



Water Balance Estimation Using Integrated GIS-Based WetSpa Model in the Birki Watershed, Eastern Tigray, Northern Ethiopia

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Authors' contributions

This work was carried out in collaboration among all authors. Author EM designed the study, performed the spatial analysis and run the model, wrote the protocol and wrote the first and final draft of the manuscript. Authors Abbadu Girmay and Amare Gebremedhin managed the manuscript by giving critical comments and suggestions of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

This study aims to estimate long-term average annual and seasonal water balance components for Birki watershed using WetSpa model with the integrated geospatial modeling approach with ten years' hydro-meteorological and biophysical data of the watershed. Both primary and secondary data were collected using both field survey and disk-based data collection methods. The WetSpa model was used for data analysis purposes. The finding showed that in the summer season the annual groundwater recharge is 24.1 mm year⁻¹ (96.5%), winter season mean groundwater recharge is 0.8 mm year⁻¹ (3.5%) and yearly mean groundwater recharge is 24.9 mm year⁻¹, Surface runoff yearly mean value is 40.6 mm year⁻¹, Soil evaporation yearly mean value is 10.8 mm

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year⁻¹, Evapotranspiration yearly mean value is 60.8 mm year⁻¹, Intersection loss yearly mean value is 17 mm year⁻¹, and Transpiration loss yearly value is 6.8 mm year⁻¹ in the entire watershed. The mean annual precipitation, which is 573 mm, is contributed to 7.4%, 7.1% and 85.5% recharge to the groundwater, to surface runoff, and evapotranspiration, respectively. Annually 1.1205 million m³ water recharges into the groundwater table as recharge from the precipitation on the entire watershed. The contribution of this study could be used as baseline information for regional water resource experts, policy makers and researchers for further investigation. It can also be concluded that integrated WetSpa and GIS-based models are good indicators for estimating and understanding of water balance components in a given watershed to implement an integrated watershed management plan for sustainable utilization and sustainable development.

Keywords: WetSpa; water balance components; GIS; birki watershed; recharge.

1. INTRODUCTION

1.1 Background and Justification

The water resource is the most important and crucial element of life which is needed in sufficient quantity and acceptable quality to meet the ever-increasing humans demand used for different purposes [1,2,3,4,5]. Its availability and distributions are limited both in time and space in which 97.5% of the global water is saline and exists in the oceans and only 2.5% is considered to be fresh water. 68.7% is fresh water which is locked up in glaciers while 30.1% and 0.9% represent groundwater, surface water, and other fresh waters respectively [6]. It is scarce, but very crucial and multifunctional natural resource found irregularly, despite the demand for fresh water is increasing worldwide as the world population is growing [7]. Due to this, proper planning and management of such resource in terms of distribution, management, utilization, and environmental functions which demands series time period data to optimizing the resource use sustainably [7].

Groundwater recharge or deep drainage or deep percolation is a hydrologic process where water moves downward from surface water to groundwater. This process usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (i.e., "artificial groundwater recharge"), where rainwater and or reclaimed water is routed to the subsurface. In arid and semi-arid areas, its assessment is a key challenge in determining sustainable yield of aquifers. Recharge is estimated by water-balance method, water budget model method or by multiplying the magnitude of water-level fluctuations in wells with the specific yield of the aquifer material. But

commonly groundwater recharge is determined to a large extent as an imbalance at the land surface between precipitation and evaporative demand.

Now, with the advent of Geographic Information Systems (GIS), physical-based hydrologic modeling has become important in contemporary hydrology for assessing these parameters as well as the impact of the human intervention and/or possible climatic change on basin hydrology and water resources. Hence, WetSpa was built as a physically based methodology for estimation of the long-term average, spatially varying, water balance components: surface runoff, actual evapotranspiration and groundwater recharge [8,9,10]. It is an acronym for Water and Energy Transfer between Soil, Plants, and Atmosphere under Quasi-Steady-State that was built upon the foundations of the time-dependent spatially distributed water balance model as cited by [11].

The water resource is the crucial element of life with a limited extent, so looking to estimate the amount and water balance components of a given area is important to research point of view to accurate estimations of water balance in semi-arid and sub-humid tropical regions, where water resources are scarce compared to water demand. The water balance estimation techniques, one of the main subjects in hydrology are a means of a solution of important for both theoretical and practical hydrological problems. On the water balance approach, it is possible to make a quantitative evaluation of water resources and their change under the influence of man's activities and the impact of climate change. So, for effective and sustainable management of water resources, understanding of the spatial and temporal variability of various water balance components and groundwater recharge is required. In this study, we applied the

WetSpss model to simulate the water balance and to estimate the average annual and seasonal water balance components, such as surface runoff, evapotranspiration and groundwater recharge [12].

In Birki watershed, there is surface water availability but the amount and the water balance components were not yet estimated in that specific area which is important for proper planning, future utilization of water resources and to sustain the watershed. The main objectives of this research paper were that i) to estimate long-term annual and seasonal groundwater recharge, surface runoff and potential-evapotranspiration using WetSpss simulation model and ii) to estimate water balance components on the entire watershed for sustainable utilization and management purpose. Therefore, this study was carried out with the above-mentioned objectives for Birki watershed using integrated GIS-Based WetSpss model for further understanding the hydrological and biophysical elements of the watershed for proper management, wise utilization, future planning and sustainable utilization of the resource considering sustainable development. Understanding the hydrological characteristics of the watershed is also crucial for implementing integrated water resources and watershed management approach for improving water resource utilization among the upstream and downstream user communities for multipurpose benefits and minimizing conflicts of interest.

2. LITERATURE REVIEWS

Hydrologic models are among those methods frequently used for groundwater investigation. Groundwater modeling techniques can be used to estimate the water balance components based on the biophysical characteristics of the watershed and climatic time-series data. The application of groundwater modeling techniques is also important for forecasting water resources for the future time horizon [8]. A number of hydrological models are available today for estimating groundwater resources are designed to work based on spatial and temporal distributions of the complex hydrological systems.

Understanding seasonal and annual variations of the water resources, especially runoff, evapotranspiration, and recharge, is indispensable for efficient and sustainable management of groundwater [9]. Since groundwater, resources are sensitive functions of

climatic factors, geological formation, topography, soil properties, and land-use types [10], so, understanding of watershed physical and biological characteristics are important. Accurate quantification of groundwater resources and water balance components involves identification of hydrological and biophysical characteristics of the watershed.

For estimating groundwater resources, a variety of methods exist [10]. Northern Ethiopia is mainly characterized by a shortage of surface water resources due to the erratic nature of rainfall. As a result, optimum crop production is not achieved even in the rainy season. Traditionally, most people settled in the upstream part of the watershed, while the available surface water is found at the downstream part of the watershed in the form of springs and perennial river bodies. Hence, the use of groundwater is inevitable to fulfill the demands for domestic water supply and agricultural water required for sustainable economic development [9].

In this study, a WetSpss model was used to estimate long-term spatial surface runoff, evapotranspiration, and groundwater recharge, since its development, WetSpss has been used worldwide [4]. It has successfully applied in Belgium [9] and other environments such as Gaza Strip, Palestine [11], Geba catchment, Ethiopia [13,14]. Hence, we used this model to simulate water balance parameters in the Birki watershed of the Geba River basin.

