



Spatial groundwater recharge estimation in Raya basin, Northern Ethiopia: an approach using GIS based water balance model

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Received: 15 January 2018 / Accepted: 23 July 2018 / Published online: 28 July 2018
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Abstract

Understanding the spatial variability of groundwater recharge in response to distributed Land-use, soil texture, topography, groundwater level, and hydrometeorological parameters is significant when considering the security of groundwater resource development. Thus, this study was aimed at estimating the spatial groundwater recharge of Raya valley, northern Ethiopia using spatially distributed water balance model (WetSpass). Input data for the model were prepared in the form of grid maps using 90 m grid size and the parameter attribute tables were adjusted to represent the Raya valley condition using expert knowledge and scientific literatures. The results of the model indicated that the long-term temporal and spatial average annual rainfall of 710 mm was partitioned as 57 mm (8%) of surface runoff, 598 mm (84%) of evapotranspiration, and 55 mm (8%) of recharge. The recharge corresponds to 137 million cubic meters (Mm³) for the Raya basin (with area of about 2500 km²) from which 84% of the recharge takes place during summer season, while the remaining 16% takes place during the winter (dry) season. The analysis of the simulated result showed that WetSpass works well to simulate water balance components of Raya valley and is especially suitable for studying the effects of Land-use changes on the water regime in the basin.

Keywords Water balance components · Distributed recharge · Raya valley

Introduction

Water is one of the most essential commodities for mankind and the largest available source of fresh water is obtained from groundwater (Arkoprovo et al. 2012). Groundwater is a very important and dependable source of water supply in all climatic regions due to its inherent qualities such as consistent temperature; widespread occurrence and continuous availability; excellent natural quality; limited

vulnerability, low development cost and draught reliability (Todd and Mays 2005). However, groundwater is a finite and vulnerable resource which should be used properly and efficiently for present and future generations (Arkoprovo et al. 2013). Therefore, knowledge of groundwater resource potential which is directly dependent on recharge is important for sustainable use and management of groundwater resources (Tilahun and Merkel 2009). Quantifying the rate of groundwater recharge is a prerequisite for efficient and sustainable groundwater resource management and is practically vital in arid regions where such resources is often the key to economic development (De Vries and Simmers 2002). Techniques of recharge estimation vary based on source and process of recharge mechanisms such as direct measurements, water balance methods, tracer techniques and empirical methods (Simmers et al. 1997). According to Scanlon et al. (2002), important considerations in choosing a technique include space or time scales, range, and reliability of recharge estimates based on different techniques. For this research, distributed water balance model (WetSpass) was adapted to estimate the long-term average spatially distributed groundwater recharge as a spatial variable dependent on

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land cover, soil type, topography and hydrometeorological factors. This is because understanding the spatial variability of groundwater recharge in response to distributed Land-use, soil texture, topography, groundwater level, and hydro-meteorological parameters is significant when considering security of groundwater resource development.

Despite the highly variable rainfall (raining in one or two rainy seasons, followed by a relatively long dry season), agriculture is mainly rainfed in Ethiopia (Belete 2007). The shortage and variability of rainfall during the growing season often leads to low production rates. Tigray region, in north Ethiopia, has a mean annual evapotranspiration rate ranging from 1900 to 2100 mm that is greater than the mean annual precipitation, which ranges from 300 to 800 mm (MoA 1998). According to MoA (1998), the region has a growing period of about 60 days and annual air mean temperature ranges from 16 to 27 °C. Hence, supplementing the rainfed agriculture via irrigation practice is vital for the food security of the region.

Raya valley is one of the groundwater based irrigation areas located in the southern zone of Tigray region (Tadesse et al. 2015). Due to the erratic nature of the rainfall (both time and space) distribution in the area, people often fail to maintain the soil moisture requirement for growing crops. Thus the need of agricultural development using groundwater resource in the area is growing continuously. However, the ambitious plans for expanding irrigation have not been adequately strengthened through the assessments of groundwater reserves and spatial groundwater recharge estimations. Previous groundwater study efforts in the area (German Agency for Technical Cooperation LTD 1977; Ayenew et al. 2013; Nadew 2003; Fenta et al. 2014) focused on delineation of potential sites for the purpose of developing the groundwater, considering point estimates of recharge. However, groundwater estimation needs a reliable method to quantify its spatial and temporal variability (Rwanga 2013). Therefore, the main objective of this research was to estimate long-term seasonal/annual average spatial groundwater recharge in the Raya valley Northern Ethiopia by adapting GIS-based WetSpas model (Batelaan and De Smedt 2001).

Study area

Raya Valley is located in northern part of Ethiopia between latitude of 12°05′–12°55′N and longitude of 39°21′–39°55′E (Fig. 1). The study area is bounded by the North-Western Ethiopian Plateau in the west and the Afar Rift in the east with an area of about 2500 km². It is among the sub-basins on the western edge of the Danakil basin that consists of a number of small closed basins separated by volcanic mountains which include Maglala–Renda Coma, Dergaha–Sheket,

Guf–Guf (the study area), Menebay–Hayk, and Borkena (Tesfaye et al. 2003).

The main physiographic features prevailing in the area are north–south oriented mountains in the west, a steep fault scarp in the east, a major graben and isolated hills within the graben. The study area is elongated intermountain graben filled with quaternary sediments, bordered to the east and west by rugged volcanic mountains with relatively high elevation. The average altitude of the area ranges from 1382 meters within the valley floors to 3688 meters above sea level in the western mountain ridges. The area of interest is characterized by an erratic, bimodal rainfall pattern with main rainy season lasting from late June to early September. The highest rainfall record occurs in July and August, whereas the short spring rainy season extends from February to March. Average monthly temperature of the Raya valley varies from a minimum average of 4.7 °C in the Korem plateaus to a maximum average of 35.5 °C at Waja lowlands. The highest temperature is recorded in June and lowest value in November. Raya valley consists of three major drainage systems emerging dominantly from the western mountain ranges, partly from the eastern margin and the drainage system of Sulula River. The western mountainous part of the area is highly dissected by streams and steep slope topography which favors high runoff. As a result, the valley floor is seasonally recharged via the incoming runoff from the nearby hills (Ayenew et al. 2008). Thus rainfed agriculture by diverting seasonal flush floods is a common practice (Fenta et al. 2014).

Data sources and methods

Data source

The main data sources used were remote sensing data, ancillary data and ground truth data. The remote sensing data were obtained from the Digital Elevation Model (DEM and Landsat image). The ancillary/secondary data used were composed of topographic maps, borehole data, and meteorological data. Ground truth observations were used to produce the required input data for the water balance model (WetSpas).

