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SWAT based hydrological assessment and characterization of Lake Ziway sub-watersheds, Ethiopia

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ABSTRACT

Study region: Lake Ziway watershed, Ethiopia.
Study focus: Lake Ziway and its watershed play a significant role in supporting the livelihoods of people in the region. However, the study region is currently under heavy human pressures mainly associated with the ever increasing of human population and the subsequent intensification of agricultural development activities. The present study therefore aims at quantifying and comparing water balance components, feeder rivers' discharge and evapotranspiration (ET) in the study region using SWAT (Soil and Water Assessment Tool) model. Flow data from 1988 to 2000 and from 2001 to 2013 were used for model calibration and validation periods respectively.
New hydrological insights for the region: Results show that infiltration, surface runoff, base flow and aquifer recharge were large in Katar sub-watershed while ET and lateral flow were large in Meki sub-watershed. However, surface and base flows showed decreasing trends in both sub-watersheds, yet Katar sub-watershed showed major contribution of water to Lake Ziway. The model estimated Lake Ziway and its watershed mean annual ETs as 1920 mm and 674 mm respectively, but plantation showed more ET than other land cover types in the watershed. If the current trends in irrigation development continue in the region, it is suspected that Katar and Meki Rivers are likely to cease to exist after seven decades, and so is then Lake Ziway to dry out.

1. Introduction

Water resources are one of the most critical resources needed to support the socioeconomic development of the human society (Huang and Cai, 2009). However, the degradation of these resources is among the many critical environmental problems (Vitousek et al., 1997; Ramankutty and Foley, 1999). The adverse impacts on water resources have occurred by human pressures, especially in developing countries due to the large demands of an ever-increasing human population, which are further aggravated by poverty (Olson and Maitima, 2006; Huang and Cai, 2009). Watershed degradation is also one among many critical environmental problems, mainly associated still with human interventions (Bach et al., 2011). However, many of the causes for these critical environmental problems arise at the local scale from these interventions. Roth et al. (1996), Brooks et al. (1997), and Tomer and Schilling (2009) asserted that land cover changes are important drivers of changes in watershed hydrology and processes, leading to a decreased availability of different products and ecological services (Moshen, 1999). Degradation of watersheds due to such land cover changes can have adverse impacts on water resources and associated biological communities (Brooks et al., 1997).

Watersheds serve as semi-closed systems for water whose single source is precipitation so that they provide a convenient logical

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unit for hydrologic analyses (Hwang et al., 2015). The physical processes of precipitation, evapotranspiration (ET), overland flow, infiltration, recharge or discharge, and groundwater flow and their interactions in the atmosphere, land surface and sub-surfaces are involved in water movement dynamics and distribution from one system to the other within the hydrologic cycle (Delfs et al., 2013; Niu et al., 2014). Thus, watersheds are balanced by all of the sinks in the system − stream flow at the watershed outlet, ET, and anthropogenic water consumption for urban and agricultural purposes (Frey et al., 2013; Condon and Maxwell, 2014; De Schepper et al., 2015).

Lake Ziway and its watershed play a significant role in supporting the livelihoods of approximately 2 million people (CSA, 2013). The watershed also inhabits 1.9 million livestock (Tsegaye et al., 2012). The lake is a source of drinking and domestic water for nearby towns, water for open and closed farm irrigation, and fish supply to huge market centers in the country. A large number of anglers, both in cooperatives and individually, depend on this lake for their livelihoods, including women and children involved in processing and selling the fish. According to Vuik (2008), Lake Ziway and its watershed support unique ecological and hydrological characteristics in addition to its economic and livelihood values.

However, Lake Ziway is currently under heavy pressures associated with the increasing population (Jansen et al., 2007), climate change (Zeray et al., 2006) as well as the intensification of agricultural development activities in the watershed. Thus, water abstraction from the lake feeder rivers for irrigation farming (Ayenew, 2004; Scholten, 2007) and land cover change in the upstream areas of the watershed (Hengsdijk and Jansen, 2006) have been affecting the lake hydrology. In recent years, the rivers flowing into Lake Ziway are being diverted into farmlands for irrigation. Such multiple problems have the potential for damaging the hydrological and ecological integrity of Lake Ziway.

Upon this backdrop, a study was necessary to assess the current status of Lake Ziway and its watershed from hydrological point of view using a mix of methods and tools. Accordingly, this study has been conducted using SWAT (Soil and Water Assessment Tool) model with the aim to quantify and compare water balance components, feeder rivers discharge, and ET in Katar and Meki sub-watersheds including Lake Ziway. In this respect, this article is timely to understand the current state of Lake Ziway watershed and the lake ET.

2. Materials and methods

2.1. Study area

Lake Ziway falls between 7° 22′36 longitude (Fig. 1). The watershed includes the rift floor, two escarpment are" and 8°18′21" latitude and 37°53′40" and 39°28′9"as, two major river inlets − the Katar and Meki Rivers − and one river outlet − the Bulbula River. Lake Ziway watershed has two sub-watersheds − Meki sub-watershed in the northwestern part and Katar sub-watershed in the southeastern part. The remaining part of the watershed covers the rift floor which is predominantly flat.

The watershed lies in two Ethiopian administrative regions − 73.6% in Oromia National Regional State (ONRS) and the remaining part in Southern Nation Nationalities and People Regions (SNNPRS) − rising over 3500 m above sea level (masl). Katar sub-watershed is entirely located within ONRS while Meki sub-watershed is scattered over ONRS and SNNPR. About 2 million human populations (CSA, 2013) and about 1.9 million livestock (Tsegaye et al., 2012) inhabit the Lake Ziway watershed.

Lake Ziway extends over an area of approximately 434 km^2 and has a maximum of 9 m depth with a shoreline length of 137 km (Hengsdijk and Jansen, 2006). It is the most upstream of the Central Rift Valley (CRV) lakes of Ethiopia. Runoff from the watershed drains into the lake through the two feeder rivers − the Katar and the Meki − which represent the opposing faces of the rift escarpments (Fig. 1). The lake is an important element of the Ethiopian Central Rift Valley region because it currently serves as the water source for closed and open farm irrigation, and as the only potable water supply for Ziway Town. It also supports the livelihoods of the fishing community. It is a habitat for biological diversity.

Lake Ziway sub-watersheds have tropical climate with no uniform spatial and temporal climatic conditions. According to the 30 years (1984–2014) average climate data, Katar sub-watershed has a minimum and maximum annual precipitation of 729.8 mm and 1227.7 mm respectively, and Meki sub-watershed with a minimum and maximum annual precipitation of 859.3 mm and 1088.1 mm respectively. The mean annual temperature is 16.3 °C and 18.5 °C respectively for Katar and Meki sub-watershed. The wet season − June to September − accounts for about 55 percent of the annual precipitation, while the dry season contributes 45percent (Billi and Caparrini, 2006).