3. MATERIALS AND METHODS

3.1 Geographical Location of Birki Watershed

The study area, Birki watershed, is located in the Geba river basin of Eastern Tigray, Northern Ethiopia (Fig. 1). The watershed is found in two districts, which are Kilde-awelaelo and Atsebi-Wenberta. Geographically, it is located at latitudes of 13.65° to 13.75° Northing and longitudes of 39.60° to 39.71° Easting with an elevation ranging from 1999 to 2514 m.a.s.l with spatial area coverage of 45 km² (own processing). It receives a mean annual rainfall of 573 mm. The Birki River flows from the eastern escarpment of the Eastern Zone of Tigray to the west contributing the flow of Geba River a tributary of Tekeze River. It is a perennial river, but flows are extremely low in the dry season and high floods during the wet season of July to September (personal observation).

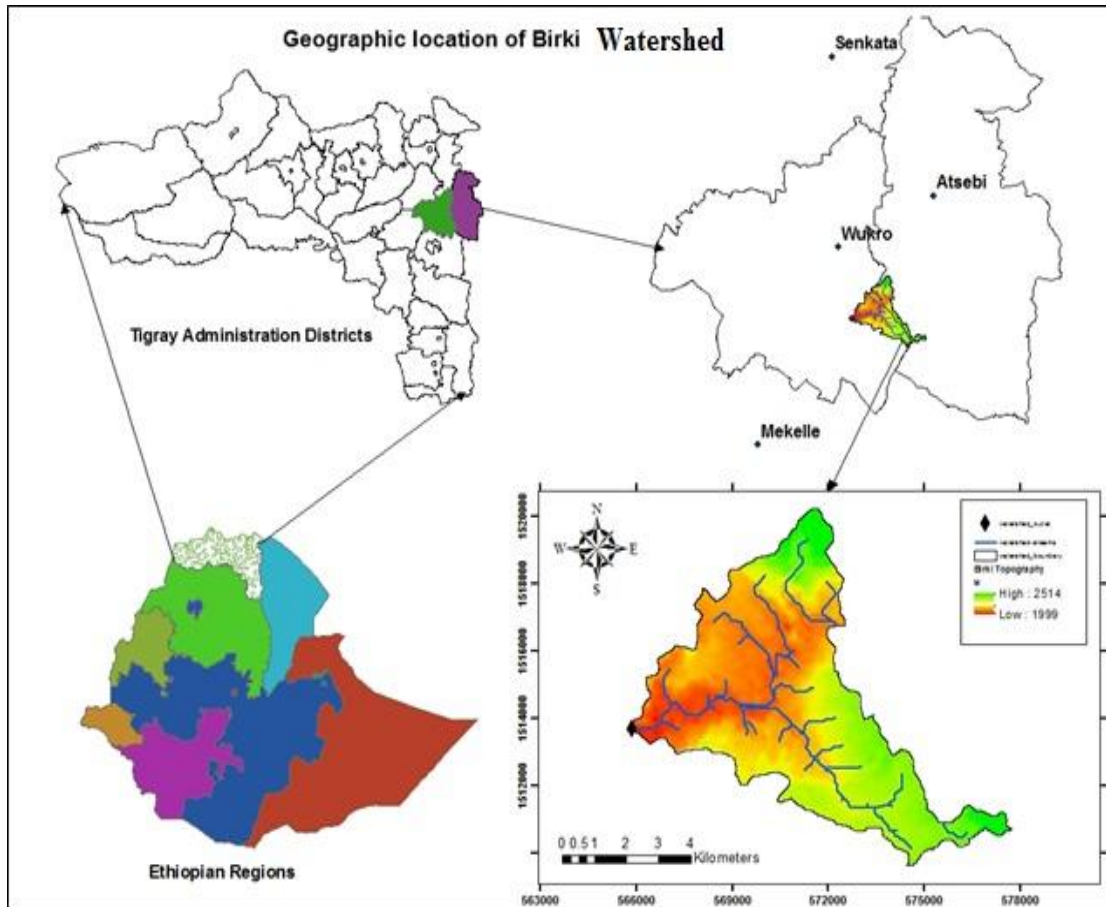


Fig. 1. Map of the Birki watershed, Northern Ethiopia (Source: Autor generated map)

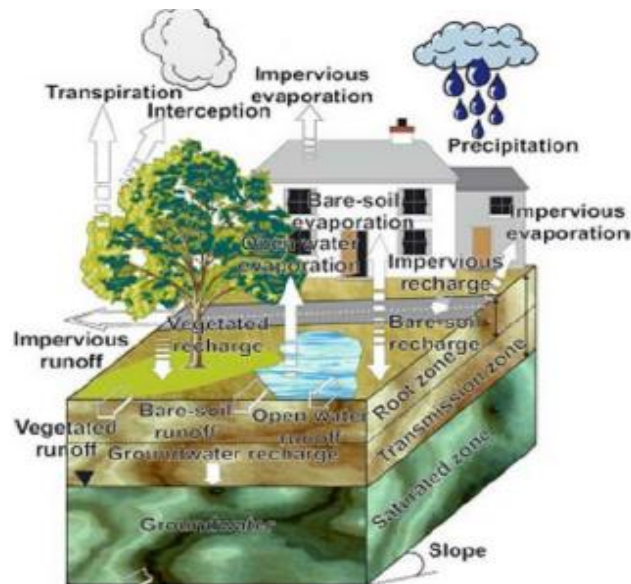


Fig. 2. Schematic representation of the water balance of a hypothetical raster cell showing surface and sub-surface processes, after Batelaan and De Smedt (2001)

Table 1. Input parameters and their sources for WetSpass model

Id	Input parameter	Sources	Resolution
1	Soil texture	Map from soil sample analysis	30*30M
2	DEM (Topography and slope)	Glovis.usgs.gov & own processing	30*30M
3	Land use/cover(Summer & winter)	Glovis.usgs.gov & own process	30*30M
4	Temperature (Summer & winter)	NMA & own-processing	30*30M
5	Precipitation (Summer & winter)	NMA & own-processing	30*30M
6	PET (Summer & winter)	NMA & own-processing	30*30M
7	Wind speed (Summer & winter)	NMA & own-processing	30*30M
8	Groundwater depth (Summer & winter)	Regional water resources	30*30M
9	Soil parameter lookup table	WetSpass User Guide & Literature review	
10	Runoff coefficient lookup table	WetSpass User Guide & Literature review	
11	Land use parameters (Summer & winter) lookup table	WetSpass User Guide & Literature review	

Table 2. Characteristics of Landsat-8OLI downloaded from glovis.usgs.gov for land use land cover map preparation

Winter landsat-8OLI			Summer landsat-8OLI		
Id	Characteristics	Descriptions	Id	Characteristics	Descriptions
1	Path/Row	168,51	1	Path/Row	168,51
2	Cell size	30*30meter	2	Cell size	30*30meter
3	Date of capturing	2015-01-05	3	Date of capturing	2015-09-02
4	Map projection	UTM	4	Map projection	UTM
5	Datum	WGS84-Zone-37N	5	Datum	WGS84-Zone-37N
6	Source	Glovis.usgs.gov	6	Source	Glovis.usgs.gov

