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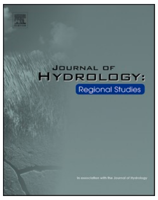

Implications of water abstraction on the interconnected Central Rift Valley Lakes sub-basin of Ethiopia using WEAP

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ABSTRACT

Study region: Central Rift Valley Lakes sub-basin, Ethiopia.
Study focus: The competition for water is rapidly increasing in Central Rift Valley lakes sub-basin due to the combined effect of various water resources developments. However, the impacts of recent and future water resources development pathways on the water balance of the three interconnected lakes (i.e. Lake Ziway, Langano and Abiyata) are unknown. The Water Evaluation And Planning (WEAP) model was used to assess the development impacts on the lakes' water resources. We considered three development pathways that are, recent (2009–2018), short-term (2019–2028) and long-term development (2029–2038). Lake Ziway water inflows from six catchments were estimated using the Hydrologiska Byråns Vattenbalansavdelning (HBV) rainfall-runoff model. Crop water requirements for irrigation schemes were estimated by the CROPWAT model.
New hydrological insights for the region: WEAP simulations show a total water demand of 102.3 Mm^3 under the recent development pathway that increases by 46% and 118% for short-term and long-term development pathways, respectively. This will notably affect the water balance of the interconnected lakes and cause an unmet water demand of 47.9 Mm^3 for the long-term (2028–2038)· For Lake Ziway and Abiyata, water levels will decrease substantially to cause water scarcity in the long-term, and developments in Lake Ziway will significantly affect water

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Abbreviations: ASTER, Advanced Space-borne Thermal Emission and Reflection Radiometer; CHG, Climate Hazards Group; CHIRP, Climate Hazards Infrared Precipitation; CRV, Central Rift Valley; CWR, Crop water requirement; CROPWAT, Crop water requirement model; CSA, Central Statistical Agency; DEM, Digital Elevation Model; EFR, Environmental Flow Requirement; GDEM V2, Global Digital Elevation Modelversion 2; HBV, Hydrologiska Byråns Vattenbalansavdelning; IWMI, International Water Management Institute; LULC, Land Use Land Cover; MoWiE, Ministry of Water, Irrigation and Electricity; NMA, National Meteorological Agency; NSE, Nash-Sutcliffe efficiency; PET, Potential evapotranspiration; RVE, Relative volume error; SMHI, Swedish Meteorological and Hydrological Institute; WAS, Water Abstraction Survey; WEAP, Water Evaluation And Planning Model.

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storages in Lake Abiyata. Overall, future developments will threaten the water resource of the interconnected lake system.

1. Introduction

Competition for water among various water sectors threatens the sustainability of the water resources of many basins worldwide (Alemayehu et al., 2010; Mehta et al., 2013; Adeba et al., 2015; Chinnasamy et al., 2015; Gedefaw et al., 2019). Such also applies to the Central Rift Valley lakes (CRV) sub-basin in Ethiopia that is of interest to this study. The sub-basin is a preferred location for irrigation due to the short distance from major cities including the capital city of Addis Ababa, Ethiopia. Over recent years, CRV has become the focus area for large and small-scale irrigation developments and other human activities that withdraw considerable amount of water from the lakes and their tributary rivers. The water resources of the sub-basin are used for irrigation, for soda ash production, fish farming and recreation, and provide water to eco-systems with a wide variety of endemic birds and wild animals (Ayenew, 1998, 2004; Jansen et al., 2007). Past studies presented environmental problems of the rapidly growing use of water resources in each of the sub-basin's lakes separately (Zinabu et al., 2002; Ayenew, 2004; Desta and Lemma, 2017). In the near future, the impacts can be exacerbated by the future developments (Awulachew et al., 2007; Jansen et al., 2007; MoWiE, 2012) including uncontrolled irrigation developments by individual farmers, absence of water allocation plans, and mismatch between hydrological and administrative boundaries that complicates tracking of water withdrawals.

Over the past decades, changes have been observed on the behavior of the Rift Valley lakes and their environments. Lake areas for Lake Abiyata and Lake Ziway have reduced as a consequence of excessive water abstractions (Zinabu et al., 2002; Seyoum et al., 2015; Goshime et al., 2020), but lake areas of Lake Beseka and Lake Awassa increased (Ayenew and Legesse, 2007; Ayenew and Gebreegziabher, 2006), possibly due to increased surface runoff inflows from percolated irrigation water and land use changes, respectively. In the interconnected lakes of Ziway, Abiyata and Langano, the average level of Lake Ziway decreased by approximately 0.5 m between 2002 and 2007 (Jansen et al., 2007) that caused a reduction in the discharge of Bulbula River that subsequently resulted in 40% reduction in the size of Lake Abiyata. Asfaw et al. (2020) indicates 4 cm water level decline per annum and 20.4 Mm^3 reduction of water storage of Lake Ziway between 2009 and 2018. Downstream connected Lake Abiyata and Lake Langano experienced smallest change as compared to other lakes in the sub-basin.

Findings of previous studies reported that the climate and land use changes (conversion of the woodlands into agricultural lands and settlements areas) will affect the water balance of the interconnected Ziway, Abiyata and Langano lakes (Legesse et al., 2004; Seyoum et al., 2015; Desta and Lemma, 2017; Desta et al., 2017). The reductions in the lake sizes can be related to use of water from the inflowing rivers and lake catchments, and lake water abstractions, that is aggravated intermittently by climatic and land use changes (Ayenew and Legesse, 2007; Ayenew and Tilahun, 2008; Desta et al., 2017; Abrhama et al., 2018). Seyoum et al. (2015) argues that reductions in lake size can be attributed more too human activities than climate change. Water supply to irrigation and industrial processing purposes from these lakes is threated by future uncontrolled abstraction of water that will inevitably alter the hydrologic balance of the lakes. If the human interventions are not managed, then Lake Abiyata water level may continue to decline that potentially leads to ecological collapse, likewise to what has occurred in Lake Alemaya (Lemma, 2003; Alemayehu et al., 2007; Alemayehu and Furi, 2007).

Several studies have investigated the hydrology of the CRV sub-basin (Vallet-Coulomb et al., 2001; Legesse et al., 2003, 2004; Ayenew, 2007). Most of the studies focused on the likely impact of socio-economic influences on land and water resources at catchment level (Hengsdijk and Jansen, 2006; Legesse and Ayenew, 2006; Jansen et al., 2007). Only few studies are available on lake water balance simulation and assessment under natural conditions (Vallet-Coulomb., 2001; Legesse et al., 2003, 2004; Belete et al., 2016), but studies ignored water abstractions that serve agricultural production. Goshime et al. (2019a, 2020) performed water level simulation of Lake Ziway by water balance assessment using satellite rainfall estimates. These studies did not assess the impacts of present and future water demands by planned developments (MoWiE, 2012) and how impacts propagate in the interconnected lakes system. The effect of a barrage that, since 2016, regulates the outflow of Lake Ziway also was not investigated by past studies.