Remote sensing data

The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with 90 m resolution was used to extract slope and related topographic features. Cloud-free Landsat Operational Land Imager (OLI) images for the year 2015, with bands 3, 4, and 5, were used to produce the Land-use/land cover. For the OLI images, Bands 3, 4, and 5 represent electromagnetic radiances at wavelength

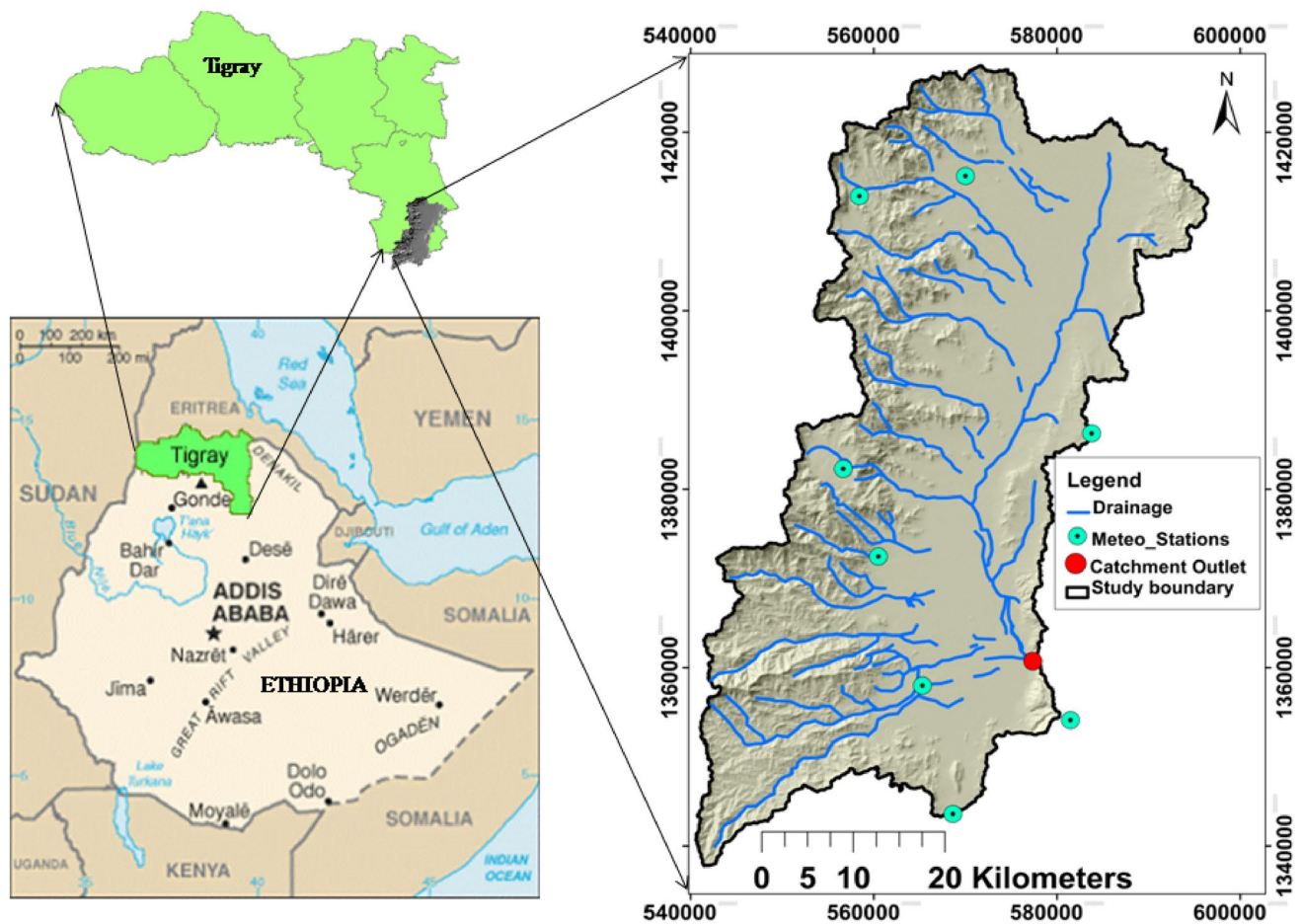


Fig. 1 Location map of Raya valley and location of meteorological stations

ranges of 0.53–0.59 μm (green), 0.64–0.67 μm (red), and 0.85–0.88 μm (near infrared) respectively with a resolution of 30 m.

In addition to the remote sensing data, secondary data; including soil map of FAO (1998) and 17 years (2000–2016) mean monthly meteorological variables for eight stations from the National Meteorology Agency (NMA) of Ethiopia were used. Field observation was also carried out to collect ground truths/training samples to classify the Landsat OLI image into different Land-use/cover types and assess the classification accuracy. Initial groundwater depth was taken from 313 boreholes drilled in Raya valley (from 2008 to 2016), mainly by the Tigray region water bureau and Relief Society of Tigray. To extract the required input variables for the WetSpa model, remote sensing and ancillary/secondary data were processed using remote sensing and GIS software packages. GIS applications are the sole tools used to handle spatial and temporal variability (Tilahun and Merkel 2009).

WetSpa model description

WetSpa is an acronym for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi Steady State (Batelaan and De Smedt 2007). It is a physically based model for estimation of the long-term average spatial patterns of groundwater recharge, surface runoff and evapotranspiration from long-term average meteorological data together with Land-use, soil, and groundwater level grid maps by employing physical and empirical relationships (Batelaan and De Smedt 2001). WetSpa gives the various hydrologic outputs on a yearly and seasonal (summer and winter) basis (Batelaan and De Smedt 2001). The model is integrated in ArcView as a raster model and coded in Avenue and Visual Basic. Parameters such as land-use and related soil type are connected to the model using attribute tables of the land-use and soil raster maps. The attribute tables also allow defining new land cover or soil types easily, as well as changes in the parameter

values, which permits analysis of future land and water management scenarios (Batelaan and De Smedt 2007).

WetSpaas model treats a basin or region as a regular pattern of raster cells (Batelaan and De Smedt 2007). The total water balance for a raster cell is split into independent water balances for the vegetated, bare-soil, open-water and impervious parts of each cell (Fig. 2). 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 and the processes in each part of a cell are set in a cascading way (Batelaan and De Smedt 2001).

Since WetSpaas model is a distributed water balance model, the water balance computation is performed at raster cell level. As described by Batelaan and De Smedt (2001), individual raster water balance is obtained by summing up independent water balances for the vegetated, bare soil, open water and impervious fractions of a raster cell as follows:

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

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

$$R_{\text{raster}} = a_v R_v + a_s R_s + a_i R_i \tag{3}$$

where ET_{raster} , S_{raster} , R_{raster} are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell

respectively, each having vegetated, bare soil, open water and impervious area fractions denoted by a_v , a_s , a_o and a_i respectively, E is evaporation.

Precipitation was taken as starting point for the calculation of the water balance for each of the components of a raster cell. Other processes (interception, runoff, evapotranspiration and recharge) followed in an orderly manner; which becomes a prerequisite for the seasonal time scale to compute the processes. Evapotranspiration is calculated as the sum of evaporation of the precipitation intercepted by the vegetation, transpiration by the vegetation, and evaporation from bare soil and open water bodies (Batelaan and De Smedt 2001). For simulation of surface runoff, WetSpaas model uses the runoff coefficient which on the other hand is a function of vegetation type, soil texture and slope. As discussed by Batelaan and De Smedt (2007), in WetSpaas, the surface runoff (S_v) is simulated in two stages. First, the potential surface runoff (S_{v-pot}) is calculated as a coefficient times the precipitation minus the interception (Eq. 4).

$$S_{V-Pot} = C_{sv}(P - I) \tag{4}$$

Where, C_{sv} (as function of vegetation type, soil type and slope) is a surface runoff coefficient for vegetated infiltration areas based on the rational formula (Smedema and Rycroft 1988; Pilgrim and Cordery 1992; and; Chow et al. 1988). However, the potential surface runoff is conceptualized to occur only on groundwater saturated areas (Batelaan and De Smedt 2007). Rubin (1966) indicated that, in the second stage, the potential surface runoff is actualized for recharge areas by taking into account differences in precipitation intensities in relation to soil infiltration capacities (Eq. 5).

$$S_v = C_{Hor} S_{V-Pot} \tag{5}$$

where C_{Hor} is a coefficient that parameterizes the part of the seasonal precipitation which is actually contributing to the (Hortonian) surface runoff. As explained by Batelaan and De Smedt (2001), in groundwater discharge areas all intensities of precipitation contribute to surface runoff, i.e. C_{Hor} is 1. In infiltration areas, only high-intensity storms will generate surface runoff.