Table 3. Materials and software used in this research

No	Software's and Materials	Functions/ used for
1	GPS-Garmin-60	GCP data, outlet and soil sample data collection.
2	ArcGIS software 10.3	Grid data preparation, spatial data analysis, interpolation of point data and interpretation of the simulated Results.
3	Erdas Imagine	Layer stacking, LULC classification, and Accuracy assessment.
4	Arc Hydro tools	Dem Hydro-processing, flow direction, flow accumulation, Streams network, Watershed Delineation.
5	Arc View 3.2 and WetSpass Extensions	Running the WetSpass model.
6	Cropwat-8	Evapotranspiration estimation.
7	Google Earth	Ground truth collection and features Identification, and to take GCP for inaccessible areas.
8	XLS to DBF Converter software	To prepare lookup parameter tables of Soil texture, Land use land cover, runoff coefficient in DBF format.
9	Ms-Office-2010	Reporting and presentation of results

3.2 Research Methodology

3.2.1 Basic concepts of WetSpass model

WetSpass is an acronym which stands for Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State [14,15]. It uses both physical and hydro-meteorological

input files for simulation of the long-term average spatial patterns of surface runoff, actual evapotranspiration and groundwater recharge which is suitable for studying long-term effects of land-use changes on the water regime in a watershed region [14,16,17]. The application of this model is compatible and integrated with GIS ArcView software during the simulation

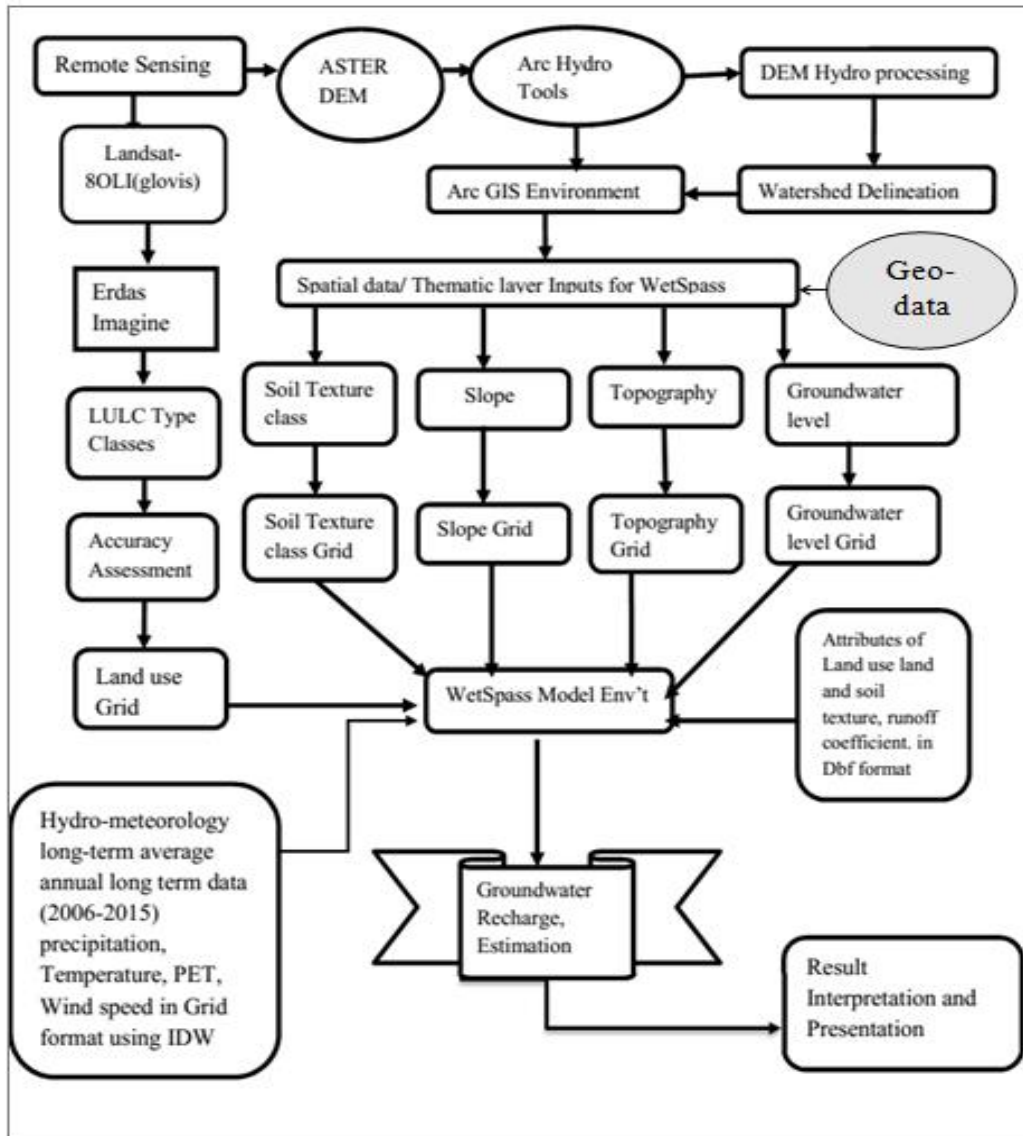


Fig. 3. Research methodology frameworks, different activities, and tools used to achieve the research objectives

process. It estimates the spatial difference of groundwater recharge at the seasonal and annual basis and it was successfully applied in different countries by different authors, as a result, the findings of those authors showed that groundwater recharge estimation was successfully estimated with a good result [12].

The WetSpaSS model [14,16–19] was used in their study to simulate temporal average and spatial differences of surface runoff, actual evapotranspiration, groundwater recharge and other water balance components in seasonal and

annual basis for Birki watershed. Generally, to run the WetSpaSS model two basic input parameters were needed (hydro-meteorological and biophysical data) related to the watershed and they should be prepared in grid and database file (DBF) formats.

3.2.2 WetSpaSS model description

The total water balance for a given raster cell (Fig. 2) is split into independent water balance components for the vegetated, bare-soil, open-water and impervious parts of each cell. This

allows one to account for the non-uniformity of the land-use per cell, which is dependent on the resolution of the raster cell. The processes in each part of a cell were set in a cascading way. This means that an order of occurrence of the processes, after the precipitation event, is assumed. Defining such an order is a prerequisite for the seasonal timescale with which the processes will be quantified. The quantity determined for each process is consequently limited by a number of physical and hydro-meteorological constraints of the given area under investigation [20].

3.2.3 Water balance calculation using WetSpa model

Water balance components of vegetated, bare-soil, open water and impervious surfaces are used to calculate the total water balance of a raster cell as follows;

$$ET_{\text{raster}} = a_v ET_v + a_s E_s + a_o E_o + a_i E_i \quad (1)$$

$$S_{\text{raster}} = a_v S_v + a_s S_s + a_o S_o + a_i S_i \quad (2)$$

$$R_{\text{raster}} = a_v R_v + a_s R_s + a_o R_o + a_i R_i \quad (3)$$

Where ET_{raster} , S_{raster} , R_{raster} are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell respectively, each having a vegetated, bare-soil, open-water and impervious area component denoted by a_v , a_s , a_o , and a_i , respectively.

Precipitation is taken as the starting point for the computation of the water balance of each of the above-mentioned components of a raster cell, the rest of the processes, like interception, surface runoff, evapotranspiration, and recharge follow in an orderly manner.

