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Spatial and temporal simulation of groundwater recharge and cross-validation with point estimations in volcanic aquifers with variable topography

Alemu Yenehun [a,b,*], Mekete Dessie [c], Fenta Nigate [a], Ashebir Sewale Belay [a,b], Mulugeta Azeze [c], Marc Van Camp [b], Derbew Fenetie Taye [f], Desale Kidane [e,f], Enyew Adgo [f], Jan Nyssen [g], Ann Van Griensven [d], Kristine Walraevens [b]

[a] *School of Earth Sciences, Bahir Dar University, Bahir Dar, Ethiopia*
[b] *Laboratory for Applied Geology and Hydrogeology, Department of Geology, Ghent University, Ghent, Belgium*
[c] *Faculty of Civil and Water Resources Engineering, Bahir Dar University, Bahir Dar, Ethiopia*
[d] *Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Brussel, Belgium*
[e] *Department of Soil Physics, Ghent University, Belgium*
[f] *Department of Natural Resources, Bahir Dar University, Ethiopia*
[g] *Department of Geography, Ghent University, Belgium*

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ABSTRACT

Study region: This study is performed for the volcanic aquifers of semi-humid Lake Tana basin in northwest Ethiopia, the source region of Blue Nile basin.
Study focus: estimating groundwater recharge at required spatial and temporal scale is a challenge in groundwater management, sustainability and pollution studies. In this study, the physically-based WetSpass model is applied. The recharge by WetSpass is validated with estimations by water table fluctuation (WTF) and chloride mass balance (CMB) methods. Evaluating the groundwater recharge estimation mechanism for the volcanic aquifers lying at different topographical setting, that represents wide part of the world groundwater aquifers, and suggesting more appropriate methods will benefit different similar studies.
New hydrological insights for the region: the mean annual rainfall, recharge, surface runoff, and evapotranspiration are estimated at 1431 mm, 315 mm, 416 mm, and 770 mm, respectively. The recharge varies from 0% to 57% of the rainfall. A high variation is also noted using WTF and CMB methods showing the strong heterogeneous nature of the hydro(meteoro)logical characteristics of the area. WetSpass is effective in aquifers where diffuse recharging mechanism is the predominant type and recharge is controlled by rainfall. Hence, it is found less effective in the storage-controlled flat floodplain, alluvial and fractured rock aquifer areas. In these areas, the point estimates by the WTF and CMB are effective and can be considered as reliable values.

1. Introduction

Groundwater recharge is all water that reaches the groundwater aquifer from any direction (Scanlon et al., 2002). In specific terms,

* Corresponding author at: School of Earth Sciences, Bahir Dar University, Bahir Dar, Ethiopia.
E-mail address: abrexyene@email.com (A. Yenehun).

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it is defined as the height of the water column that enters the saturated zone after crossing the vadose zone in a specific period (Manna et al., 2016). Understanding recharge processes and its quantification is vital for sustainable management and protection of the groundwater resources (Ferede et al., 2020; Healy and Cook, 2002; Uugulu and Wanke, 2020). However, it is one of the most difficult water budget components to be evaluated with acceptable accuracy (Hornero et al., 2016). This is particularly true in areas with wide heterogeneity of geological, topographical, and hydro-climatic conditions. Thus, groundwater managers should take recharge estimations and their uncertainty into account in the management plans (Hornero et al., 2016). As recharge processes significantly vary from area to area, there is no guarantee that one method effectively apply for one locality gives reasonable results for another (Obuobie et al., 2012). Different methods are developed for recharge estimation. However, choosing appropriate methods is often challenging. Important considerations in choosing a technique include space/time scales, range, and reliability of recharge estimates which in turn depend on the goal of the study (Scanlon et al., 2002). For instance, groundwater resources assessment of an area may be achieved at a small space/time scale but flow and contaminant modeling need quantification of recharge amounts at large spatial as well as temporal scales.

There is a strong groundwater recharge variability across the Ethiopian volcanic rock aquifers (Alemayehu and Kebede, 2011; Ayenew et al., 2008; Demlie et al., 2008, 2007; Kebede et al., 2005). Lake Tana basin, which is one of the major basins in the Ethiopian volcanic plateau, has high hydrogeological and topographical variabilities. Furthermore, the area has a climate with long dry winters and short rainy summer seasons. Hence, the groundwater recharge-discharge processes are expected to vary highly both spatially and temporally. There are a number of recharge estimation methods their effectiveness depend on the recharge mechanism (Healy and Cook, 2002). Hence, understanding and identifying the recharging mechanism of aquifers and the assumptions of different estimations methods is a key to effectively choose among the different techniques (Scanlon et al., 2002; Tilahun et al., 2009). On fractured aquifers where preferential flow dominates, focused recharge is a major recharge mechanism rather than the diffuse recharge. Water balance models estimate better the diffuse recharge (Zhu et al., 2020), while water point measuring-based methods such as water table fluctuation are preferable for focused recharge mechanisms (Scanlon et al., 2002). One of the challenges for the point recharge estimation methods is their incapability to estimate it in a spatially distributed way. Given the high spatial variability of recharge, due to variations in geology, topography, soil texture, land use, and meteorological variables, it is unwise to extrapolate or regionalize the result by the conventional point recharge estimation techniques (Tilahun and Merkel, 2009). In this study, a physically-based water balance model called WetSpass, which simulates recharge in a spatially and temporally distributed manner is applied. Water table fluctuation and chloride mass balance methods have been used to identify the recharge mechanisms, to compare and cross-validate the result by the WetSpass model. These methods have been applied in several studies. The WetSpass model for example in Batelaan and De Smedt (2007) for Dijle, Demer and Nete river catchements in northeast Belgium; Gebreyohannes et al. (2013) for Geba river basin, northern Ethiopia; Graf and Przybyłek (2018) for Obra river basin, Poland; Salem et al. (2019) for Drava Basin, Hungary; Ashaolu (2020) for Osun river basin, Nigeria; Yenehun et al. (2020) for Upper Kliti river basin, northwest Ethiopia. The WTF method have been also applied in several studies, for example, by Sophocleous (1991) for the plain aquifers of central Kansas plains, USA; Healy and Cook (2002) tested for different alluvial and fracture aquifers of the world; Moon et al. (2004) for aquifers of south Korea; Crosbie et al. (2005) for the Tomago sand beds near Newcastle, Australia; Marechal et al. (2006) for a small watershed in Hyderabad, India; Mikunthan and De Silva (2009) for the limeston aquifer of Jaffna district; Nigate et al. (2020) for Infranz catchment, northwest

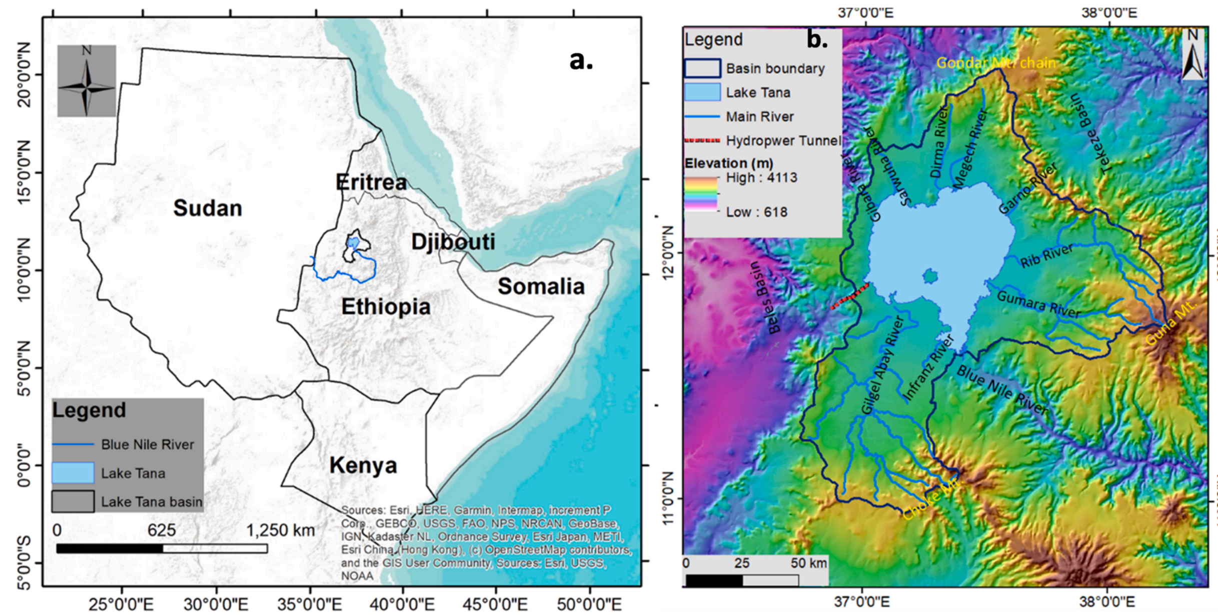

Fig. 1. Location map of Lake Tana basin showing the location of the Lake Tana basin within Ethiopia and its neighbors (a), and topographical setup and main rivers (b). The Beles, the Blue Nile, and the Tekeze basins are the major adjacent basins for Lake Tana Basin.

Ethiopia. Similarly, the CMB method has also been used, for example, by Allison and Hughes (1978) for unconfined aquifer of Gambier plain of Gambier Islands; Allison (1988) for semi-arid areas groundwater aquifers; Guan et al. (2010) in the Mount Lofty Ranges, a coastal hilly area in south Australia; Somaratne and Smettem (2014) for karst aquifers in southern Australia; Uugulu and Wanke (2020) for different rainfall gradients of Tsumeb, Waterberg, and Kuzikus regions of Nambia.

Many hydrological models for different areas (small catchment-scale to large basins) are developed for estimating groundwater recharge. However, evaluation of the methods with point estimations based on direct water level measurement (WTF) and chemical tracer (CMB) may give a good insight for future recharge estimation techniques for similar aquifer types wherever they are located in the world. Evaluating the groundwater recharge estimation mechanism for the volcanic aquifer lying at different topographical setting, that represents vast major part of the world groundwater aquifers, and able to suggest more appropriate methods will benefit different similar studies. This study can be seen as a dual purpose: evaluating the physical based hydrological model (and so other similar models), and giving spatial recharge rate map for the important basin. In general, the specific objectives of this study are: (1) to determine groundwater recharge of the Lake Tana basin in a spatially distributed way; (2) to identify controlling factors for the spatial variability of the recharge in the basin; (3) to compare and evaluate the recharge estimation methods; (4) to evaluate the effect of land use change over the hydrology of Lake Tana basin, and (5) to determine the spatial and seasonal variation of runoff and evapotranspiration in the basin.

