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Exploring Future Global Change Induced Water Imbalances in the Central Rift Valley Basin, Ethiopia

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Abstract

Lake Ziway, the only freshwater lake in Ethiopia's Central Rift Valley basin, has been the source for irrigation, floriculture, fish farming, and domestic water supply in the region for the last few decades. This study examined the impacts of the planned future agricultural developments and climate change on the lake water balance by an integrated application of the Soil Water Assessment Tool and Water Evaluation and Planning models. The future projections of precipitation and temperature from the Coordinated Regional Downscaling Experiment, CORDEX-AFRICA, under the Representative Concentration Pathways 4.5 and 8.5 were used for the climate change impact assessment. Nine irrigation development and climate change scenarios were developed and simulated to examine the separate and combined impacts on the lake water balance and supply coverages. The study showed that the planned future agricultural developments could result in a mean annual lake water level decline by about 0.15 m, with a considerable reduction (27% to 32%) in the outflow to the downstream Bulbula River. Climate change could increase evaporation losses from the shallow lake resulting in a drastic decrease in the lake water level, especially during the dry season. It could also significantly reduce (by about 74%) the amount of water flowing out of the lake. The combined impacts of future development and climate change are likely to reduce the supply coverages of most of the competing demands. Approaches need to be studied to minimize the lake water evaporation losses and explore water demand/supply management options.

KEYWORDS: Climate change; Lake Ziway; Socio-economic change; SWAT model; WEAP model.

1. Introduction

The Great East African Rift Valley comprises several endorheic lakes, which are increasingly facing pressure from economic development and population rise (Getnet et al., 2014). The Central Rift Valley (CRV) of Ethiopia is a closed basin in the Rift Valley where relatively small anthropogenic interventions may result in a far-reaching consequence on the scarcely available water resources and environmental quality (Ayenew, 2004; Jansen et al., 2007; Legesse et al., 2004). The basin has a unique freshwater ecosystem with both aquatic and terrestrial biodiversity, comprising lakes Ziway, Langano and Abiyata which are interconnected, and Shala which has independent drainage sub-basin. It contains essential agricultural economic activities such as floriculture, commercial fish farming, and recreational areas, including the Shala-Abiyata national park, known for its wealth of unique birds found only in Ethiopia (Legesse and Ayenew, 2006).

Lake Ziway is the only freshwater lake in the CRV and, therefore, sustains consumptive water uses. The Agricultural Development Led Industrialization policy was introduced in the country in 1992 (Hengsdijk and Jansen, 2006a) and resulted in the introduction of foreign investment in floriculture and rapid expansion of both large scale and smallholders' vegetables and fruits irrigation in the basin (Scholten, 2007). This involved a considerable increase in claims on land and water resources in the basin starting from the mid of the 1990s (Getnet et al., 2014; Hengsdijk and Jansen, 2006b). It resulted in a reduction in the volume of the discharges from the upstream lakes and a considerable decrease in size (by 50%) of the downstream terminal Lake Abiyata (Desta and Lemma, 2017; Desta et al., 2019; Getnet et al., 2014; Legesse and Ayenew, 2006).

Few studies have been conducted to investigate the impacts of irrigation water abstraction, climate change, and land-use change on the water resources of the CRV basin. Legesse and Ayenew (2006) employed hydrogeological mapping, surface, and groundwater modeling and hydro-chemical analyses to examine the significant environmental changes in the Ethiopian Rift Valley lakes due to improper utilization of land and water resources. The result of the study revealed a drastic decrease in the terminal lake water level and increased salinity. Abraham et al. (2006) studied the impact of climate change on Lake Ziway water availability and showed that the average annual inflow into Lake Ziway is expected to decrease. Jansen et al. (2007) assessed the land and water resources in the CRV basin and found that the decrease in the water level of Lake Ziway was about 0.5 m, and the outflow through Bulbula River was reduced to 50 million m^3 in 2003 and 2004. Climate change over the last four decades was also estimated to increase the amount of water evaporation from the lakes by nearly 40 million m^3 per year. Getnet et al. (2014) quantified the impacts of the historical climate and land-use changes and irrigation water abstraction on the water system of the CRV basin. They also estimated that an increase in temperature evaporated an additional 62 million m^3 of water from the lakes' surface, and change in land-use affected the amount of surface runoff. However, these initial studies recommended a detailed analysis for better understanding and management of the water resources in the CRV basin.

Despite the findings of the previous studies carried out in the area and the visible decline in the volume of the downstream lake and environmental degradation (Ayenew, 2004), smallholders' irrigations are expanding recently (Getnet et al., 2014). Additional irrigation projects to abstract more water from Lake Ziway and the main upstream rivers are also under the feasibility and pre-feasibility stages (Halcrow, 2010). Thus, a detailed analysis of the impacts of different irrigation project scenarios in combination with climate change is necessary to develop a reliable assessment to support decision-makers. This study conducted an in-depth investigation of the future water balance of Lake Ziway by integrating the physically-based hydrologic model; the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) and the water resources systems model Water

Evaluation and Planning (WEAP) (Yates et al., 2005) taking into consideration the future climate change and planned agricultural expansions. It also sets the basis for future adaptation studies contributing to fill the knowledge gap for the sustainable planning and management of the scarce water resources in the area.

2. Materials and Methods

2.1. Study Area

Lake Ziway sub-basin with a total area of 7,300 km^2 is located in the top northern part of the Ethiopian Rift Valley basin at about 165 km distance south of the capital Addis Ababa. It falls between gradients 38°12′36″E to 39°24′36″E longitude and 7° 22′12″N to 8° 28′12″N latitude with two escarpments in the northwestern and southeastern parts and the rift floor in between. The shallow depth Lake Ziway with an area of about 450 km^2 located at 1636 m above sea level, is fed by the two main upstream rivers, Ketar and Meki, from the eastern and western highlands, respectively, with an estimated mean annual inflow between 675 to 695 million m^3,

Lake Ziway is the only freshwater lake in the CRV basin known for its commercial fish farming. Smallholders' irrigation, large-scale private and state irrigation schemes, and closed vegetable and flower production firms are concentrated around the lake, upstream of Bulbula, and the downstream parts of Meki and Ketar rivers. The recent agricultural expansions abstract a significant amount of water from the lake and inflowing and outflowing rivers. Lake Ziway also serves as the source of the domestic water supply for the nearby Ziway town. The natural discharge from the lake through Bulbila River (when water levels are 0.48 m above local datum) is about 200 million m^3 per year (Jansen et al., 2007) which, excluding the water abstractions on Bulbila River, covers the principal amount of the annual inflow to the downstream terminal Lake Abiyata.