The predominant land cover in the watershed is smallholder agricultural lands. The vegetation cover is characterized by extensively overgrazed Acacia Combretum in open woodland (Woldu and Tadesse, 1990), whereas deciduous woodlands occupy the escarpments (Mohammed and Bonnefille, 1991). The settlement pattern is typical of rural communities across Ethiopia (Stellmacher, 2015). Livelihoods largely depend on smallholder agriculture. Land cover change is massively and rapidly taking place, as elsewhere in the Ethiopian CRV (Dadi et al., 2016).

2.2. SWAT model

SWAT is a relatively recent model used to assess the watershed hydrology (Arnold et al., 1993; Arnold et al., 1998; Jha, 2011). According to Kannan et al. (2007) and Jha (2011), it is the best among the different hydrological models due to its capability for application to large-scale watersheds (> 100 km^2), interface with a Geographic Information System (GIS), continuous-time simulations performance, and generation of the maximum number of sub-basins and ability to characterize the watershed in enough spatial detail.

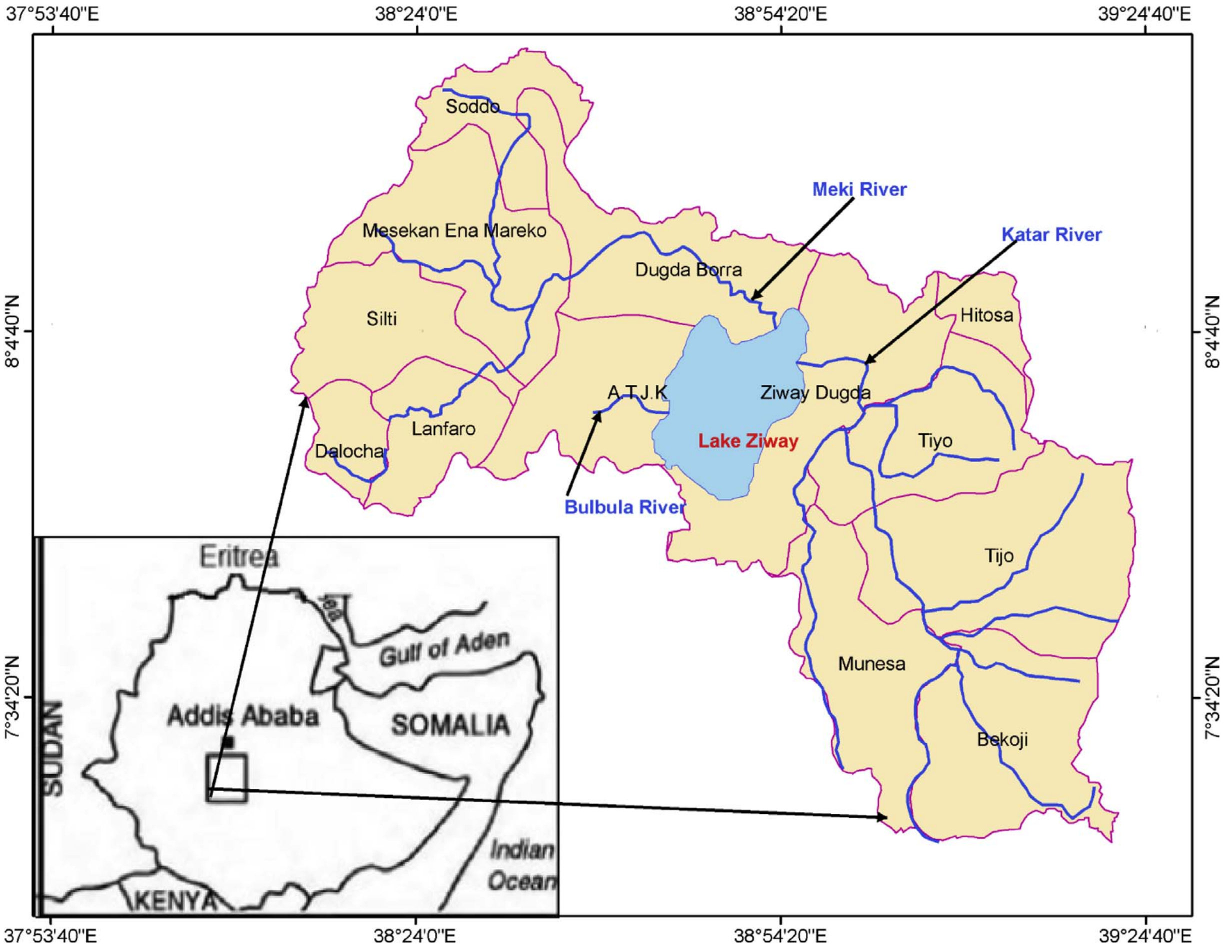

Fig. 1. Location of Lake Ziway and its watershed boundaries.

2.3. SWAT input data used

2.3.1. Digital elevation model (DEM)

It is a common data source for developing topography dependent models. It is required to calculate the flow accumulation, stream networks, slope, and watershed delineation. Hence, 20 m by 20 m meter grid resolution DEM in raster format was used and projected to Transverse Mercator (UTM) on the spheroid of WGS84 to correct the errors and fit into the model requirement. It is obtained from the USGS (United States Geological Survey) web source.

2.3.2. Land use map

It defines the land use types in the watershed and influences the hydrological properties of a watershed. The land use map was made from LANDSAT ETM+ images with a resolution of 30 m with path 168 and rows 54 and 55 taken on January 10, 2014, from the USGS.

2.3.3. Soil data

This is associated with all the information to describe the physical and chemical properties of the soil − texture, water content, hydraulic conductivity, bulk density, organic carbon content, depth of horizon, and percentage of sand, silt, and clay for each soil horizon. It is obtained from the FAO digital soil map of Ethiopia (FAO-UNESCO, 1976).

2.3.4. Climate data

The Climate data used covered 30 years period from January 1984 to December 2014. Daily precipitation, daily maximum and minimum air temperature, daily relative humidity, daily wind speed, and daily solar radiation were used. Precipitation and temperature were obtained from the National Meteorological Agency of Ethiopia while the relative humidity, wind speed and solar radiation were taken from the global climate data. However, some of the missing data were filled using predictions with linear regression equations. Finally, the weather data were prepared in text file format as required by the SWAT model.

Table 1
Parameters used for sensitivity analysis.

Parameter Name	Description
CN2	SCS runoff curve number
GW_DELAY	Groundwater delay
ALPHA_BF	Baseflow alpha factor
GW_REVAP	Groundwater "revap" coefficient
ESCO	Soil evaporation compensation factor
SOL_K	Saturated hydraulic conductivity
SURLAG	Surface runoff lag time
EPCO	Plant uptake compensation factor
CH_K2	Effective hydraulic conductivity in main channel
SLSUBBSN	Average slope length
SOL_AWC	Available water capacity of the soil layer
RCHRG_DP	Deep aquifer percolation fraction and
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur
GWQMN	A threshold minimum depth of water in the shallow aquifer for base flow to occur

2.3.5. River discharge data

Katar and Meki Rivers are the two major rivers in Lake Ziway watershed. Daily discharge data of these rivers (from 1984 to 2013) were obtained from the Ethiopian Ministry of Water, Irrigation, and Electricity. The data were used for calibrating and validating the Katar and Meki sub-watersheds. However, some of the missing discharge data were filled using a linear regression equation. The study was then performed by ArcSWAT12.0.