2. Study area location, geology, and hydrogeology

The Lake Tana Basin (Fig. 1) consists of the Lake Tana water body which is the largest natural lake in Ethiopia. It is the source and

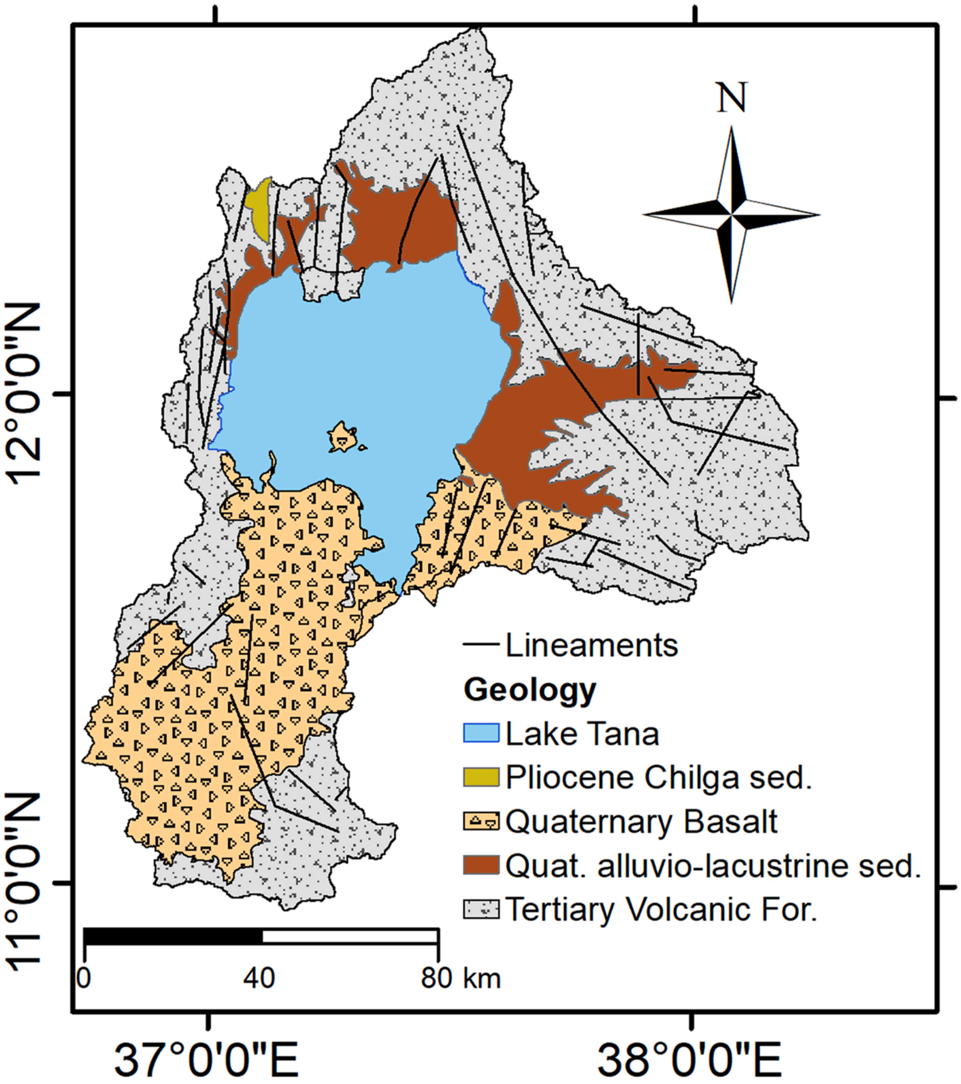

Fig. 2. Geological map of Lake Tana basin modified after Nigate (2019).

head of the upper Blue Nile Basin which is the major tributary to the Nile Basin. The Nile Basin is shared by eleven riparian countries and is the lifeline for more than 238 million people living in the basin (Dile et al., 2018). Lake Tana Basin has a total drainage area of approximately 15,077 km^2, of which the lake covers about 3077 km^2. It is a shallow lake, which is situated in the northwestern Ethiopian highlands and receives flow from more than 40 rivers (Dessie et al., 2015, 2014; Rientjes et al., 2011; Wale et al., 2009).

The Lake Tana basin is perched on a topographic high which is within an overall configuration of an uplifted dome that was active during the Tertiary volcanic events. The Lake Tana basin was formed by the junction of three grabens (Chorowicz et al., 1998). It acquired its present form through damming by Quaternary lava flow aged to 10,000 years on its southern part (Jepsen and Athearn, 1961). Stratified Tertiary volcanic rock piles in northwestern Ethiopia overlie Mesozoic sedimentary rock stratigraphical sequence (Chorowicz et al., 1998). They have an average thickness of 1–1.5 km (Jepsen and Athearn, 1961; Minucci, 1938), and covers a significant area of the basin (Fig. 2). Quaternary basalt covers most of the southern part of the Tana Basin (Jepsen and Athearn, 1961). Sedimentary deposits such as the Pliocene Chilga sediment and recent alluvio-lacustrine sediments on the extensive floodplains of the northern and eastern catchments are also among major lithological coverages (Fig. 2).

The complex nature of the aquifers, owing mainly to multi-stage volcanism at different volcanic centers, and hence the presence of different volcanic rock types (with complex geometrical setting) in the Ethiopian volcanic plateau, has led to a strong spatial groundwater potential and recharge variability (Alemayehu and Kebede, 2011; Ayenew et al., 2008; Demlie et al., 2008, 2007; Kebede et al., 2005). The groundwater level for aquifers lying at different topography and geology in the highlands of the Lake Tana basin responds differently to the rainfall and has a different recharging mechanism (Yenehun et al., 2020).

3. Data and methods

3.1. WetSpass model

For this study, the WetSpass model written in Python (WetSpass-M) is applied. The WetSpass (an acronym for Water and Energy Transfer in Soil, Plants, and Atmosphere under quasi Steady State) was first developed by Batelaan and De Smedt (2001) and later modified by Batelaan and De Smedt (2007). It is a numerical model to simulate long-term average spatial distributions of hydrological parameters and processes at a basin-scale in quasi-steady state. It means the model is restricted to temporal variations only at the seasonal or monthly time scale. That means years of seasonal or monthly time series data are averaged into single seasons or months. The model subdivides the precipitation into the runoff (to refer only to surface component of the river flow in this paper), evapotranspiration, and groundwater recharge, and estimates long-term seasonal values as distributed spatial maps.

$$P = S + ET + R \tag{1}$$

Where P is precipitation [L], S is runoff [L], ET is evapotranspiration [L], and R is groundwater recharge [L].

$$S = f_1 * P_n \tag{2}$$

Where f_1 is a runoff factor that depends on land use and vegetation characteristics, soil texture, and slope. P_n is the net precipitation reaching the ground surface (total precipitation minus interception by the plant canopy).

$$ET = f_2 * EP \tag{3}$$

Where f_2 is an evapotranspiration factor which depends on land use and vegetation characteristics and soil texture, and EP is the potential evaporation of open water [L].

Groundwater recharge is estimated as the closure term of Eq. (1).

The WetSpass-M model calculates each hydrological term at pixel scale by subdividing each pixel into open water, impervious surface area, bare soil, and vegetated area. Percentage values of these subdivisions of a pixel are assigned for all possible land use classes in the parameter table of the model. However, some percentage values have been modified based on local expert judgment.

In this study, the model is developed at 90 m x 90 m grid resolution. All the nine input parameter grid maps are resampled to the same grid size. The model area is equally meshed and has 1824 columns and 2223 rows. WetSpass has parameter tables as an input besides the grid maps. Some land-use parameter values and the number of rainy days are modified into local contexts based on measured data and our expert knowledge whereas the default values of soil-related parameters have been kept. In the model parameter table, each land use type has given impervious, bare land, vegetation, and open water percentages. In the default parameter table of the WetSpass model, the vegetation area coverage for the bush and shrubland is 100%. This is based on the observation of the land use class type in the temperate zone (the Netherlands and Belgium) (Batelaan and De Smedt, 2001). However, the bush and shrubland land use type in the Ethiopian (tropics) context is different: the vegetation is sometimes sparsely distributed, and is with some bare land component, during the field verification on the land use type, estimation (on sample parcels of land on) using simple areal measurement and visual observation has been made, and came up with about 10% is bare land and the rest 90% is consisting of vegetation. Similar adjustments have been made by Gebreyohannes et al. (2013) during their application of the model for Geba catchment, in northern Ethiopia. Similarly, the sub-afro-alpine vegetation land use type found in our area (consisting of about 0.3% of the total area coverage) is not present in the default land use classes of the WetSpass model. However, we made an equivalent with wet meadow land use type, and following a similar procedure, we modified the land use percentage to 80% vegetation and 20% bare land (it was 100% vegetation for wet meadow land cover type in the model parameter table). Furthermore, the root depth for forest land use is changed

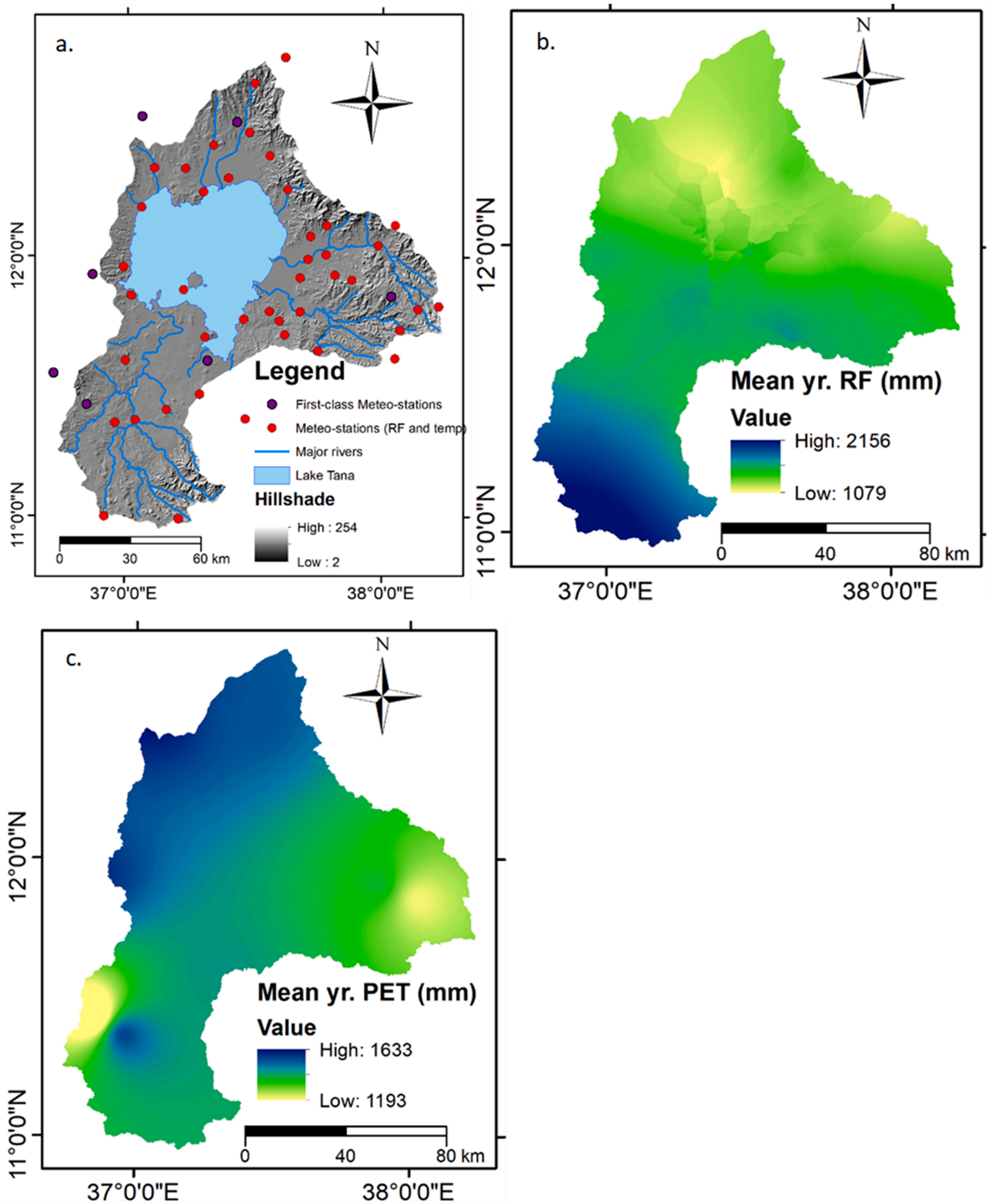

Fig. 3. (a) There are a total of 50 meteorological stations among which eight stations are measuring minimum and maximum temperatures, rainfall, windspeed, relative humidity, and sunshine hours. (b) The mean annual rainfall map is produced by Kriging interpolation using data from the 50 meteorological stations. (c) The long-term mean annual PET map is produced through IDW interpolation from the seven fully fledged meteorological stations. The point PET data were calculated by the Penman-Monteith method.

from 2 m to 5.5 m, because eucalyptus (the dominant forest tree in the area) is deep-rooted. A similar modification was made by Yenehun et al. (2020) for the highland part of the Gilgel Abay catchment.