Since Lakes Langano and Abiyata are relatively saline lakes, most of the existing and planned irrigation expansions are mainly concentrated around Lake Ziway (Getnet et al., 2014). Smallholder open-field vegetable and fruits production, closed-vegetable and flower production of private firms and open-field vegetable and fruits production owned by both private and state farms are the central production systems in the sub-basin (Hengsdijk and Jansen, 2006a). The water abstraction from the upstream rivers is less compared to the direct pumping from Lake Ziway and the downstream Bulbula River.

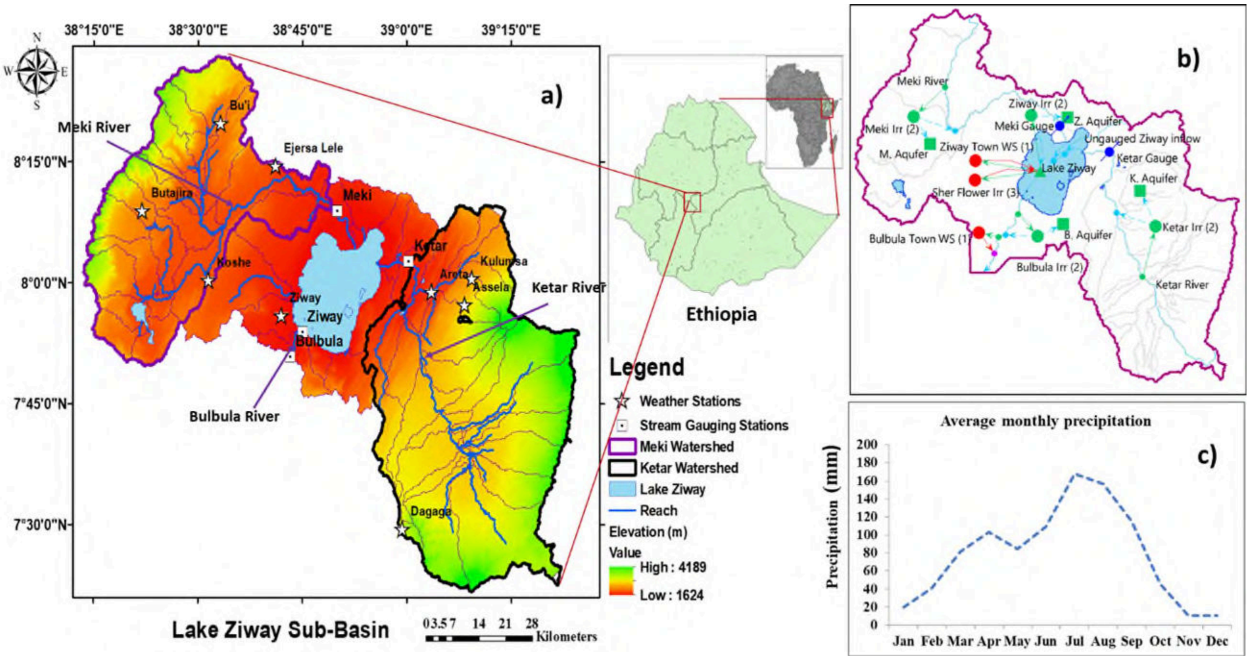

Fig. 1. *Location map of the study area a) Lake Ziway sub-basin showing Meki and Ketar watersheds and gauging stations b) WEAP model setup with water demand, and supply nodes and c) Observed average monthly rainfall distribution.*

2.2. Data

Meteorological data (from 1980 to 2014) of nine stations in the sub-basin were obtained from the National Meteorological Agency of Ethiopia. Discharge data (from 1980 to 2005) of Ketar and

Meki rivers and water level data of Lake Ziway used for the calibration and validation of the models were collected from the Ministry of Water and Energy of Ethiopia. A Digital Elevation Model (DEM) of 30-m resolution downloaded from the Shuttle Radar Topographic Mission was used to delineate the watersheds. Land cover data were reclassified using ERDAS Imagine 2016 from downloaded satellite images. The soil properties information was extracted from the Food and Agriculture Organization (FAO) digital soil map. Data such as demand sites, population, water use rate, crop types, and cropping pattern, and water requirement of flower irrigation used for Ziway pressurized irrigation project study were obtained from Oromia Irrigation Development Authority (OIDA) for year 2005 considered representative for the reference simulation period. Hydro-meteorological datasets for the period from 1985 to 2005 were chosen for reference simulation.

2.3. Methods

In this study, the impacts of climate change and irrigation water abstractions on the hydrologic system of Lake Ziway were assessed by an integrated application of the SWAT and WEAP models. SWAT is a well-tested, physically based, semi-distributed, and continuous simulation hydrologic model (Arnold et al., 1998). The model can be applied in small and large complex watersheds to assess the impacts of climate changes and different land management practices on water quantity and quality (Neitsch et al., 2011). The SWAT hydrologic model was calibrated and validated using the discharge data measured from 1980 to 1993 at Meki and Ketar gauging stations. The model was setup and calibrated separately for both Meki and Ketar watersheds (Musie et al., 2019). The calibration and validation periods were selected based on the availability of continuous data. The SWAT Calibration and Uncertainty Program was applied to perform the global sensitivity analysis of the parameters used for the calibration. The results showed that CN2, HRU_SLP, ESCO,

RCHRG_DP, ALPHA_BNK, SOL_AWC, EPCO, REVAPMN, and BIOMIX were sensitive parameters for the calibration of streamflows for Ketar watershed (Musie et al., 2020a). The SWAT model was applied to simulate the baseline and future climate scenario streamflows.

WEAP is a well-designed, comprehensively integrated, and policy-oriented model developed to evaluate a wide range of water resources development and management scenarios (Mersha et al., 2018; Sieber, 2006). The model can serve as an integrated water resource management decision support system tool seamlessly integrating a range of hydrologic processes with water uses and the management of infrastructures (Yates et al., 2005). The WEAP model was used for the lake water balance analysis and supply coverage assessment under different water abstraction and climate change scenarios. Town water supplies and vegetation irrigations were given the first and second priority rank. Whereas, "Sher Ethiopia flower" farm was given the third priority rank (Figure 1). The crop water requirement was estimated using the WEAP-MABIA module. The feature uses the FAO Irrigation and Drainage Paper No. 56 algorithms (dual Kc approach) to calculate the daily irrigation requirements based on the soil moisture levels (Schneider et al., 2019). The WEAP model was calibrated (from 1985 to 1999) and validated (from 2000 to 2005) using the observed water level of Lake Ziway for the baseline period. The model calibration was performed by changing the values of the Top of Conservation of the reservoir. The Top of Conservation which is the maximum volume of water in the reservoir in each year was used as it represents the maximum observed level of a lake with unregulated outflow.