3.2.4 Vegetated area

The water balance for a vegetated area depends on the average seasonal precipitation (P), interception fraction (I), surface runoff (S_v), actual transpiration (T_v), and groundwater recharge (R_v) all with the unit of $[LT^{-1}]$, with the relation given below

$$P = I + S_v + T_v + R_v \quad (4)$$

3.2.5 Surface runoff

Surface runoff is calculated in relation to precipitation amount, precipitation intensity,

interception and soil infiltration capacity. Initially, the potential surface runoff ($S_v - \text{pot}$) is calculated as

$$S_v - \text{pot} = C_{sv} (P - I) \quad (5)$$

Where, C_{sv} is a surface runoff coefficient for vegetated infiltration areas, and is a function of vegetation, soil type, and slope. In the second step, actual surface runoff is calculated from the $S_v - \text{pot}$ by considering the differences in precipitation intensities in relation to soil infiltration capacities.

$$S_v = C_{Hor} S_v - \text{pot} \quad (6)$$

Where C_{Hor} is a coefficient for parameterizing that forms part of seasonal precipitation contributing to the Hortonian overland flow. C_{Hor} for groundwater discharge areas is equal to 1.0 since all intensities of precipitation contribute to surface runoff. Only high-intensity storms can generate surface runoff in infiltration areas.

3.2.6 Evapotranspiration

A reference value of transpiration is obtained from open-water evaporation and a vegetation coefficient for the calculation of seasonal evapotranspiration:

$$T_{rv} = c E_o \quad (7)$$

T_{rv} = the reference transpiration of a vegetated surface $[LT^{-1}]$;

E_o = potential evaporation of open water $[LT^{-1}]$
and c = vegetation coefficient [-]

This vegetation coefficient can be calculated as the ratio of reference vegetation transpiration as given by the Penman-Monteith equation to the potential open-water evaporation, as given by the Penman equation,

$$C = \frac{1 + \frac{\gamma}{\Delta}}{1 + \frac{\gamma}{\Delta} \left(1 + \frac{r_c}{r_a}\right)} \quad (8)$$

Where; γ = Psychrometric constant $[ML^{-1} T^{-2} C^{-1}]$;

Δ = Slope of the first derivative of the saturated vapor pressure curve $[ML^{-1} T^{-2} C^{-1}]$;

r_c = Canopy resistance $[TL^{-1}]$ and

r_a = aerodynamic resistance $[TL^{-1}]$ given by;

$$r_a = \frac{1}{k^2 u_a} \left(\ln \left(\frac{z_a - d}{z_o} \right) \right)^2 \quad (9)$$

3.3 WetSpass Model Data Inputs Preparation and Their Sources

GIS-based hydrological models integrated with WetSpass model were used for analyzing the biophysical, hydrological and metrological data of the study area in order to estimate the hydrological systems in a steady state condition. However, this demands long-term average hydro-meteorological data and spatial patterns. The model needs the parameters in seasonal basis, as a result, four months of June, July, August, and September are considered as summer (main rainy season) and the remaining eight months are considered as winter (dry season) in the case of Ethiopian condition particularly in the study area. Grid maps and parameter tables are required (Table 1) as inputs for the model and they are prepared with the help of ArcGIS tools and Erdas Imagine software. These grid maps were a land-use and land cover, soil texture, slope, topography, groundwater levels, precipitation, potential evapotranspiration, and wind speed and in line with these grid maps lookup tables of soil type, land use and runoff coefficient were prepared. Detail input parameters was mentioned on the overall research methodology framework

adopted for estimation of water balance components using GIS-based WetSpass model for Birki watershed as illustrated in (Fig. 3) and used nineteen input parameters to stimulate the model, and out of these, fifteen parameters were in the form of grid data and four in database file format. Characteristics of Landsat-8OLI downloaded from glovis.usgs.gov for land use land cover map preparation are described in Table 2.

3.4 Materials and Software

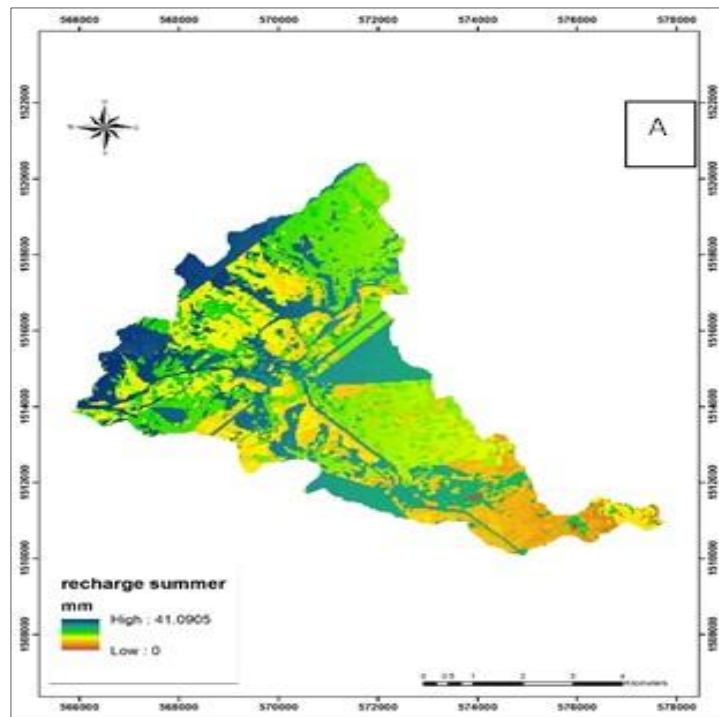
The materials and software used in the entire research work were presented as follows in Table 3.

The overall research methodology framework adopted for estimation of water balance components using GIS-based WetSpass model for Birki watershed was mentioned as illustrated in (Fig. 3).

4. RESULTS AND DISCUSSION

4.1 Annual and Seasonal Groundwater Recharge Estimation

The recharge rate during the main rainy season from June to September ranges from 0 to