The developed WetSpass model is calibrated manually by adjusting the global model parameters, such as rainfall intensity, soil moisture alfa coefficient (α), LP coefficient (a calibration parameter for adjusting the potential evapotranspiration depending on the soil moisture), interception parameter (a), and runoff delay factor (x). In the calibration process, the goodness of fit between the simulated and measured runoff for major rivers was being checked and has been used for further model optimization. The WetSpass gives the surface runoff and recharge rates as an output whereas the measured stream flow is the total discharge amount (including both surface runoff and baseflow). Due to this fact, for the calibration, the measured total river flow has been compared with the sum of the simulated surface runoff and groundwater recharge, assuming the baseflow is equal to the recharge. Furthermore, the point recharge values determined by the WTF method and extracted recharge of the WetSpass spatial map are compared, thereby validating the result. For model calibration, the recent land use (land use 2014) (Fig. 4c) has been used. After the model is calibrated to the optimal possible using this land use, the model is run for land uses 1986 and 2000 (Fig. 4a and b). Hence, the effect of land use change on the seasonal water balance terms has been evaluated.

3.1.1. Data for WetSpass model

Meteorological data consisting of rainfall, temperature (minimum, maximum, average), relative humidity, sunshine hours, and wind speed, and GIS spatial maps including land use, soil texture, elevation, slope angle, and groundwater level have been used for the WetSpass model. The meteorological data were collected from the Ethiopian National Meteorological Agency (NMA), Bahir Dar branch, and simple meteorological stations (measuring only rainfall and temperature) which are established by the Institutional University Cooperation with Bahir Dar University (IUC-BDU) project, funded by the Flemish Inter-university Council-University Cooperation for Development (VLIR-UOS). The WetSpass model uses the long-term average raster grid maps of rainfall, potential evapotranspiration (PET), mean temperature, and wind speed (Batelaan and De Smedt, 2007, 2001). The WetSpass model calculates the water balance of an area at a relatively coarse time scale (per month to the finest). However, for semi-humid tropical regions where most of the months are dry winter, applying the model at the seasonal time scale is preferable. Hence, preparation of these data for summer and winter is done. The wet summer consists of months from June to September and the dry winter from October to May. Gebreyohannes et al. (2013) worked similarly for their application of the method at the Geba catchment in northern Ethiopia.

The long-term seasonal average point rainfall amount is prepared from 50 meteorological stations distributed mainly from the basin and a few from the surroundings (Fig. 3a). 42 of the stations were from NMA, and the remaining 8 were those established by the IUC-BDU project. The daily data from those 42 stations (from 2012 to 2016) were summed and averaged to mean monthly. However, the data availability limited to take similar period data for all stations. As a matter of fact, for six stations, such as, Arb Gebiya (2014–2016), Aykel (2010–2015), Chimba (2009–2013), Dengel Ber (2012–2013), Enjibara (2005–2014), Sekela (2012–2014), and Shawura (2011–2015), different period data sets have been used. The data from recently established (BDU-IUC sponsored) stations were short-term ones, comprising only two years data (2017 and 2018). The reason why such different period rainfall data used for interpolation is in order to address the high spatial rainfall variation and to have more realistic rainfall raster map (Fig. 3b). Actually there is inter-annual rainfall temporal variations, at some stations (reaching up to 100–150 mm), however, compared to the spatial variations, these temporal variations are smaller, and would not bring significant change with results and conclusions of this research output. The areal rainfall amount maps for both summer and winter are produced through the kriging interpolation since the number of input stations was relatively high and appropriate for this interpolation technique. Mean annual temperature raster maps for both

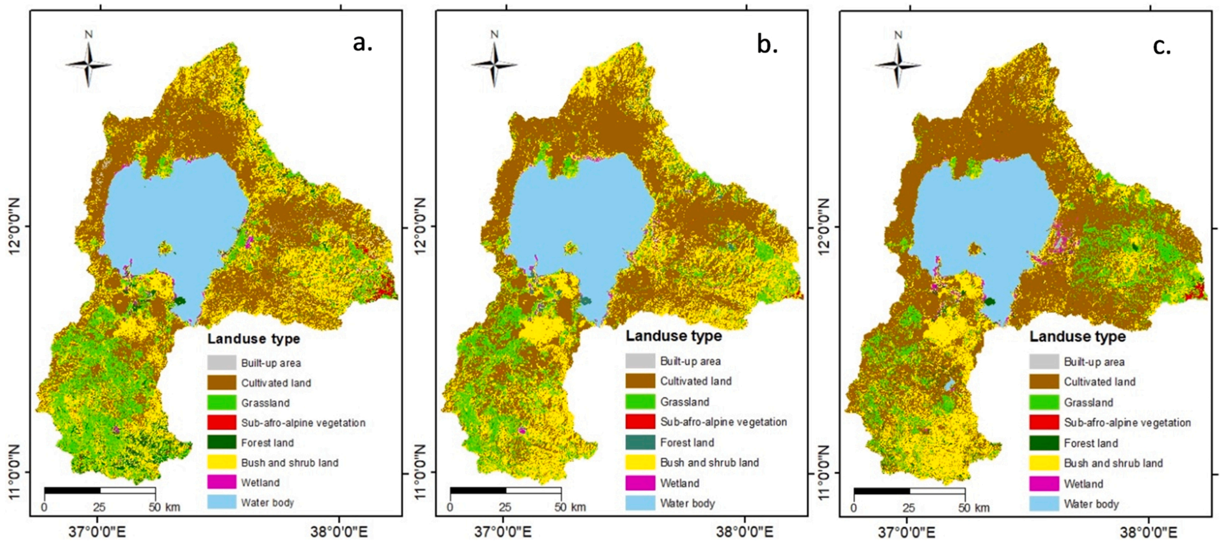

Fig. 4. Land use map of 1986 (a), 2000 (b), and 2014 (c) prepared by the Amhara Design and Supervision Water Works Enterprise.

the summer and winter seasons are prepared from 30 stations using the daily data from 2012 to 2016 except from NMA stations, Arb Gebiya (2014–2016), Aykel (2010–2015), Dengel Ber (2012–2013), Sekela (2012–2014), Shawura (2011–2015); and Rib Bridge piezo (2017–2018), Rib Dam Piezo. (2017–2018) and L.Megech Piezo (2017–2018) from BDU-IUC. Inverse distance weighting (IDW) method has been used as an interpolation technique. Similarly, IDW is applied for windspeed using data from only 7 meteorological stations (Fig. 3a). The temporal variation for temperature and windspeed is small, but the spatial variation is significant which could be due to high elevation variation of the study area.

For the potential evapotranspiration, the Penman-Monteith method, modified by Allen et al. (1998), is applied to calculate point PET values at 7 stations (Fig. 3a). The daily minimum and maximum temperature, windspeed, relative humidity, and sunshine hours from 2012 to 2016 have been used to calculate the daily PET values. However, for two stations: Aykel (2010–2015) and Shawura (2011–2015) have been considered, due to unavailability of complete data for these stations during 2016. These daily values are changed into mean seasonal. For the spatial interpolation, IDW is applied and maps for both summer and winter are produced. The mean annual PET map is presented in Fig. 3c. The groundwater depth grid map is needed in the WetSpass model primarily to calculate evapotranspiration from the groundwater, and for delineation of wetlands, so that water balance calculations include seepage fluxes (Batelaan and De Smedt, 2007; Gebreyohannes et al., 2013). The groundwater level grid maps for both summer and winter seasons are prepared using time series groundwater level data collected for this study. First, an average depth to water table raster map by classifying the area into high, middle and low elevations is prepared using our groundwater monitoring points. Then this raster map consisting of three different depth to water table raster values is subtracted from the DEM of the area to obtain the hydraulic head raster ASCII map which is the input of the WetSpass model. A similar method is followed for both summer and winter. Furthermore, the WetSpass model is calibrated using river flow data measured at different major rivers of the basin. Mean annual river discharge data measured at seven main rivers (Fig. 1b) in the years 2012–2016 have been taken, and used to calibrate and validate the model.

The rainfall has high spatial variation, with minimum and maximum mean annual of 1079 mm and 2156 mm, respectively (with a standard deviation of 216 mm). The rainfall is generally higher in the southern, and lower in the northern parts of the study basin (Fig. 3b). The lower is recorded in the flat floodplain of the northern (Megech) catchment, and highest at the southern highlands (Figs. 1 and 3a, b). There is a poor correlation between rainfall and topographical elevation, similar to what was reported by Dessie et al. (2014). The maximum and minimum potential evapotranspiration are 1633 mm and 1193 mm, respectively, and with a mean of 1478 mm and a standard deviation of 70 mm. The higher values on the northwestern, and lower towards the south and eastern highlands (Fig. 3c). There is no generally a good correlation between elevation and PET values. The relatively few numbers of meteorological stations for PET interpolation is one of the limiting factors in this study.

GIS spatial maps are taken from different sources and adapted according to the model requirement of the WetSpass model. The historical land use maps were prepared by the Amhara Design and Supervision Water Works Enterprise (ADSWE) (ADSWE, 2015a). They had prepared land use maps for the years 1986, 2000, and 2014 using satellite images (SPOT and Landsat) and Google Earth, as well as ground-truthing. Each land use type coverage and change of the classification periods are presented (Table 1). The coding number assigned for land use types in the WetSpass model is given for each class so that the model can read and related with land use parameter table. Code matching between the land use classes and the model parameter tables has been made.