Simulation of lake water levels of the interconnected Ziway, Abiyata and Langano sub-basin requires a model that can simulate both water supply and demand in an integrated manner. For such purpose, the Water Evaluation And Planning (WEAP) model (https://www.weap21.org/) has been applied in various lake basins in Ethiopia and Kenya. For instance, WEAP was used to evaluate the likely impact of planned water resources development (irrigation and water supply) on Lake Tana water level (Alemayehu et al., 2010). It was also used to simulate the surface water resources allocation of Didessa sub-basin in the Abbay River basin considering future developments (Adgolign et al., 2015). Gedefaw et al. (2019) applied the WEAP model to assess the potential impact of irrigation expansion and climate change scenario on the water resources in Awash River Basin of Ethiopia. Alfarra (2010) conducted a study using the WEAP model to better understand alignment of water resources, to identify problems on water resources, and to suggest solutions for Lake Naivasha, Kenya. Hence, the WEAP model was selected in this study as it allows for scenario-based analyses of water demands and supplies by considering various water resources and hydrological components. The model also allows simulation of domestic, irrigation, and ecological water consumption in time and space which is required for integrated water resources assessment. Reference is made to https://www.weap21.org for wide range of applications of WEAP in water resources management.

The main objective of the present study is to quantify the present and future water demands and to evaluate the impact of recent and future water resources development pathways on the water balance of three interconnected lakes (i.e. Ziway, Langano, Abiyata) and the effect of the constructed barrage in 2016. The study will help to quantify the spatio-temporalunmet demand for irrigation water and other users in the sub-basin. The assessment was by integration of in-situ, satellite and survey datasets for state-of-the-art modeling based on the combined rainfall-runoff, crop water requirement model (CROPWAT) and a water resources planning model (WEAP). Findings of this study provide information that may serve to improve the water resources management at local and basin scale and contribute to scientific literature on hydrological impacts of human intervention.

2. Study area

The Central Rift Valley (CRV) Lakes sub-basin is located in the central section of the main Ethiopian Rift. The sub-basin, which constitutes the interconnected Ziway, Langano and Abiyata lakes, is situated between 7º10’-8º30’ N and 38º10’-39º30’ E. The total drainage area of Ziway, Langano and Abiyata is 10,769 km^2. Elevation of the study area ranges from 4200 m.a.s.l. at the western and eastern escarpments, to 1580 m.a.s.l. at the central rift valley floor (Fig. 1).

Table 1 shows the key characteristics of Lake Ziway, Langano, Abiyata and Shala. Ziway is the largest surface area whereas Lake Abiyata has the smallest surface area. Lake Abiyata is a terminal lake and is upstream connected to Lake Langano and Lake Ziway through the Horakela and Bulbula Rivers. Lake Shala is the deepest lake and is separated from Abiyata by a volcanic caldera rim. Lake Shala is a closed lake and is highly alkaline that makes irrigation water abstraction from the lake impossible. Hence, this study only considered a chain of three interconnected CRV lakes (Lake Ziway, Langano and Abiyata).

Lake Ziway receives most of its surface runoff inflows from Meki and Katar rivers that drain the western and eastern plateaus, respectively. Meki’s catchment area is 2824 km^2 including both gauged and ungauged areas. Rivers in the catchment originate in the highlands of Gurage and travel about 100 km from the highlands (3600 m altitude) to the lake (about 1600 m altitude). The Meki river is supplemented by Rinzaf and Wijo minor tributaries before draining into Lake Ziway. The Katar River has a catchment area of 3750 km^2. It drains the Arsi highlands (4200 m altitude) towards the western part to supply Lake Ziway (1636 m altitude). The major tributaries that are contributing to the Katar River include Chuifa, Sagure, Ashebeka, Timala, and Wolkesa. The catchments of Meki and Katar rivers cover a total of 6574 km^2. The altitude of Lake Ziway is higher than that of Abiyata by 56 m hence it supplies water to Abiyata. Lake Ziway has an outflow through Bulbula River that in turn flows to the downstream Lake Abiyata, being a terminal lake.

The tributaries of Lake Langano are Gedemso, Huluka, Lepis and Boku Rivers that cover a total drainage area of 2006 km^2. Since Lake Langano is 4 m higher in altitude than Lake Abiyata, it feeds Lake Abiyata via the Horakelo River. Lake Ziway and Langano are open lakes with overflow (i.e. drainage) to Lake Abiyata whereas Lake Abiyata and Shala are closed lakes without any surface water

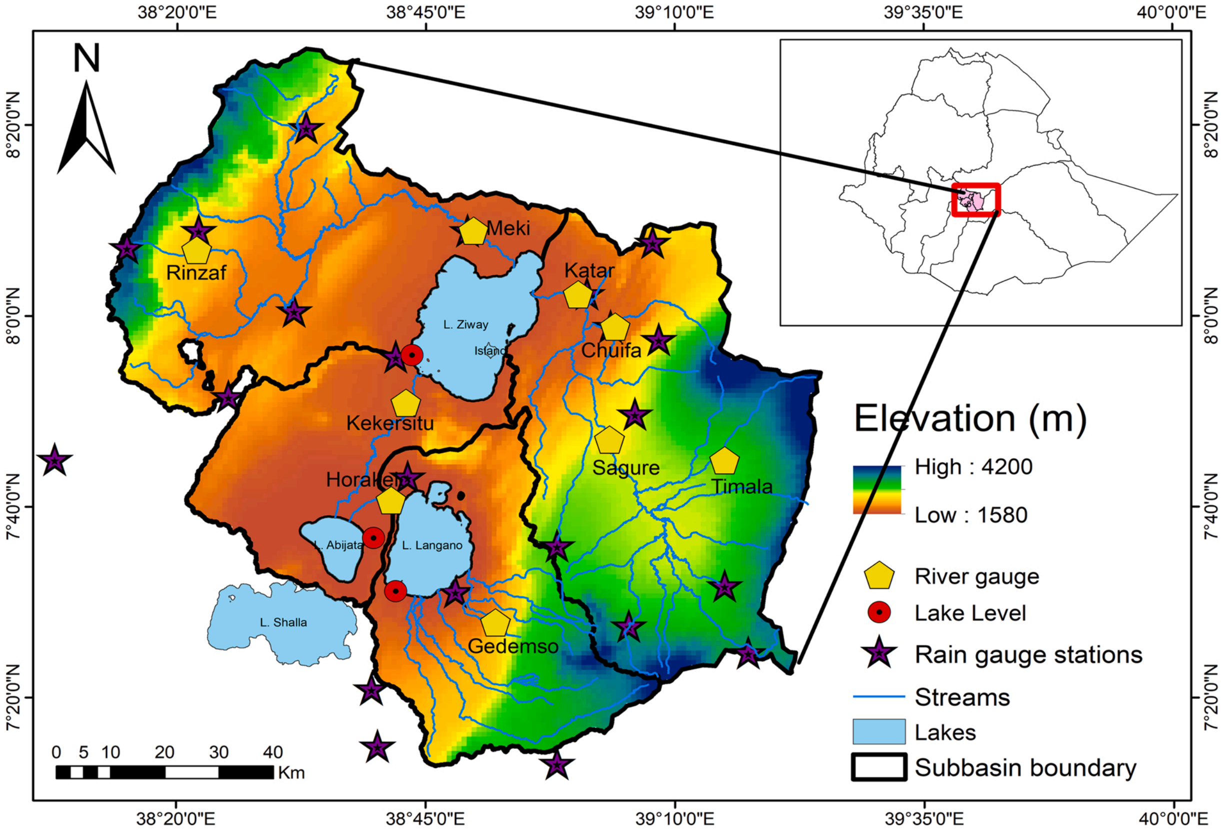

Fig. 1. Location map of the study area showing terrain elevation, hydro-meteorological stations, and stations that monitor water level of rivers and lakes.