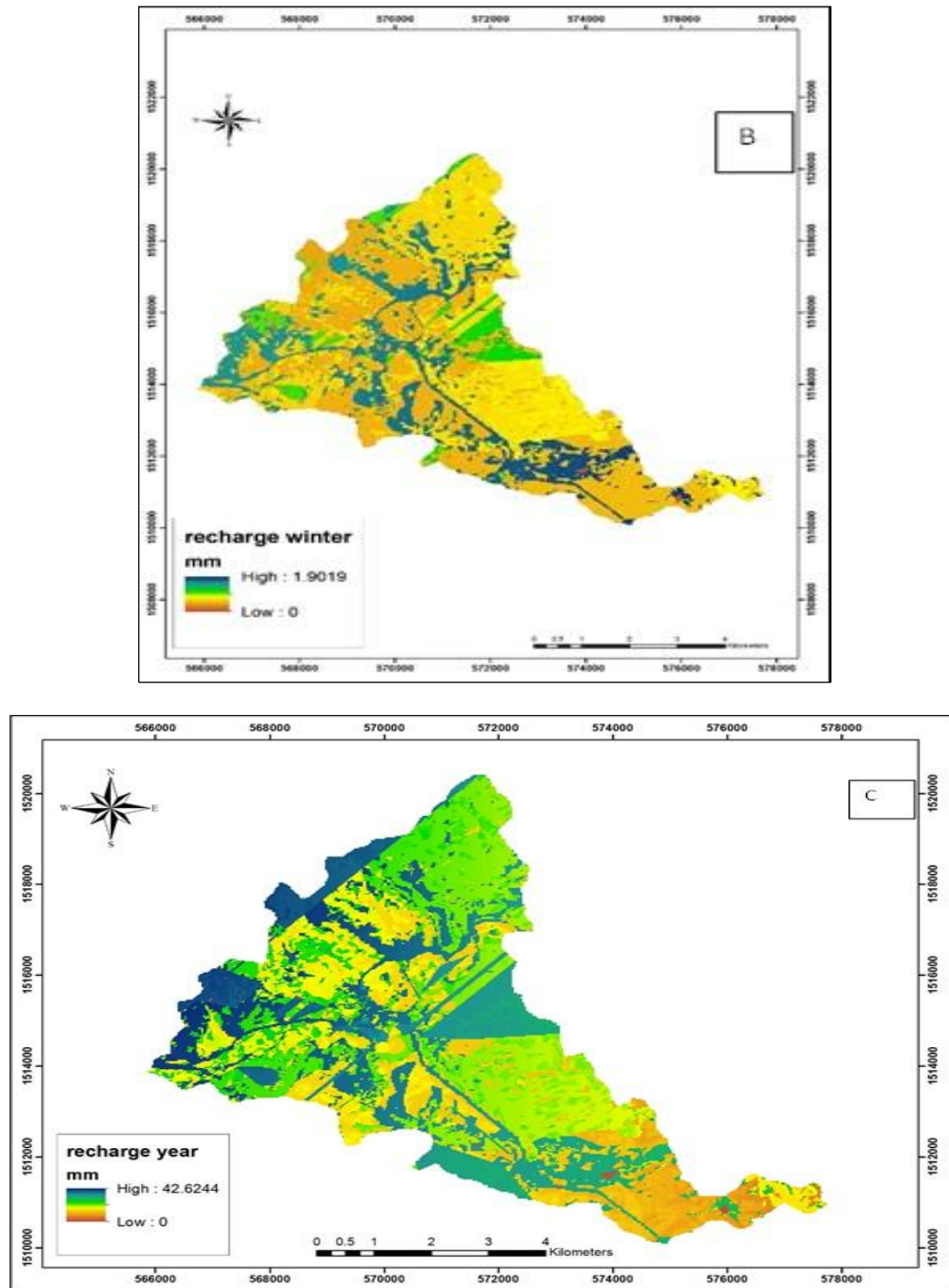


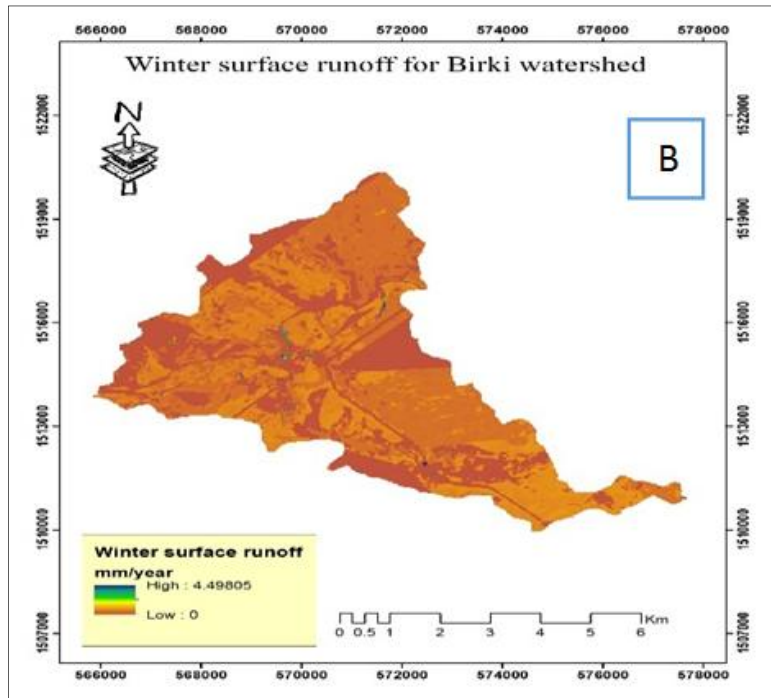
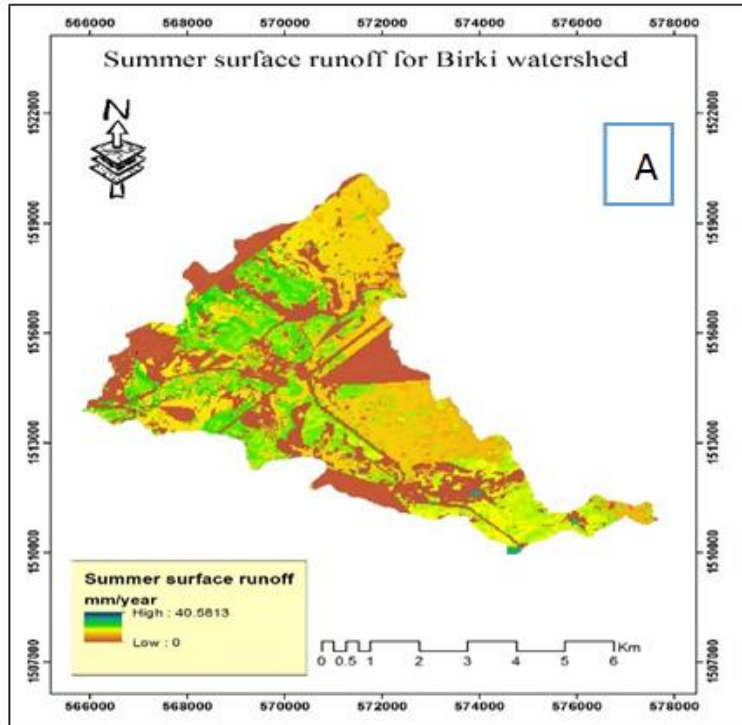
Fig. 4. WetSpass model-based groundwater recharge simulation during summer season (A), winter season (B) and annual (C)

41.09 mm year⁻¹ with a mean value of 24 mm year⁻¹ (look Fig. 4A), while the recharge during the long dry season varies from 0 to 1.53 mm year⁻¹ with mean value of 0.82 mm year⁻¹ (Fig. 4B), similarly, the mean annual groundwater recharge ranges from 0 to 42.6 mm year⁻¹ with

mean value of 24.9 mm year⁻¹, which accounts 7.4% of the total long-term mean annual precipitation 573 mm on the entire watershed as shown in (Fig. 4C). The recharge rate was higher in the summer season than winter because of high rainfall amount, intensity,

duration than the winter season [21,2] and due to intensive watershed management interventions, which is important for water resource development activities like creating

boreholes, springs by the regional water resource experts and could be a baseline information for policymakers for the future intervention.