The soil map of the Tana basin used for the modeling is prepared by ADSWE (ADSWE, 2015b). It was prepared through a detailed field survey, sampling, and analysis aided by satellite image information. The soils of the basin were identified and classified based on soil genesis, morphological and surface characteristics according to FAO (1998, 2006) soil map of the world. The results of this soil resource assessment reveal that twelve major agricultural soil types are present in the study area. However, WetSpass needs textural soil classes. Textural classes have been given for most of the 101 mapping units. But for a few of the mapping pixels, the textural class column was found blank in the attribute table of the soil map, and thus we have filled it based on the association of major soil type and common texture in the other mapping units. We have also used our expertize area knowledge in filling these gaps. Finally, codes for each of the seven textural soil classes (Fig. 5a) are assigned, as per in the WetSpass model.

A digital elevation model (DEM) with 20 m resolution is found from the Global Land Cover Facility (http://gdem.ersdac.jspace-systems.or.jp/). After filling the possible holes, resampling to 90 m was done and the final raster map for elevation has been prepared (Fig. 5b). Similarly, the slope angle is extracted in ArcGIS 10.3 from the DEM and resampled to 90 m resolution (Fig. 5c).

Table 1
Classified land use types areal coverage in km^2 and percentage of each cover type to the total area of the Lake Tana basin at different years.

Cover type	Area coverage (in km^2) in the classification years and % of each class					
	1986	%	2000	%	2014	%
Built-up area	148.7	1	42.8	0.3	43.6	0.3
Cultivated land	5530.2	36.7	6151.9	40.8	7383.6	49
Grass land	1822.2	12.1	1575.9	10.5	1434.6	9.5
Sub-afro-alpine vegetation	122	0.8	10.6	0.1	38.2	0.3
Forest land	656.8	4.4	349.2	2.3	271.6	1.8
Bush and shrub land	3640	24.1	3784.7	25.1	2688.1	17.8
Wetland	107.1	0.7	100.2	0.7	118.2	0.8
Water body	3051.2	20.2	3062.9	20.3	3100.4	20.6
Total	15,078	100	15,078	100	15,078.2	100

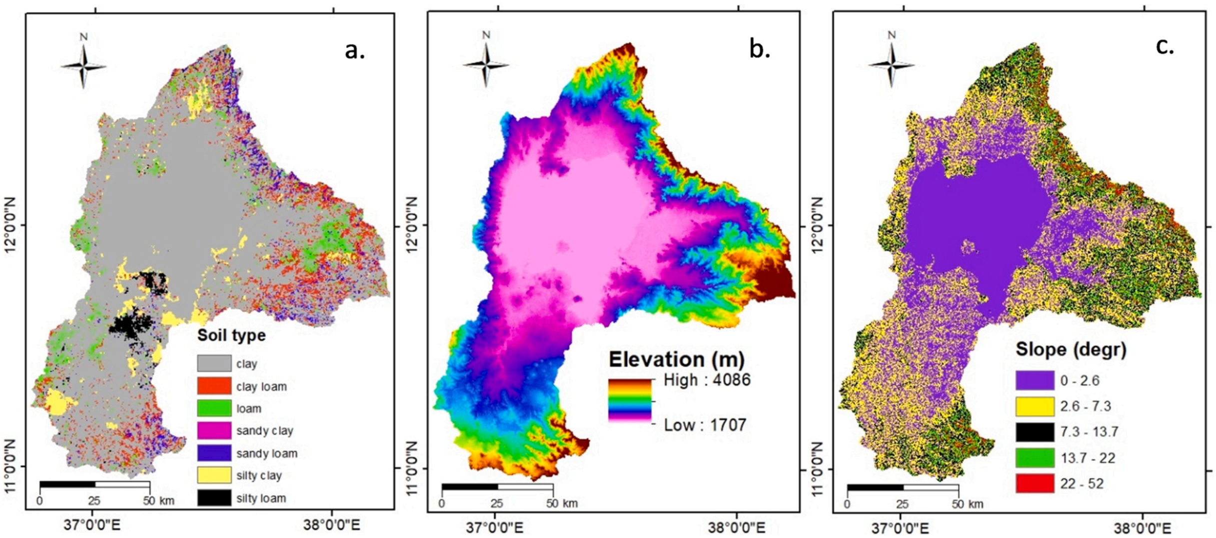

Fig. 5. The soil (a), the elevation (b), and the slope angle (c) spatial maps of the Lake Tana basin with a resolution of 90 m.

3.2. Water table fluctuation (WTF) and Chloride mass balance (CMB) methods

The WTF method is among the most widely used techniques for groundwater estimation of aquifers (Healy and Cook, 2002). The method uses the following formula to calculate recharge:

$$Recharge = Sy\frac{\Delta h}{\Delta t} \tag{4}$$

where Δh is the head change comparing before and after the rainfall season, Sy is the specific yield, and Δt is the time interval for the recharge period.

According to Delin et al. (2007) and Healy and Cook (2002), for the application of the WTF method, the following assumptions should be satisfied: (1) sharp water level rises and declines in response to only groundwater recharge and discharge; (2) the aquifer system needs to be unconfined with shallow water level; (3) the specific yield should be known and constant. Hence, the monitoring well hydrographs are evaluated, and only those which are more or less in line with these assumptions are considered for the point recharge calculation of this study. Similar to the suggestion of Healy and Cook (2002), the graphical method is applied to extrapolate the recession of the pre-recharge water level to the recharge period so that the water level fluctuation is accurately considered. The main source of uncertainty for the application of the method is the possible errors in the estimation of the specific yield (Healy and Cook, 2002; Yenehun et al., 2020). In this study, both literature from Johnson (1967), and an empirical formula developed by Beretta and Stevenazzi (2018) have been applied. Beretta and Stevenazzi (2018) developed a relationship between Sy and hydraulic conductivity (k). Hence, using the formula, Sy values for monitoring wells were determined using the k values analyzed from our single well pumping and slug test results. A test on 31 hand-dug wells were successfully executed, and analyzed.

Similar to WTF, the chloride mass balance (CMB) method is a widely applied technique for estimating recharge (Somaratne and Smettem, 2014). The main concept in the method is that the increase in the concentration of chloride in the groundwater compared to the rainwater is due to evapotranspiration in the vadose zone during infiltrating/percolating (Allison and Hughes, 1978; Allison, 1988; Guan et al., 2010; Somaratne and Smettem, 2014). It means chloride anion is a conservative ion and its concentration increment during its movement in the vadose zone is merely in response to evapotranspiration. Mathematically, groundwater recharge (GWR) is calculated in the following way:

$$GWR = \quad Pe * \frac{Cl_p}{Cl_{gw}} \tag{5}$$

Where GWR is groundwater recharge, Cl_p is chloride concentration in precipitation, Cl_{gw} is chloride concentration in groundwater, Pe is effective precipitation, which is the total precipitation minus runoff amount of the period.

In reference to the similar study done by Gebru and Tesfahunegn (2019) and the hydrogeological nature of this study, the applied CMB method assumes: (1) the only source for chloride concentration for the groundwater in the aquifers is the chloride from the atmosphere (2) there is negligible source of extra chloride from fertilizers and pesticides in the area (3) the possible long-term chloride concentration in the rainfall is not take into account (the short-term concentration is assumed to represent the long-term) (4) chloride ion is assumed geochemically inactive with soil medium (there is neither sinks nor precipitation of the chloride ion) (5) there is no transport of chloride ion with evapotranspiration water (6) there is no storage of chloride in the vadose zone. Furthermore, the method is more effective in estimating diffuse recharge; however, inappropriate when focused recharge components (recharge from discrete

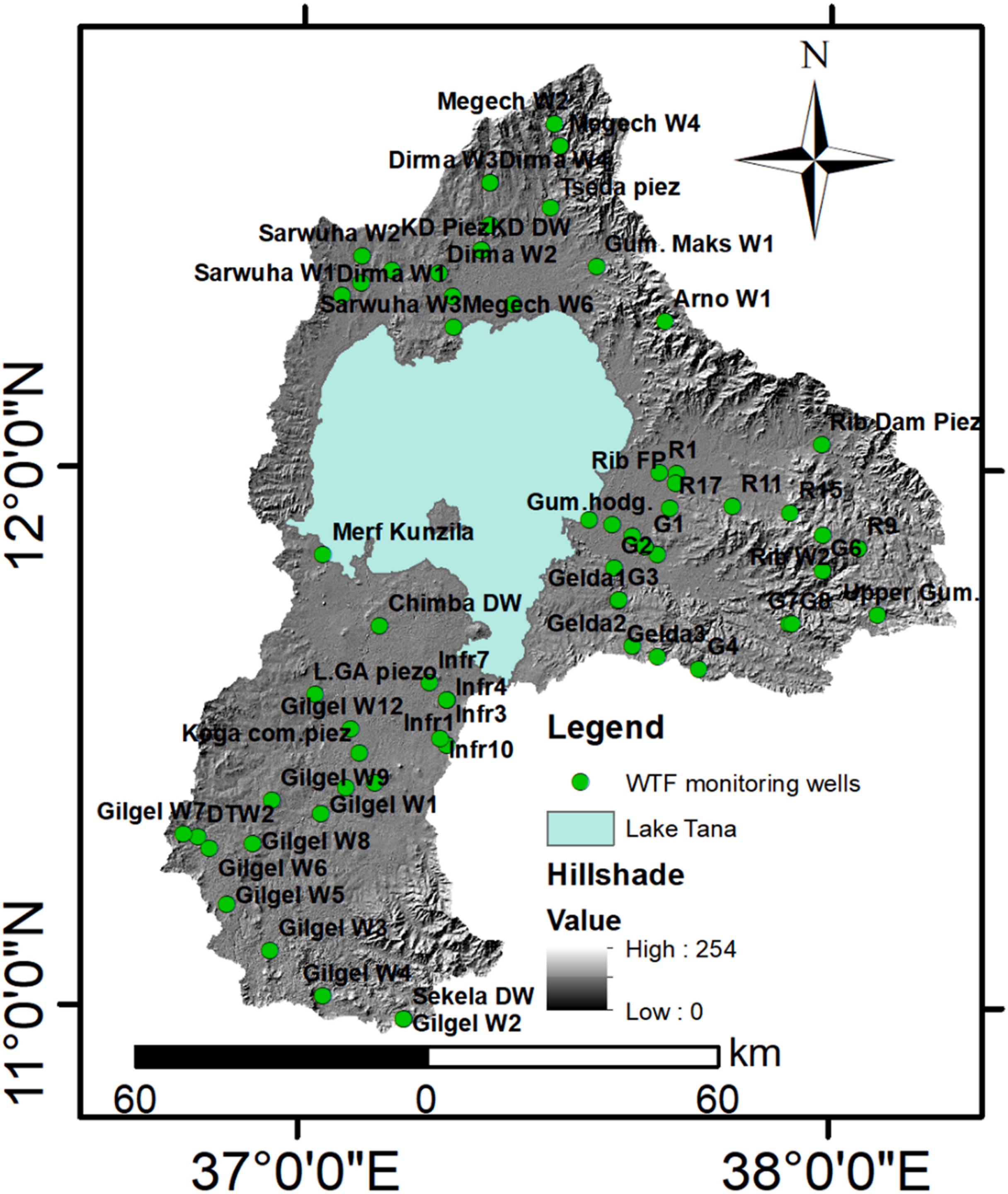

Fig. 6. location of 65 monitoring wells used for WTF estimation. Monitored both manually and automatically by data logger sensor. Fairly distributed depending on topography and geology.

locations) are prevalent in the area (Somaratne and Smettem, 2014). In general, the geological and hydrogeological features of this study area seem to be favorable for diffuse recharge as a dominant recharging mechanism, making the technique appropriate except the additional preferential recharge in fractured basaltic aquifer.