The most common way of estimating recharge by the water budget method is the indirect or residual approach, whereby all of the variables in the water budget equation except recharge are estimated, and recharge is set equal to the residual (Scanlon et al. 2002). In WetSpaas, groundwater recharge is calculated as a residual term of the water balance (Eq. 6).

$$R_v = P - S_v - ET_v - I \tag{6}$$

where P is the average seasonal precipitation [LT^{-1}], ET_v is the actual evapotranspiration [LT^{-1}], S_v is the surface runoff [LT^{-1}], T_v is the evaporation from bare soil between

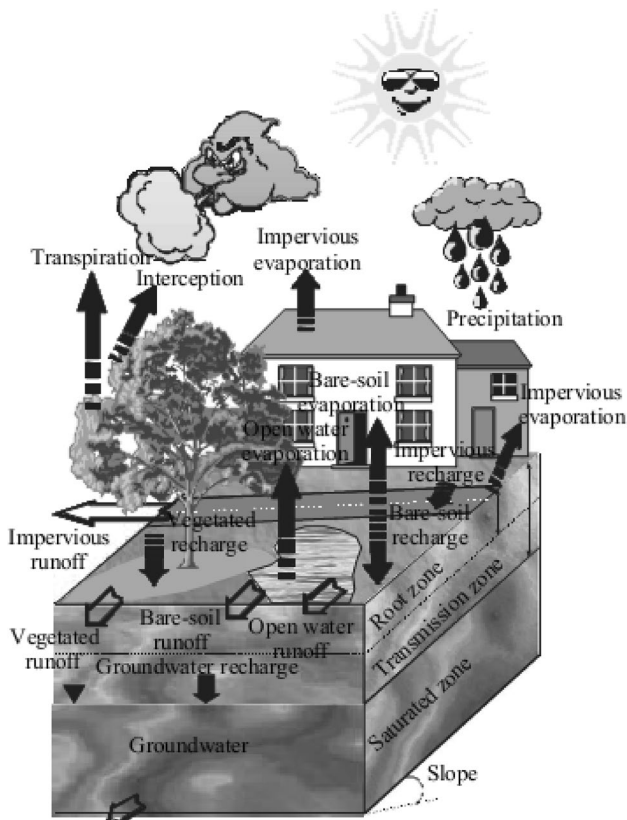


Fig. 2 Schematic water balance of hypothetical raster cell (Batelaan and De Smedt 2001)

vegetation [LT^{-1}], I is the interception by vegetation [LT^{-1}], and R_v is the groundwater recharge, all variables have the unit of [LT^{-1}].

Preparation of input thematic layers

Preparation of thematic layers involves digitizing existing maps, digital image processing of remote sensing data, and integration of field data for the extraction of pertinent information. As described by Rwanga (2013), two types of inputs are required for the WetSpss model: arc Info grid maps and parameter dbf tables. De Vries and Simmers (2002) noted that interaction of climate, geology, morphology, soil condition, and vegetation determines the recharge process. As such, the input data were prepared in the form of grid maps of meteorological, hydrological, and geographical elements in the basin. All input grid maps were prepared using grid cell size of 90×90 m which is similar to the shuttle radar topography mission digital elevation model.

Meteorological data

Meteorological data obtained from of eight stations of the Ethiopian national Meteorological Agency (EMA) were used for the preparation of metrological input data for the WetSpss model. Missing meteorological data record was a common problem in the stations of the study area. However, the selected stations for the 17 years (from 2000 to 2016) had relatively consistent data records. Each station's data was analyzed for the calculation of the seasonal and annual meteorological values. Precipitation and temperature data were available for all the eight stations while wind speed, sunshine hour and relative humidity were recorded only at Kobo, Maichew and Chercher meteorological stations. The Penman–Monteith method (Allen et al. 1998) was used to calculate potential evapotranspiration at the three stations (Kobo, Maichew and Chercher). Penman–Monteith method is recommended as the sole standard method to calculate potential evapotranspiration where the required meteorological data is available (Su et al. 2015).

The seasonal and annual grid maps of the climatic variables were developed using an interpolation method to predict values from a limited number of sample data points at unknown geographic point data. Inverse Distance Weighted (IDW) interpolation method was applied as it gives consistent result with known values. The WetSpss's input grid maps of major meteorological parameters of Raya valley (Fig. 3) indicated high spatial variation as a function of topography. For example, there was a significant spatial variation of rainfall in the basin which is strongly influenced by orographic effect wherein the Korem highland receives high rainfall as compared to the valley bottoms.

Land-use/land cover

Land-use/land cover map was produced from cloud-free Landsat OLI images of February 6, 2015 (path 68, rows 50 and 51) using the standard supervised image classification. The classification was based on identifying and delineating training sites using ground truth observation points, interpreting Google Earth images, and own acquaintance with the basin land-use characteristics. A pixel-based supervised image classification with maximum likelihood classification algorithm was used to map the land-use land cover classes (Lillesand and Kiefer 2000). A total of four hundred ground truth points collected from the field were used for image classification and accuracy assessment using 200 ground truth points each. Confusion matrix (Table 1) was used to describe the image classification accuracy of Raya valley. Foody (2002) indicated that measure of classification accuracy can be derived from a confusion matrix (cross-tabulation of the mapped class level against that observed in the ground). The most popular classification accuracy measures are the percentage of cases correctly allocated (that indicates the overall accuracy of the classification). As calculated from the confusion matrix, the overall image classification accuracy of the Raya valley was 84.6% and this is very close to the commonly recommended 85% target.

The land-use/land cover classification of the study area (Fig. 4a) resulted in eight classes comprising of settlement (10.2%), bare land (13.3%), cultivated land (26.6%), grassland (1.5%), wetland (0.5%), woodland (23.8%), forest (4.2%) and shrubland (19.9%) of the of the Raya valley.

Soil texture

Soil texture and permeability are important in recharge estimation because coarse-grained soils generally result in higher recharge rates than do fine-grained soils (Cook et al. 1992). Soil map of the Raya basin was derived from the Soil and Terrain database for northeast Africa developed by the Food and Agricultural Organization of the United Nations (FAO 1998). As the FAO soil map was coarse scale (1 km), the soil map for the study area was modified using field observation and secondary soil texture data (Raya development study 2007 unpublished report). The soil texture classification was verified by collecting representative soil samples that were analyzed in the soil laboratory of Mekelle University. Soil type classes of FAO were translated into soil texture classes, using the percentage of the topsoil textures (coarse, medium and fine) from the universal soil texture triangle. According to the soil map the Raya basin (Fig. 4b), clay loam and sandy clay together covers (9%), sandy loam (8%), silty loam (51%), sandy clay (30%) and silty clay (2%).

