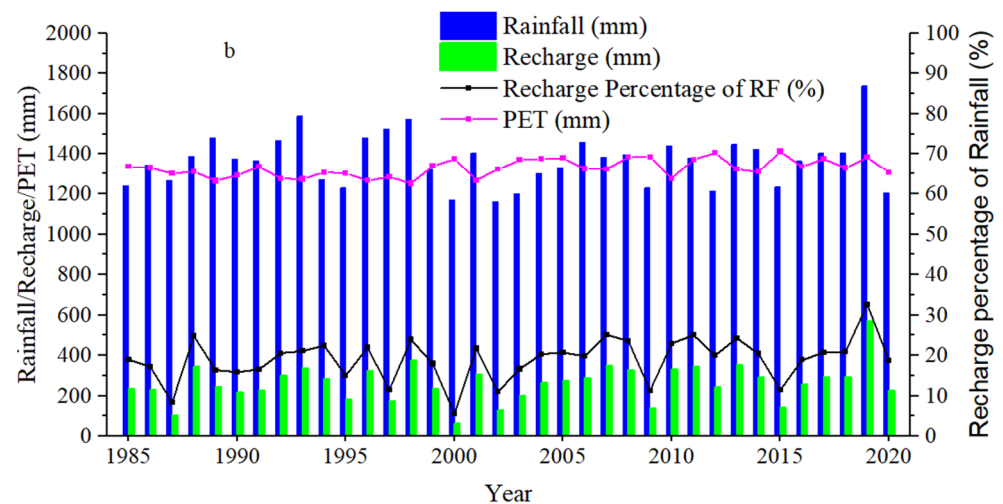


Figure 8. Recharge percentage of annual rainfall and annual recharge trend: (a) Seka Chekorsa station and (b) Sekoru Station.

Based on the SMB estimates, the seasonal groundwater recharge of the catchment was estimated to be 4 mm, 237 mm, 72 mm, and 0 mm in spring (March–April–May), summer (June–July–August), autumn (September–October–November) and winter (December–January–February), respectively. The groundwater recharge in summer accounts for 76% of the annual recharge of the catchment. Summer and autumn together account for 99% of the annual recharge, whereas spring receives only 1% of the annual groundwater recharge. Based on the monthly time scale, the groundwater recharge of the catchment varies from 0 to 105 mm (Table 5). The catchment receives significant monthly recharge from June to October. Even though some rainfall occurs, the recharge is nil in the remaining months because of the soil moisture deficit and high evapotranspiration demand during these months. Comparing the amount of recharge in May and November, the recharge percentage of rainfall in November is higher than that of May.

Table 5. Average monthly recharge and rainfall of Gilgel Gibe catchment (1985–2020).

Months	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
RF (mm)	30	42	92	122	168	225	259	245	184	100	42	29
R (mm)	0	0	0	0	4	31	101	105	51	19	2	0
Recharge % of RF	0	0	0	0	3	14	39	43	28	19	5	0

Figure 9 describes monthly rainfall, evapotranspiration, and recharge for the Seka Chekorsa and Sekoru stations. These stations are situated in the upstream and downstream parts of the catchment (Figure 4). Even though they do not represent the entire upstream and downstream part of the catchment, the results can be compared and cross-validated with the estimates from the BFS method of corresponding sub-catchments, Seka and Bidru Awana. The PET is more or less higher for all months running from September to May for both stations.

The significant difference in the recharge percentage of rainfall in May and November could be due to soil moisture difference. Since May is preceded by dry months and November is preceded by wet months, the significant soil moisture deficit in May decreased the contribution of rainfall to groundwater recharge. From June and August, there is an abundance of rainfall, soil moisture reaching field capacity, and a decrease in PET, all of which contribute to increased groundwater recharge. For the Seka Chekorsa station, which is located in upstream of the catchment, the recharge occurs from May to November (Figure 9a).