In this study, the recharge calculation using the CMB has been made by subdividing the basin into southern, eastern, northern, and western catchments. Hence, the average chloride concentration in the analyzed groundwater and rainfall sampled in the specific sub-area is considered. These subdivisions are based on similar runoff characteristics and runoff coefficients in the four distinguished catchments (Dessie et al., 2015). The mean annual rainfall within the respective areas, and mean annual runoff coefficient estimated by Dessie et al. (2015) separately for the four sub-areas are considered for the effective precipitation calculation.

3.2.1. Data for WTF and CMB methods

Water level data were being collected from May 2017 to June 2019 using 65 shallow hand-dug and piezometer wells using community-based manual daily measurement and automatic measuring sensors at every half an hour interval. We trained the local people, mostly the well owners, and sometimes their neighbors in cases where the owners are illiterate. Afterward, we supplied them with a measuring meter and a rope tied with a steel rod having a length of about half a meter. Every morning before fetching water, they insert this rope tied with the steel rod into the well until it reaches some depth below the water level, and then immediately get it out and measure the depth from the head of the well to the tip of the moist surface on the metal plate. 52 of the monitoring wells were

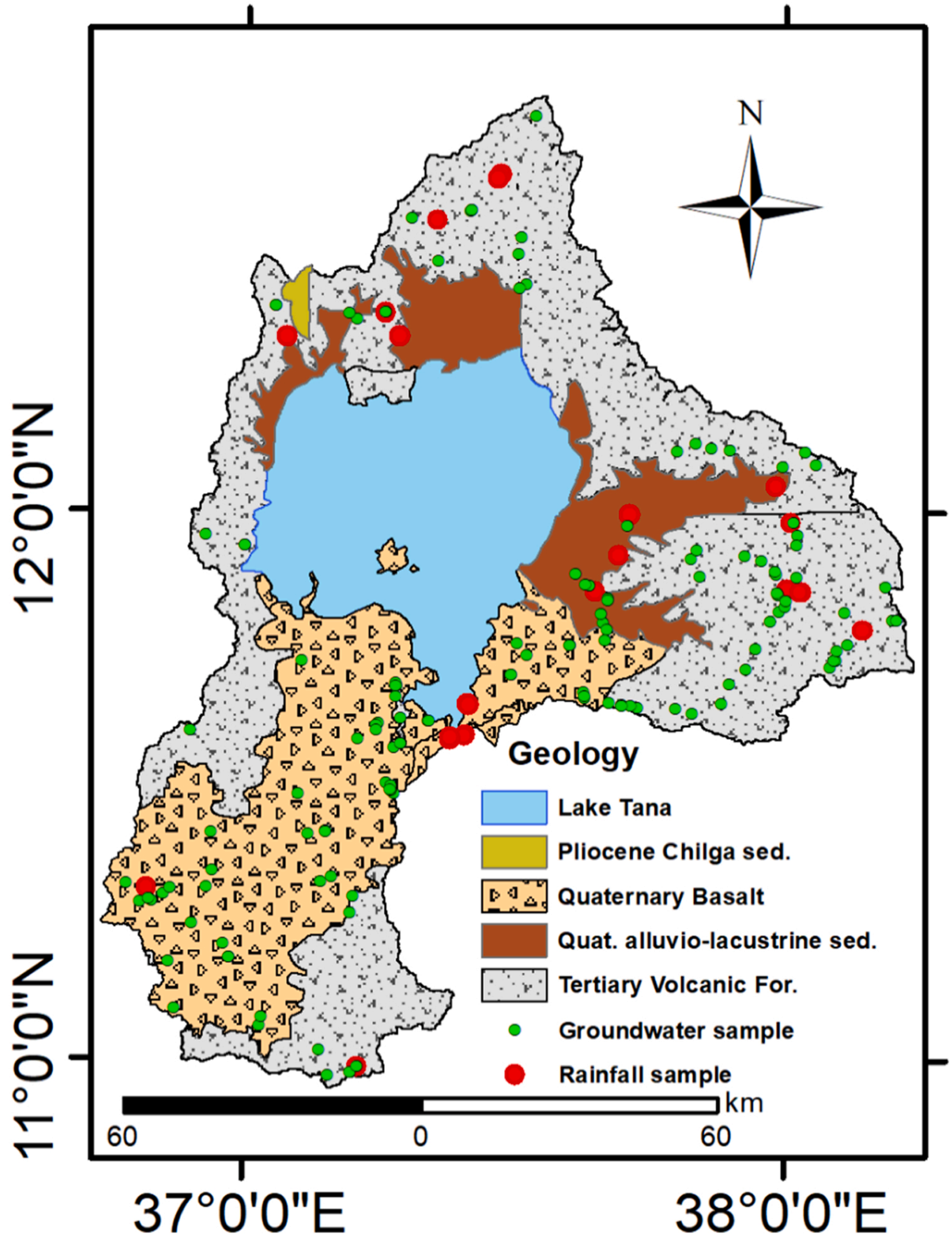

Fig. 7. location of 138 groundwater samples (including groundwater from hand-dug wells and springs) and 25 rainfall sample locations used for the CMB calculation. Some of the rainfall samples were taken at similar places but on different days (2016–2018).

large diameter hand-dug wells and had been measured manually using such simple equipment, whereas the other 13 wells were being monitored using automatic data loggers. These 13 wells were both shallow piezometers and deep wells (9 shallow piezometers and 4 shallow borehole wells). The measuring time interval for the manual readings was daily, and for the automatic logging, it was every half an hour. Some of the hand-dug wells are active water supplying wells where the owners fetch water for domestic and/or backyard irrigation purposes. These monitoring wells are well distributed over the studied basin and representing the various geological and topographical settings. The depth of these shallow wells range from 5 m to 25 m.

The seasonal recharge values calculated for 2017, 2018, and some for 2019, are averaged out. Many rises and declines within the overall recharging season are not considered. Only the seasonal highest rise and extrapolated antecedent decline during the highest rise (using the graphical technique) has been taken into account. As a result, the calculated recharge is the total recharge that joined the groundwater.

The specific yield was values estimated both by using Johnson (1967), and Beretta and Stevenazzi (2018), are highly variable depending on primarily geology and degree of weathering. Hydrogeologically, the shallow monitoring wells are placed on four hydrogeological units: weathered basaltic regolith, pyroclastic rocks, fractured Quaternary basalt (with intermediate weathering grade), and alluvio-lacustrine formations. The Quaternary basalt was found with the highest Sy value (ranging from 0.08 to 0.1), while for the pyroclastic and alluvio-lacustrine deposits, values as low as 0.02 and as high as 0.074 were found. The weathered basaltic regolith has a specific yield ranging from 0.04 to 0.08.

Water sampling for chemical analysis of the groundwater had been undertaken from 2016 to 2019. Water samples for chemical analysis were collected in clean polyethene bottles and the bottles were rinsed three times with the sample water before being filled. The rainwater samples were collected at raised heights (1.6–2 m) above the ground to prevent contamination of samples from ground dust. To prevent sample water evaporation, the collectors had been closed immediately after the rain event had finished. Then, the rainwater samples were taken from these collectors to polyethylene container bottles and treated like the groundwater samples. The groundwater sampling sites were distributed throughout the study area representing the different aquifer types and topographical settings, considering geology and topography. Well-distributed samples from fractured basalt, pyroclastic material, basalt regolith, and alluvio-lacustrine shallow aquifers have been collected and analyzed. Similarly, rainfall samples had been collected in similar periods at the lower, middle, and upper topography of the basin so that possible topographical influences on the rainfall water chemistry are taken into consideration. In total, about 255 groundwater samples and 25 rainfall samples have been collected and analyzed at Ghent University, Department of Geology, Laboratory of Applied Geology and Hydrogeology. However, among the 255 samples, 138 are on shallow groundwater where the chemistry is not much evolved due to long rock-water interaction, and those which are pollution-free are selected for the calculation. These 255 samples are those sampled and analyzed for the hydrochemical characterization of the basin groundwater. In other words, it includes those sampled from the deep wells (deep groundwater which is expected to have undergone significant geochemical evolution and supposed to many years of water mixing which is with quite different time with the sampled rainfall water). As a result, those sampled from the deep wells were excluded from the CMB calculation. In addition, the possibility of chloride ion increment due to pollution has been taken into acount. Few samples from the shallow groundwater with relatively higher chloride concentration and are inline (correlated) with the concentration of nitrate and/or sulfate ions, are also omitted from use in the calculation as they might consist of some pollution. Finally, it is only 138 groundwater samples (Fig. 7) that are from shallow groundwater and with insignificant pollution additives are considered in the estimation of the recharge.

The number of groundwater samples for each sub-area, and the concentration of chloride (range and mean values) are shown in Table 2. The number of samples for northern and western catchments is small compared to the eastern and southern. The mean concentration values for the formers are a bit higher than the latter ones (Table 2).

4. Result and discussion

4.1. Spatial and temporal variation of groundwater recharge and other water balance components

The annual groundwater recharge (calculates over the period 2012–2016), using the calibrated WetSpass model, ranges from 0 mm to 1085 mm (Fig. 8a) and has a mean value of 315 mm (22% of rainfall amount). Recharge is assumed 0 mm at water bodies and wetlands in the WetSpass model. Hence, recharge is 0 mm at Lake Tana and a dam reservoir in the Gilgel Abay catchment and wetlands in the lower reaches of Rib river catchment (Figs. 4c and 8a). No recharge at water body is the general assumption of the WetSpass model. Fortunately, this assumption is in line with previous studies (e.g. Kebede et al., 2006; Mamo, 2015; SMEC, 2008), which had concluded that there is insignificant percolation beneath the lake floor. Higher recharge is estimated on the southern (Gilgel Abay) and

Table 2
number of the groundwater samples, the mean, and the range of chloride concentrations for the different catchments grouped based on similar runoff characteristics, and used for the CMB calculations.