2.4. Sub-watershed delineation

ArcSWAT (ArcWAT-2012 interface for ArcGIS 10.2)[1] was used to delineate the spatial heterogeneity of Lake Ziway sub-watersheds and topographic features − elevation and slope − using a 20 m by 20 m resolution DEM data following the step-by-step procedure outlined in the SWAT user guide (Winchell et al., 2013).

2.5. Sensitivity analysis, model calibration and validation

Fourteen hydrologic parameters (Table 1) were manually adjusted for sensitivity analysis based on Lenhart et al. (2002), Misgana and Nicklow (2005), and White and Chaubey (2005). The average monthly streamflow data of 13 years (1988–2000) were used in both Meki and Katar sub-watersheds to compute the sensitivity of the streams' flow. Upon the completion of sensitivity analysis, t-values were used to rank parameters for calibration and validation processes.

Calibration and validation were carried out by comparing the simulated streamflows with the measured monthly discharge values for Katar and Meki Rivers in accordance with Lenhart et al. (2002), Moriasi et al. (2007) and Winchell et al. (2013). The model was run for the simulation period of January 1, 1984, through December 2013, with the first 4 years (1984–1987) being used as a warm-up period. The stream flow data of 13 years from 1988 to 2000 were used for calibration and the subsequent thirteen years (2001–2013) were then used for validation period without any further adjustment and change in the model input parameters. The SWAT-CUP (calibration and uncertainty program) software of the program SUFI-2 was used for sensitivity analysis, calibration and validation of the model.

2.6. Goodness of fit tests

Model performance evaluations for the goodness-of-fit test were carried out based on Moriasi et al. (2007) and Nash and Sutcliffe (1970) using *graphical analysis*, a *coefficient of determination* (R^2), *Nash − Sutcliffe coefficient of efficiency* (NSE) and *the root mean square error index* (RSR).

The $\mathbf{R^2}$ is the magnitude of the linear relationship between the observed and the simulated values, and was calculated as (Moriasi et al., 2007):

$$R^2 = \left\{ \frac{\Sigma_{i=1}^{n}(O_i - \overline{O})(S_i - \overline{S})}{[\Sigma_{i=1}^{n}(O_i - \overline{O})^2]^{0.5}[\Sigma_{i=1}^{n}(S_i - \overline{S})^2]^{0.5}} \right\}^2 \tag{1}$$

Where: O_i is the observed flow for the i^{th} day of the simulation, S_i is the modeled flow for the *ith* day of the simulation, and $\overline{O}$ is the long term mean of the observed flow and $\overline{S}$ is the long term mean of the simulated flows.

NSE is used to indicate how well the plot of observed versus simulated value fits the 1:1 line, and was calculated as (Nash and Sutcliffe, 1970):

[1] http://swat.tamu.edu/software/arcswat/.

$$NSE = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \bar{o})^2} \tag{2}$$

where O_i, S_i and $\bar{O}$ are the same as Eq. (1).

RSR indicates errors in the unit of the quantity analyzed and was calculated as (Moriasi et al., 2007):

$$RSR = \frac{\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - \overline{Y_i^{sim}})^2}} \tag{3}$$

Where:

Y_i^{obs}=observed discharge at time step i

Y_i^{sim}=simulated discharge at time step i

$\overline{Y_i^{sim}}$=mean of observed discharge

$STDEV_{obs}$ = Standard deviation of the sample

n = number of observation

2.7. Performance rating

Performance evaluation of the monthly hydrological model outputs for both calibration and validation periods were carried out based on Moriasi et al. (2007).

2.8. Annual water balance

The hydrologic cycle that takes place in a watershed is explained by the water balance equation. Water balance equation after Neitsch et al. (2005) was used:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - \mathrm{E}_a - W_{seep} - \mathrm{Q}_{gw}) \tag{4}$$

Where:

SW_t is the soil water content at time t; SW_O is the initial soil water content on day *i*; *T* is time (days); R_{day} is the amount of precipitation on day *i*; Q_{surf} is the amount of surface runoff on day *i*; E_a is the amount of evapotranspiration on day *i*; W_{seep} *is the* amount of water entering the vadose zone from the soil profile on day *I; and* Q_{gw} is the amount of return flow on day *i*.

2.9. Evapotranspiration (ET)

ET for both the Lake Ziway and its watershed was estimated using SWAT model. SWAT estimates ET by the Penman–Monteith method (PMM) using climate data − daily solar radiation, daily minimum and maximum air temperature, daily humidity, and daily wind speed data (Neitsch et al., 2005).

3. Results

3.1. Sub-basins

Katar and Meki sub-watersheds were delineated from the entire Lake Ziway watershed which encompasses an area of 7032 km^2, of which Katar sub-watershed covers an area of 3337.7 km^2 and Meki sub-watershed has 2049.3 km^2. Thus, the computed runoff from each sub-watershed is routed through the Katar and Meki Rivers' network to the main watershed outlets, Lake Ziway.

3.2. Spatial distribution of elevation and slope classes

The spatial distributions of elevations in Lake Ziway watershed are found within a range of 1601–4213 m above sea level (m.a.s.l): 1604–4213 m.a.s.l in Katar sub-watershed and 1601–3612 m.a.s.l. in Meki sub-watershed (Fig. 2). Areas with higher elevations are located along the southeastern and northwestern ridge of the watershed whereas areas with lower elevation are located in the central portion of the watershed, all along the rift floor at both sub-watersheds' outlets.

The spatial distributions of slope classes in Lake Ziway watershed showed that 89% of the total watershed falls in a slope range of 0–30% whereas 9% of the total watershed area is within the range of 30- 60% while the remaining areas (2%) have a slope of > 60% (Table 2).