Table 1

Basic physical characteristics of the selected CRV lakes from 1986 to 2000 (Source: This study and Ayenew and Legesse, 2007).

Lake	Lake Area (km^2)	Catchment area (km^2)	Elevation (m.a.s.l)	Mean Depth (m)	Maximum Depth (m)	Volume (Mm^3)
Ziway	435	7022	1636	3.0	8	1148
Langano	233	2006	1584	12.2	44.1	5565
Abiyata	148	1528	1580	7.3	13	1276
Shala	310	2300	1550	8.6	256	37,000

outflow.

The climate of the study area is characterized by semi-arid to sub-humid climatic condition. We analysed the climate of the sub-basin of the interconnected Ziway, Langano, and Abiyata lakes using data collected from the National Meteorology Agency (NMA) for the period from 1986 to 2018. The inter-annual and seasonal variability of temperature over the study are relatively constant with mean annual maximum temperature ranging from 23.6 ℃ to 26.3 ℃ and minimum temperature ranging from 9.3 ℃ to 11.9 ℃, with long-term annual average of 17.5 ℃. The mean annual rainfall over the sub-basin varies from 514.6 to 1086.5 mm, with long-term average of 882.6 mm as estimated for the period 1986–2018. The highest rainfall mostly occurs during the rainy season (July -September). The potential evapotranspiration (based on Penman-Monteith) varies between approximately 1330–1502 mm, with long-term average of 1480 mm. The inter-annual variation of the potential evapotranspiration is much less than the inter-annual variation in rainfall.

The water system of Central Rift Valley lakes is preferred by various water sectors for irrigation, domestic and industrial activities. The major land uses in the basin include intensive and moderately cultivated lands with onion, tomato, maize, cabbage, green beans and pepper as the dominant irrigated crops grown in the study area.

3. Data availability

In this study, hydro-meteorological time series, water demand and water supply data were used. The hydro-meteorological dataset includes streamflow, satellite and gauge rainfall, and climate data required for estimation of evaporation and evapotranspiration. Daily satellite and gauge rainfall datasets were obtained from Climate Hazard Group (CHG) and National Meteorology Agency (NMA), respectively.

Daily rainfall data (1984–2018) were obtained from 20 stations in Lake Ziway catchment and 6 stations in Abiyata and Langano catchments. After data screening, 20 stations out of 26 were used in this study for further use. Six (6) stations were excluded because of too short observation period and/or substantial missing data records. The rain gauge observations were used to serve bias correction of the Climate Hazard InfraRed Precipitation (CHIRP) satellite rainfall estimates that are available at daily time step and 5.5 km × 5.5 km spatial resolution for the period 1984–2018 (See Goshime et al., 2019a).

Streamflow and lake water level data were obtained from the Ethiopian Ministry of Water, Irrigation and Energy (MoWIE). Streamflow data was collected for stations in major rivers (Meki, Katar, Bulbula, Horakelo and Gedemso) and minor tributaries (Rinzaf, Chuifa, Sagure Timala, Huluka, Lepis and Boku). The collected data was available for the period 1984–2010. Lake water level data (Ziway, Langano and Abiyata) were obtained from MoWIE for the period 1986–2014. Streamflow and lake water level data were used as a reference to calibrate and evaluate the hydrological and lake water balance models, respectively.

Data on irrigation sites were collected by a field survey and consultation of governmental organizations. A field survey was undertaken from 16 to 21 September 2019 for Lake Ziway contributing catchments (i.e. Meki and Katar), Bulbula River, Langano and Abiyata lakes. The survey includes identification of the location of demand sites, type of scheme, water sources, potential irrigated area, crop type, cropping pattern and intensity. The survey data was used to estimate site-specific crop water requirements in the study area (Section 4.2.1). Additionally, irrigation data was obtained from water and agricultural offices, from the basin master plan, and extracted from water planning documents of the study area. For Lake Ziway, the water abstraction survey data of Goshime et al. (2019b, 2021) were used in this study to estimate water demand from the lake. Data was collected during the period 20th of October to 5th of November 2018.

Base data on population sizes, domestic and industrial water demands were extracted for the year 2007 from the provided by the Central Statistical Agency of Ethiopia (CSA) and water supply from the water supply authorities. By absence of a more recent report, respective data for the base year 2007 was adopted.

The Digital Elevation Model (DEM) of ASTER GDEM V2 with a spatial resolution of 30 m × 30 m was used to delineate the sub-basin and to extract its drainage network. The land use land cover (LULC) map was obtained from MoWIE of Ethiopia for the year 1996. We note that LULC of the sub-basin is characterized by intensive cultivation land, water bodies and wetlands and shrub lands. The lake bathymetric maps that were prepared by MoWIE for the three lakes were used in this study. For all the three lakes, a bathymetric survey was conducted in 1984. However, an additional survey was conducted for Lake Ziway in 2013 and hence was used in this study.

4. Methods

In this study, the impacts of recent and future water development pathways were evaluated using the WEAP model (Yates et al., 2005; Arranz and McCartney, 2007; Mounir et al., 2011; McCartney and Girma, 2012; Hassan et al., 2019). Inputs to the WEAP model were obtained from multiple sources including simulated streamflow, simulated crop water requirements, satellite products, a field survey, the basin master plan and design documents. The HBV rainfall-runoff model was used to simulate lake water inflow by streamflow to Lake Ziway. Simulations (1984–2018) were for 6 river gauge stations at major and minor tributaries. The irrigation water demand was estimated using a water abstraction survey, CROPWAT model simulations and a literature survey. This study assumes that the climate of the recent development pathway will not change so to isolate aspects that, potentially, could relate to climate change impacts for future pathways. Finally, we evaluated the impacts of the development pathways on water availability in the rivers and on volume, water level, and surface areas of the three interconnected lakes (i.e. Lakes Ziway, Lake Langano and Lake Abiyata).

4.1. *Model calibration and simulation*

The available streamflow datasets covered a short observation period with substantial missing records. To overcome this limitation, the Hydrologiska Byrans Vattenbalansavdelning (HBV) rainfall-runoff model (Bergström,1997) was used to fill observation gaps and to prepare long streamflow time series. For application, the model was calibrated and validated for respective gauges. The main inputs to the model include rainfall, potential evapotranspiration (PET), land use land cover and Digital Elevation model (DEM). Meteorological observations at 12 stations (Fig. 1) were used to estimate PET using the Penman-Monteith equation (Allen et al., 1998) that were subsequently used as input to the HBV model. The 1996 land cover map that was obtained from MoWIE also served as HBV input. In this study, eight parameters (Alfa, BETA, CFLUX, FC, LP, K4, Khq and PERC) were selected for calibration following previous studies in the study area (Goshime et al. 2019a; Goshime et al. 2020). For detailed descriptions about the HBV model reference is made to (Lindström et al. 1997; Rientjes et al., 2011; Johansson, 2013).