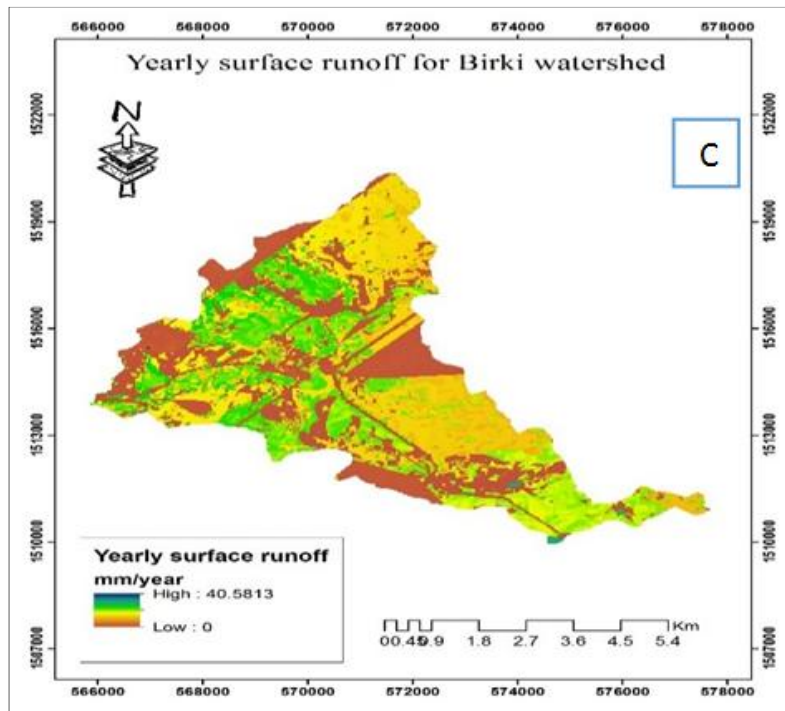
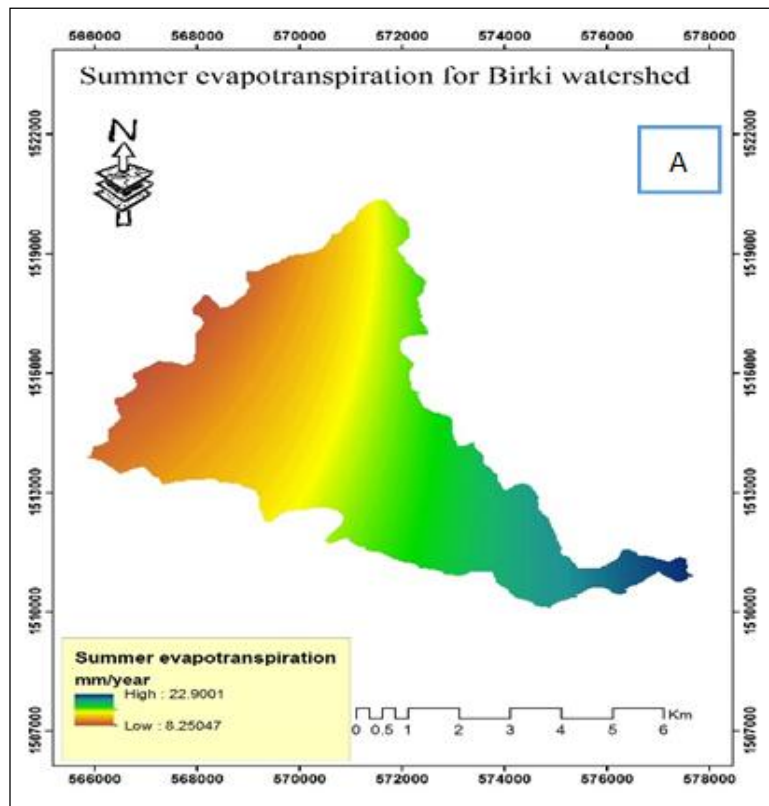


Fig. 5. Summer (A), winter (B) and annual (C), surface runoff simulated for Birki watershed