3.3. Sensitivity analysis

Fourteen selected SWAT hydrology input parameters were analyzed using the measured Katar and Meki Rivers flow data. The

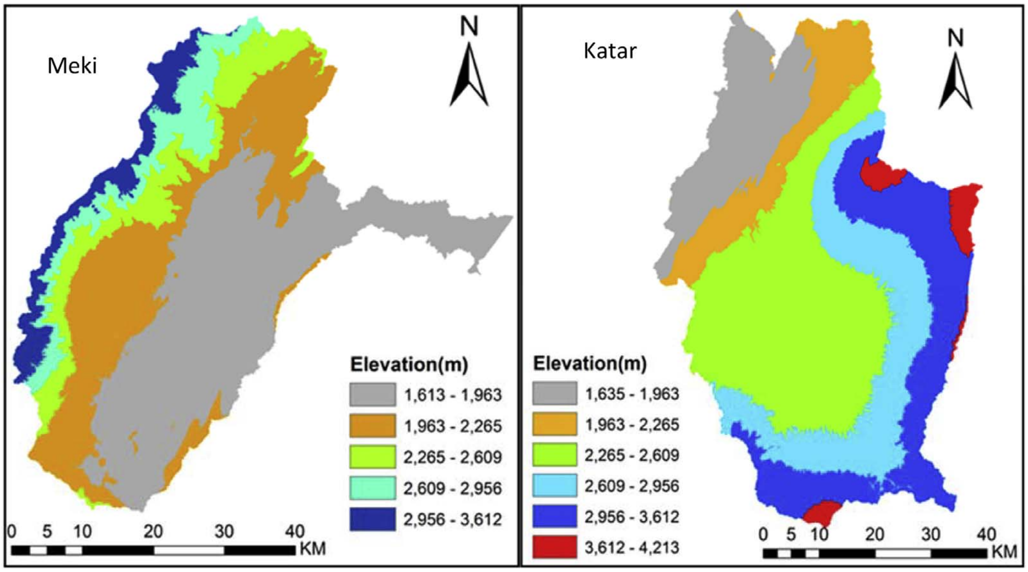

Fig. 2. Elevation in the Lake Ziway sub-watersheds.

Table 2
Slope percent converge in the whole Lake Ziway watershed.

Sub-watersheds	Slope area (km^2)			
	0–30(%) (level to moderately steep)	30–60 (%) (Steep hills and mountains)	> 60 (%) (Very steep hills and mountains)	Area (km^2)
Meki	1921.09 (85.3%)	271.45 (12.1%)	59.43(2.6%)	2251.97
Katar	2754.28(88.2%)	353.27(11.3%)	14.35 (0.5%)	3121.90
Lake Ziway surrounding	1630.65	26.87	0.91	1658.43
TOTAL	6306.02	651.59	74.69	7032.30

results showed that nine parameters were found more sensitive than others in both sub-watersheds, but with different sensitivity rank (Table 3).

3.4. Model performance (Efficiency) assessment

Model calibration is necessary to reduce the uncertainty in model outputs. Thus, the calibration results showed a good agreement between the simulated and observed monthly discharges in both sub-watersheds. The hydrographs and correlation for both sub-watersheds are indicated by graphical representations and model evaluation statistics (Figs. 3a–6b) , which shows that the timing of runoff events is well predicted by the model.

The result for simulated and observed monthly discharge in both sub-watersheds was evaluated against R^2, NSE and RSR during calibration and validation. The values in Katar sub-watershed fulfills the requirement of $R^2 > 0.6$, and both ENS and RSR > 0.5 and

Table 3
SWAT sensitivity analysis of the two sub-watersheds.

Parameter Name	Description	Sub-watershed		Sub-watershed	
		Meki	sensitivity Rank	Katar	sensitivity Rank
RCHRG_DP	deep aquifer percolation fraction	−17.74	1	−20.09	1
SOL_K	saturated hydraulic conductivity	16.35	2	10.64	4
CN2	SCS runoff curve number	16	3	11.55	3
GWQMN	a threshold minimum depth of water in the shallow aquifer for base flow to occur	−11.86	4	−20.07	2
ESCO	soil evaporation compensation factor	−9.22	5	4.73	7
SLSUBBSN	average slope length	−5.94	6	−5	6
GW_REVAP	groundwater “revap” coefficient	3.61	7	−10.25	5
SOL_AWC	saturated hydraulic conductivity	−1.29	8	−1.91	8
ALPHA_BF	Baseflow alpha factor	1.49	9	1.01	9

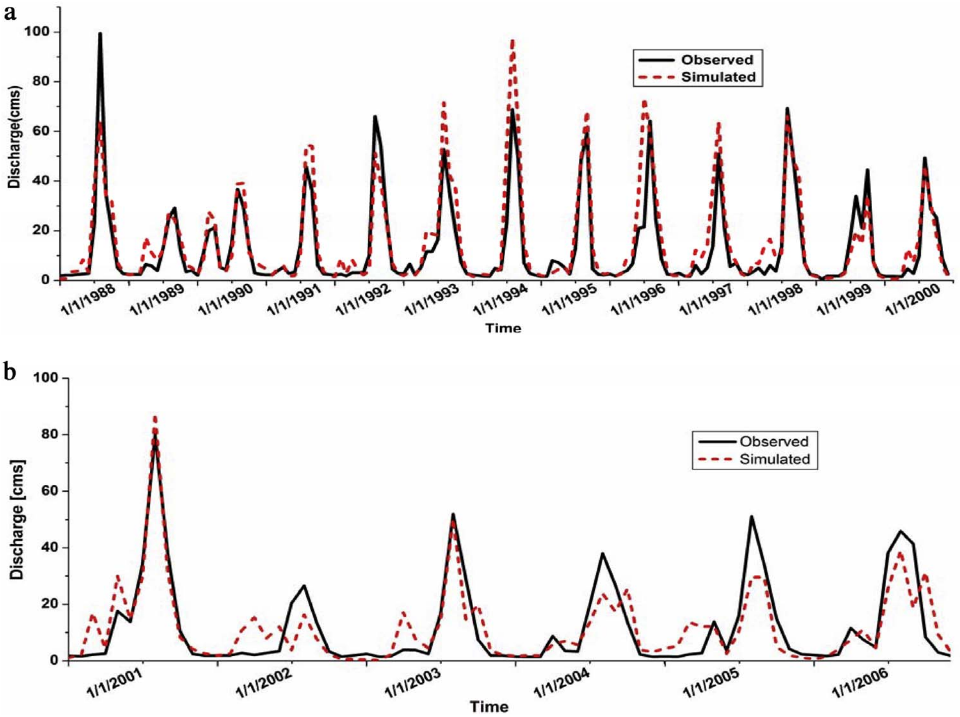

Fig. 3. a Hydrograph of the observed and simulated average monthly flow from the outlet of Katar sub-watershed for the calibration period. b. Hbydrograph of the observed and simulated average monthly flow from the outlet of Katar Sub-watershed for the validation period.
Graphical comparisons of Katar sub-watershed.

similarly the values in Meki sub-watershed also fulfills the requirement of $R^2 > 0.6$ and ENS > 0.5, but RSR showed slight variation (> 0.5 during validation while < 0.5 during calibration). Thus, according to the goodness-of-fit measures, the results show that simulated and observed monthly discharge was in very good agreement during calibration and validation for Katar sub-watershed whereas satisfactory to very good correlation for Meki sub-watershed. Thus, the overall model performance for Lake Ziway watershed is acceptable according to the performance evaluation criteria.

3.5. Annual water balance

The water balance ratios of the two sub-watersheds are shown in Table 4. For the calibration period, about 69% and 64% of the mean annual precipitation that respectively occurs in Meki and Katar sub-watersheds returns to the atmosphere through evaporations. For the validation period, these values increase to 72% and 69% in Meki and Katar sub-watersheds respectively. The annual discharge for the calibration period was estimated 20% (consisting of 13% surface runoff and 7% baseflow components of the annual rainfall) for Meki sub-watersheds and 27% (14% surface runoff and 13% baseflow components) of the annual rainfall for Katar sub-watershed. For the validation period, however, the simulated discharge was 18% (12% surface runoff and 6% baseflow) and 22% (12% surface runoff and 10% baseflow) of the annual precipitation for Meki and Katar sub-watersheds respectively.