To warm, calibrate and validate the model, time periods 1984–1985, 1986–1991 and 1996–2000 were selected, respectively at 6 (six) gauge stations in Lake Ziway sub-basin. Long-term streamflow time series (1986–2018) were prepared using the bias-corrected CHIRP rainfall data as input. For bias correction, a non-linear power method was selected and rain gauge data were served as a reference at daily time-step with the parameters varying for each of the 12 months of a year. For a detailed description on bias correction for this study area reference is made to Goshime et al. (2019a). The bias-corrected CHIRP satellite rainfall estimates were used to estimate lake area rainfall, and to simulate Lake Ziway inflow by means of a rainfall-runoff model. The streamflow from the ungauged part of the study area was estimated using a simple regionalization method based on the area-ratio method where streamflow from the gauged area is rescaled for the ungauged part of the catchment.

The performance of the HBV model for available streamflow time series was first evaluated by visual inspection of the match between the simulated and observed hydrographs. Next, the Nash-Sutcliffe efficiency (NSE), relative volumetric error (RVE) and coefficient of determination (R^2) were used for evaluation of the model performance. NSE is a popular performance indicator that measures the relative magnitude of the residual variance of the simulated flow compared to the observed flow. It indicates how well the pattern of the simulated hydrograph fits that of the observed hydrograph (Nash and Sutcliffe, 1970). RVE measures the average tendency of the simulated streamflow volume to be larger or smaller than the observed counterparts (Gupta et al., 1999). The coefficient of determination (R^2) is the measure of the fraction of the variation in the observed streamflow data that is replicated in the simulated streamflow data (Moriasi et al., 2007). Table 2 provides the equations for the three objective functions with additional descriptions.

4.2. *Water demand assessment*

4.2.1. *Irrigation demand*

In this study, irrigation water demand was estimated using a combination of water abstraction survey and the crop water requirement model CROPWAT 8.0 (FAO, 2018) of Food and Agricultural Organization of the United Nations (FAO). CROPWAT estimates the water requirements of the crop (CWR) using climate, soil and crop phenological data. Its inputs include reference

Table 2
The objective functions used to evaluate the performance of the HBV model.

S.no	Performance Measures	Equations	Value range	Best fit value and rating
1	NSE	$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{sim,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2}$	$-\infty$ to 1	• 1 shows perfect fit • 0.75–1 is very good • > 0.5 satisfactory
2	RVE	$RVE = \left[\frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})}{\sum_{i=1}^{n}Q_{obs,i}}\right]$	$-\infty$ to ∞	• ± 5% ± 5% is best fit • ± 10% ± 10% is good • ± 25% ± 25% is satisfactory
3	R^2	$R^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_{sim,i} - \overline{Q_{sim}}\right) \times \left(Q_{obs,i} - \overline{Q_{obs}}\right)\right]^2}{\left[\sum_{i-1}^{n}\left(Q_{sim,i} - \overline{Q_{sim}}\right)\right]^2 \times \left[\sum_{i=1}^{n}\left(Q_{obs,i} - \overline{Q_{obs}}\right)\right]^2}$	0–1	• 1 is for best fit0.7–0.9 is very good • >0.5 satisfactory

where: Q_{sim} and Q_{obs} represent simulated and observed streamflow, respectively ($m^3\ s^{-1}$) and the over-bar symbol denotes the mean of the observed and simulated streamflow values; *i* is the time step; *n* is the number of sample size.

evapotranspiration, rainfall, soil, crop type and crop pattern. Twelve (12) meteorological stations that are located close to the demand sites were used to estimate reference evapotranspiration using Penman-Monteith equation which is considered a standard method (Allen et al., 1998), and to specify daily rainfall at each demand site.

During the field survey it appeared that the main irrigated crops of the study area include onion, tomato, maize, cabbage, green beans, pepper, alfalfa and grapes. Crop planting and harvesting dates, irrigation scheduling and irrigated area of each crop were also obtained from the survey. Managers and irrigators were interviewed to collect the basic information, as well as information on their

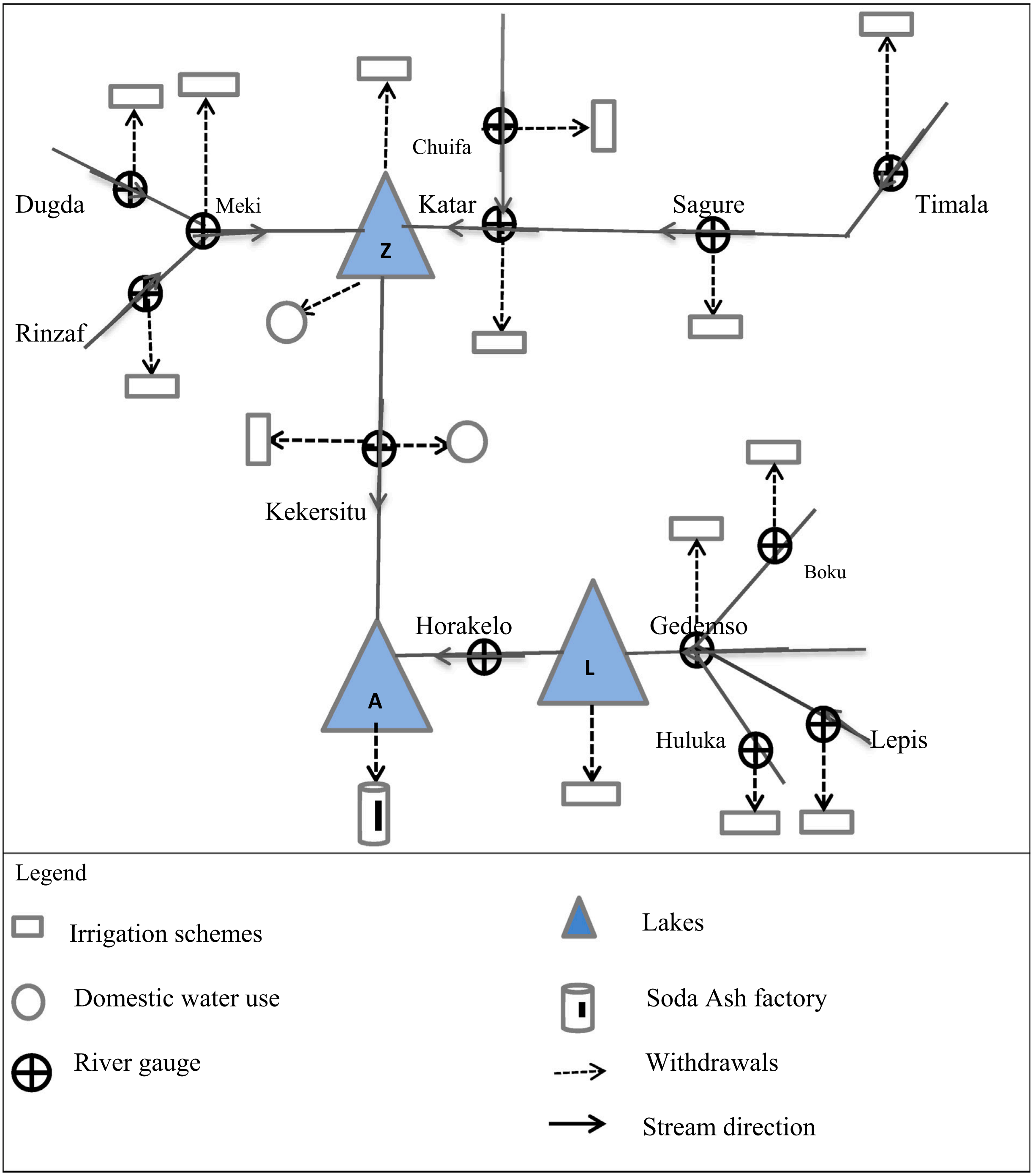

Fig. 2. Schematic for the WEAP model of the CRV lakes sub-basin (letter Z, A and L denotes Lake Ziway, Abiyata and Langano, respectively). The triangle, rectangle, circle, broken and solid lines represent the three lakes, irrigation schemes, water supply, withdrawals and river system, respectively.

respective development pathways. Crop characteristics, growth stage, and soil characteristic data on soil moisture storage and depletion were obtained from FAO 56 (Irrigation and Drainage paper), the basin master plan and irrigation project design documents.