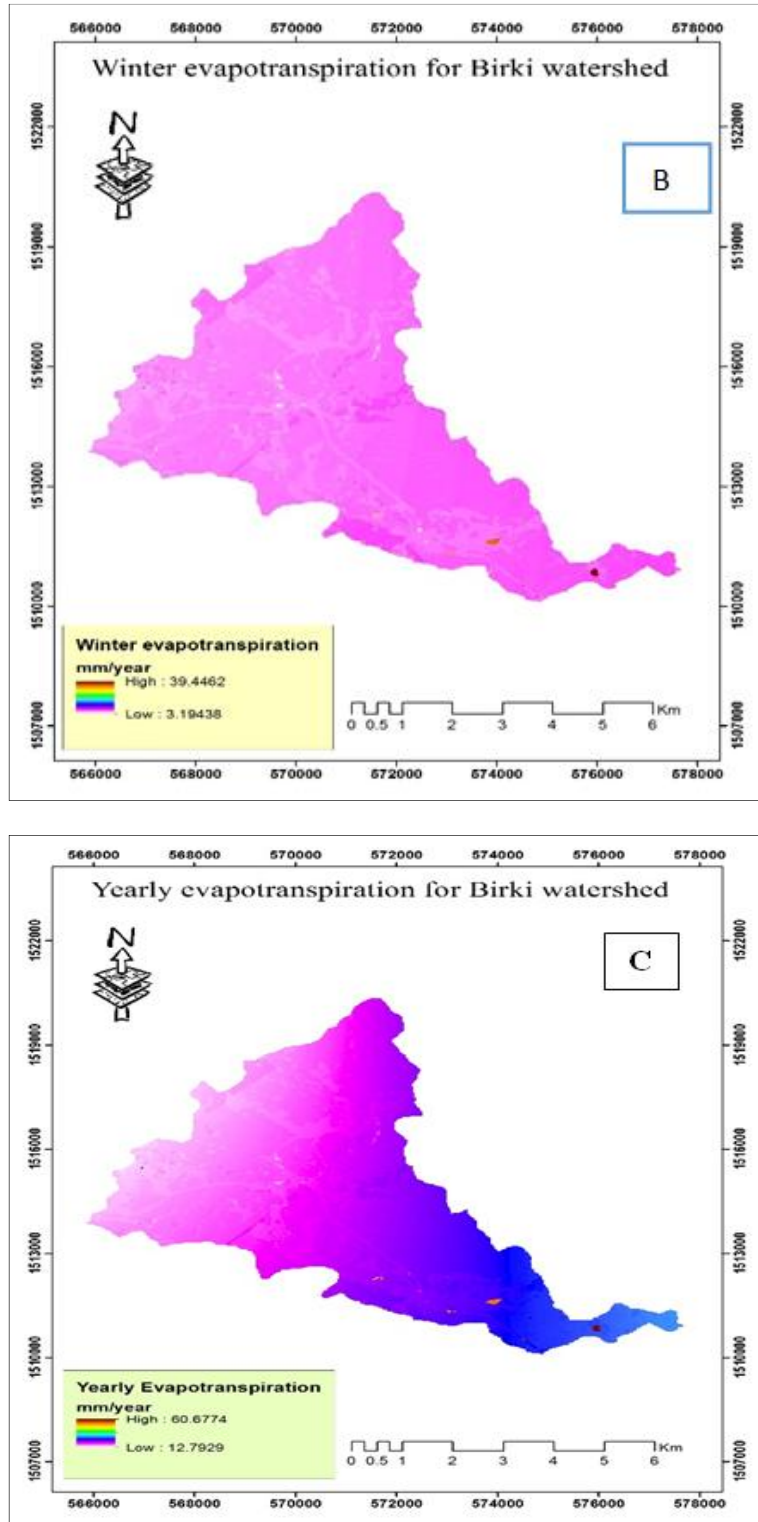
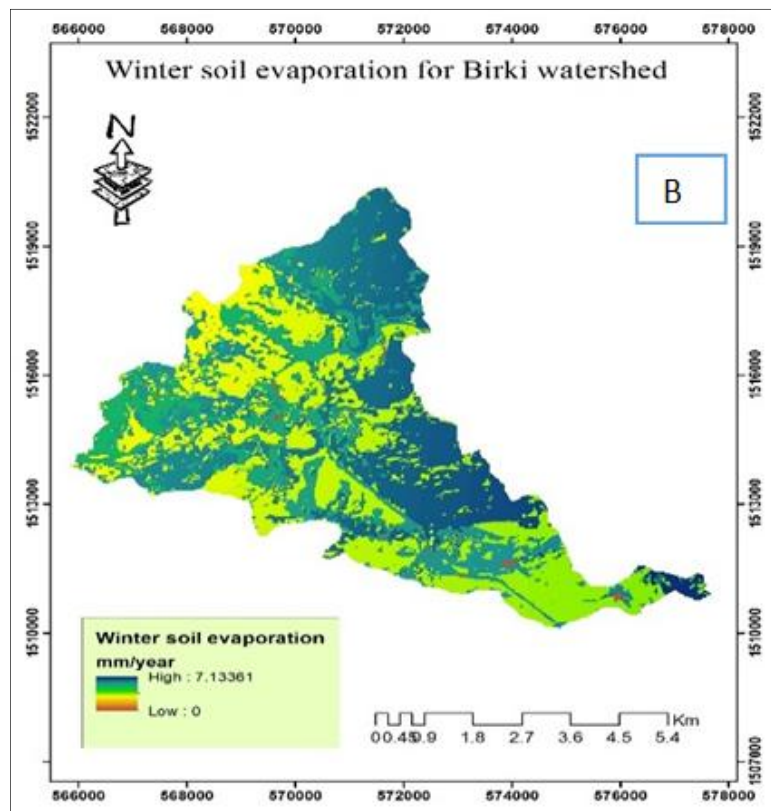
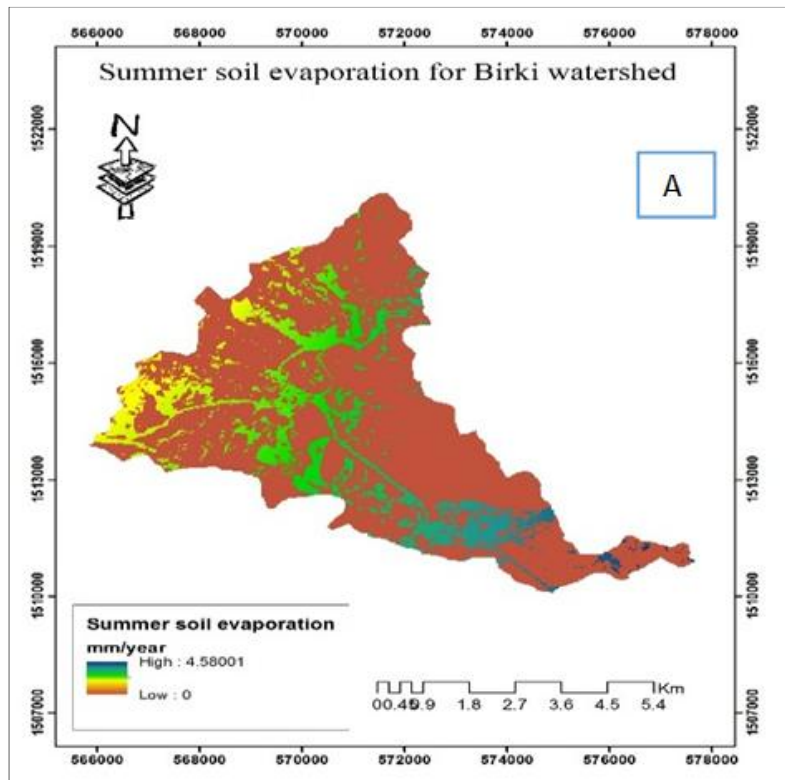


Fig. 6. Summer (A), winter (B) and annual (C), evapotranspiration simulated by WetSpas model



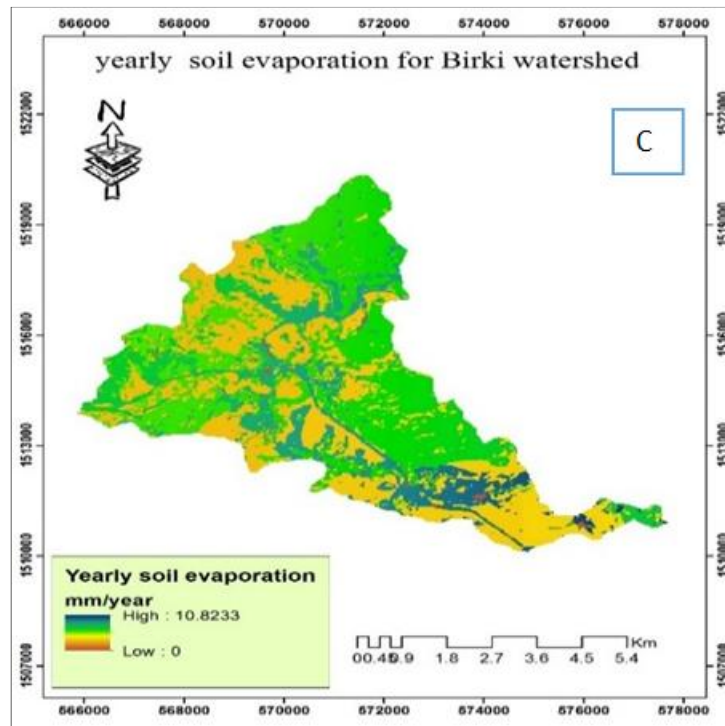


Fig. 7. Summer (A), winter (B) and annual (C), Soil evaporation simulated for birki watershed

4.2 Annual and Seasonal Surface Runoff Estimation

The surface runoff during the main rainy season from June to September ranges from 0 to 40.5 mm year⁻¹ with a mean value of 10.9 mm year⁻¹ (Fig. 5A), while the surface runoff during long dry season was found from 0 to 4.5 mm year⁻¹ with mean value of 0.4 mm year⁻¹ (Fig. 5B), and mean annual surface runoff ranges from 0 to 40.6 mm year⁻¹ with mean value of 10.9 mm year⁻¹, which accounts 7.1% of the total long-term mean annual precipitation 573 mm on the entire watershed as shown in (Fig. 5C). The surface runoff is higher in summer season than winter as the biophysical and hydro-meteorological characteristics vary in seasons and directly related to rainfall amount [2] and this is used for implementing conservation practices to reduce runoff and soil erosion on the watershed.