2.4. Climate projections and bias correction

Detailed analysis of the hydrologic impacts of future climate change on Lake Ziway sub-basin streamflow and water balance components was conducted in our previous study (Musie et al., 2020b). Climate projections from sixteen models from the Coordinated Regional Downscaling

Experiment (CORDEX-AFRICA) and the NASA Earth Exchange (NEX) Global Daily Downscaled Projections (GDDP) datasets were evaluated. Streamflow simulated using the climate model projections during the reference (1985–2005) and future period (2040–2059) were compared to the simulations using the observed meteorological data. Performance indicator such as the percentage bias (PBIAS), coefficient of determination (R^2), correlation coefficient (Correl.), standard deviation (SD), and the normalized SD of discrepancies (SD_D) were used for the hydrologic evaluation. In addition, the following criteria and threshold values were used to further categorize and select the climate models.

- The reference period average annual streamflow simulated by a model must satisfy the seasonality requirement with $R2 \geq 0.70$. If a model fails to fulfill this, it is assumed as inferior.
- The volumetric deviation of the reference period average annual streamflow simulated by a model must not exceed a PBIAS of ± 25 %.
- The volumetric change in the average annual streamflow simulated by a model for the near future period (RCP8.5) compared to the reference period should not exceed ± 30 %.

Based on these analyses only five regional climate models (RCMs) from the CORDEX-AFRICA models that satisfied the criteria set for the evaluation were selected for the climate change impact assessment.

An ensemble of the five RCMs from the CORDEX-AFRICA downscaled from five Global Climate Models (GCMs) (Table 1) of the Climate Model Inter-comparison Project Phase 5 were used in the current study to project climatic variables into the middle of the century (2040-2060). The RCMs evaluated (hydrologically) and selected are the latest version of the RCMs developed by the Swedish Ross Centre Regional Atmospheric model (RCA4) (Samuelsson et al., 2011). As compared to the previous versions such as RCA3, the latest version (RCA4) is designed with an improved physical and energy flux parametrizations (Strandberg et al., 2015). The spatial resolution of the CORDEX-AFRICA domain RCA4 model outputs is 0.44° × 0.44° (approximately 50 km × 50 km). Two Representative Concentration Pathway scenarios, RCP4.5 and RCP8.5, were considered in the study. RCP 4.5 corresponds to intermediate emissions and a low stabilization scenario, where RCP 8.5 represents a high-end emission scenario (Stocker et al., 2013). Distributed mapping was applied using the CMhyd software (Rathjens et al., 2016) to bias correct the future precipitation and temperature projections. Observed precipitation and temperature data at the nine gauging stations found in the sub-basin were used for the bias correction of the selected regional climate models data.

Table 1. Description of the CORDEX-AFRICA regional climate model (RCA4) simulations.

Institution	**Name**	**Country**	**GCM Resolution**
Canadian Centre for Climate Modelling and Analysis	CanESM2	Canada	2.8° ×2.8°
Centre National de Recherches Meteorolo-Giques/Centre Europeen de Recherche et Formation Avanceesencalcul scientifique	CNRM-CM5	France	1.4° ×1.4°
Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology	MIROC5	Japan	1.4° ×1.4°
Norwegian Climate Centre	NorESM1-M	Norway	1.9° ×2.5°
Institut Pierre-Simon Laplace	IPSL-CM5A-MR	France	1.25° ×2.5°

2.5. Scenario selection

Nine scenarios were developed to evaluate the impacts of irrigation and domestic water abstractions and climate change on the water balance of Lake Ziway and the outflow from the lake to the downstream Lake Abiyata (Table 2). The scenarios for water use change were developed based on the previous master plan and irrigation projects proposal studies. According to the Rift Valley Lakes Basin Integrated Resources Development Master Plan Study Project, there are plans to implement a pressurized irrigation project to develop up to 15,500 ha by directly pumping water from Lake Ziway. However, only 5,500 ha of new irrigation can be supported in the CRV basin with no further abstraction along the downstream river (Halcrow, 2010). Based on the master plan study, the feasibility and detailed design study to develop an additional 5000 ha (surface irrigation) was carried out by the Ethiopian Water Works Design and Supervision Enterprise (WWDSE, 2008). Japan International Cooperation Agency (JICA), in collaboration with Oromia Irrigation Development Authority (OIDA), also studied an irrigation and rural development project in the basin and recommended 2,300 ha of additional irrigation by diverting water from Meki River.

Table 2. Descriptions of the simulated future development and climate change scenarios.

Scenarios	Abbreviation	Climate data
Reference		
• Baseline scenario	Base	Observed (1985-2005)
Climate change		
• Climate change under RCP 4.5 scenario	RCP 4.5	RCP 4.5 (2040-2059)
• Climate change under RCP 8.5 scenario	RCP 8.5	RCP 8.5 (2040-2059)
Future agricultural developments		
• Ongoing and feasibility stage scenario	OFS	Observed (1985-2005)
• Future development scenario	FDS	Observed (1985-2005)
Future agricultural developments with climate change		
• Ongoing and feasibility stage + climate change under the RCP4.5	OFS-RCP4.5	RCP 4.5 (2040-2059)
• Ongoing and feasibility stage + climate change the under RCP 8.5	OFS-RCP8.5	RCP 8.5 (2040-2059)
• Future development + climate change under the RCP 4.5	FDS-RCP4.5	RCP 4.5 (2040-2059)
• Future development + climate change under the RCP 8.5	FDS-RCP8.5	RCP 8.5 (2040-2059)

Base means with existing irrigation and domestic water supply, OFS = Ziway pressurized project + "Sher flower Ethiopia" expansion, and FDS = Ziway pressurized project + "Sher flower Ethiopia" expansion + Meki River diversion project.

The “base scenario” represented the existing irrigation water abstractions and domestic water supply for the baseline period from 1985 to 2005. The existing irrigation water abstractions refer to the pumping of water to irrigate about 1,250 ha from the upstream two rivers, 2,000 ha from Lake Ziway, and 1,100 ha from the downstream Bulbula River. Based on the Ziway irrigation project study obtained from OIDA the water abstraction was supposed to irrigate for two seasons each year. The two future agricultural development scenarios were set up to analyze the impact of the additional irrigation projects. The ongoing and feasibility stage (OFS) scenario represented the impact of the 5000 ha Ziway irrigation project (“Ziway Irr” in Fig. 1) and 500 ha expansion of the “Sher Ethiopia flowers” floriculture (“Sher Flower Irr” in Fig. 1) by directly pumping water from Lake Ziway. The future development scenario (FDS) represented the OFS scenario plus the 2,300 ha irrigation project by diverting water from Meki River (“Meki Irr” in Fig. 1). The climate change scenarios were intended to study the impacts of the future streamflow and lake evaporation under climate projections of RCP 4.5 and RCP 8.5 for the period from 2040 to 2060. The results presented show the average of the ensemble outputs. Besides, four additional scenarios combining agricultural developments with climate change were developed to represent impacts of future global change on the system.