4.2.2. *Domestic water demand*

The latest population and housing census of Ethiopia was conducted in 2007. Therefore, 2007 was defined as the base year for the WEAP simulation. The 2007 population size and housing census of Ethiopia showed that the population of Ziway and Bulbula towns was 43,660 and 5000, respectively (Central Statistical Agency of Ethiopia, CSA). In 2007, the water supply authorities of the two towns were distributing 3450 and 430 $m^3\ d^{-1}$ of water for Ziway and Bulbula towns, respectively and hence this was used in the WEAP model simulations for the current account or base year. For future developments, the domestic water demand was extrapolated using population size, geometric population growth rate (2.9%) and water use (liter per capita per day) data. To estimate the domestic water demand, the water use rates were multiplied by the population size.

4.2.3. *Industrial water demand*

Demands for industrial uses only apply to Lake Abiyata whereas a Soda Ash factory abstracts water from the lake since 1985. In 2007, it was reported that 15,000 ton of soda ash was produced that was used for the current account in WEAP simulations. According to the Rift Valley Lakes basin master plan, the factory produces 25,000 tons of soda ash per year (2009–2018) with a water requirement of 150 m^3 per ton of production for the recent development pathway. An increment of 25,000 ton for future development pathways from reference was used to construct the future production capacity as per the Rift valley lake basin master plan report (MoWiE, 2012) and design documents.

4.2.4. *Environmental flow requirement*

The environmental flow is the water that serves the river ecosystem to maintain the downstream ecological balance. In this study, requirements on environmental flows were not available and thus allowance only made for main rivers. Requirements were simply expressed as a percentage of the mean annual flow, following Tennant (1976) who reported to use approximate 15–20% of mean annual flow as downstream water requirement. Hence, the environmental flow is specified as 20% of the mean annual flow. In this study, environmental flow requirement was specified downstream of Bulbula River to regulate Lake Ziway and to attribute to downstream flow to Lake Abiyata (see also Shumet and Mengistu, 2016).

4.3. *Water evaluation and planning (WEAP) model*

The WEAP model was developed by Stockholm Environment Institute at Boston, USA to evaluate water demands, associated priorities and water supply for current and future periods. The model allows specifying alternative scenarios (i.e., plausible futures based on “what if” questions) to assess the impact of different development and management options. It optimizes water use in the catchment with the objective to maximize the water delivered to demand sites, according to a set of user-defined priorities (Yates et al., 2005). The demand sites are assigned a priority between 1 and 99, where 1 is assigned for the highest priority and 99 is for the lowest priority.

Some of the input data of WEAP are water supply, river head streamflow, water use (demand), water levels, elevation-storage-area relationship, and the spatial location of the water system. For a more detailed description about WEAP model reference is made to (Yates et al., 2005; SEI, 2015).

Fig. 2 shows the schematization of the CRV lakes sub-basin based on existing and planned water demand and supply sources. In the schematization, the type of scheme, the supply sources and the location of the demand sites were considered. The demand priority was assigned considering the recent pathway in which the upstream demand sites receive priority. Hence, the first priority was assigned to the most upstream demand sites; the next priority was assigned to the next downstream demand sites and so on (i.e., priority was varied from upstream to downstream). Accordingly, highest priority 1 was assigned for demand sites that receive water from Timala, Chuifa, Dugda, Rinzaf, Boku, Huluka, Gedemso and Lepis rivers. Priority 2 was assigned to demand sites that receive water from Meki, Sagure, Bulbula and Horekelo rivers. The demand sites along the Katar River were assigned priority 3. Demand sites withdrawing water from Lake Ziway and Langano were assigned equal priority of 98, lowest priority 99 was assigned for Lake Abiyata but with priority 1 for environmental flow demands.

4.4. *Effect of barrage regulation*

The barrage regulator at the outlet of Lake Ziway at Bulbula river may reduce Lake Ziway outflow affecting the storage of the downstream Lake Abiyata. Hence, the barrage should be operated not only to regulate the lake storage but also to fulfill the irrigation water demand along the Bulbula river, as well as environmental flow requirements (EFR).

Lake Ziway receives water from river streamflows and from lake rainfall, and loses water through abstraction, evaporation and outflow. To simulate changes in the lake level, two regression relationships between observed water level and outflow time series were developed. The first relation was developed for the period January 2009–May 2016 and the second relation was developed for the period June 2016–2019 which covers the period the barrage is in operation. The outflow discharge time series that were simulated for respective periods were subsequently used in WEAP model for recent development pathway. For the future development pathways, the second relationship between observed water level and river outflow discharge was specified in WEAP in the form of mathematical equation. Similarly, the recent and future outflow from Langano was specified using the observed Langano water level and Horakelo outflow discharge.

4.5. Water resources development pathway

In this study, three development pathways are considered. These pathways include recent development (2009–2018), short-term development (2019–2028) and long-term development (2029–2038). The development pathways were constructed based on the information from Rift Valley Lakes basin master plan (MoWiE, 2012), feasibility studies, design documents and consultation of stakeholders during the field survey. The data or information source that reflects the current stage of the development pathways was selected to extract the information for WEAP modeling.

For this study, as a reference to change assessments by respective pathways, a base year 2007 was specified using the water abstraction in 2007 (Jansen et al., 2007) for which detailed water abstraction survey data was prepared for the CRV basin master plan and the national population and housing census was conducted. Table 3 shows the summary and descriptions for base year and for each water resources development pathway.

4.6. Impact of water resources development

After determining the water demand for all development pathways, WEAP was used to simulate the water level of the lakes. For this, the monthly water balance of the three lakes was estimated for a base line period of 15 years (1986–2000). The period served as a baseline for comparison of changes by each development pathway. This period was selected because it best represents the undisturbed water level regime with minimum water withdrawal from the lakes and tributaries. Furthermore, it represents the period before construction of outflow regulator at Bulbula River. Also, Goshime et al. (2020) indicated significant water abstraction from Lake Ziway for the period 2001–2014. For the 2016–2018 of the recent development, and the entire period of the short-term and long-term development pathways, the regulatory barrage was set to provide flows to the Bulbula River so that environmental flow requirements (EFR) are met at downstream Lake Abiyata. Then, the impact of the three development pathways was evaluated by comparing the WEAP simulations for these pathways against the simulations for the baseline period 1986–2000. Furthermore, water scarcity threshold levels for all three lakes were established based on a basin master plan document (MoWiE, 2012). The water scarcity level represents a minimum water level to sustain the fish habitat and their food chain. Hence, irrigation water abstraction should be ceased before the water level drops below this level.