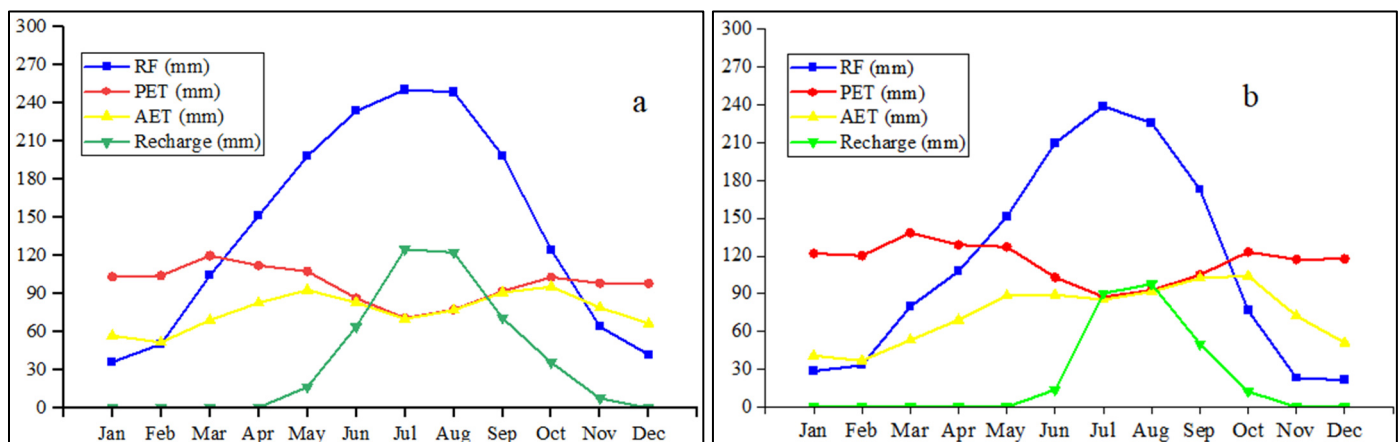


Figure 9. Monthly RF, PET, AET, and recharge, (a) Seka Chekorsa and (b) Sekoru.

However, for Sekoru station, which is located downstream of the catchment, recharge occurs for relatively a shorter period, from June to October (Figure 9b). Considering the results from all stations, from June to October, rainfall potentially recharges the groundwater through the catchment (Table 5).

In general, the estimate using the SMB method is reasonably acceptable. Previous studies conducted in the upper Gilgel Gibe catchment showed that the mean annual recharge was 298 mm, as estimated using the water balance method [8] which is comparable with the present result, 312 mm. Another study exclusively conducted in the Bulbul sub-catchment showed that the annual groundwater recharge as estimated using the water balance method was 351 mm [13].

3.2. Baseflow Separation (BFS)

Six BFS techniques were applied to the main catchment and six sub-catchments to estimate the annual groundwater recharge for the respective sub-catchments. However, the annual baseflow estimated at Awetu station is extremely large (600 mm), even greater than the maximum annual value estimated using the SMB method. The reason could be the measurement error and/or contribution of wastewater released from Jimma City to the Awetu River. The river flows through Jimma City from the northeast to the southwest. During field observations, several drainage outlets that feed wastewater into the Awetu River were noticed. The Kito River also drains a part of the city and is exposed to similar problems. For this reason, the results from both stations were intentionally rejected and only four sub-catchments and the main catchment were considered for the groundwater recharge estimation (Table 6). The seasonal and annual groundwater recharge of the main catchment and four sub-catchments, as estimated using six BFS techniques, is presented in Table 6. The average value was adopted for groundwater recharge estimation. The analysis period varies from station to station based on the availability of streamflow data.

The highest annual recharge was estimated for the Seka sub-catchment, followed by Bulbul and Asendabo (Table 6). However, the Asendabo sub-catchment encompasses Seka, Bulbul, Kito, Awetu, and other ungauged catchments (Figure 4), and the result shows the aggregated result of these sub-catchments. Since the catchment area of Asendabo station is much larger than that of Awetu and Kito, the aforementioned problems can be neglected.

The average annual recharge of the overall catchment was computed from the baseflow estimated at the main outlet of the catchment (Gilgel Gibe), which is 314 mm (Table 6). A previous study showed that the annual groundwater recharge estimated at the upper Gilgel Gibe catchment using the BFS method was 338 mm [8], which is comparable with the present estimate.