3. Results

3.1. Climate projections and lake evaporation under climate change

Future annual precipitation is expected to decrease by similar magnitude (27.3% and 27.1%) under RCP 4.5 and 8.5, respectively, compared to the baseline. However, the changes are uneven throughout the year. The expected changes in the monthly means between the future projections under the two climate change scenarios and the historical were quantified as displayed in Fig. 2. Most climate models estimated a notable decrease in monthly precipitation, especially during the low rainfall season (February to May) while during the wet season (June to September) the signal is less consistent across RCMs but generally indicates decrease. Increase and decrease of precipitation tend to be more marked under RCP 8.5. The decline in precipitation during the rainy seasons were expected to result in a reduction of streamflows.

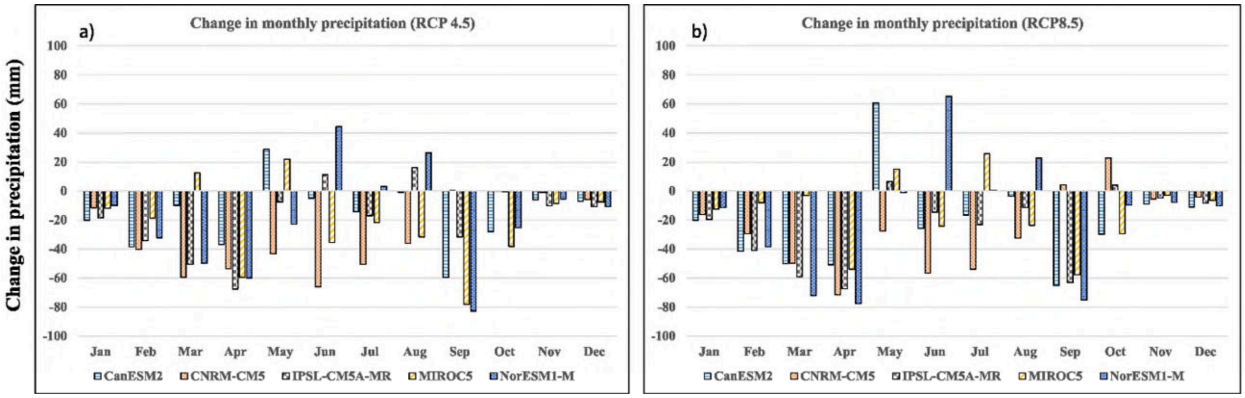

Fig. 2. *Absolute changes in monthly precipitation projected by the CORDEX-AFRICA regional climate models under RCP 4.5 (a) and RCP 8.5 (b) compared to the base period gauge measurement.*

Average annual temperature across Lake Ziway sub-basin will increase significantly, 2.34°C under RCP 4.5 and 3.17°C under RCP 8.5 with some seasonal differences. The projected changes in the monthly mean temperature are presented in Fig. 3. Under both the climate change scenarios, the mean monthly temperature estimated by all the models showed a consistent pattern of increase for the period from 2040 to 2060 compared to the historical period. However, the projected changes are higher in magnitude under RCP 8.5 than RCP 4.5. The average increase estimated by the models ranges from 1.54 ^{0}C to 3.32 ^{0}C under RCP 4.5, while it ranges from 2.25 ^{0}C to 4.13 ^{0}C under RCP 8.5, with the highest increases occurring during the warmest months (i.e. December to February). The projected change in temperature is expected to increase the potential evapotranspiration of the system and specifically to affect the shallow lake surface water evaporation.

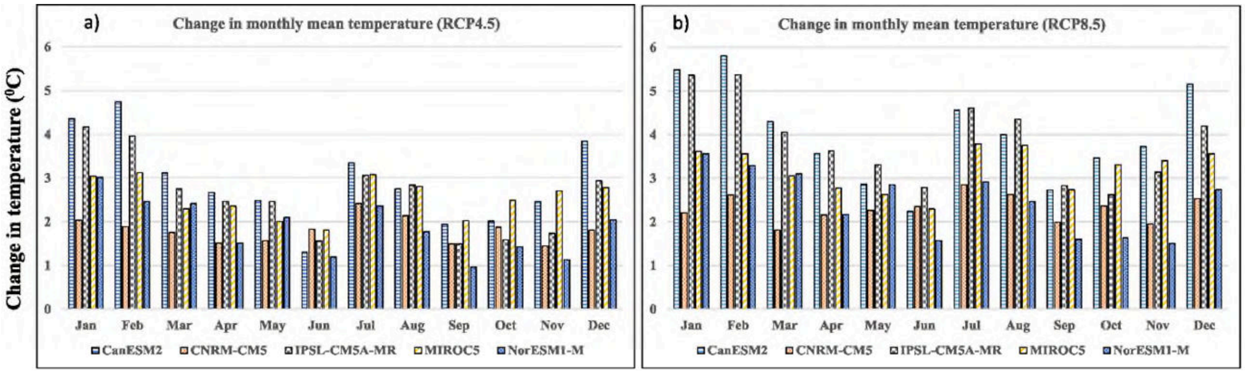

Fig. 3. *Absolute changes in monthly mean temperature projected by the CORDEX-AFRICA regional climate models under RCP 4.5 (a) and RCP 8.5 (b) compared to the base period gauge measurement.*

Lake water evaporation is the principal and most challenging component of the lake water balance to estimate in the African tropical lakes and it is required as input to WEAP. Vallet-Coulomb et al. (2001) estimated the annual evaporation from Lake Ziway using the Complementary Relationship Lake Evaporation Model (CRLE), the Penman formulation, and the energy balance methods. They found values ranging from 1730 mm/year to 1870 mm/year. They also concluded that the application of the Penman equation with land data is expected to overestimate the monthly lake evaporation by nearly 10%. Fig. 4 shows the historical and future projected net lake evaporations estimated using the FAO ETo calculator, assuming the Kc value of one for a shallow water body. The mean annual lake evaporation estimated for the historical period was 1785 mm/year, which is in good agreement with the previous findings. The net evaporation from the lake surface showed a marginal increase in the months from October to December, under both climate change scenarios. However, a higher change is shown in the months from January to September.