5. Results and discussion

5.1. Streamflow simulation

Fig. 3 shows a comparison of the simulated and observed streamflow hydrographs for the calibration period (1986–1991) at Meki and Rinzaf gauging stations that indicate river flows to the lake from the western side. The model fairly captured the pattern of the observed hydrograph (including recession and rising limbs) of both catchments. However, it did not satisfactorily capture most of the observed peak flows especially for Rinzaf gauge station. The agreement between the simulated and observed streamflow was better for Meki than Rinzaf river catchment. The latter has relatively small size that resulted in high streamflow variability, and relatively high peaks. Streamflow was observed two times per day and thus limits to provide representative data on streamflow volume for the small catchments. Another cause of mismatch could be the stage-discharge relations that often are inaccurate to convert high water level measurements into representative discharges.

Fig. 4 shows the simulated and observed streamflow for the calibration period (1986–1991) at Katar, Chuifa, Sagure and Timala gauge stations that drain into Lake Ziway from the eastern plateaus. HBV well captured the overall pattern of the observed hydrograph for most of the gauge stations. However, the rising limb and related peaks of the observed hydrograph were not satisfactorily captured. The model better captured the observed flow for the Katar catchment that has highest streamflow discharges. However, some observed peaks were not satisfactorily simulated for smaller tributaries, for instance at Sagure and Chuifa river gauge stations.

Table 4 presents the calibrated values of the model parameters and objectives functions. The calibrated values of Alfa, K4 and

Table 3
Summary of the water resources development pathway for this study.

Development Pathways	Time Frame	Descriptions
Base year	2007	The 2007 water use rate withdrawing water for 5534 ha of irrigated lands and 15,000 ton of Abiyata soda ash production
Recent Development	2009–2018	The 2007 water use rate plus additional irrigation expansion up to 3150.5 ha (total irrigated area = 8684.5 ha) and 25,000 ton of Abiyata soda ash industrial expansion
Short-term Development	2019–2028	Recent development plus additional expansion of up to 4195.5 ha of irrigated lands (total irrigated area = 12,880 ha) and 50,000 ton soda ash production
Long-term Development	2029–2038	Short-term development plus all potential scheme developments to be operational in the study area with an additional expansion of 6391 ha of irrigated area (total irrigated area = 18,920 ha) and 75,000 ton soda ash production

Note: Domestic water demand for Ziway and Bulbula town, and environmental flow at Bulbula River for downstream Abiyata were also considered in each development pathway.

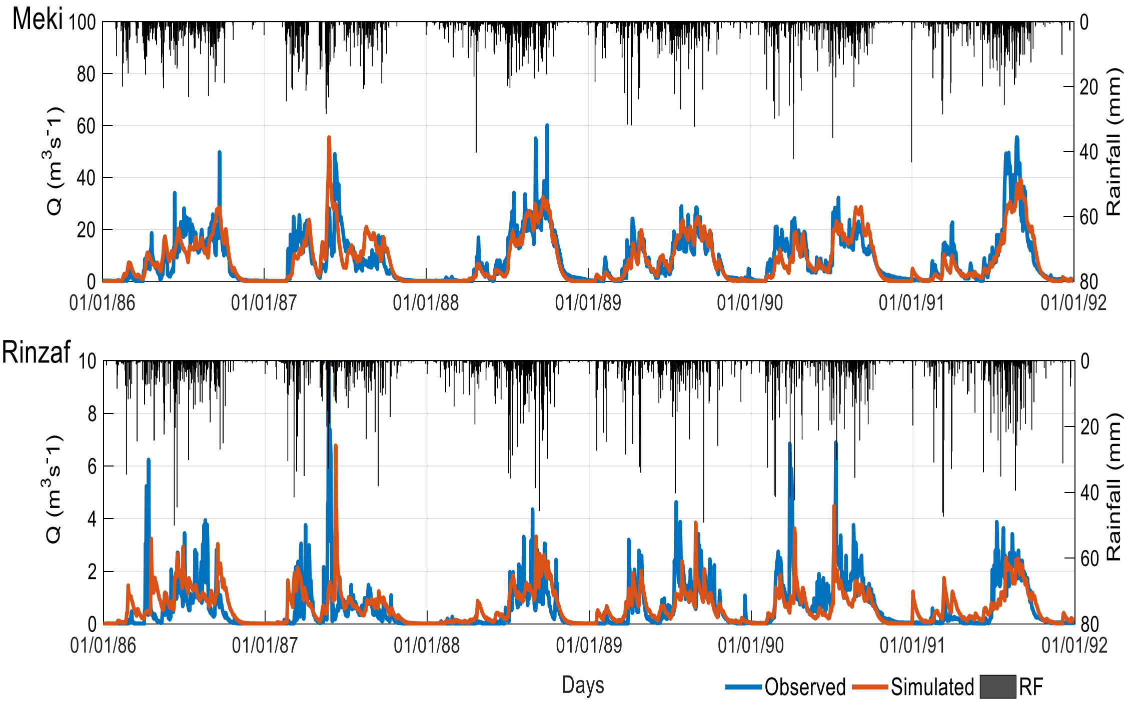

Fig. 3. The simulated and observed hydrographs of Meki and Rinzaf catchments for the calibration period (1986–1991).

CFLUX do not significantly vary across the catchments. The recession parameter K4 influences the recession part of the base flow of the hydrographs. Alfa is used to simulate rapid responses of the shallow subsurface and affects the peak discharges. The parameters FC, BETA Khq and LP show differences across the catchments (Table 4). This typically suggests hydrologic variability between catchments in terms of rapid streamflow responses but also evapotranspiration fluxes. A higher Khq results in higher peaks and more dynamic