The aquifer system in the Seka sub-catchment consists of alluvial deposits, trachyte, pyroclastic, and fractured basaltic rocks, with relatively good water-bearing capacity. A 200 m well drilling was observed during the field campaign and the samples of well logging

consist of alluvial deposits of mainly river gravels and sands. The well data collected from the Jimma Water and Energy Office indicate that the water-yielding capacity of the available wells located in the Seka sub-catchment ranges from 10 to 23 L/s. The Seka sub-catchment has good tree cover and soils, with a moderate infiltration capacity which is favorable for the recharge process. The higher annual groundwater recharge estimated for the Seka sub-catchment agrees with the hydrogeological condition of the sub-catchment. Hence, the result obtained from the BFS would be realistic.

Table 6. Seasonal and annual recharge estimated using BFS methods for the main catchment and sub-catchments.

Gauging Stations	Period	Fixed Interval	Sliding Interval	Local Minimum	Eckhardt	BFLOW	PART	Average
Asendabo (1985–2019)	Spring	22	22	22	20	22	18	21
	Summer	183	182	172	156	175	158	171
	Autumn	132	132	125	135	144	132	133
	Winter	18	18	18	19	20	19	19
	Annual	355	355	337	329	361	327	344
Bidru Awana (1985–2014)	Spring	20	20	20	18	19	18	19
	Summer	91	90	84	79	80	68	82
	Autumn	62	62	60	59	61	58	60
	Winter	20	20	21	17	20	20	20
	Annual	194	192	185	173	179	165	181
Bulbul (1986–2018)	Spring	13	13	12	10	11	11	12
	Summer	222	221	203	170	187	182	197
	Autumn	172	172	161	158	168	165	166
	Winter	14	14	14	13	14	14	14
	Annual	420	420	390	352	380	371	389
Gilgel Gibe (1985–2003)	Spring	19	18	17	17	18	17	18
	Summer	166	167	161	142	159	146	157
	Autumn	123	122	111	124	132	126	123
	Winter	16	16	16	17	18	18	17
	Annual	324	323	307	300	328	306	314
Seka (1985–2014)	Spring	44	43	42	37	40	38	41
	Summer	197	198	190	169	183	174	185
	Autumn	152	152	146	145	153	144	148
	Winter	37	37	37	35	38	37	37
	Annual	429	430	414	386	414	393	411

Likewise, the present estimate of the 389 mm annual recharge for the Bulbul sub-catchment is hydrogeologically plausible. The aquifer system of the catchment is porous and fissured, consisting of volcanic and sedimentary rocks. The sub-catchment also has good LULC and soil for infiltration. It receives high rainfall based on the data derived from CHIRPS. However, there are no ground-based rainfall measurements in the area to verify at a local level. The nearby station is Serbo station, but it is located in a lower area and the data from this station may not represent the Bulbul sub-catchment which is situated at a higher elevation. Well data are also not available to verify the result. However, previous studies revealed that the catchment receives high annual groundwater recharge, with a value of 406 mm as estimated using the BFS method [13].

Lower annual groundwater recharge was estimated via the BFS methods for the Bidru Awana sub-catchment, which is located in the southwestern part of the Gilgel Gibe catchment. Based on the estimates from BFS methods, the sub-catchment receives 56% less annual recharge than the Seka sub-catchment. However, the annual rainfall variation between the two stations is only 20%. The higher recharge variation could be due to the geologic characteristics of the localities. The aquifer system of the Bidru Awana sub-catchment consists of slightly fractured basaltic rocks with lower well yields ranging from

0.5 to 5 L/s, which is attributed to a low baseflow contribution observed at the Bidru Awana gauging station.

Figure 10 describes the seasonal baseflow contribution of the main catchment and sub-catchments based on the average estimates of BFS methods for the period of observed data depicted in Table 6. The estimated seasonal baseflow shows that the sub-catchments contribute 45 to 51% of the annual baseflow during summer, 33 to 43% during autumn, 4 to 11% during winter, and 3% to 11% during spring (Figure 10). Asendabo and Bulbul sub-catchments contribute a higher percentage of annual baseflow during summer and autumn and a lower percentage during spring and winter compared to other sub-catchments. Bidru Awana and Seka contribute a lower percentage in summer and autumn but a higher percentage in spring and winter compared to the other sub-catchments.