4.3 Annual and Seasonal Evapotranspiration Estimation

The evapotranspiration during the main rainy season (June to September) ranged from 8.2 to 22.9 mm year⁻¹ with a mean value of 14.4 mm year⁻¹ (Fig. 6A). Evapotranspiration during the

long dry season was ranged from 3.1 to 39.4 mm year⁻¹ with a mean value of 6.7 mm year⁻¹ (Fig. 6B). Overall, the mean annual evapotranspiration ranged from 12.8 to 60.8 mm year⁻¹ with a mean value of 21.1 mm year⁻¹, which accounted 85.5% of the total long-term mean annual precipitation 573 mm on the entire watershed as shown in (Fig. 6C).

4.4 Annual and Seasonal Soil Evaporation Estimation

The soil evaporation during the main rainy season ranged from 0 to 4.6 mm year⁻¹ as shown in (Fig. 7A), and during the long dry season, it ranged from 0 to 7.1 mm year⁻¹ with a mean value of 4.9 mm year⁻¹ (Fig. 7B). The mean annual soil evaporation ranged from 0 to 10.8 mm year⁻¹ on the entire watershed as shown in (Fig. 7C). The main driver for all hydrological processes is precipitation and soil evaporation is directly related to rainfall amount, soil type, land use land cover type and other biophysical characteristics of a given watershed [2]. This information was used to understanding the soil moisture status of the soil for irrigation purpose, the lowest soil evaporation has high soil moisture and vice versa.

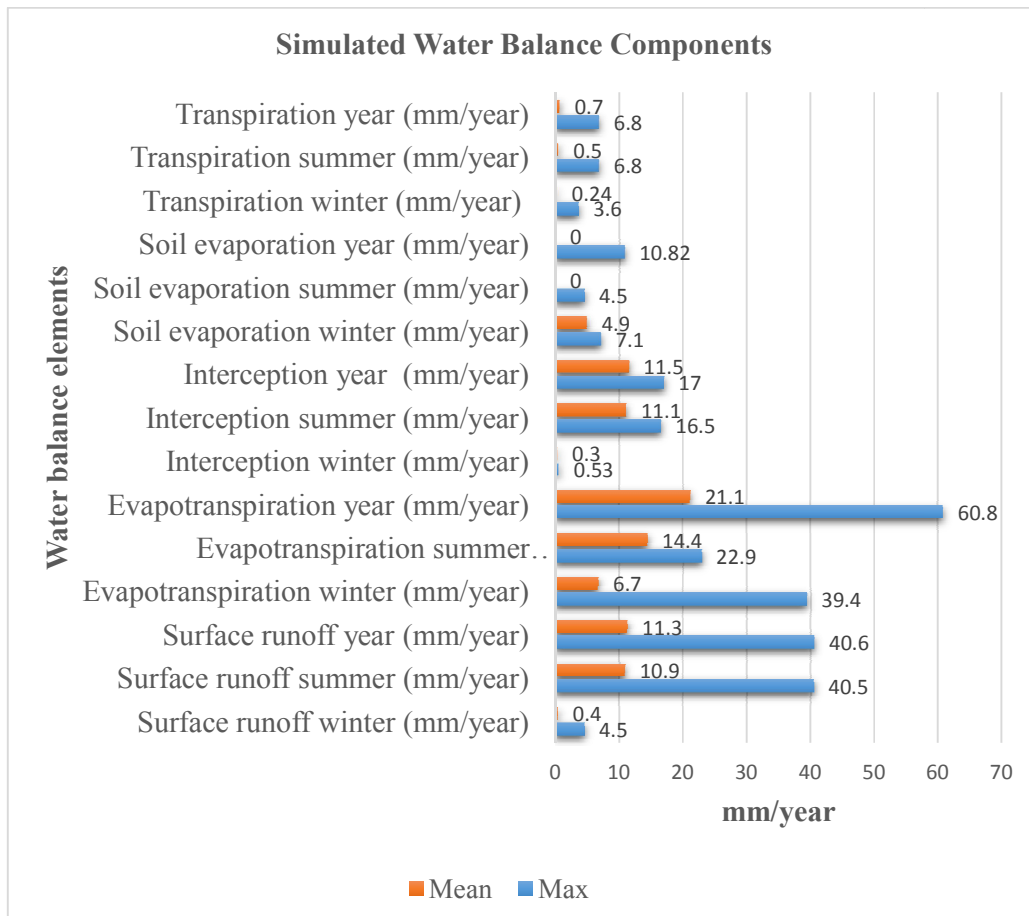


Fig. 8. Water balance components simulated using WetSpass model for Birki watershed

4.5 Water Balance Components Estimated

The WetSpass model has the capability to simulate water balance components of a given watershed. Annual and seasonal surface runoff, evapotranspiration, interception loss, soil evaporation, and transpiration losses were simulated for Birki watershed. As a result, high values of surface runoff, interception, and transpiration losses were observed in the summer season but low values in the winter season. High values of evapotranspiration were observed in the summer season than the winter season as illustrated in (Fig. 8) which is related to the high rainfall amount, duration and intensity during this season compared to the dry season [2,21,22,23]. Understanding the water balance of a given watershed is important for water budgeting and pricing purpose to conserve the resource for sustainable utilization on the area and to implement integrated watershed

management approach by the community to sustain the watershed as it is.

5. CONCLUSIONS

The development and application of GIS and remote sensing techniques coupled with other hydrological models like WetSpass model make the assessment and understanding of water resources easy and effective to maximize its wise utilization, proper management for sustainable use of the resource.

The WetSpass model, a simulation model based on biophysical and hydro-meteorological properties, is robust to estimate long-term annual average water balance components in terms of seasonal and annual basis to see pattern and status of the resource. Also used for a future master plan of water resources development for a given watershed for easily implementing practically.

There are high groundwater recharge and evapotranspiration with low surface runoff in the watershed because of the watershed is the conserved type of watershed with high coverage of shrublands in which this facilitates infiltration rate and evapotranspiration, but decreases runoff production.

Based on GIS-based physical simulation model on the arid and semi-arid regions of Tigray, the information is used for implementing soil and water conservation strategies, implementing an integrated watershed management approach. Moreover, used for preparing future planning program by policymakers, regional water resource experts and researchers for proper management, wise utilization and sustainable development using the resource within the watershed.

6. RECOMMENDATIONS

- This result serves as baseline information for policymakers and water resource experts for further investigation on groundwater recharge modeling and future planning of the watershed.
- Lack of hydro-meteorological data is the main problem in running hydrological models, so the hydro-meteorological data handling system should be improved at a country level.
- Awareness creation on integrated watershed management for the community is important for the sustainable use of water resources and to sustain the ecosystem healthy.
- Model results validation is important to check the goodness of the model; this should be considered in doing groundwater recharge modeling and hydrological components estimation using hydrological models.
- The watershed is the conserved type of watershed this improves groundwater recharge and reduces surface runoff, so the community should keep up such conservation practices/mechanism to minimize soil erosion and to enhance groundwater recharge rate in the watershed.
- The main limitation of this current research is that the model is designed only for the temperate regions of the world only, but it is better to develop for all the world countries and in this research work we implement the model by changing the input

parameters from temperate conditions to semi-arid conditions based on the agro-ecological classification of the watershed and using literature reviews which is implemented this model in arid and semi-arid conditions.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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