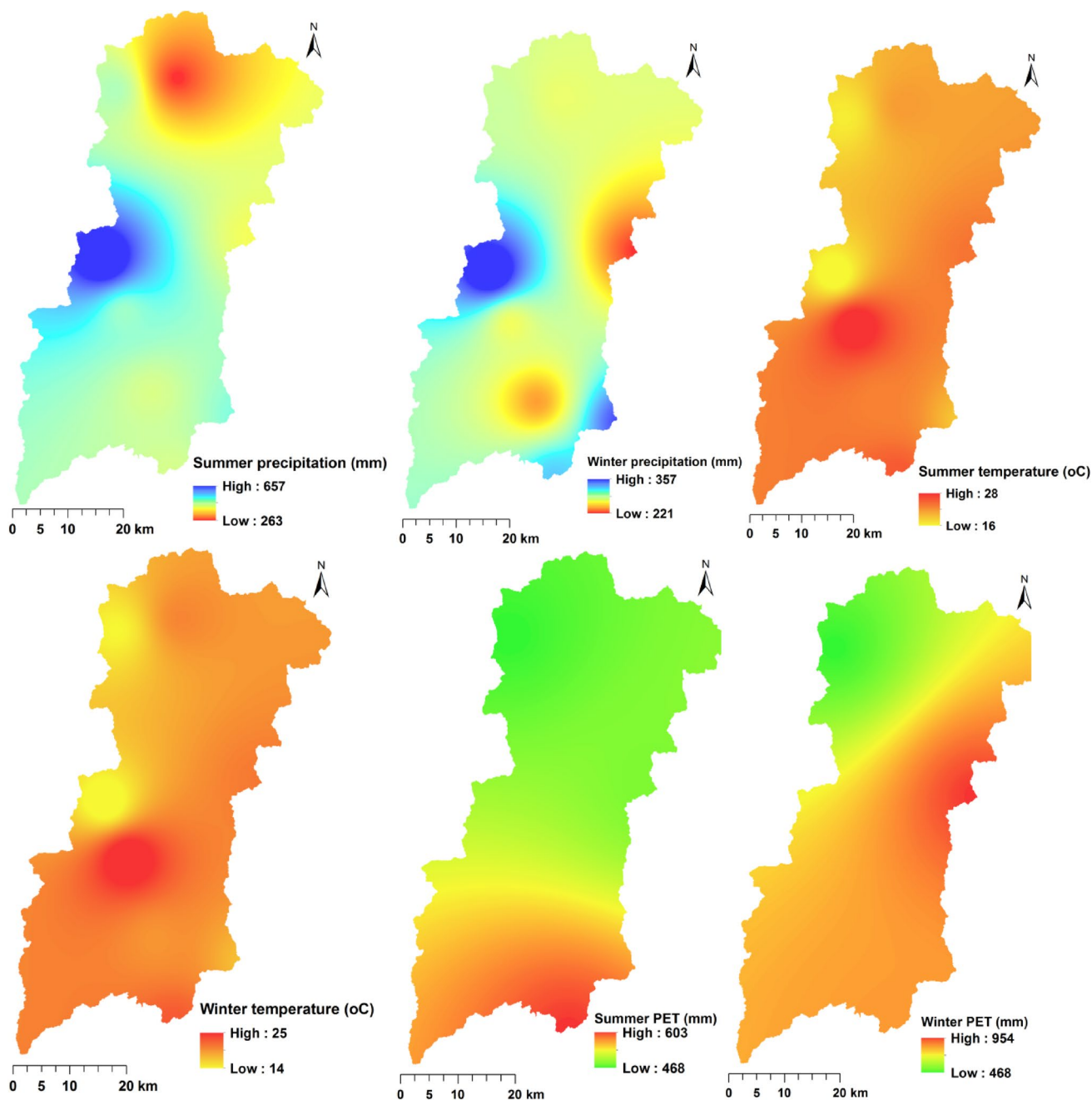


Fig. 3 WetSpass’s input grid maps of major meteorological parameters in Raya valley

Groundwater depth

Groundwater depth data was produced from the elevation of static water level measurements in boreholes and springs. Overall 313 static water level measurements which were mostly concentrated in the valley area were used for interpolation to produce the groundwater depth grid map (Fig. 4c).

Topography and slope

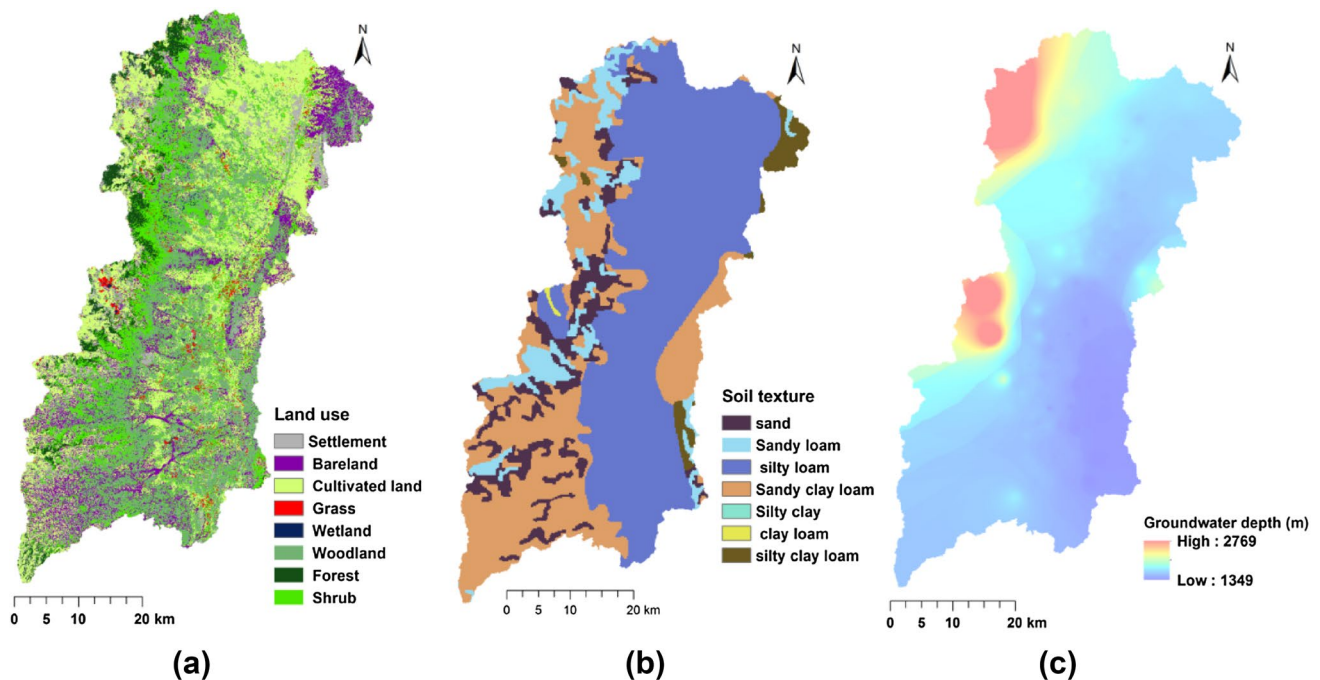
Based on the 90 m resolution of the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), the topography and slope grid maps of the study area were derived using ArcGIS (Fig. 5a, b).