The calibration statistics of the water balance for Katar sub-watershed show that surface runoff has the highest annual variability followed by the discharge whereas in the validation period baseflow show the highest annual variability followed by the discharge (Table 5). In Meki sub-watershed, however, the statistics of the water balance in both calibration and validation period show that baseflow has the highest annual variability which was closely followed by the discharge and surface runoff. The annual variations in ET and rainfall are relatively very low in both calibration and validation period for both sub-watersheds.

The predicted mean annual surface runoff is higher in the calibration period than the validation period in Katar sub-watershed while almost similar in Meki sub-watershed. For the same reasons, predicted ET is higher during validation than during calibration in both sub-watersheds. Of the two sub-watersheds, the major contributor of water to Lake Ziway is the Katar sub-watershed through the perennial Katar River which flows throughout the year. From the periods 1987–2013, the result showed that the water yield decrease by 75 mm (30%) to an average of annual 268.5 mm. Similarly, the proportions of the flow components such as surface runoff, lateral and groundwater flow have changed considerably between 1988 and 2013; SURQ decrease by 18.8 mm (16%) from 142.7 to 123.9 mm, GWQ decrease by 53.3 mm (47%) from 138.34 to 85.04 mm and LATQ decrease by 0.41 mm (1.3%) from 33.74 to 33.33 mm.

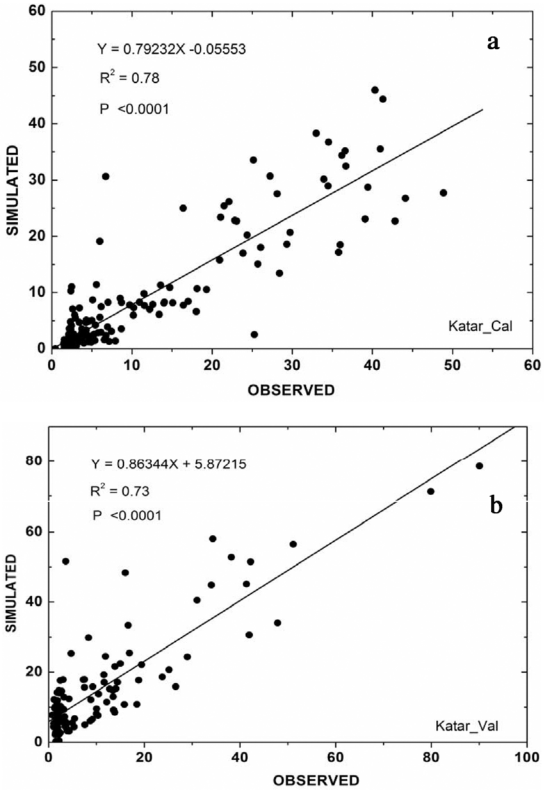

Fig. 4. a Correlation for observed and simulated monthly flow for calibration period of the Katar Sub-watershed. b. Correlation for observed and simulated monthly flow for validation period of the Katar Sub-watershed..
Graphical comparisons of Katar sub-watershed.

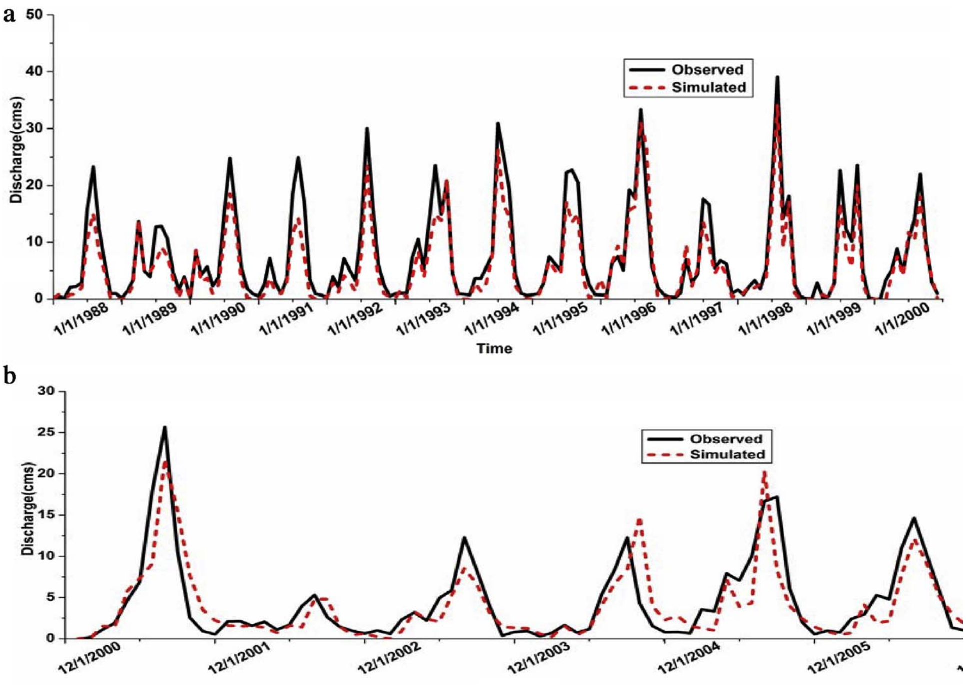

Fig. 5. a Hydrograph of the observed and simulated average monthly flow from the outlet of Meki Sub-watershed for the calibration period. b. Hydrograph of the observed and simulated average monthly flow from the outlet of Meki Sub-watershed for the validation period.
Graphical comparisons of Meki sub-watershed.

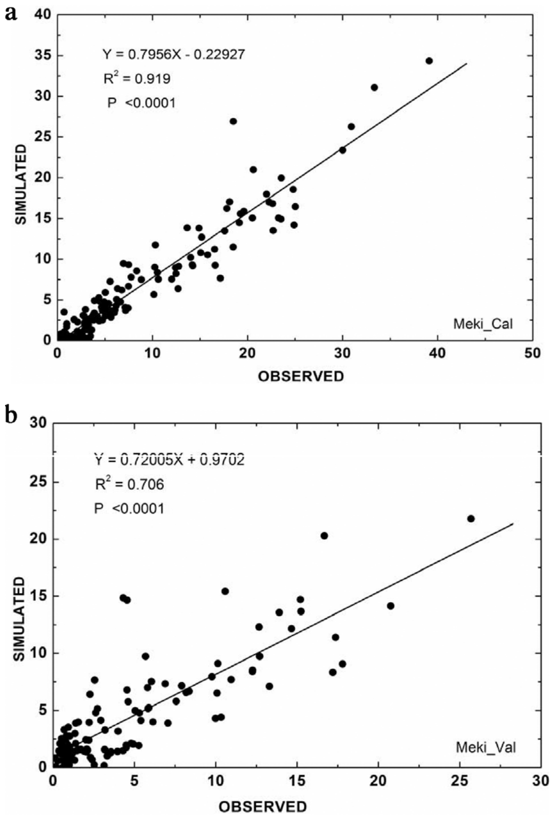

Fig. 6. a Correlation for observed and simulated monthly flow for calibration period of Meki Sub-watershed. b. Correlation for observed and simulated monthly flow for validation period of Meki Sub-watershed.
Graphical comparisons of Meki sub-watershed.