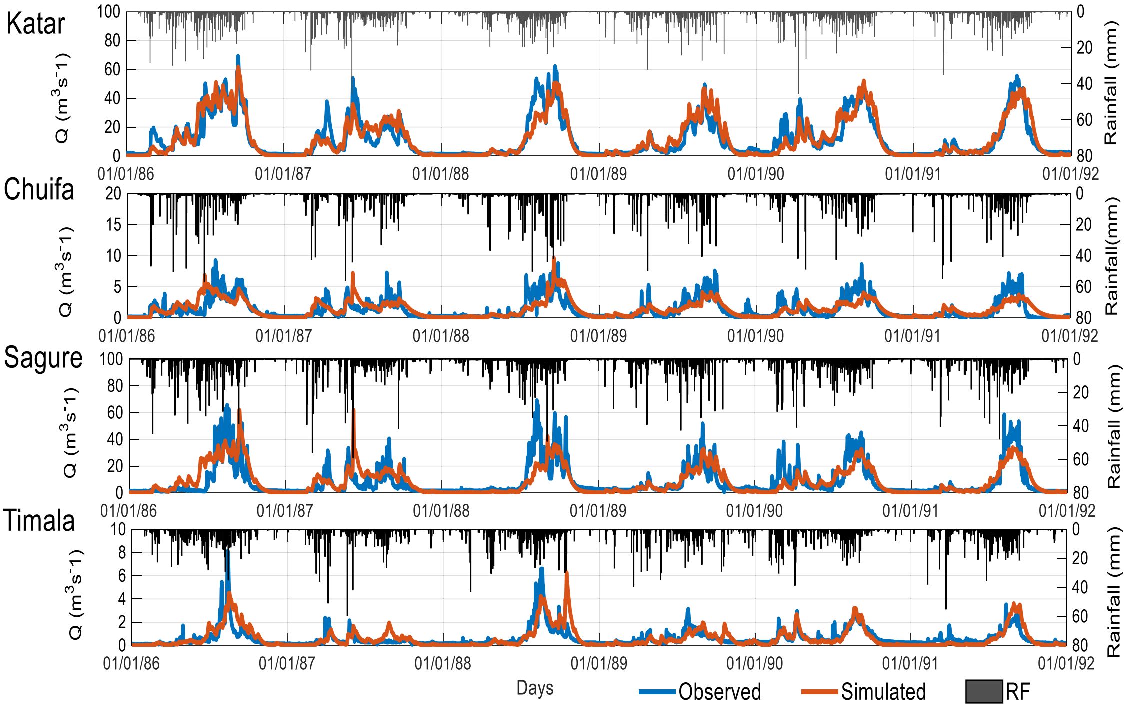

Fig. 4. The simulated and observed hydrographs of Katar, Chuifa, Sagure and Timala catchments for the calibration period (1986–1991).

responses in the hydrograph. PERC values were calibrated so that dry season flows of the catchments are well represented by the model.

The HBV model performed satisfactory for most of the catchments during the calibration period. Performance measures indicate that the model performed better for Meki and Katar catchments (NSE > 0.7, RVE $< 5\%$ and $R^2 > 0.7$) than for smaller catchments. For the minor tributary of Rinzaf, the NSE is lower than 0.5 for both calibration and validation period. Considering poor data quality, the model performance is acceptable for studying streamflow volume although caution should be exercised when the interest is in capturing the hydrograph shape.

When evaluated for the validation period, the model performance deteriorated for most catchments but with noticeable magnitude especially for small catchments such as Rinzaf and Timala. For instance, the negative value of the RVE (−14.3%) indicates that the mean simulated streamflow discharge is smaller than the mean observed discharge. However, these RVE values can also indicate deterioration of the quality of observed streamflow data for these two stations. The calibration was targeted more on RVE than NSE since the main target of this study related to inflow and outflow water volumes to respective lakes.

5.2. Water demand and development pathways

There is an on-going and planned water abstraction across all catchments of the CRV sub-basin (Fig. 5) although the abstraction sites are mostly concentrated around Lake Ziway. Irrigation demands were from both smallholder and large irrigation schemes. Water abstraction is commonly through pumping directly from Lake Ziway in the three districts (Adami Tulu, Dugda and Ziway Dugda) and along the Bulbula River. However, there are some diversions that pump water from Meki, Katar and Bulbula Rivers. The canal diversions are situated mostly at Katar, Meki and Langano tributary rivers. Particularly, the canal diversions are very dense along the most downstream stretch of Meki River.

For the base year (2007), the surface water system of CRV sub-basin supplied water to a total irrigated area of 5534 ha. Katar, Meki and Bulbula rivers provided water for large irrigated lands in the sub-basin (Table 5). A large irrigated area with intensive smallholder irrigated farmers, flower farms and modern irrigation schemes rely on abstractions from Lake Ziway. Compared to the base year 2007, the irrigated areas increased by 36%, 57% and 71% for the recent, short-term and long-term development pathways, respectively. Irrigation is the largest water user in the study area. In addition, water is used for soda ash, domestic and environmental flow at Bulbula River for downstream Lake Abiyata. The domestic water demand and environmental flow remains almost nearly the same for the three development pathways.

Fig. 6 shows the summary of annual water abstraction from the main water sources in the entire CRV sub-basin for the base year (2007). The figure indicates that Lake Ziway has largest water abstraction accounting for 39% of water withdrawal from the main surface water sources. Water withdrawal was the second largest for Katar and Bulbula Rivers whereas the withdrawal from Lake Langano is the smallest.

The summary of total annual water demand, supply and unmet demand for the three development pathways is presented in Table 6. Findings indicate that the annual water demand for the short-term development pathway (2019–2028) is 149.4 Mm^3 that corresponds to 46% increase as compared to the demand under recent development (102.3 Mm^3). If all the planned long-term water resources developments will be fully implemented, the annual water demand will amount to 223 Mm^3, and signifies an increase by a factor of 2.2, as compared to the recent development. This is mainly because of the increase in the projected irrigated area during this period. The annual water supply does not match the demand for all the development pathways. Table 6 also indicates that unmet demand will increase to 47.9Mm^3 in the long-term development.

Table 7 presents the water demand, supply delivered and unmet demand across the watersheds for the three development pathways. The water demand of water users from the lakes (Lake Ziway, Langano and Abiyata) was fully met for all development pathways as expected since there is no limit to water abstraction from the lakes. This indicates that water abstraction from the lake system is

Table 4

Calibrated model parameter values for respective catchments and objective functions.

Parameter	Meki	Rinzaf	Katar	Chuifa	Sagure	Timala
FC	860	840	820	860	830	870
BETA	1.96	1.2	3.05	2.2	2.8	3.15
LP	0.5	0.6	0.7	0.9	0.52	0.4
K4	0.1	0.1	0.1	0.05	0.08	0.1
Khq	0.1	0.08	0.12	0.04	0.20	0.15
Alfa	0.8	0.5	1.1	1.0	1.2	1.05
CFLUX	0.01	0.02	0.005	0.002	0.002	0.002
PERC	1.15	5.8	2.75	5.5	3.2	5.5
			Calibration			
NSE	0.71	0.35	0.80	0.52	0.57	0.50
RVE	-1.47	1.51	-1.28	-2.08	-0.13	-1.04
R^2	0.73	0.38	0.82	0.53	0.58	0.58
			Validation			
NSE	0.64	0.30	0.74	0.48	0.50	0.35
RVE	3.84	-14.3	3.04	-12.2	-14.8	-2.47
R^2	0.65	0.32	0.75	0.50	0.54	0.38