Table 1 Image classification confusion matrix

Predicted classes	Actual classes									
	Grass-land	Wet-Land	Water	Forest	Shrub-land	Settlement	Agriculture	Wood-land	Bare-land	Total
Grassland	11	1	0	0	0	0	0	0	0	12
Wetland	0	6	0	0	0	0	0	0	0	6
Water	0	0	6	0	0	0	0	0	0	6
Forest	0	0	0	5	1	0	0	0	0	6
Shrub land	0	0	0	0	10	0	3	0	0	13
Settlement	0	0	0	0	0	9	0	0	2	11
Agriculture	0	0	0	1	3	0	14	0	0	18
Woodland	0	0	0	0	0	0	2	7	0	9
Bareland	0	0	0	1	0	0	0	0	9	10
Total	11	7	6	7	14	9	19	7	11	77

Overall accuracy = 84.6%

The highlighted elements in the main diagonal of the matrix represent the cases where the class levels in the image classification and ground data set agree, whereas the off-diagonal elements contain those cases where there is disagreement in the labels

**Fig. 4** Land-use/land cover (a), soil texture (b) and groundwater depth of Raya basin

Adaptation of WetSpss to the case of Raya Valley (WetSpss-Raya)

WetSpss is originally developed for conditions in the temperate regions in general and Europe in particular (Batelaan and De Smedt 2001, 2007). Later the model was applied all over the world under different conditions by modifying its parameters (Aish et al. 2010; Arefaine et al. 2012; Pandian et al. 2014; Armanuos et al. 2016). The modified WetSpss model was applied in semi arid region of Ethiopia to

simulate the hydrological water balance of the Geba basin (Gebreyohannes et al. 2013) and long-term average recharge in Dire Dawa, (Tilahun and Merkel 2009).

The land-use classes and textural composition and classification of soils for tropical countries like Ethiopia are apparently different than the case in the temperate regions. Even though some similar land-use classes literally exist in both temperate and tropical regions, they are not the same in characteristics. Furthermore, summer and winter seasons of temperate regions are not the same as those of the tropical

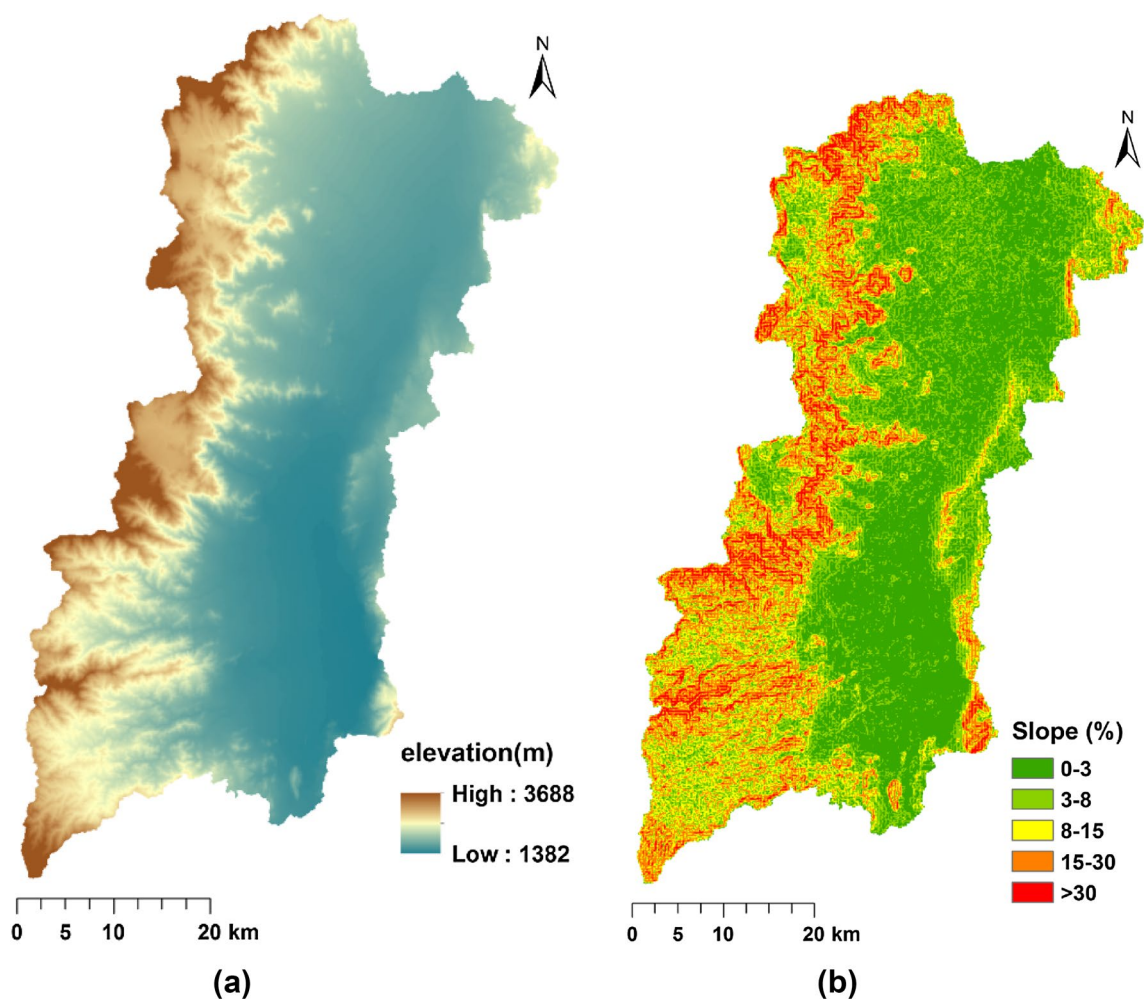


Fig. 5 Elevation (a), slope (b) map of study area

regions. Taking the case of Ethiopia, winter is the dry season while summer is the main rainy season. Hence, before doing any watershed simulation modification of the model is required so as to adopt it for the Ethiopian condition.

Thus, a modified WetSpass model, named as “WetSpass Raya” was developed, where the land-use parameter tables (summer and winter seasons) for Raya basin were modified and adjusted to represent the condition of Raya basin using expert knowledge and scientific literatures. Land-use (summer and winter), soil and runoff coefficient are the parameter tables used by WetSpass. The land-use attribute table includes parameters such as land-use type, rooting depth, leaf area index, and vegetation height. The soil parameter table contains soil parameters such as textural soil class, plant available water contents and others. Whereas, the runoff coefficient attribute table contains parameters for runoff classes of various land-uses, slope, runoff coefficient etc. Necessary modification was done on the land-use parameters mainly for the leaf area index, crop height, interception

percentage, to fit the condition of Raya valley. Moreover, the vegetative area, bare area, impervious area, and open water area proportions of each land-use class in Raya basin have been modified (Tables 2, 3).

The year was divided into two seasons’ summer (from June to September) and winter (from October to May) with their respective input data (land-use, precipitation, potential evapotranspiration, temperature, and wind speed and groundwater depth).

Analysis and grid maps combination

WetSpass gives various hydrologic outputs on a yearly and seasonal (summer and winter) basis (Batelaan and De Smedt 2001). The results from the WetSpass model can be analyzed in various ways (Al Kuisi and El-Naqa 2013). The spatial variations of recharge and runoff can be obtained as a function of land-use and soil type. As all output from the model are grid maps and not tabular values, it would be

Table 2 Summer land-use parameter table modified for the Raya basin

Number	Luse_type	Runoff_veg	Num_veg_ro	Num_imp_ro	Veg_area	Bare_area	Imp_area	Openw_area	Root_depth	Lai	Min_stom	Interc_per	Veg_height
2	Settl	Grass	2	2	0.5	0.2	0.3	0.0	0.3	0.20	100.0	10.0	0.12
7	Bare	Bare soil	4	0	0.0	0.7	0.3	0.0	0.05	0.00	110.0	0.0	0.001
21	Agri	Crop	1	0	0.8	0.1	0.1	0.0	0.4	0.20	180.0	35.0	0.7
23	Grass	Grass	2	0	1.0	0.0	0.0	0.0	0.3	2.00	100.0	10.0	0.2
28	Wetl	Grass	2	0	1.0	0.0	0.0	0.0	0.3	2.00	100.0	10.0	0.3
31	Wood	Forest	3	0	0.8	0.0	0.2	0.0	2.0	5.00	250.0	25.0	15.0
33	Forest	Forest	3	0	0.80	0.0	0.20	0.0	2.50	3.50	310.0	50.0	10.00
36	Shrub	Grass	2	0	0.80	0.0	0.2	0.0	0.6	6.00	110.0	42.0	2.50