Catchments	Number of analyzed GW samples	Chloride conc. (mg/l)	
		range	mean
Southern	51	0.3–12.5	4.12
Eastern	65	0.5–10.6	4.23
Northern	15	3.46–10.5	6.61
Western	7	3.46–10.83	6.93

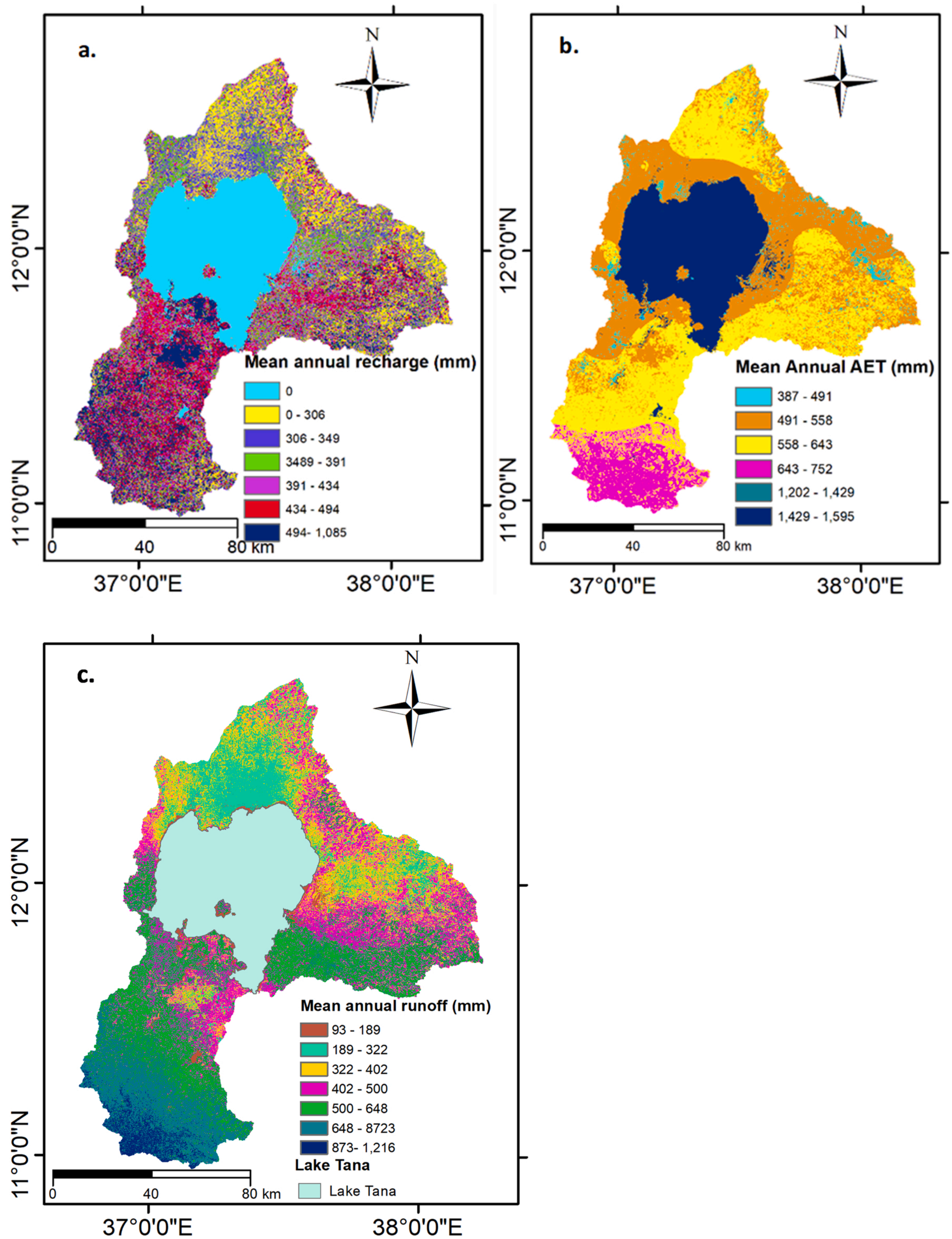

Fig. 8. Long-term mean annual groundwater recharge(a), mean annual actual evapotranspiration (b), and mean annual runoff (c) spatial maps produced from the WetSpass water balance model.

eastern (Gumara) river catchments (Figs. 1b and 7a), and lower on the northern part of the Lake Tana basin. This is mainly due to the lower rainfall amount in the northern catchments compared to southern catchments (Figs. 3b and 8a). Apart from the rainfall, the spatial distribution of the recharge seems highly controlled by the slope angle, followed by the soil type, and the land use type. Forest land covering only 1.8% has high recharge (mean annual of 542 mm). Cultivated land and water body consisting of about 49% and 21% of the total areal coverage, have annual mean recharge values of 370 mm and 0 mm, respectively, dominating over the total average value. Clay soil type, covering about 77% of the total basin area, has a mean annual value of about 276 mm, the lowest amount estimated compared to all other soil types. The major recharge is taking place during the summer season while only a small amount recharges during the winter: about 237 mm is recharged in the summer and 78 mm in the winter seasons. The mean annual recharge is about 22% of the total mean basin precipitation.

The mean annual runoff for the whole basin is about 416 mm, accounting for about 29% of the average precipitation. About 92% of the runoff is taking place during the summer season, while the remaining is taking place during the long winter season. Relatively higher runoff is observed in the southern and eastern basins, and lower runoff has been noted in the northern and northeastern (Rib) river catchments (Fig. 8c). This is in line with the study by Dessie et al. (2015). In some areas (e.g. in northern and northeastern), low runoff values has been observed on the cultivated land and clay soil types where a high runoff coefficient is expected (Figs. 4c, 5a, and 8c). This is due to the relatively low rainfall amount on these parts of the Lake Tana basin (Fig. 3b). This shows that compared to the rainfall, the soil type and the land use have less influence over the runoff. The rainfall amount is highly controlling the spatial distribution of runoff (Figs. 3b and 8c). The zonal statistics for the land use and soil classes types show a high variation of runoff over the single class types. For example, for clay soil with cultivated land cover type, the runoff ranges from 212 mm to 1216 mm (15%−84% of mean rainfall), and with an average of 485 mm accounting for about 34% of the rainfall. This variation is found mainly due to the variation in the rainfall amount, which is varying from 1097 mm to 2155 mm for the aftermentioned soil and land use class combination. However, it does not mean that the other runoff controlling variables such as the slope are not playing a significant role for such variations.

The evapotranspiration of the Lake Tana basin is mainly the sum of the direct evaporation from the lake and wetland and evapotranspiration over the other land cover types. The mean evaporation over the lake is about 1485 mm. In the WetSpass model, the Penman method is used to estimate the open water evaporation (Batelaan et al., 2007). The average total evapotranspiration over the basin is 770 mm, which is 53% of the mean basin precipitation. About 56% of total evapotranspiration is happening during summer and the other 44% occurs during winter. The mean evapotranspiration of the basin is about 52% of the mean potential evapotranspiration. The spatial distribution of the evapotranspiration over the basin is highly controlled by the rainfall and the land cover types relative to the other physical and meteorological variables (Figs. 3b, 4c, and 8b). It is higher over the lake and wetlands because it is open water where there is no limitation of water availability, and evaporation is equal to the potential evaporation capability of the air. The variation over the lake (Fig. 8b) is due to the variation of the potential evaporation (Fig. 3b and c). Next to the water body and wetlands, grassland, forest, bush and shrubland cover types have high evapotranspiration values.

The direct lake water evaporation is compared with other studies estimated by different methods (Table 3). The result is very close to that of Kebede et al. (2006) and Chebud and Melesse (2009) which both used the similar Penman method (Table 3). However, it is lower than the value estimated by Dessie et al. (2015) which used recent data from six stations. This could be due to the application of different period data (from 2012 to 2013, while it is from 2012–2016 in this study) or the time scale applied (seasonal versus daily) for the calculation or it might be due to the method they used (Table 3). Time scale affects evaporation calculations, which are higher for fine time scales (e.g. daily), and relatively lower for coarser time scales (e.g. seasonal or monthly) (Bakundukize et al., 2011; Yenehun et al., 2020).

4.1.1. Model verification

The developed model is verified using two ways. First, the mean annual total river discharge, using the daily time scale data of river discharge of 2012–2016 at seven major rivers, is compared with the corresponding WetSpass model results (Fig. 9). Part of these data (annual mean of 2012–2013) have been used for the calibration of the model. The river discharge amount for these major perennial rivers is the total flow amount (comprising both surface and baseflow). However, the WetSpass model calculates the runoff (only the

Table 3
Simulated mean annual evaporation over the lake of the WetSpass water balance model, and other studies. The time scale for the modeling, the period that the meteorological data used and the number of meteorological stations, and the estimation technique are indicated.

Literature	Timescale	Data period used	Number of stations	Estimation method applied	Annual over-lake evaporation (mm)
This study	seasonal	2010–2018	7	Penman (WetSpass)	1458
Wale et al. (2009)	daily	1992–2003	2	Penman-combination equation	1690
Rientjes et al. (2011)	daily	1994–2003	1	Penman-combination equation	1563
Kebede et al. (2006)	daily	1960–1992	1	Penman	1478
SMEC (2008)	monthly	1960–2005	2	Penman	1697
	monthly	1960–1995		Energy balance	1657
Mamo (2015)	monthly	1995–2009	1	Penman	1544
Setegn et al. (2008)	daily	1978–2004	not explicitly mentioned (probably 2)	Hargreaves	1248
Dessie et al. (2015)	daily	2012–2013	6	Penman-combination	1789
Chebud and Melesse (2009)	monthly	not mentioned	1	Penman	1458

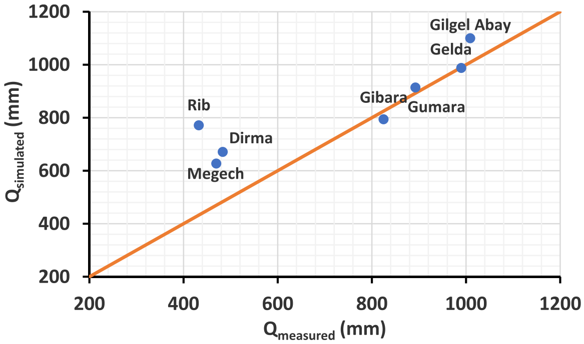

Fig. 9. A graph showing a correlation between measured mean annual river flow (2012–2016) and simulated mean annual river flow by WetSpass water balance model for the major rivers in the Lake Tana basin. The simulated river flow is calculated by summing up the runoff and the groundwater recharge values of each catchment by assuming all the recharge in the upper catchments emerges as an outflow in the lower floodplain parts.

surface runoff) but not the total discharge. Hence, to estimate the total river flow at the catchment outlets of each river, we applied a similar technique that Gebreyohannes et al. (2013) had followed. Based on groundwater balance in the aquifers, the long-term average annual groundwater drainage and possible abstractions are equal to the long-term average annual recharge. Given the river gauging stations are usually at the groundwater discharge zones (on the floodplain), the flow measurements are assumed to catch the baseflow component except for a very small amount that may pass through deep percolations. Besides, the groundwater abstractions using different shallow and deep wells can be assumed small compared to natural drainage and recharge as there is no large development of the groundwater in the basin. Using ArcGIS 10.3 tools, both annual runoff and groundwater recharge outputs of the WetSpass model, are accumulated at the river outlets. Finally, the accumulated raster maps of runoff and recharge for each major catchment are summed up to produce the spatial total river discharge map. The total river discharges estimated in this study and those observed in the measurements (2012–2016) are compared (Fig. 9). The overall coefficient of determination (R^2) between the simulated and the observed river discharge values of the different rivers is about 80%. However, for Rib, Dirma, and Megech river catchments, the simulation by WetSpass is higher compared to the observation (Fig. 9). This could be due to significant deep percolation of the groundwater that is not caught by the river flow measurements i.e. the baseflow is far less than the groundwater recharge. The model is best simulated for Gilgel Abay, Gumara, Gelda, and Gibara rivers (Fig. 9). The reason for these can be associated to the hydrogeological nature of the catchments. For Gumara and Gilgel Abay, this could be due to the capturing of the baseflow in the flow measurements as most of the groundwater discharges through different springs in the lower reach of the rivers. Similarly, SMEC (2008), and later Dessie et al., (2015, 2014) came up with the conclusion that there is significant groundwater contribution for Gilgel Abay and Gumara rivers flow while only little for Megech and Rib. Furthermore, Setegn et al. (2008) had estimated the groundwater (as baseflow) contribution of the whole basin to be 50% of the total river inflow to the lake. A similar geological nature also appears for Gelda river, the highly fractured Quaternary basalt, that might cause a relatively high baseflow that the river measuring station could have captured. However, the geological nature of Gibara river is different. The reason why there is good correlation between observed river discharge and sum of simulated recharge and surface runoff might be due to limited deep percolations that could pass underground at the river measuring station, with only shallow aquifers that are recharged and discharge immediately to the nearby small stream tributaries. In general, it should be noted that the WetSpass model applied is quasi-steady state, and uses long-term average seasonal rainfall, whereas, in reality, the rainfall characteristics (intensity, frequency and duration) vary within fine time scales. This is limiting the effectiveness of the model in simulating runoff.