Table 4
Katar and Meki sub-watershed water balance ratios (in mm) at different periods.

Ratios	1988–2000		2001–2013	
	Meki	Katar	Meki	Katar
Stream flow/Precip	0.27	0.32	0.24	0.27
Base Flow/Total Flow	0.53	0.57	0.50	0.55
Surface Run-off/Total Flow	0.47	0.43	0.50	0.45
Perc/Precip	0.13	0.20	0.11	0.16
Deep recharge/Precip	0.01	0.01	0.01	0.01
ET/Precip	0.69	0.64	0.72	0.69

Table 5
Statistics of the water balance in the Katar and Meki Sub-Watershed (in mm).

		Rainfall	AET	PET	Baseflow	Surface runoff	Discharge
Katar Sub-watershed							
Calibration	Mean	992.34	662.21	1614.22	127.57	127.74	255.36
	CV	1.09	0.59	0.42	2.43	2.89	2.55
Validation	Mean	933.41	674.69	1731.53	91.89	100.65	192.54
	CV	0.92	0.55	0.20	3.52	2.44	2.80
Meki Sub-watershed							
Calibration	Mean	937.90	653.72	1800.49	71.99	110.29	182.28
	CV	1.02	0.72	0.34	4.09	2.29	2.86
Validation	Mean	959.11	693.08	1956.65	57.89	110.94	168.84
	CV	1.03	0.70	0.21	4.90	2.73	3.28

Table 6
Rainfall and runoff for the data management period of 1984–2013.

Parameters	Sub-watershed	
	Katar	Meki
Mean annual rainfall(mm)	966.6	951.7
Coefficient of variation(Rainfall)	12.8	13.1
Mean annual runoff(mm)	122.4	126.7
Coefficient of variation(Runoff)	34.8	29.3
Mean annual runoff coefficient(mm)	0.1	0.1
Coefficient of variation (runoff coefficient)	22.4	21.3

3.6. Surface runoff distribution and baseflow recharge estimates

The result showed that most of the surface runoff and baseflow (shallow groundwater recharge) which contributes to the river discharge in Lake Ziway watershed are generated in the high-elevation areas. Therefore, the mean annual recharge to the shallow groundwater in Katar sub-watershed as simulated in SWAT is 13% and 9% of the mean annual rainfall for calibration and validation periods, respectively, while it is 7% and 6% of the mean annual rainfall for calibration and validation periods, respectively, in Meki watershed.

3.7. Rivers discharge

The water balance result depicted that about 18% and 24% of the rains falling in Meki and Katar sub-watersheds, respectively, end up in Lake Ziway as total discharge. The temporal variability of the mean annual runoff is higher than the temporal variability of the mean annual rainfall in both sub-watersheds; however, the temporal variability of the mean annual runoff coefficient is higher in Katar than Meki sub-watershed (Table 6).

Comparing the two sub-watersheds with respect to discharge and water yield, Katar sub-watershed showed higher discharge and water yield than Meki sub-watershed. However, the long-term mean annual runoff showed a decreasing trend in both Meki and Katar sub-watersheds. Long-term mean annual discharge of Meki and Katar Rivers is shown for calibration and validation periods (Fig. 7).

3.8. Evapotranspiration (ET)

Plantation land cover type showed higher mean annual ET than other cover types in Lake Ziway watershed. The estimated mean annual ET in Lake Ziway watershed is 674 mm. This takes up 70% of the mean annual precipitation in the whole watershed. From 1987–2013, the result showed that ET increased by 30 mm (4.5%) to an average annual of 666.9 mm. However, the estimated long-term (26 years) mean annual ET for Lake Ziway is 1920 mm, with the maximum value in March (185 mm) with the trend shown in Fig. 8. When comparing the two sub-watersheds, ET is higher in Meki than Katar sub-watershed. But, the maximum values were recorded in March and lowest in July and August in both sub-watersheds.

4. Discussions

4.1. Water balance components

The values of infiltration, surface runoff, baseflow and aquifer recharge, ET, etc. are not similar in Katar and Meki sub-watersheds. The total mean annual surface runoff in Meki is higher than the Katar sub-watershed while vice versa for annual discharge/inflow. Besides, Meki sub-watershed has high ET (Tables 9) whose level of change also showed an increased trend, but this is more or less uniform in Katar sub-watershed. This might likely be associated with the differences in rainfall volumes, land cover patterns, topography and geological setups (Costa et al., 2003; Wang et al., 2006; Merz and Bloschl, 2009; Nosetto et al., 2012; Wang et al., 2014; Panday et al., 2015) assuming comparable temperature and elevation exist in both sub-watersheds. Thus, Meki sub-watershed has lower storage capacity and fast response to rainfall than Katar sub-watershed (JICA, 2002). The baseflow estimation in this study yielded 72 mm and 57.9 mm for calibration and validation periods, respectively, for Meki sub-watershed. However, Ayenew (2008) also estimated the baseflow between 80.1 and 62.7 mm for this sub-watershed using different models. Such difference might happen due to the changes occurring in land cover patterns through time in the watershed (Wang et al., 2006). In general, despite the differences in the values of hydrological components, the water balance in both sub-watersheds showed changes over time as reflected in the flow reduction of the Katar and Meki Rivers (Fig. 7).

4.2. Rivers discharge

Katar sub-watershed is 1.4 times larger than Meki sub-watershed, and their annual rainfall amount is also different. This could make differences in the amount of water contribution to their respective Katar and Meki Rivers whose flows determine the hydrology