Table 3 Winter land-use parameter table modified for the Raya basin

Number	Luse_type	Runoff_veg	Num_veg_ro	Num_imp_ro	Veg_area	Bare_area	Imp_area	Openw_area	Root_depth	Lai	Min_stom	Interc_per	Veg_height
2	Settl	Grass	2	2	0.4	0.50	0.10	0.0	0.3	0.2	100.0	10.0	0.12
7	Barel	Bare soil	4	0	0.00	0.70	0.3	0.0	0.05	0.0	110.0	0.0	0.001
21	Agri	Crop	1	0	0.20	0.40	0.4	0.0	0.35	2.0	180.0	22.0	0.6
23	Grass	Grass	2	0	0.60	0.30	0.10	0.0	0.30	1.0	140.0	10.0	0.12
28	Wetl	Grass	2	0	0.60	0.30	0.10	0.0	0.30	1.0	140.0	10.0	0.2
31	Wood	Forest	3	0	0.20	0.80	0.0	0.0	2.00	4.0	250.0	10.0	15.0
33	Forest	Forest	3	0	0.80	0.10	0.10	0.0	2.00	4.0	340.0	42.0	10.0
36	Shrub	Grass	2	0	0.65	0.30	0.05	0.0	0.60	3.0	110.0	30.0	2.0

Luse_type land-use type, *Runoff_veg* runoff class for vegetation type, *Num_imp_ro* impervious runoff class for impervious area types, *Veg_area* vegetated area, *Bare_area* bare area, *Imp_area* impervious area, *Openw_area* open-water area, *Root_depth* Root Depth, *Lai* Leaf Area Index, *Min_stom* minimum stomatal opening, *Interc_per* interception percentage, *Veg_height* vegetation height

helpful to combine two or more grid maps. The Arc GIS function called ‘combine’ is used to combine different grids to produce database files for further analysis and graphical presentations. Accordingly, the land-use and soil maps were combined with surface runoff, recharge and evapotranspiration maps to visualize the impact of different land covers and soil texture on evapotranspiration surface runoff and groundwater recharge.

Result and discussion

The results of the WetSpss model were comprised of digital images of the spatial distribution of annual and seasonal average values of actual evapotranspiration, surface runoff and groundwater recharge for the 17 year period from 2000 to 2016. These maps are raster format in which every pixel represents the magnitude of the respective component of the water balance.

Actual evapotranspiration

The annual summer and winter actual evapotranspiration maps are presented in Fig. 6a–c, respectively. The WetSpss simulated mean annual evapotranspiration of the basin was 598 mm constituting about 84% of the annual average precipitation of the area. This indicated that evapotranspiration was the main process of water loss in the basin mainly due to

the high rate of radiation and existence of strong dry winds. The higher evapotranspiration took place during the summer season (58%) while the remaining 42% took place during the winter season. The actual evapotranspiration during the summer season was only 6% higher than the simulated actual evapotranspiration that took place during the winter period which indicates the bimodal nature of the precipitation in the study area. The annual evapotranspiration map (Fig. 6a) showed high annual rate at the central west part of the study area which is attributed to the higher precipitation and dense forest cover. Similarly, high evapotranspiration was observed in areas that received higher precipitation which is the case in Geba basin (Gebreyohannes et al. 2013).

The mean annual evapotranspiration was combined with different land-use and soil classes to analyze spatial variations of the evapotranspiration as a function of land-use and soil types. High evapotranspiration was observed in the forest, grassland or wetland, and woodland with clay loam soil texture that could be due to water availability in soil texture and high transpiration from the vegetation (Table 4).

Surface runoff

The annual, summer and winter surface runoff of the Raya basin varied spatially with topography and other catchment characteristics (Fig. 7a–c). The simulated annual surface runoff in the Raya basin ranges from one mm to a maximum of 331 mm with a mean of 57 mm. The mean value

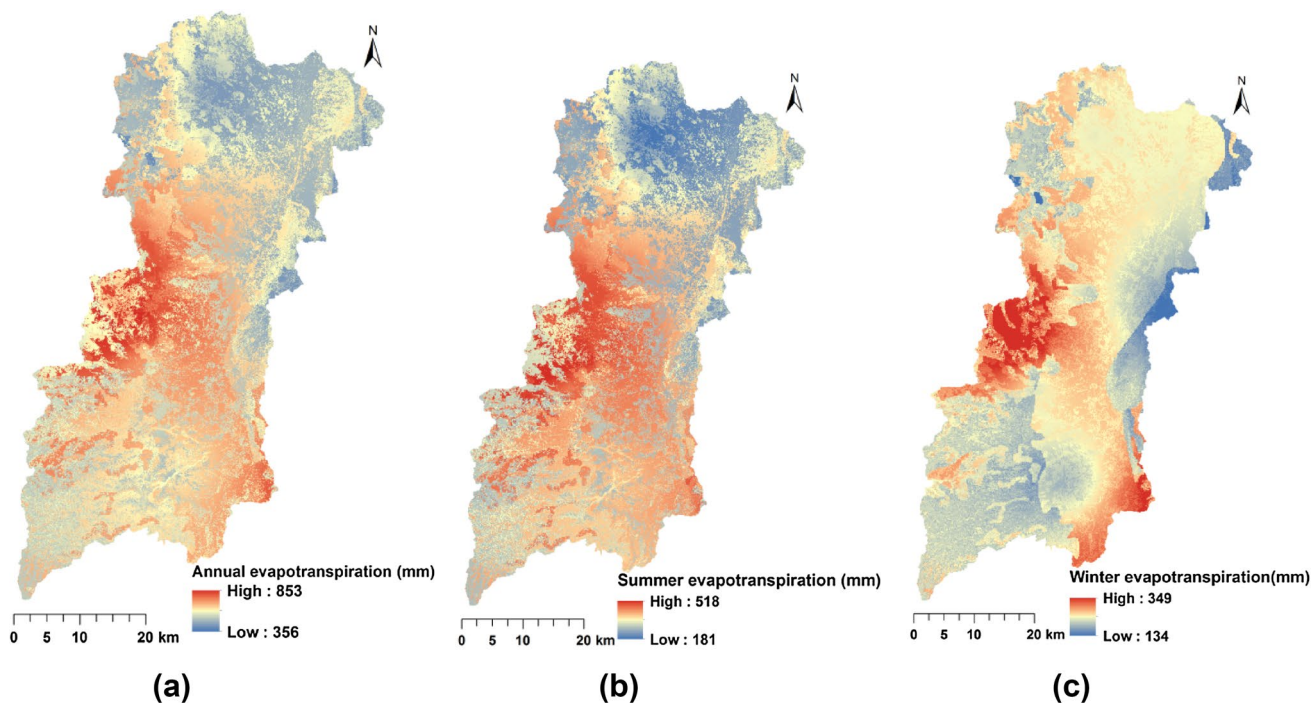
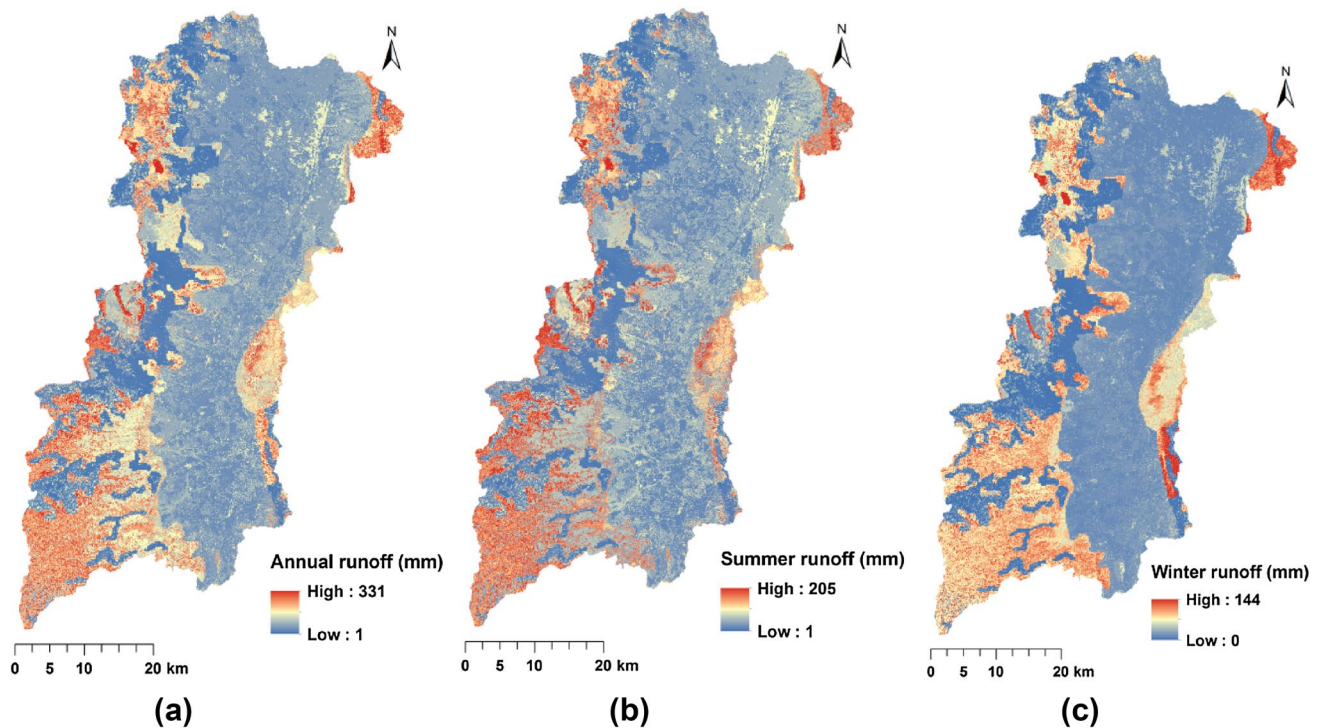