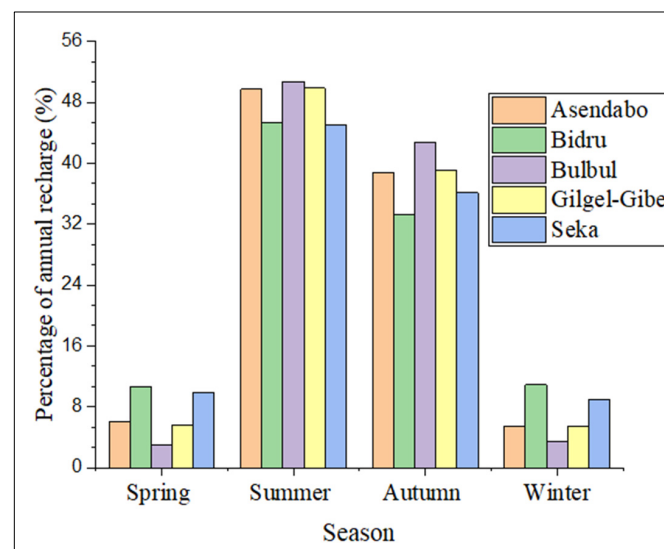


Figure 10. Percentage of annual recharge in catchments.

The seasonal baseflow estimated using BFS methods at the Gilgel Gibe catchment was comparable with the average value estimated at the sub-catchments (Figure 10). However, most of the gauged streams are located in the northwestern part of the catchment (Figure 4). This area is characterized by porous geological formations and receives higher annual rainfall (ranging from 1582 to 1758 mm). The gauged streams located in this region, including the Bulbul and Seka stations experienced higher baseflow (Table 6). The result of hydrograph analyses also shows that the BFI of the Bulbul and Seka stations are higher, 0.76 and 0.77, respectively. On the contrary, the southeastern part of the catchment, specifically, the Deneba, Kidame Gebeya, Sekoru, Saja, and Natri areas, are geologically less permeable due to the presence of massive basaltic layers and receive low annual rainfall ranging from 1129 to 1373 mm. The hydrograph analysis at Awana Dawa, the only gauged station in this area, shows low baseflow and BFI (181 mm and 0.56, respectively). Therefore, the average recharge estimated by averaging the baseflow obtained from only gauged stations would be higher than the actual recharge because there is only one gauged station representing the southeastern part of the catchment where the baseflow is expected to be lower.

The trend in average annual groundwater recharge estimated using the BFS methods for the main catchment and sub-catchments with their respective baseflow index (BFI) is shown in Figure 11. The groundwater recharge varies in response to rainfall variability and other climatic parameters, whereas the baseflow index (BFI) decreases with time for all catchments. This shows that the groundwater contribution to streamflow is decreasing, which could be attributed to the groundwater abstraction increasing in response to demand. The Bulbul sub-catchment has a relatively higher BFI than other sub-catchments with an average value of 78%. On the other hand, the Bidru Awana sub-catchment has a lower BFI, with an average value of 56%.