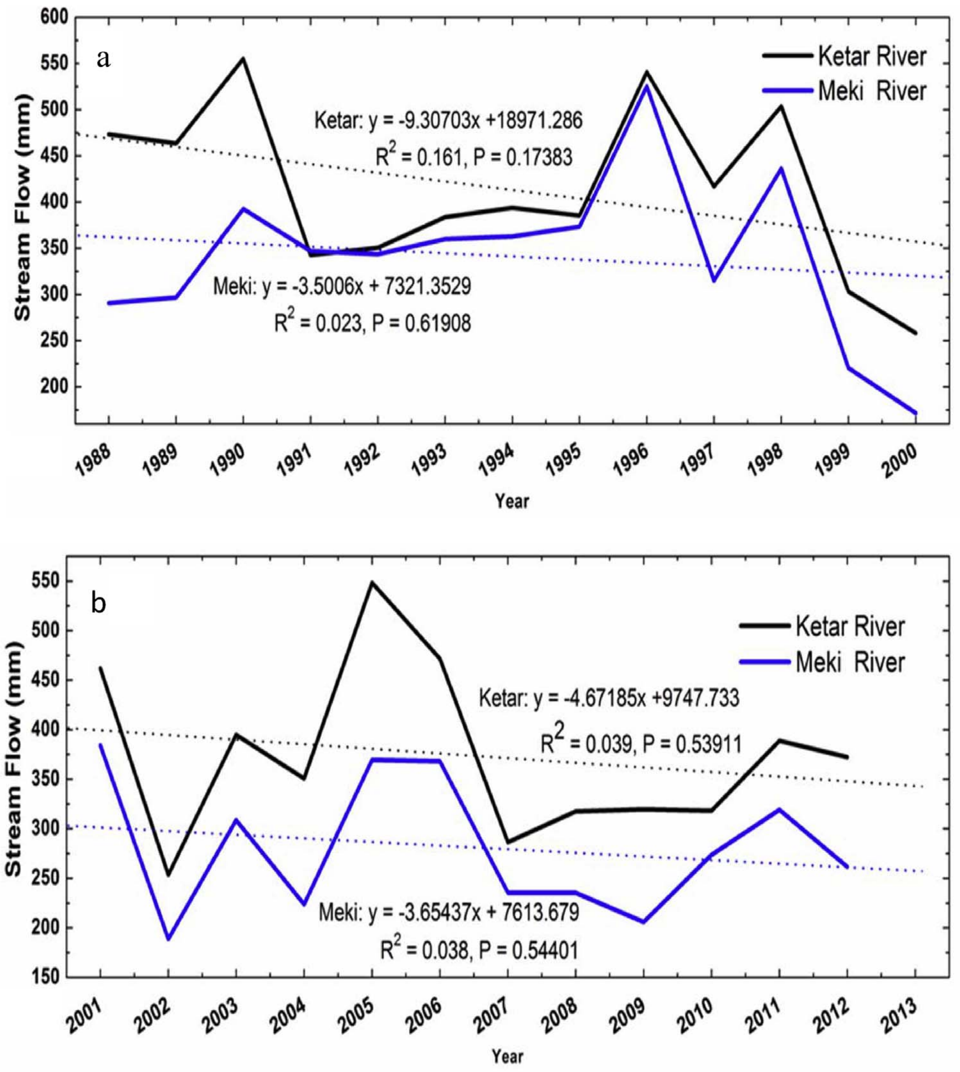

Fig. 7. Long-term mean annual discharge of Meki and Katar Rivers: (a) calibration and (b) validation periods.

of Lake Ziway. However, these rivers showed different flow regimes and temporal variability despite their similar highland origins. This variation might be caused by the different distribution of rainfall in their respective sub-watersheds − 24 percent rainfall collection in Katar and 18 percent in Meki sub-watershed to both finally feed Lake Ziway. Thus, the volume of Lake Ziway thus starts increasing at its maximum in rainy season (August − September) due to the Meki and Katar rivers' peak discharge levels while at its lowest levels during the dry season (January − March). However, increased irrigation farms in the sub-watersheds have contributed to the remarkable feeder rivers' flow reduction and in turn the Lake Ziway water level (Ayenew, 2004; Tamiru et al., 2006; Jansen et al., 2007; Scholten, 2007; Michael and Seleshi, 2007; Spliethoff et al., 2009; Kloos and Legesse, 2010; Pascual-Ferrer et al., 2014). This could affect the terrestrial hydrological cycle (Long et al., 2015; Lv et al., 2016) and increase ET in the sub-watersheds (Haddeland et al., 2006).

The analysis of water volume contributions to Lake Ziway through runoff coefficient (total runoff/total rainfall) shows that Katar sub-watershed has higher contributions than Meki sub-watershed (Table 6). However, the long-term mean annual runoff coefficient shows decreasing trends in both Meki and Katar sub-watersheds. This could likely to be due to land cover and climate changes (Merz and Bloschl, 2009; Zhang et al., 2009; Sriwongsitanon and Taesombat, 2011; Desta, 2016) and human and livestock population pressures (CSA, 2013; Tsegaye et al., 2012). The presence of vegetation cover increases the runoff coefficients, but agriculture and disturbed vegetation cover decreased the runoff coefficients (Wang et al., 2014).

Besides the climate phenomenon (Döll, 2009; Seneviratne et al., 2010; Trenberth, 2011) and land cover changes (Nosetto et al., 2012; Wang et al., 2012), anthropogenic factors such as direct human use negatively affect the water balance system (Famiglietti et al., 2011; Rodell et al., 2009). Thus, Katar and Meki Rivers are likely to cease to exist after 70 years and 67 years, respectively

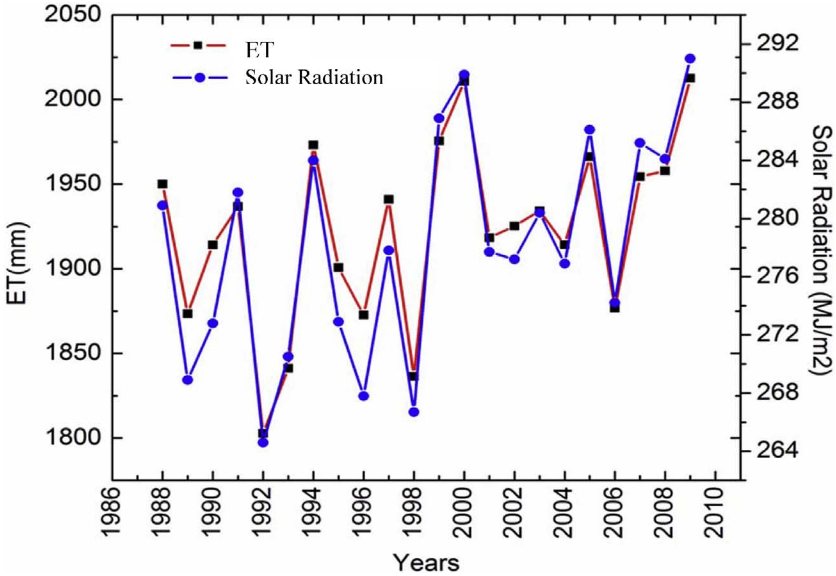

Fig. 8. Mean annual evapotranspiration of Lake Ziway (1986–2010).

(Fig. 7) if the current water abstraction, land cover changes, and other human impacts continue as is in the watershed. This decreases the water level of Lake Ziway and may turn the lake into saline (Jansen et al., 2007). Eventually, according to this scenario, the lake may dry out within seven decades, keeping other causes of lake volume reduction constant. If this happens as predicted, local communities who depend on the lake water for their domestic water supply, irrigation, and livestock watering will be affected. Further, the contribution of surface and groundwater from Lake Ziway to the downstream system of Lake Abijata will decline, jeopardizing this lake ecosystem (Vallet-Coulomb et al., 2001; Legesse and Ayenew, 2006; Wood and Talling, 1988). Such a phenomenon may, in general, be comparable to what has happened to Lake Haramaya (Alemaya) of Eastern Ethiopia (Lemma, 2002, 2003).