Fig. 6 Spatial maps of simulated evapotranspiration: annual (a) summer (b) and winter (c)

Table 4 Simulated mean annual evapotranspiration for combinations of land-use and soil texture

	Settlement	Bare land	Agriculture	Grass land	Wet land	Wood land	Forest	Scrub land	Mean	Sd.dev.
Sand	608	610	576	665	688	678	717	686	654	49
Sandyloam	619	637	594	689	708	681	671	700	662	41
Siltyloam	569	593	543	645	674	632	618	607	610	42
Sandyclayloam	568	572	539	601	641	611	654	616	600	39
<i>Silty clay loam</i>	505	507	518	575	584	559	–	541	541	32
<i>Clay loam</i>	634	644	641	736	653	681	710	690	674	37
<i>Silty clay</i>	451	441	431	413	–	424	514	473	450	35
Mean	565	572	549	618	658	609	648	616		
Std. dev	66	74	66	105	43	94	75	85		

**Fig. 7** Spatial simulated surface runoff: annual (a) summer (b) winter (c)

represented about 8% of the total mean annual precipitation of the area (about 142 million cubic meters for the whole basin). About 70% of the runoff occurred during the summer season while the remaining 30% occurred during the winter season. High annual and seasonal surface runoff rate was observed in the western and southwestern mountainous parts of the area attributed to high rainfall and steep slope topography.

The highest mean annual surface runoff occurred on silty clay soils with settlement, bare land and grassland, while the lowest runoff occurred in sand and sandy loam soils with woodland, forest and Shrub land (Table 5). The standard deviation of the runoff for the different soil types was higher

than the standard deviation of the runoff for the different land-use classes and this indicated that surface runoff was more influenced by soil type than by land-use. The influence of the precipitation was also noticeable by the fact that areas around Korem and Maychew high lands, that have higher precipitation, had higher runoff than the valley floors.

Groundwater recharge

The amount of infiltration to the groundwater depends on the vegetation cover, slope, and soil composition, depth to the water table, and the presence or absence of confining beds (Al Kuisi and El-Naqa 2013). Natural vegetation cover,

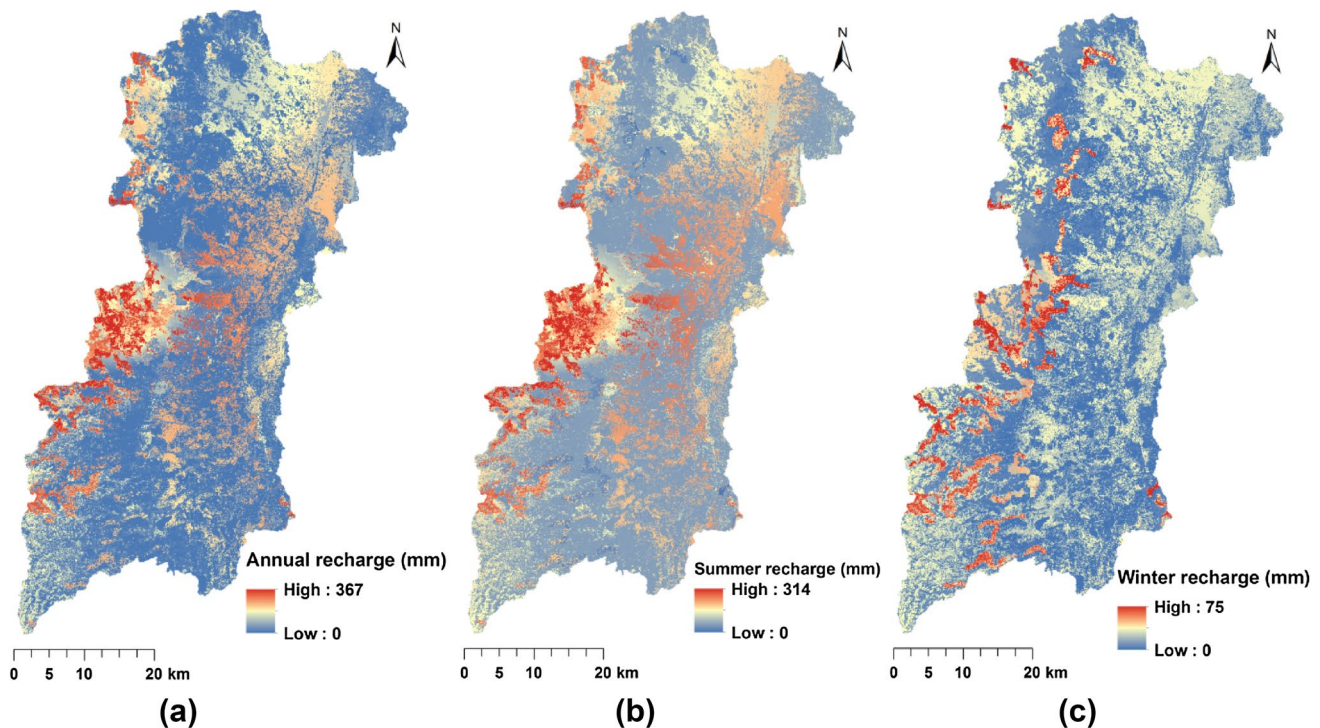
Table 5 Mean annual surface runoff for different combinations of land-use and soil texture