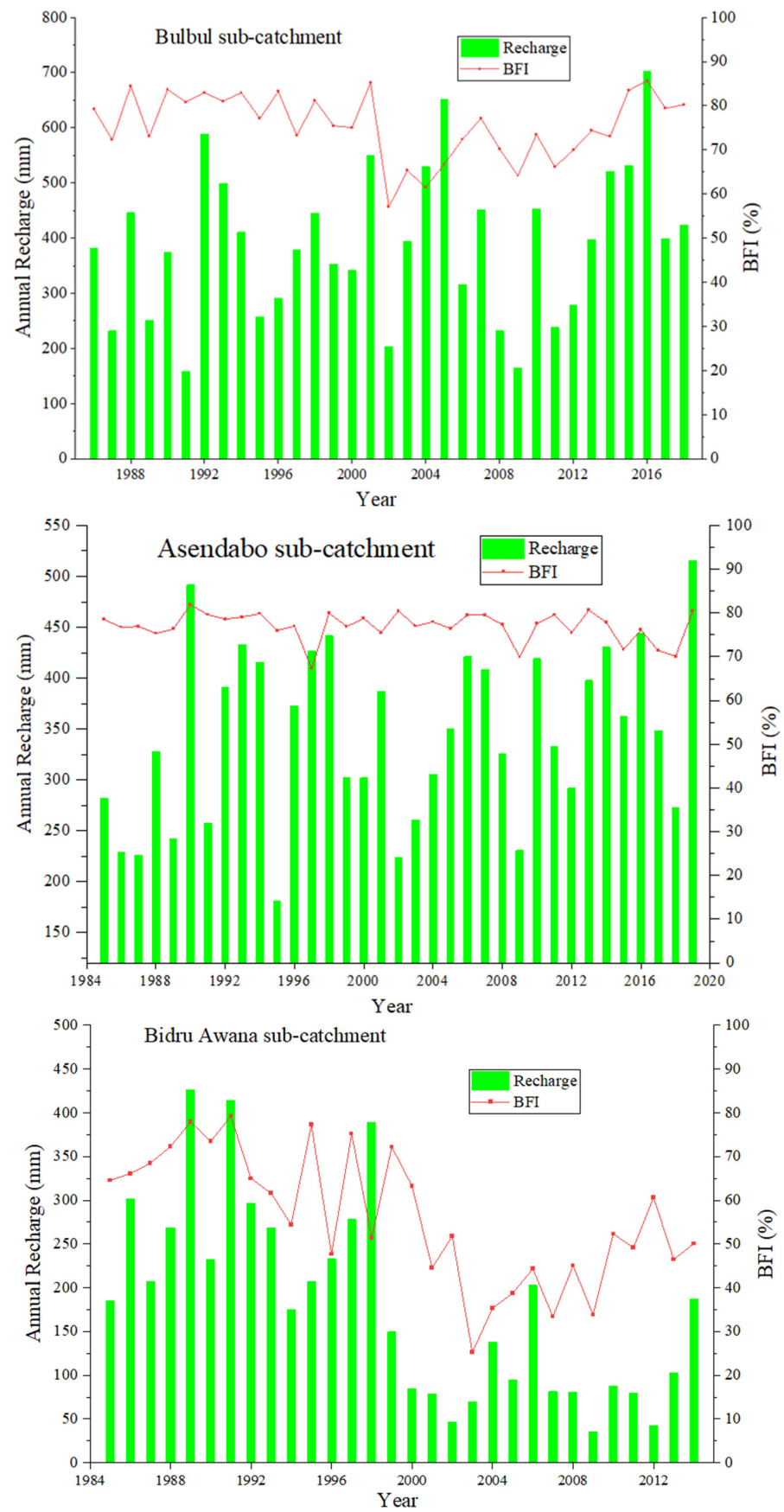


Figure 11. Cont.