The second way that the developed WetSpass model verification made is through its performance in estimating groundwater recharge. The point recharge estimated using the WTF method has been used to compare the model performance at those points. The extracted recharge values of the model were correlated against the WTF results calculated at 65 monitoring stations (Fig. 10a). The overall correlation was fair (with a coefficient of determination, $R^2 = 35\%$). However, Yenehun et al. (2020) evaluated the performance of the WetSpass model in estimating recharge at a small catchment in the upper Gilgel Abay river catchment and found that the technique is less effective at storage controlled flat floodplain areas and at aquifers where focused recharge (through rock fractures) is an important recharging mechanism. Therefore, we excluded WTF results estimated at aquifers on those topographies, and then the correlation coefficient (R^2) is found to be 84% (Fig. 10c). When only two wells located at storage controlled floodplain aquifer named DTW2 and at exceptionally highly fractured aquifer called Sarwuha W1 (Fig. 6) are excluded, the R^2 raised to 71% (Fig. 10b). Hence, the WetSpass method is found effective in estimating the groundwater recharge in most parts of the study basin. However, at the flat floodplain alluvial aquifer and fractured rock aquifers where the hard rock is exposed to the surface, water balance techniques such as the WetSpass are found less effective. The interannual variations of the rainfall and evapotranspiration (though small compared to spatial variation as mentioned earlier), would have its own impact in comparing the results by the WetSpass and WTF methods: the WTF is estimated using recently measured water level data while the WetSpass includes earlier period meteorological data.

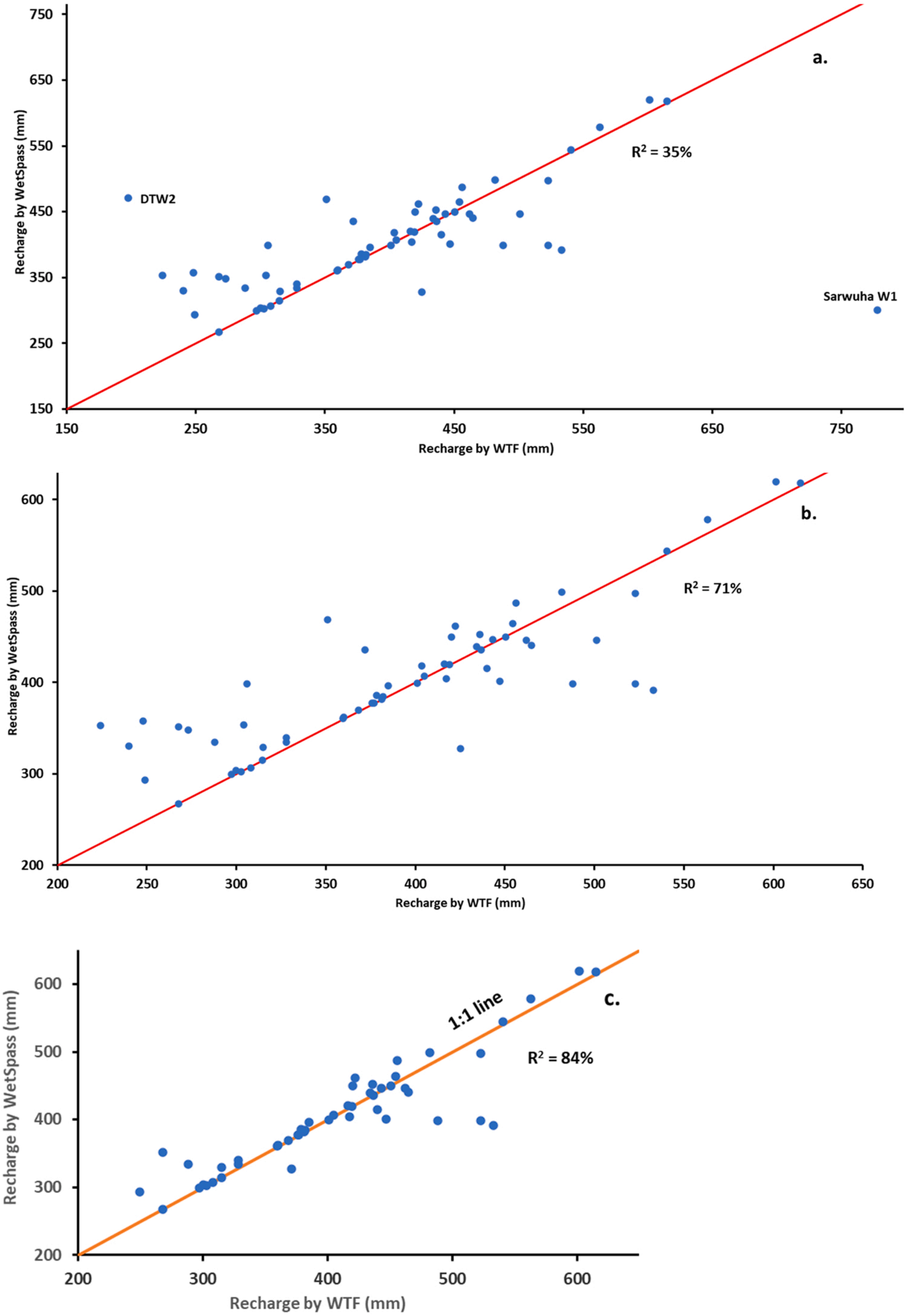

Fig. 10. a) Mean annual recharge by WTF and WetSpass methods at all groundwater monitoring wells. The recharge values estimated using WetSpass are extracted at 65 water level monitoring points. It has a total correlation of 35%. b) A 1:1 plot of mean annual recharge by WTF versus extracted recharge by WetSpass method for monitoring points excluding Sarwuha W1 and DTW2 those strongly affected by focused recharge and limited with aquifer storage, respectively. c) A 1:1 plot of mean annual recharge by WTF versus extracted recharge by WetSpass method for monitoring points excluding those affected by focused recharge and those which are storage controlled on the flat floodplain areas. It has a correlation coefficient of 84%.

4.2. Effect of land use change on groundwater recharge and other water balance components

The effect of land use change on groundwater recharge, runoff, and evapotranspiration has been assessed in this study. This assessment has been made using the same long-term average meteorological data that have been used in the WetSpass model, and hence possible variation due to temporal increasing or decreasing of the meteorological variables have not been taken into consideration.

The value of water balance terms changes with land use changes. There is a decrease in recharge by 13 mm or 195.9 * 10^6 m^3 in the years 1986–2014 (Table 4) in the Lake Tana basin. This is about 4% of the mean annual recharge estimated with the applied WetSpass model. This is inline with the increase of cultivated land area (from 36.7% to 49%), mainly from grass, bush and shrub, and forest lands. Similarly, there is an increase of runoff but it is only by 4 mm or 60.3 * 10^6 m^3 in the 28 years (about 1% of the total mean runoff). Similarly, the evapotranspiration shows an increment by 9 mm or 135.6 * 10^6 m^3 in these 28 years (about 1.2% of the total mean annual AET). The trend is in line with the studies by Abate et al. (2017), Enku et al. (2014), Gebremicael et al. (2013), Hurni et al. (2005), Tesemma et al. (2010), and Woldesenbet et al. (2017), which showed the shifting of the river discharge more to overland flow mechanism in the last four to five decades in the upper Blue Nile basin. However, the rate of hydrological change found in this study is relatively small compared to the rate of land use change. This reinforces the idea that the land use is not the primary important controlling factor compared to rainfall amount (discussed above in detail). Similarly, Birhanu et al. (2019) found a negligible change of the water balance components for Gumara catchment for the land use change of 1986–2015 using HBV model. Gashaw et al. (2018) had also evaluated the effect of changing land use on the hydrology of Andassa catchment (neighboring small catchment, south of Lake Tana basin) over the same period (1986–2015) using SWAT model. Compared to this study, they found a similar amount of reduction in baseflow (supposed to be equivalent to groundwater recharge), but a bit more runoff increment.

4.3. Groundwater recharge estimation using WTF and CMB methods

The mean annual groundwater recharge using the WTF ranges from 125 mm to 778 mm, accounting for about 9–54% of the mean basin rainfall. In general, the southern and eastern (Gumara river catchment) part of the Lake Tana basin has higher recharge than the northern part (Fig. 11). This is also similar to the result of the WetSpass model (Fig. 8a). It has an overall basin average of 369 mm (26% of the rainfall), which is a bit higher than the mean average estimated by the WetSpass model (22%). This could be due to the ability of the WTF method to capture the focused recharge through rock fractures, and/or lateral groundwater flow besides the diffuse recharge from the direct precipitation that Yenehun et al. (2020) had thoroughly discussed. The spatial variation of recharge depends on topography and geology. In steep sloping topography aquifers, where low recharge is expected, higher recharge values by WTF compared to WetSpass is estimated (Figs. 5c and 11). This is due to the additional recharge from the upstream area by lateral groundwater flow in addition to the diffuse recharge from the direct rainfall. Furthermore, on the flat floodplain areas, the recharge estimated by the WTF is small. This is due to the limitation of the aquifer storage. It means the aquifer is more or less fully recharged in the early to middle of the recharge period (usually end of July to mid-August) but the model keeps on adding the recharge as there is unlimited aquifer storage. In general, the WetSpass method is less effective in the fractured aquifers, where focused recharge is the important recharging mechanism, and on flat floodplain alluvio-lacustrine aquifer areas, where storage limits further recharge. In addition, it performs less in steeply sloping aquifers where fast groundwater flow accumulates additional recharge through lateral groundwater flow.

In general, The values estimated by WetSpass is over-estimated in the storage-controlled floodplain aquifer as it assumes infinite aquifer storage. Hence, using physical hydrological models like WetSpass models for similar aquifers is not recommended, rather methods like WTF and CMB are the best alternatives. Similarly, on fractured aquifers where major recharge is happening through open fractures (preferential recharge), WetSpass underestimates recharge while WTF, which is based on the real water level measurement, estimates best.

Similar to WetSpass and WTF methods, the recharge calculation using the CMB method shows strong spatial variability. The groundwater recharge in the southern and eastern catchments is higher than in the northern, and western catchments. The mean annual recharge by the CMB method is about 346 mm (24% of the rainfall). The spatial distribution is more or less similar to the spatial distribution map simulated by WetSpass (Fig. 8a), and the point recharge distribution of the WTF method (Fig. 11).