4.3. Elevation and slope

Long-term transport of soil particles via erosion has a relationship with elevation in a watershed (Willgoose, 1994). The slope classes in Lake Ziway watershed are spatially distributed along with elevation. Enactments of FDRE (2005), ONRS (2007) and SNNPR (2007) on the management of rural lands state that: (i) lands with a slope gradient of < 30% can be cultivated with soil conservation and water harvesting practices; (ii) cultivation on a slope gradient of 30–60% is only allowed by making terracing; and (iii) lands with a slope gradient of > 60% are only allowed for tree plantations. However, practically against such enactments, lands with 30–60%, i.e., about 54% (239 km^2) and > 60%, i.e., about 34% (50 km^2) of the total Lake Ziway watershed are generally under cultivation neglecting the fact that such landscapes could easily be affected by land degradation. This shows that cultivated lands are expanding in the upslope areas of the lake watershed by removing the natural vegetation. This accelerates soil erosion processes which certainly contribute to the massive transport of soil particles to the water bodies (Tong and Chen, 2002) particularly at flow peak rainy seasons. Thus, this affects the water level of Lake Ziway due to siltation transported by feeder rivers − Meki and Katar and surface run-off. This may, in turn, contribute to the drying of the lake by enhancing ET by making it shallower and warmer due to increasing its surface area in these times of climate change (Odada et al., 2006). Thus, addressing them is fundamental on sustainable watershed management (Bach et al., 2011).

4.4. Evapotranspiration (ET)

ET is a major hydrological variable that links water, surface energy exchanges and carbon cycles (Kampf et al., 2005; Chen et al., 2015). Its accurate estimation is necessary for the simulation of the soil-water balance, water resources management and planning (Bastiaanssen et al., 2005; Oki and Kanae, 2006; Yang et al., 2012), irrigation design (Allen et al., 1998), and climatological studies (Pielke et al., 1998; Teuling et al., 2009). Climatic and land cover changes affect the rates of ET (Jaramillo et al., 2013; Panday et al., 2015). According to Zeray et al. (2006), the climate data from 1984 to 2014 showed the progressive increase in ET in Lake Ziway watershed. This study showed that ET is higher in plantation forests than other land cover types of the watershed. This might be due to the fact that plantations evaporate more water than agricultural crops by evaporating intercepted water at higher rates throughout the year than shorter crops. Besides, the roots of plantation forests also reach to deeper groundwater than the crops to tap more soil water to maintain transpiration to lead to higher evaporation during dry periods (Calder et al., 1995). In semi-arid sub-watersheds like Lake Ziway, ET quickly depletes the unsaturated zone water during dry seasons, exposing the saturated zone to groundwater ET

Table 7
Comparison of Lake Ziway evapotranspiration estimations by months of the year.

Month	1			2			3	
	EB (mm)	PM (mm)	CRLE (mm)	PM (mm)	RM (mm)	PM (mm)	SR (mj/m^2)	SWAT (mm)
Jan.	143	154	132	150	135	159	23.9	167
Feb.	149	162	135	128	120	144	26.3	169
Mar.	152	166	149	148	142	192	25.8	185
Apr.	156	166	155	188	138	142	25	173
May	163	170	160	188	138	156	25	178
Jun.	147	168	155	135	107	137	20.9	144
Jul.	128	136	146	139	115	126	18.1	126
Aug.	136	137	136	135	115	123	19.4	135
Sep.	141	136	137	164	124	112	21.4	145
Oct.	159	162	141	200	151	170	23	161
Nov.	160	161	144	223	157	178	25.1	169
Dec.	143	157	139	225	157	130	24.3	168
Annual	1777	1875	1728	2023	1599	1799	1920	

NOTE: 1- Vallet-Coulomb et al. (2001); **2-** Ayenew (2003); **3** − This Study; **EM** stands for Energy Balance Method; **PMM** for Penman-Montheith Method; **CRLE** for Complementary Relationship Lake Evaporation Method; **PM** for Pan Method; **RM** for Radiation Method; **SAM** for Simple/Abitew Method; **SR** for Solar Radiation; **SWAT** for Soil and Water Assessment Tool Method

(Balugani et al., 2017). In Lake Ziway watershed, agricultural lands have been increasing at the expense of other land cover types since the early 1970s (Desta, 2016). This could change the biogeophysical land properties − surface albedo, roughness length, rooting depth and leaf/stem area index, which can all affect the ET rate of the surface area (Kvalevag et al., 2010; Jaramillo et al., 2013).

This study estimated the mean monthly and annual Lake Ziway ET (1920 mm) which takes about 2.4 times the yearly contribution of rainfall to the lake water budget. This was compared with earlier estimations of Vallet-Coulomb et al. (2001) and Ayenew (2003) (Table 7). The estimated amount is 5.4% lower than the estimate by Ayenew (2003) and 2.4% higher than the Vallet-Coulomb et al. (2001). Thus, the estimation fits more to the Vallet-Coulomb et al. (2001) Penman estimate than the other (Table 7). However, monthly ET is low during the rainy season (June to September) but shows an increase thereafter. Such an increase in the rate of ET would have a negative repercussion on Lake Ziway water volume. Increasing evaporation originating from increasing temperature may seem to be generally accepted with the status of global warming (Robock et al., 2000). Such magnitude of ET could affect water budget (reservoirs and stream flows) (Lentersa et al., 2005); hence, it is among the most important losses in many water resources management studies (Selim et al., 2017).

Besides ET, there is anthropogenic water loss from Lake Ziway. For example, > 1200 pumps of various capacities owned by individual farmers, farmers' associations, municipal water supply, public farms, and private companies are in operation of abstracting millions of liters of water per day from Lake Ziway (Desta, 2016). Such water withdrawal is affecting the water budget and lowering the level of Lake Ziway (Tamiru et al., 2006; Scholten, 2007; Pascual-Ferrer et al., 2014). Such level reduction in Lake Ziway could in turn affect the water level of Lake Abijata, which gets its water supply from Lake Ziway through Bulbula River (Fig. 1).

5. Conclusion

A decrease of surface and base flow and an increase of ET are observed in Lake Ziway sub-watersheds including the lake itself. This will lead in a long-term to the undesired effects on the lake. The increased irrigation development works in the watershed are one of the major drivers to reduce the flow of Katar and Meki Rivers. This can, in turn, affect the hydrology of Lake Ziway by making it shallower and increasing ET as has been observed in this study, along with increasing air temperature in these times of climate change.

Consequently, a more detailed study should be conducted to assess the influences of human pressures and climate changes on land and water resources in Lake Ziway watershed. Nonetheless, all concerned public institutions, private companies, and local communities in the watershed should be warned about the consequences that may follow on future generations because of the actions people take today without committing themselves to protect the watershed from further degradations. Otherwise, Lake Ziway will face severe problems in future and might become the second to go next to Lake Haramaya (Alemaya).

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