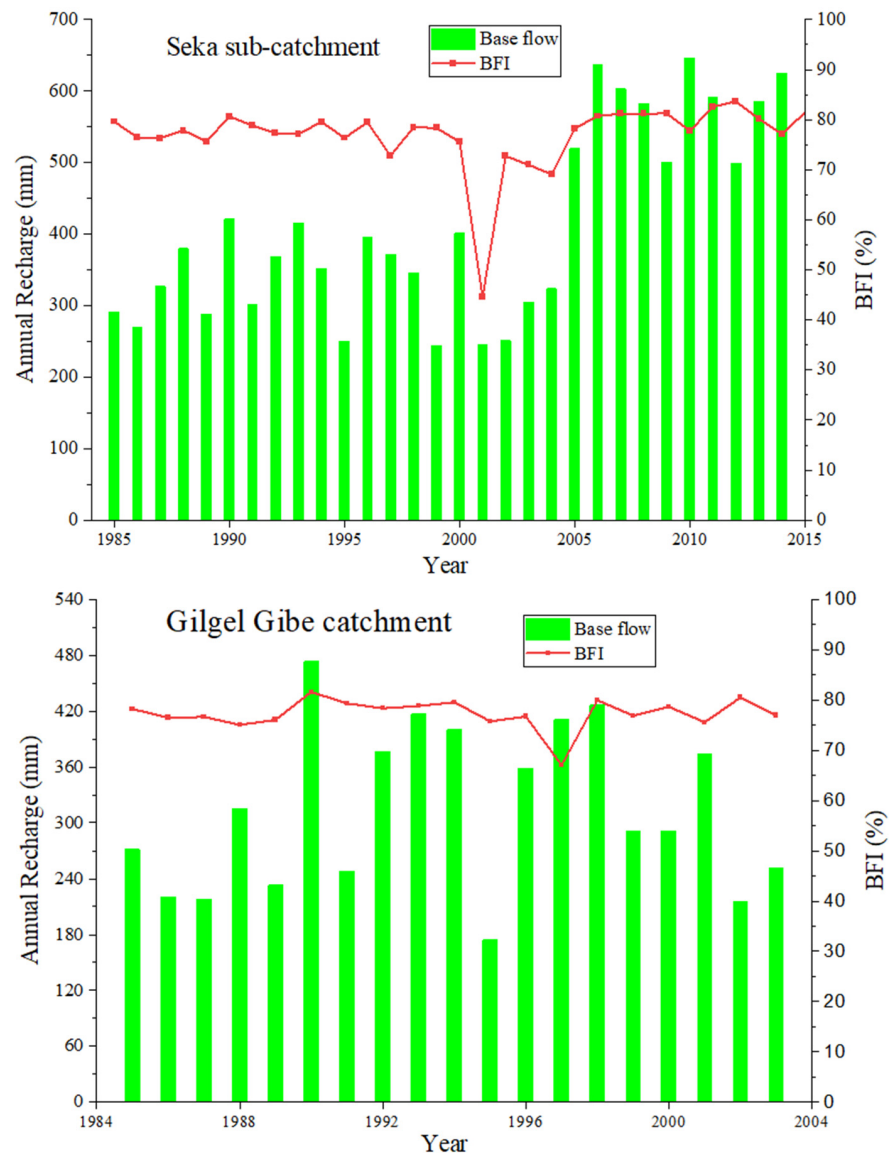


Figure 11. Annual groundwater recharge of the main catchment and sub-catchments with corresponding baseflow index (BFI).

The recharge estimated at Seka, Bulbul, and Bidru Awana was hydrologically and geologically reliable.

3.3. Comparison of SMB and BFS Methods

The groundwater recharge estimated using the SMB method based on the hydrometeorological data were compared with that of the BFS methods (Table 7). The sub-catchments considered for the BFS methods and the Thiessen polygons considered for the SMB method do not coincide with each other in the comparison. Additionally, the analysis periods for the SMB method (1985–2020) and the BFS methods differ for all sub-catchments and the main catchment. Therefore, the average estimate of the SMB method from Thiessen polygons in the sub-catchment or main catchment is used for comparison with the average of estimates of the BFS methods from the corresponding sub-catchment or main catchment.

The annual and seasonal recharge estimated using SMB and BFS methods were comparable, but the estimates using the BFS methods are greater than that of the SMB method for the Bulbul sub-catchment and the whole Gilgel Gibe catchment. For other sub-catchments including Asendabo, Bidru Awana, and Seka, the SMB method estimated higher value than that of the BFS methods. In principle, the SMB method estimates the actual groundwater

recharge and the BFS method estimates the net groundwater recharge. However, for the whole catchment, the average annual groundwater recharge estimated using SMB was 313 mm which is almost the same with that estimated using the BFS methods, which is 314 mm. However, the temporal change due to the varying analysis period is not taken into account. Several studies conducted in physiographic settings formed by volcanic eruptions during different geologic times in various parts of Ethiopia revealed that the estimate using the SMB method is lower than the estimates via other methods like BFS, WTF, CMB, and WetSpass [8,13,15,18]. This is due to the fact that the SMB method considers only diffuse recharge from rainfall but not the recharge from preferential flows. The undulating topographic setting of the region, resulting from volcanic eruptions with associated cracks, faults, depressions, and sink holes, makes the preferential flow path recharge significant.

Table 7. Comparison of SMB and BFS methods.