Table 4
Long-term mean seasonal and annual groundwater recharge, runoff, and evapotranspiration values simulated for land use of the years 1986, 2000, and 2014 using the WetSpass water balance model.

Year	season	recharge (mm)	runoff (mm)	total evapotranspiration (mm)
1986	summer	247	379	424
	winter	81	33	337
	annual	**328**	**412**	**761**
2000	summer	243	381	427
	winter	79	33	338
	annual	**322**	**414**	**765**
2014	Summer	237	383	428
	winter	78	33	342
	annual	**315**	**416**	**770**

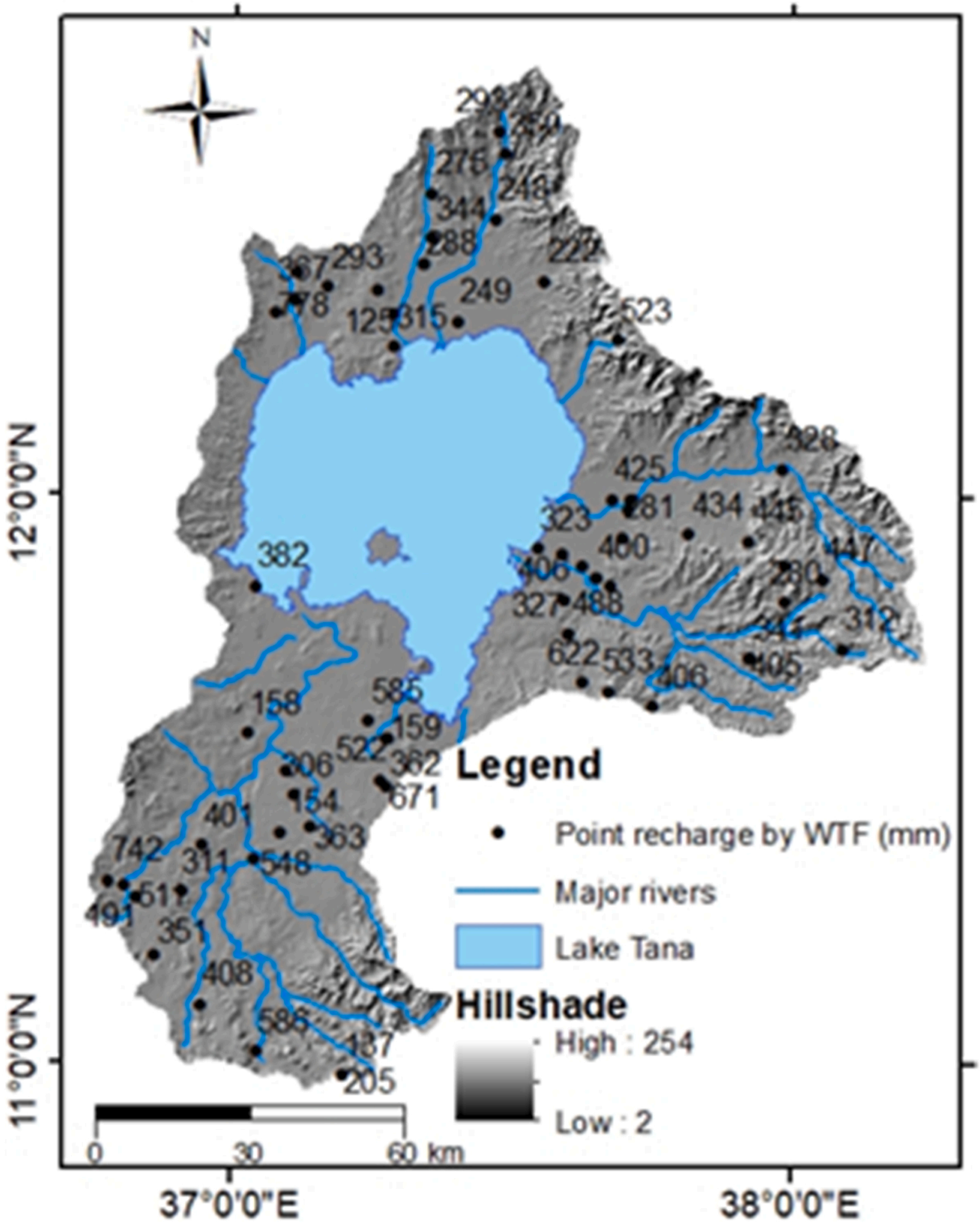

Fig. 11. Point values of annual groundwater recharge estimated at 65 groundwater level monitoring wells. The wells include shallow hand-dug wells, piezometers, and a few boreholes being monitored both manually and using automatic pressure transducer device.

The mean annual groundwater recharge values using the CMB method ranges from 164 mm to 404 mm. The relatively smaller range for CMB is due to the consideration of average values in the four distinguished zones rather than at 138 groundwater sampling points. Otherwise, the range of values would have been higher, given the wider range of chloride values (0.3–12.5 mg/l) of the

Table 5
mean annual groundwater recharge values estimated for the different catchments by all CMB, WetSpass and WTF methods.

Catchments	Groundwater recharge by CMB (mm)	Groundwater recharge by WetSpass (mm)	Groundwater recharge by WTF (mm)
Southern	404	453	439
Eastern	355	372	435
Northern	164	315	303
Western	206	357	445

groundwater samples (Table 2). The heterogeneity in recharge processes and recharge rates over the basin is well notified by the higher range of values by the WetSpass and WTF methods.

Generally, recharge in the eastern and southern catchments is higher than in the northern catchments (Table 5), primarily due to higher rainfall and favorable geology (highly fractured Quaternary basalt) (Fig. 2). The recharge by the CMB in the northern, and somewhat in the western part is much smaller compared to the values by the other two methods (Table 5). This could be due to some recharge from the river water which elevates the chloride concentration of the groundwater which hence decreases the recharge value according to Eq. 5. The chloride concentration in the river water is higher due to exposure to open water evaporation before infiltration and percolation to the groundwater zone. Significant amount of groundwater recahrge by river water is observed in the Megech catchment (the main river catchment of northern area). From about 356.51 * 10^6 m^3 total mean annual river discharge recorded at the upper river measuring (at the foothill of the catchment) station (in period 2012–2016), about 107.91 * 10^6 m^3 is lost or not recorded by the downstream measuring station. This water amount might mainly be recharge the groundwater in the flood aquifers. This supports the above hypothesis of river water recharges groundwater in this part of the Lake Tana basin. Besides, it might be also due to the small number of samples that results much uncertainities and as well as lack of time series chloride data contray to its need (this aspect is throughly discussed by Aishlin and Mcnamara (2011)).

In general, Aishlin and McNamara (2011) noted the necessity of more years of chloride measurement so as to decrease the effect of stored chloride in the vadose zone in the pre-recharge period. However, our groundwater samples are only one time and such an effect might be included in the observed CMB results. Tekleab et al. (2014), using stable isotope, concluded that the rainfall source is different for the region where this study area is located i.e. both from freshwater and seawater. The Atlantic–Indian Ocean, Congo basin, Upper White Nile and the Sudd swamps are the potential moisture sources during the main rainy (summer) season, while the Indian–Arabian and Mediterranean sea moisture are during little rain (spring) and dry (winter) seasons. This shows the chloride concentration of the rainwater is temporally highly variable. In this study, our rainwater sampling was not so frequent to address such possible variations. However, we have looked strong variations of chloride concentration: higher during May-June, and low during the high rainy season (July-August). This might have its own effect on the calculated recharge values, and for the disparity with other methods for northern and western catchments (Table 5).

5. Conclusion

The physically-based water balance model, WetSpass has effectively been applied to simulate the water balance components of Lake Tana basin, containing the largest lake of Ethiopia. The model simulates the mean annual major river inflows with a coefficient of determination (R^2) of 80%. The model better simulated flows for some of catchments than for the other catchments where deep percolation might conceal the base flow from measurement by the gauging stations. On the other hand, the WetSpass model applied is a quasi-steady state that used long-term average seasonal rainfall amounts, though the rainfall characteristics vary within fine time scales. This might limit the effectiveness of the model in simulating runoff amounts. The annual groundwater recharge using WetSpass ranges from 0% of rainfall, at the water bodies where infiltration is impossible, to 57% in the flat, silty loam, and bushland cover type. It has a mean annual value of 315 mm (22% of the precipitation amount), of which 237 mm is recharged in summer and the other 78 mm in the winter season. Similarly, the WTF and CMB methods have also shown strong spatial variability, with higher recharge values in the southern and eastern catchments, and lower in the northern and partly in the western parts, primarily due to rainfall distribution and geology. There is good correlation between point recharge values by the WTF and extracted recharge from the WetSpass spatial maps. However, there is a high disparity on wells located on the storage-controlled flat floodplains and focused recharge affected fractured rock aquifers. Hence, though water balance models estimate recharge at fine spatial scales that help for water management in specific areas, its capacity is limited for aquifers where only diffuse recharge is the main recharging mechanism and for those aquifers that are not fully saturated early in the recharge period.

The mean annual runoff for the whole basin is about 416 mm (29% of the average precipitation) and evapotranspiration is about 770 mm, which is 53% of the mean basin precipitation. The precipitation amount is highly controlling the spatial distribution of the runoff, more than the land use and soil. The mean evaporation over the lake is about 1485 mm. The spatial distribution of the evapotranspiration over the basin is highly controlled by the rainfall and the land cover types. The hydrology of the basin has not much changed in the last three decades though cultivated land has expanded significantly.

Many hydrological models for different areas (small catchment-scale to large basins) are developed and used for estimating groundwater recharge and other water balance components. However, evaluation of the methods with point estimations based on direct water level measurement (WTF) and chemical tracer (CMB) gives a good insight for future recharge estimation techniques for similar aquifer types wherever they are located in the world. In this study, identifying topographical and geological characteristics, and thus the appropriate recharge mechanisms have found an important factor and starting point in selecting recharge estimation methods.

The study also pointed out that the common approach that is being implemented i.e. calculating recharge by a multitude of methods and averaging out the results of the different methods is found unreliable. Rather selecting an appropriate one or few technique/(s) and considering that as the optimal result is recommended.

CRediT authorship contribution statement

Alemu Yenehun: Conceptualization, Investigation, Formal analysis, Writing – original draft. **Mekete Desssie:** Project administration, Conceptualization, Investigation, Writing – review & editing. **Fenta Nigatie:** Conceptualization, Investigation, Writing – review & editing. **Ashebir Sewale Belay:** Conceptualization, Investigation. **Mulugeta Azeze:** Conceptualization, Writing – review & editing. **Marc Van Camp:** Conceptualization, Formal analysis, Software. **Derbew Fenetie Taye:** Data collection. **Desale Kidane:** Writing – review & editing. **Enyew Adgo:** Project administration, Funding acquisition, Writing – review & editing. **Jan Nyssen:** Project administration, Funding acquisition, Writing – review & editing. **Ann Van Griensven:** Conceptualization, Investigation. **Kristine Walraevens:** Conceptualization, Writing – review & editing, Project administration, Supervision, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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