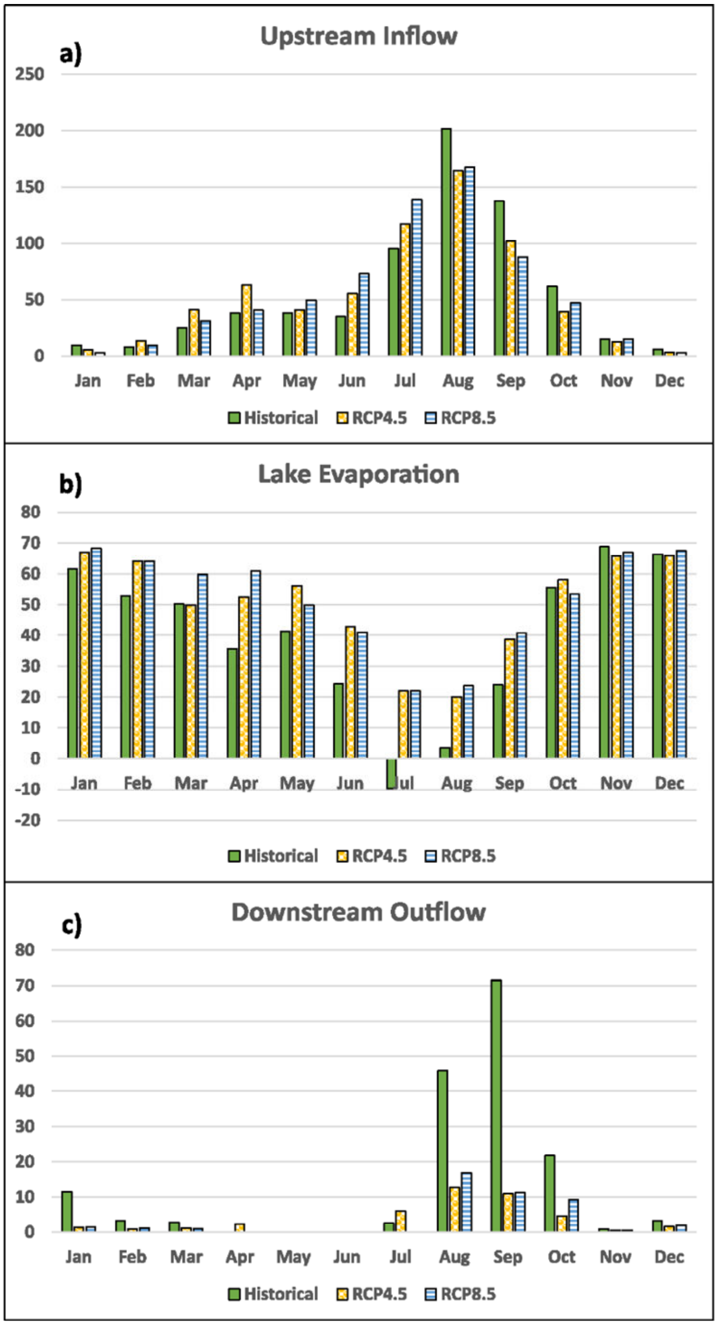

Fig. 4. *Estimated mean monthly upstream inflow (a), lake net evaporation (b) and downstream outflow (a) using the historical and future projected climate variables under RCP 4.5 and RCP 8.5.*

3.2. Model calibration and validation

The SWAT hydrologic model simulated the discharge from Meki watershed with goodness-of-fit values of NSE 0.75, PBIAS 7.60%, and RSR 0.50 for the calibration and NSE 0.70, PBIAS 0.08%, and RSR 0.55 for the validation periods, respectively. It was also able to simulate the discharge from Ketar watershed with values of NSE 0.83, PBIAS 7.10%, and RSR 0.41 for the calibration and NSE 0.75, PBIAS -5.02% and RSR 0.50 for the validation periods, respectively. After the affirmation of the model's simulation of streamflows from the two upstream watersheds, it was run for the baseline and future periods and used as input in the WEAP model.

Similarly, the calibrated WEAP model was able to simulate the level of the lake with acceptable goodness-of-fit values of NSE 0.80, PBIAS 0.28%, and RSR 0.44 for the calibration period and values of NSE 0.75, PBIAS -1.73% and RSR of 0.50 for the validation period (Fig. 5). The baseline simulation of the lake water level and the observed data are displayed in Fig. 5. The model performance metrics and the visual comparison demonstrate that both SWAT and WEAP models have a very good ability to simulate streamflow and water levels in Lake Ziway (according to the generally accepted performance rating criteria for NSE and PBIAS of (Moriasi et al., 2007)), indicating that the models are useful to explore global change impacts.

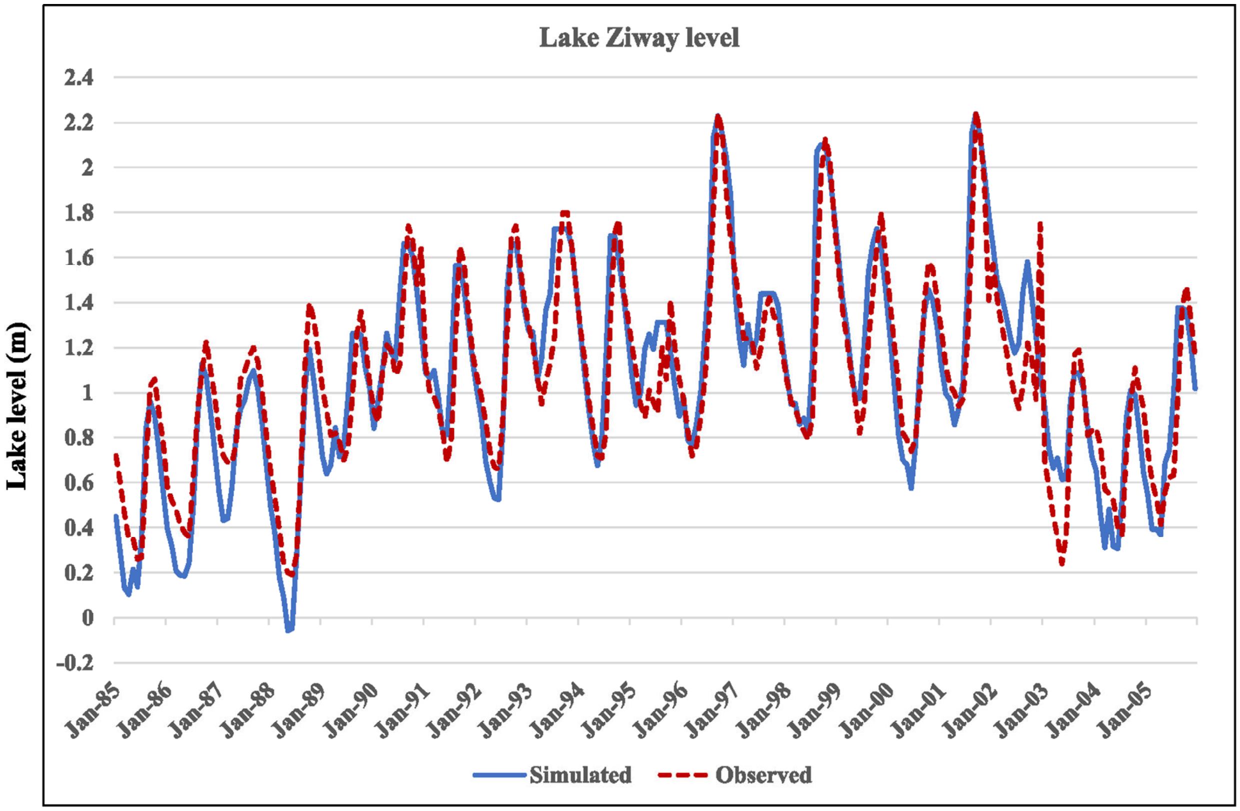

Fig. 5. *WEAP model-simulated and observed water levels of Lake Ziway for the base period from 1985 to 2005.*