Stream Gauging Stations	Area of Catchment (km ²)	Recharge from BFS Method (mm)	Recharge from SMB Method (mm)	Hydrometeorological Stations
Asendabo	2966	344	368	Seka Chekorsa, Dedo, Jimma, Serbo, Shebe and Yebu
Bidru Awana	41	181	264	Sekoru
Bulbul	526	389	337	Serbo
Gilgel Gibe	5145	314	313	All stations
Seka	280	411	442	Seka Chekorsa

Considering the sub-catchments, the groundwater recharge estimated using BFS for the Seka sub-catchment was 411 mm and the result from the SMB method for the area was 442 mm. The recharge estimated using SMB was greater than that of the BFS method. For the Bidru Awana sub-catchment, the recharge estimated using BFS and SMB were 181 mm and 264 mm, respectively. The result from the SMB method is greater than the result from the BFS method by 31%.

The seasonal recharge (Figure 12) shows that both methods estimated maximum recharge in summer followed by autumn. Based on the SMB method, the groundwater recharge estimated in winter was nil, both at the Seka Chekorsa and Sekoru stations. It is also nil in spring at the Sekoru station, whereas a small recharge value was estimated at the Seka Chekorsa station. However, the BFS methods estimated a significant amount of groundwater recharged in spring and winter in the Seka and Bidru Awana sub-catchments, where the Seka Chekorsa and Sekoru stations are located, respectively. This is attributed to the fact that the recharge that occurred during rainfall will not be discharged at the outlet immediately; it takes groundwater residence time to reach the outlet. BFS methods are not convenient for estimating the groundwater recharge at a daily, monthly, or seasonal time scale but for the annual scale. The baseflow observed during the dry season is the result of recharge during the rainy season. Due to this fact, the comparison should be made on an annual basis for decision-making.

In general, for smaller sub-catchments in our study area, the estimate of the SMB method is larger than that of the BFS method and vice versa except for the Asendabo sub-catchment. The reasons could be the following: (1) The gauging station located at the outlet of the larger sub-catchment has a high possibility of monitoring a higher proportion of groundwater discharge from the aquifer system in the catchment. For the smaller sub-catchments, there could be a possibility for the portion of baseflow to flow through the aquifer to the main outlet without being observed at the gauging stations. (2) The preferential flow path recharge may have a significant contribution to the larger sub-catchment. The recharges from all potential sources, including diffuse recharge and preferential flow path recharge, are captured using BFS methods, whereas the SMB method does not capture the preferential flow path recharge. There is also a high possibility for the surface runoff to terminate into fractures, cracks, and sinkholes, which is not considered

in SMB method; (3) the uncertainties introduced during streamflow measurement and assumptions taken may be another reason for their discrepancy. Haile et al. [88] highlighted that the lack of an updated rating curve with changing river morphology in the catchment could be a source of uncertainties in stream flow measurement.

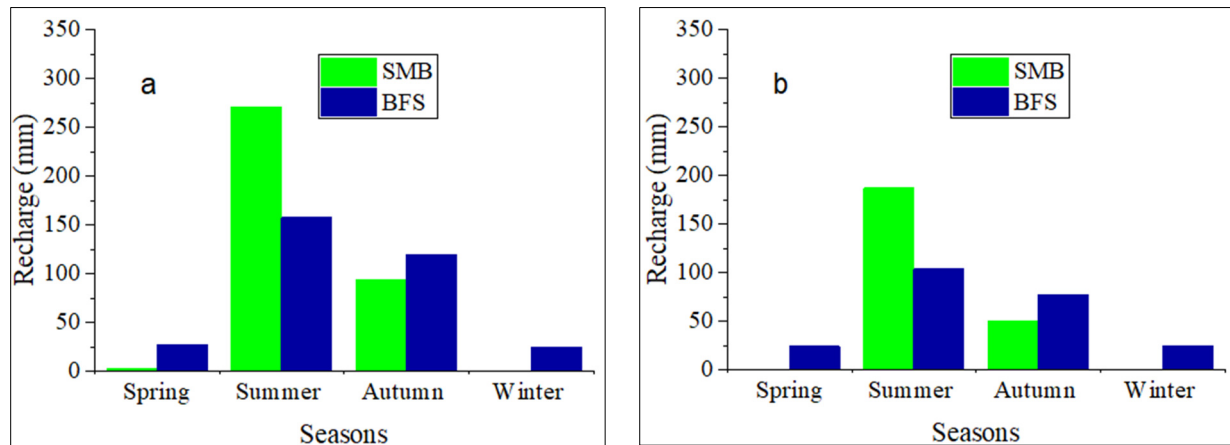


Figure 12. Seasonal recharge estimated using SMB and BFS: (a) Seka Chekorsa and (b) Bidru Awana.