	Settlement	Bare land	Agriculture	Grass land	Wet land	Wood land	Forest	Shrub land	Mean	Sd. dev.
Sand	38	28	31	27	13	16	17	18	23	9
Sandy loam	34	26	30	23	13	16	14	16	21	8
Silty loam	52	41	36	35	35	32	31	33	37	7
Sandyclayloam	120	114	116	92	87	95	78	94	100	15
Silty clay loam	147	134	129	116	132	124	–	127	130	9
Clay loam	208	195	191	177	215	198	173	185	193	14
Silty clay	223	225	216	236	–	239	181	212	219	19
Mean	117	109	107	101	82	103	82	98		
Std. dev	74	75	72	76	73	83	70	75		

flat topography, permeable soils, a deep water table and the absence of confining beds favors recharge. The WetSpss model simulated the long-term average spatially distributed groundwater recharge depending on soil texture, land-use, slope and meteorological conditions.

The annual summer and winter WetSpss simulated recharge to the Raya groundwater basin is presented in Fig. 8a–c respectively. The simulated annual groundwater recharge for the existing land-use ranged from 0 to 367 mm, with an average value of 55 mm and represented only 8% of the mean annual precipitation. About 84% of the annual groundwater recharge of the basin occurred during the wet summer season, while the remaining 16%

took place during the dry winter season. The mean annual spatial groundwater recharge is highly variable depending on the factors that govern groundwater infiltration (Fig. 8a). The western highlands of the Raya basin had high annual groundwater recharge due to the presence of permeable soils, high precipitation and vegetation cover. The western foothill side areas were also characterized by high groundwater recharge occurrence mainly due to the flat topography and coarse permeable soils. On the contrary, the lowlands and central southeastern of the area had low groundwater recharge due to their being discharge areas and the dominance of less permeable fine-textured soils.

**Fig. 8** Spatial maps of simulated recharge: mean annual (a) summer (b) and winter (c)

Considering the entire Raya basin (about 2500 km²), the simulated mean annual recharge accounted for about 137 million cubic meters. The highest groundwater recharge was observed in agricultural lands and sandy-textured soil class (Table 6). This is basically because of the high permeability of sandy soils, less runoff on the relatively gentler slopes of agricultural lands. On the other hand, lowest recharge was observed in wetland with silty and sand clay loam soils and this can be attributed to the shallow nature of groundwater table and the less permeability of the soils, respectively.

Model verification

The estimated recharge of the WetSpas methodology was verified by comparing it with that of the Chloride Mass Balance (CMB) method for similar hydro-meteorological conditions. For the recharge estimate using the Chloride Mass Balance method, 156 representative groundwater samples and 20 rainfall samples were used. The estimated annual average groundwater recharge using the Chloride Mass Balance method was 60 mm with the consideration of an average chloride content of 1.9 mg/l in the rainfall, 22.4 mg/l harmonic mean of chloride content in the groundwater and 710 mm mean annual rainfall. This indicated that the simulated mean annual recharge of 55 mm estimated applying the WetSpas model is comparable and is in good agreement with the chloride mass balance method. The WetSpas simulated recharge was also compared to earlier recharge estimates done in the Raya basin. Hussein (2011 unpublished PhD thesis) estimated recharge as 9% of the mean annual precipitation applying Thornthwaite method and the result was comparable to the WetSpas simulated recharge (which was about 8% of the mean annual precipitation). Nadew (2003) estimated the total amount of water entering into the groundwater system of the Raya basin as 129 million cubic meters by applying the traditional water balance method. Whereas, the WetSpas model simulated recharge in the current

study was 137 million cubic meters, which is within a comparative range to the findings of Nadew (2003). These results demonstrated that the estimation of groundwater recharge using WetSpas is in good agreement with those obtained by other studies confirming the validity of the modified WetSpas model, and we believe that the method used in this study has the potential to provide useful results for the region.

Water balance components

The overall water balance analysis of the Raya basin (Table 7) indicated that only a small fraction of the annual precipitation remains to recharge the groundwater reservoir of the basin. While the rest leaves the basin mainly through evapotranspiration and to a lesser extent via surface runoff. The higher standard deviation value revealed in the water balance component is indicating high spatial variation of the water balance element within the basin. This is mainly in response to the uneven distributions of the climatic parameters associated with variations of Land-use/land cover, soil type, topography and slope.

Table 7 Summary of annual water balance components in the Raya basin

Water balance components	Annual values (mm/year)			
	Min	Max	Mean	Std.dev.
Precipitation (PCP)	531	1016	710	82
Evapotranspiration (ET)	356	853	598	97
Runoff (Ro)	1	331	57	48
Recharge (Re)	0	367	55	66
Water balance	PCP-ET-Ro-Re = 0.0			

Table 6 Simulated mean annual recharge (mm) for the combinations of land-use and soil texture

	Settlement	Bare land	Agriculture	Grass land	Wet land	Wood land	Forest	Scrubland	Mean	Sd. dev.
Sand	133	110	184	128	59	63	94	67	105	43
Sandy loam	82	72	143	62	31	30	33	31	61	39
Silty loam	60	40	85	53	33	32	39	43	48	18
Sandy clay loam	48	36	80	38	9	16	30	22	35	22
Silty clay loam	26	22	41	35	9	15	–	21	24	11
Clay loam	130	134	142	71	121	106	92	96	111	24
Silty clay	31	37	57	51	–	40	15	20	36	15
Mean	73	64	105	63	44	43	51	43		
Std. dev	41	40	49	29	38	30	31	27		

Conclusion

In the present study, modified WetSpa model was applied for estimating spatially distributed, long-term average recharge for the Raya basin. WetSpa model showed that the mean annual recharge in the basin was 55 mm and was estimated to represent about 8% of the mean annual precipitation % (about 137 million m³/year for the Raya basin). About 84% of the recharge took place during the summer season, while the remaining 16% occurred during the dry winter season. High groundwater recharge was simulated in agricultural land and sandy-textured soil class. The high groundwater recharge could be attributed to the high permeability of sandy soils and less runoff on the agricultural lands that are of relatively gentler slopes. The lowest recharge was observed in wetland with silty and sand clay loam soil textures. This could be as a result of being discharge area of the wetland and less permeability of the silty and sand clay loam soil textures. The simulated recharge map reflected the already perceived knowledge and is in good agreement with those of previous studies. Thus it can be concluded that WetSpa is good enough to simulate groundwater recharge of the Raya basin and is especially suitable for studying the effect of land-use changes on the water regime in the basin.

WetSpa simulated mean annual evapotranspiration of the basin was 598 mm which constituted about 84% of the annual average precipitation of the area. This showed that Evapotranspiration is the main process of water loss in the basin resulting mainly from the prevailing high rate of radiation and the persistence of strong dry wind. The overall water balance analysis of the Raya basin indicated that only a small fraction of the annual precipitation remains to recharge the groundwater reservoirs, while the rest leaves the basin mainly through evapotranspiration and surface runoff.

Acknowledgements The authors would like to thank Mekelle University, Technical University of Darmstadt and World Agroforestry Centre (ICRAF) for providing the necessary support and funding to conduct the study. We are grateful to the three anonymous referees for constructive comments on an earlier version of this manuscript.

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