3.3. Comparison of water balance and supply coverages under simulated scenarios

The changes in the lake water balance components under the different simulation scenarios are presented in Table 3. The percentage of relative change in the water balance under each scenario was calculated compared to the base scenario. In addition to the lake water balance, the monthly mean lake water levels under the scenarios considered are shown in Fig. 6. The total inflow into the lake accounts for inflows from upstream rivers and the returns from some of the peripheral demands (see Fig. 1). The relative changes in this variable under the examined scenarios were marginal, ranging from -2.6% to 0.3%, showing the minimal impacts of the planned future agricultural developments and climate change.

Table 3. Changes of Lake Ziway water balance components under different scenarios considered.

Scenarios	Total Inflow (Mm^3/yr)	Relative change with baseline (%)	Irrigation and water abstraction (Mm^3/yr)	Relative change with baseline (%)	Net Evaporation (Mm^3/yr)	Relative change with baseline (%)	Downstream discharge (Mm^3/yr)	Relative change with baseline (%)
Reference								
Base	671.7		25.7		474.4		163.1	
Climate change								
RCP 4.5	658.6	-2.0	12.6	-51.0	603.0	27.1	41.9	-74.3
RCP 8.5	667.0	-0.7	12.6	-51.2	618.9	30.5	43.7	-73.2
Future agricultural developments								
OFS	673.7	0.3	76.0	195.7	470.4	-0.9	119.5	-26.7
FDS	663.1	-1.3	75.1	192.4	469.4	-1.1	110.9	-32.0
Future agricultural developments with climate change								
OFS-RCP4.5	659.5	-1.8	32.1	25.1	599.9	26.5	27.8	-83.0
OFS-RCP8.5	668.5	-0.5	28.2	9.9	613.5	29.3	35.8	-78.0
FDS-RCP4.5	654.5	-2.6	31.5	22.5	599.0	26.3	24.8	-84.8
FDS-RCP8.5	666.5	-0.8	27.7	7.7	612.9	29.2	35.0	-78.5

3.3.1. Climate change scenarios

The changes in streamflow of the two upstream rivers due to climate change were simulated to be minimal and, interestingly, reductions are smaller under the worst climate change scenario (i.e. RCP 8.5), due to the relatively equivalent reduction in annual precipitation projections under both the RCPs. Detailed analysis of the hydrologic impacts of future climate change on the streamflow and water balance components of the two watersheds was presented in our previous study (Musie et al., 2020b). The compensation effect of the projected increase in streamflow of Ketar watershed with the decrease in streamflow of Meki has also minimized the change in total inflow to the lake. Hence, the marginal decrease in total inflow, under the climate change scenarios, is mainly attributed to the decline in the amount of precipitation. The simulation results under these scenarios also showed an increase in the amount of net evaporation from the lake water surface by 27.1% under RCP 4.5 and 30.5% under RCP 8.5. Following the rise in lake evaporation, the total amount of water abstraction is projected to decrease by nearly 51% (Table 3). Similarly, the amount of downstream outflow through Bulbula River is expected to reduce by the middle of the century with similar magnitudes under RCP 4.5 and RCP 8.5. The mean monthly lake water levels simulated under the separate scenarios presented in Fig. 6a show that climate change scenarios simulated lake water levels are estimated to reduce by about 0.65 m both during the wet and dry seasons.

The percentages of the water supply coverage for the demand sites under the scenarios considered are presented in Table 4. Under the baseline scenario, the average monthly supply coverage of the domestic water was estimated to be above 99%, while the mean monthly irrigation water coverage ranges from 92.8% for Meki to 98.4% for Ziway and Bulbula irrigation schemes. Under the climate change scenarios, about 12% (RCP 4.5) and 14% (RCP 8.5) of the town water supplies and 25% irrigation water requirements are likely to be uncovered. Because of the lowest priority rank given to the “Sher Ethiopia flower” irrigation during the modeling, less than 50% of the water demand could be delivered under the climate change scenarios.

3.3.2. Agricultural development scenarios

The total amount of water abstraction from Lake Ziway and the outflow through Bulbula River estimated in this study for the base scenario are 25.7 Mm^3/year and 163.1 Mm^3/year, respectively (Table 3). These are in agreement with the estimated values of 25Mm^3/year and 168Mm^3/year, respectively, of the previous study conducted by the Ethiopian Water Works Design and Supervision Enterprise (WWDSE, 2008). The amount of water abstraction from Lake Ziway under the future agricultural development scenarios, OFS and FDS, is estimated to increase by three times the base scenario (Table 3). The increase in water abstraction is expected to reduce the water level in the reservoir and, thereby, the amount of net evaporation loss from the water surface by around 1%. The downstream outflow is also estimated to considerably decrease under both the OFS and the FDS scenarios. The mean monthly lake water levels simulated under the future agricultural developments are estimated to reduce by about 0.15 m during the months from March to June, while the changes in the lake water level during the rest of the months are less. Marginal decreases in the percentages of water demand coverage were estimated under the ongoing and feasibility stage development scenario (OFS). Whereas, under the future development scenario (FDS), the expected monthly average supply was projected to reduce to 80% for Meki irrigation and 96.7% for Ziway and Bulbula Irrigations (Table 4).

3.3.3. Combined climate change and agricultural development scenarios

Under the future agricultural development with climate change scenarios, the relative changes in the water abstractions are expected to increase marginally. However, the relative change is more for the future development with climate change under the RCP 4.5 than 8.5. The percentage increase is also less than the agricultural development scenario due to the reduction of the lake water availability following the evaporation loss due to climate change. The excessive surface water evaporation from the lake under the future climate change scenarios is expected to result in a water shortage for the planned future agricultural developments. The downstream outflow is also estimated to decrease significantly by more than 80% (under OFS-RCP 4.5 and FDS-RCP 4.5) and about 78% under OFS-RCP 8.5 and FDS-RCP 8.5 scenarios. This is attributed to the more reduction in the total inflow to the lake under RCP 4.5 than 8.5 following the precipitation projections under the two RCPs. The agricultural development with climate change scenarios simulated lake water levels are also projected to decrease further to nearly zero (datum) level in March, April and May, as shown in Fig 6b and 6c. Under the combined scenarios of climate change and future development, the amount of water available for domestic water supply is estimated to reduce to nearly 92%. Similarly, the irrigation water supply coverages range from 67.1% for Meki Irrigation to 75.7% for Ziway and Bulbula irrigation schemes (Table 4).