Regardless of the third reason, previous studies conducted in the catchment and the region revealed that the estimate using the BFS method is greater than that of the SMB method. The study conducted in the upper Gilgel Gibe catchment showed that the BFS (BF + 3) estimate was higher than that of the SMB method by 12% [8]. Another study conducted in the Bulbul sub-catchment showed that the BFS estimate was greater than that of the water balance method by 14% [13].

The SMB method along with two other recharge estimation methods (WetSpss and WTF) was applied in northern Ethiopia, in the Gumera watershed [18]. The hydrogeological characteristics of the catchment are similar to that of the Gilgel Gibe catchment. The recharge estimated using SMB (431 mm) showed that the SMB estimate was the lowest of all. Yenehun et al. [18] highlighted that the SMB method underestimates recharge specifically at mountain fronts due to the presence of groundwater interflow and at flat areas due to the contribution of temporary storage. Another study conducted in Central Ethiopia, in the Akaki River catchment, applied the SMB and CMB methods to estimate recharge. The result showed that the SMB method underestimated recharge by 62% when compared to that of the CMB method [15].

The results from the BFS and SMB methods for the entire Gilgel Gibe catchment are comparable, and the results are reasonably acceptable, despite the fact that the temporal change resulting from varying analysis periods is not taken into account. The BFS method is more reliable for the estimation of the annual recharge of the catchment, whereas the SMB method is reliable for the estimation of diffuse recharge for the specified localities having specific soil and LULC, providing that there is no other source of recharge than direct rainfall.

4. Conclusions

The groundwater recharge of the Gilgel Gibe catchment was estimated using the SMB and the BFS methods. The LULC and soil matrix with hydrometeorological data obtained from CHIRPS, NASA/POWER, and ground-based measurements from 17 stations were used in the SMB method. Six BFS methods (fixed interval, sliding interval, local minimum, BFLOW, Eckhardt, and PART) were applied to six sub-catchments, having measured daily streamflow data.

The catchment annual recharge estimated using SMB was 313 mm. The result shows that there is significant variation in recharge both spatially and temporarily. The up-stream catchment receives a higher annual recharge with a maximum value of 446 mm based on

the estimate from the SMB method. The downstream catchment receives a lower annual recharge with a minimum value of 209 mm. The temporal variation is also significant and varies from 115 mm/year to 634 mm/year. The recharge percentage of rainfall of the catchment was estimated to be 20%. BFS methods failed to estimate a realistic value at the Awetu and Kito sub-basins, which might be caused by unreliable stream flow measurement. The main catchment, Gilgel Gibe, and the two major sub-catchments, Asendabo and Bulbul, are estimated to have annual recharge values of 314, 344, and 389 mm, respectively, based on BFS methods. The recharge estimated from the BFS method at Bulbul and Gilgel Gibe was slightly higher than that of the corresponding estimate of the SMB method. Even though errors during stream flow measuring are expected, this could be mainly due to the capability of the method to take into account the recharge from all the potential sources for large catchments.

The results show that estimates from the SMB and BFS methods are comparable. However, for catchments having quality-measured streamflow and no anthropogenic effects, the BFS methods would estimate realistic annual recharge. In volcanic aquifers, where preferential flow path recharge is anticipated, this is the case. On the other hand, the SMB method is an important tool for understanding the diffuse recharge from direct rainfall, but it does not capture the recharge from other sources. The results of this study offer valuable insights for policymakers in terms of formulating strategies for managing groundwater and identifying sub-catchments that require immediate interventions to maintain groundwater sustainability.

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