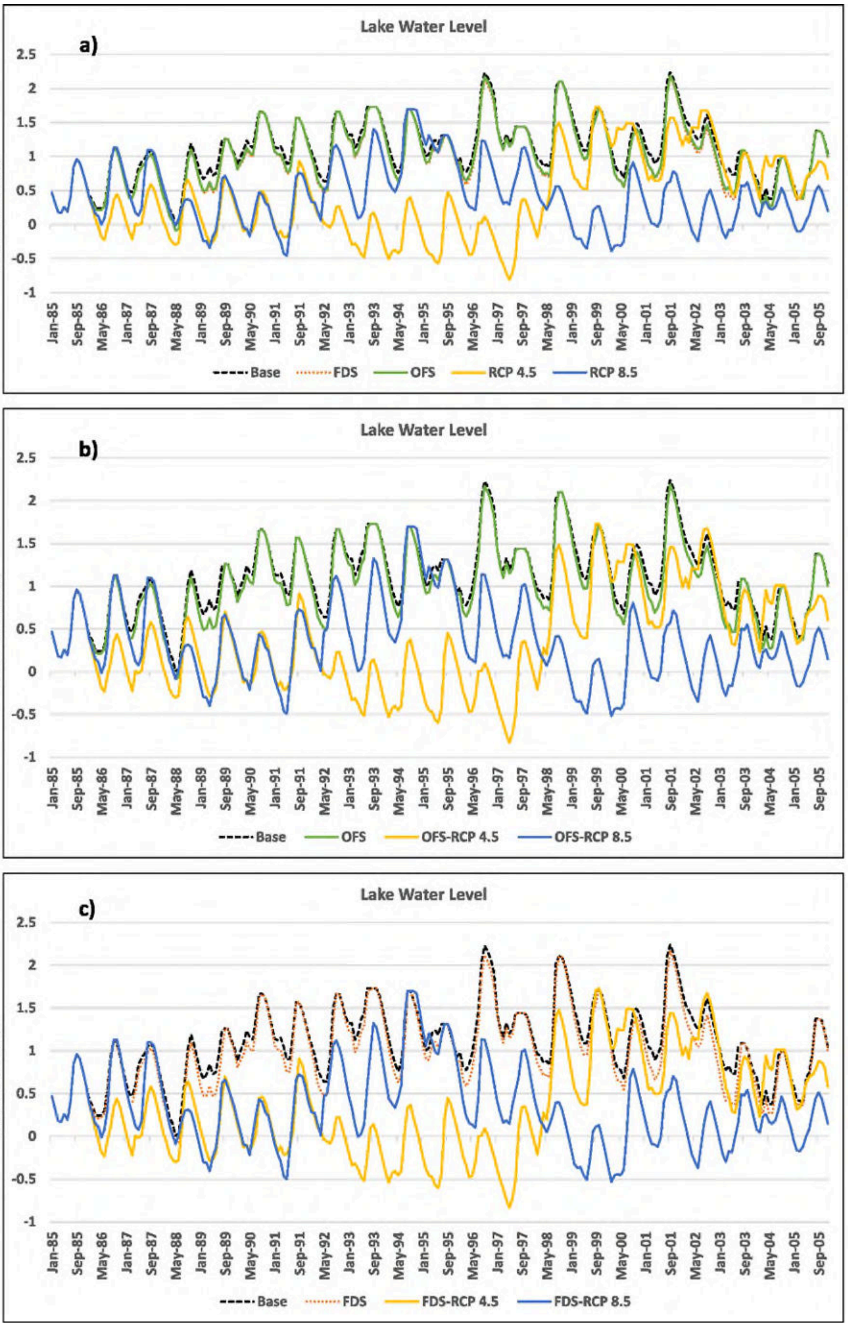

Fig. 6. *WEAP model-simulated average monthly water levels of Lake Ziway under different scenarios. (a) Future development and climate change scenarios separately, (b) ongoing feasibility stage scenarios with and without climate change, and (c) future development scenarios with and without climate change.*

Table 4. Simulated average monthly water demand coverages under the developed scenarios for different demand sites.

Scenarios	**Bulbula Irrigation (%)**	**Bulbula Town Water Supply (%)**	**Ketar Irrigation (%)**	**Meki Irrigation (%)**	**Sher Flower Irrigation (%)**	**Ziway Irrigation (%)**	**Ziway Town Water Supply (%)**
Reference							
Base	98.4	99.0	98.2	92.8	93.1	98.4	99.0
Demand (Mm^3/yr)	5.5	0.2	4.3	1.9	2.9	7.1	1.3
Climate change							
RCP 4.5	76.4	88.7	75.8	76.2	47.9	76.4	88.6
RCP 8.5	77.2	86.2	74.8	76.9	47.4	77.2	86.2
Demand (Mm^3/yr)	5.5	0.2	4.3	1.9	2.9	7.1	1.3
Future agricultural developments							
OFS	97.0	98.4	96.8	91.5	90.9	97.0	98.4
Demand (Mm^3/yr)	5.5	0.2	4.3	1.9	5.7	26.9	1.3
FDS	96.7	98.8	96.5	80.2	89.7	96.7	98.7
Demand (Mm^3/yr)	5.5	0.2	4.3	13.4	5.7	26.9	1.3
Future agricultural developments with climate change							
OFS-RCP4.5	75.7	91.7	75.1	75.4	45.1	75.7	91.7
OFS-RCP8.5	74.5	91.7	72.9	74.2	41.8	74.5	91.7
Demand (Mm^3/yr)	5.5	0.2	4.3	1.9	5.7	26.9	1.3
FDS-RCP4.5	75.4	92.2	74.9	70.3	44.5	75.4	92.2
FDS-RCP8.5	74.0	91.5	72.4	67.1	41.5	74.0	91.4
Demand (Mm^3/yr)	5.5	0.2	4.3	13.4	5.7	26.9	1.3

4. Discussion

Tropical African lakes, such as Lake Ziway, play a key socio-economic and environmental role that sustain livelihoods of millions of people in the region (Desta and Fetene, 2020; Haile and Seid, 2020; Lemi, 2019). However, historical trends generally indicate a high sensitivity to climate variability. For example since 2002, the water level of Lake Ziway has decreased by nearly 0.50 m, and the reduction in the annual discharge from the lake through Bulbula river was estimated to be from above 200 million m^3 per year to less than 50 million m^3 per year (Hassan and Jin, 2014; Jansen et al., 2007).

In shallow tropical lakes, water surface evaporation is a major component in the water balance (Bouchez et al., 2015; Kebede et al., 2006; Mbanguka et al., 2016), as has been also confirmed in the present study (Table 3). However, precipitation seems to be the most important driver of variations in lake levels (Kebede et al., 2006; Shanahan et al., 2007). Hence, with the uncertainty of changes in annual precipitation and the certainty of global warming (Niang et al., 2014), and considering the observed population increase and economic development in the region (Scholten, 2007), the prospects for these remarkable lakes are unfavorable. This calls for detailed impact studies to inform mid- and long-term water resources and land planning, as well as mitigation and adaptation strategies, which ensure their survival along with the benefits they provide.

Previous studies have tried to estimate the impacts of human activities on the Lake Ziway water balance and the downstream outflow (Desta et al., 2017; Jansen et al., 2007; Seyoum et al., 2015). estimated the amount of annual water abstractions from the lake to be about 41 million m^3. After a detailed field survey of the pumping irrigation activities GOSHIME et al. (2019) have also estimated 38 million m^3 of water abstraction to irrigate 2,000 ha area for three seasons each year. Whereas, Ayenew (2004) estimated about 28 million m^3 per year of water pumping following the recent irrigation expansions. The estimated amount of the base period total water abstractions from Lake Ziway in our study was about 26 million m^3 per year. The differences in the estimated amounts are attributed to the data availability and the studies' assumptions. The studies indicated that abstractions from the lake and the downstream river are significant contributors to the drop in Lake Ziway and Abiyata water levels.

Our study also evaluated the impacts of future climate change and agricultural developments on the water balance of Lake Ziway and the use of its water resources. Two middle of the century climate change scenarios representing the changes in meteorological variables for distinct levels of greenhouse gas emissions, i.e. RCP 4.5 and RCP 8.5, as simulated by five RCMs were analysed. A previous study (Abraham et al., 2006) in the area showed that the average annual precipitation is projected to increase by 9.4% in the period from 2001 to 2099. Meanwhile, Gadissa et al. (2019) estimated a reduction in precipitation by 7.97% and 2.55% under RCP4.5 and RCP8.5 respectively during the mid of the century. Our study is in agreement with the later but with minimal difference between the two RCPs. According to Teklesadik et al. (2017) the uncertainty in the projected discharges is mainly dominated by the differences in the GCM structures. Our previous study in Lake Ziway sub-basin also indicated that the uncertainty in the projected streamflow and water balance components of the upstream watershed were influenced by the precipitation projections by the CORDEX-AFRICA models (Musie et al., 2020b). Models such as IPSL-CM5A-MR and NorESM1-M projected higher wet season precipitations especial during the end of the century. Whereas, CNRM-CM5 projected lower precipitations during both the pre-wet and wet seasons under both the RCPs. The higher and lower precipitation projections by the member of ensemble climate models selected based on the historical hydrologic performances indicated the higher uncertainty in the projected future streamflow during the end of the century. Interestingly, the differences between RCP 4.5 and 8.5 climate projections and the related impacts (summarised through the ensemble mean of all RCMs) were not very significant during the mid of the century. However, the magnitude of the impacts was major and can be mostly explained by the increase in evaporation from the lake, which rised to values almost 30% of the total inflows. This has a direct influence on the natural outflows of the lake, which endanger the whole CRV lake system. The fact that impacts under RCP4.5 projections, being an emissions stabilisation scenario, have such devastating effects highlight the urgency of undertaking climate change mitigation actions.

The effects of future agricultural developments were examined separately for scenarios representing the near and future planned irrigation expansions. From the comparative evaluation of the simulated scenarios, it can be observed that the impacts of increased water abstractions due to the future agricultural development on the lake water balance are considerable, since the natural outflow is reduced around 30% with respect to the baseline, but not as significant as the impacts of climate change which reduce outflows more than 70% (Table 3 and Fig. 6). Although the impact of future developments on lake water level is minimal as compared to the climate change scenario, the decrease in downstream flows will have a considerable impact on the downstream terminal Lake Abiyata (Legesse et al., 2004).

According to our findings, the combined impact of both climate change and future developments will likely convert Lake Ziway to a terminal lake during the dry season. As a result, the salinity of the only freshwater lake in the CRV basin may increase, which will have a significant impact on the ecosystems in the lakes system (Lemi, 2019). As expected, the cumulative impact on the lake water balance is dominated by climate change. Climate and socio-economic changes interact non-linearly demonstrating the existence of systemic dependencies. For example, future agricultural expansion may reduce the amount of evaporation loss due to climate change to some extent (Table

3). The ongoing feasibility stage agricultural development is also expected to increase marginaly the amount of total inflows to the lake under the climate change scenario. This highlights the importance of using tools that allow considering the dynamic variation of natural (e.g. evaporation, runoff, lake outflow) and anthropic (water abstractions) water balance components such as WEAP.

The evaluation of future agricultural developments without climate change, illustrated that the system could cover more than 95% of the future and existing agricultural and domestic water demands. However, when climate change effects are accounted for, the coverage of irrigation demands reduce considerably to values ranging from ~41% to ~78%. This suggests that, for the long term sustainability of the lake water resources and the related economic activities, adaptation strategies should involve demand management measures aiming at reducing the overall water demand to increase supply coverage while reducing abstractions.

The excessive increase in lake surface water evaporation as a result of future climate change is expected to affect the scarcely available water resource in the basin, and the agricultural expansions planned to be implemented in the region. Makin et al. (1976) proposed the regulation of Lake Ziway water level by means of a sluice at the outlet of Bulbula River and deepening of the upper part of the channel to regulate the outflow from the lake and minimize the evaporation loss. The deepening of the Bulbula River outlet proposed might help in increasing the reduced dry season flow towards Lake Abiyata and minimize the related lake water evaporation loss. However, this comes at the expense of the ecosystems in the Ziway lake itself. Other solutions recommended by similar studies have also indicated the necessity of natural resources management intervention (Desta et al., 2017; Desta et al., 2019). The free-access practice for water use and uncontrolled water abstraction form the main rivers and the lake need to be dealt with different stakeholders to implement water charge policy. Water transfer of the wet spill discharge from the nearby Awash

River, taking into account the environmental and ecological impact on the downstream part of the river, can also be seen as one of the possible solutions. The complexity and multiple trade-offs linked to potential supply management adaptation measures calls for detailed investigations and demonstrates the need to focus on climate change mitigation to minimise its inextricable impacts.

5. Conclusions

This study evaluated the individual and combined impacts of water abstraction and climate change scenarios on the water resources of Lake Ziway sub-basin. The results of the overall analysis of the scenarios examined showed that the shallow depth Lake Ziway is more vulnerable to climate variability/change than to anthropogenic activities. The combined impacts of future agricultural development and climate change could result in Lake Ziway becoming a terminal lake and a significant reduction in supply coverage of both domestic and agricultural water uses. The findings and methodological approach used in this study are believed to be valuable for the decision-makers and water resources managers in the Central Rift Valley basin and African tropical lake systems to advance and address future water security and environmental challenges.

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