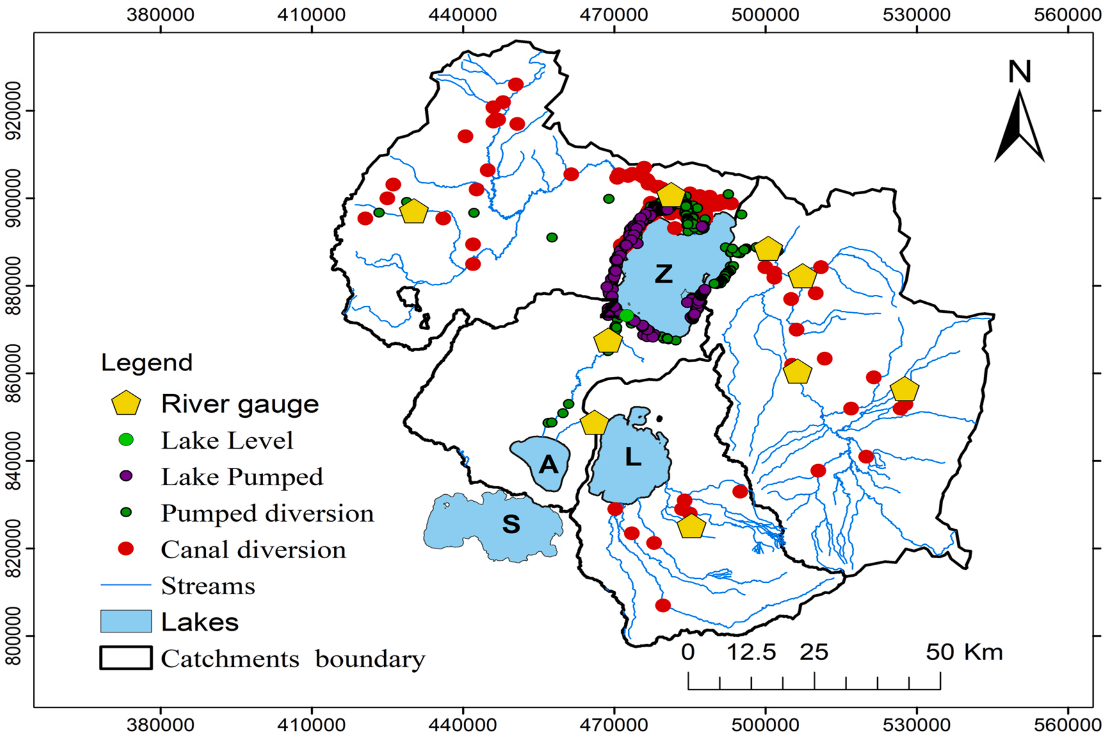

Fig. 5. Water resources abstraction sites in the Central Rift valley lakes basin (letter Z, L, A and S represents Lake Ziway, Langano, Abiyata and Shala, respectively).

Table 5
Summary of water resources development pathways in CRV lakes basin. Irrigation water demand is shown in ha whereas other demands are Mm^3.

			Development Pathways			
S. No	Water resources development	Water source	Base year (2007)	Recent (2009–2018)	Short-term (2019–2028)	Long-term (2029–2038)
I	**Size of Irrigated area (ha)**					
1	Meki Irrigation	Meki	458	708	856	1482
2	Dugda Irrigation	Dugda	187	288	474	724
3	Rinzaf Irrigation	Rinzaf	80	152	302	372
4	Katar Irrigation	Katar	781	1490	1965	3110
5	Chuifa Irrigation	Chuifa	65	123	223	423
6	Sagure Irrigation	Sagure	212	750	1000	1500
7	Timala Irrigation	Timala	335	850	1865	2200
8	Ziway flower farm	Ziway	500	640	944	1292
9	Lake Ziway Irrigation	Ziway	863	1144.5	1756	2958
10	Meki-Ziway Pump Irrigation	Ziway	128	216	400	750
11	Bulbula pumped Irrigation	Bulbula	1095	1235	1683	2000
12	Langano Tributary Irrigation	Gedemso	800	1040	1352	2028
13	Lepis Irrigation	Lepis	149	194	257	380
14	Boku Irrigation	Boku	96	125	167	244
15	Huluka Irrigation	Huluka	57	74	101	145
16	Lake Langano Irrigation	Langano	30	48	60	80
II	**Domestic water demand (Mm^3)**					
1	Ziway town WS	Ziway	1.26	1.41	1.45	1.49
2	Bulbula town WS	Bulbula	0.15	0.16	0.17	0.18
III	**Industrial water demand (Mm^3)**					
1	Lake Abiyata Soda Ash	Abiyata	3.63	7.06	7.5	10.5
IV	**Environmental Flow (Mm^3)**					
1	Abiyata minimum flow	Bulbula	3.62	3.62	3.62	3.62

uncontrolled.

The unmet demand was larger for long-term development for all demand sites. The largest unmet demand was estimated for demand sites in Katar, and catchments draining to Langano and Meki catchment. Even though, the highest priority was assigned to the

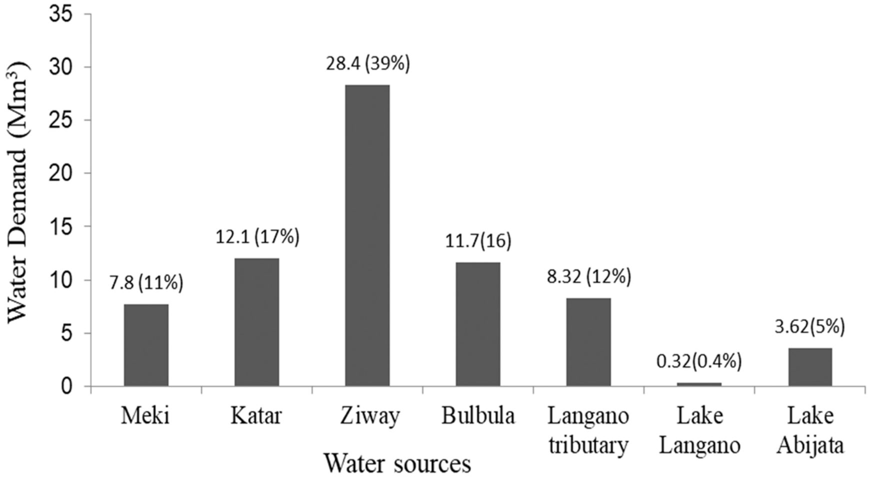

Fig. 6. Annual water demand for the base year (2007) from the main water sources in the sub-basin.

Table 6

Annual water demand and supply delivered for three development pathways (Mm^3).

Pathways	Water Demand	Supply Delivered	Unmet Demand
Recent Development	102.3	86.5	15.8
Short-term Development	149.4	120.2	29.2
Long-term Development	222.9	175.0	47.9

most upstream demand sites, larger unmet demands were estimated at upstream demand sites than downstream. The largest unmet water demand (28 Mm^3 per annum) for long-term development (Table 7) is in Katar watershed that is mainly due to large irrigated areas in Katar watersheds.

The percentage of unmet demand was also higher for demand sites with largest water demand. For long-term development, a highest unmet demand of 50% was obtained for Katar irrigation schemes, 45% for Langano tributary and 32% for Meki irrigation schemes (Table 7). Overall, this study indicates that there is unmet demand across all lake catchments. However, the unmet demand along Bulbula river is not large considering the extent of irrigation abstraction from this river. This may alter subject to the regulation of the barrage.

Fig. 7 presents the summary of monthly unmet demands for the three development pathways. The result indicates that the demand for all development pathways will be fully met for three months of the rainy season (July-September). The unmet demand for November to February is noticeable, mainly since this period is the driest season. The unmet demand in the small rainy season (March-

Table 7

Summary of spatial annual unmet demands across watersheds for the three developments.

				Volume (Mm^3)		
S.no	Catchment	Pathways	Demand	Supply Delivered	Unmet Demand	% of unmet demand
1	Meki	Recent	11.75	8.86	2.54	22
		Short-term	16.15	11.36	4.18	26
		Long-term	25.47	16.64	8.12	32
2	Katar	Recent	25.66	16.99	8.67	34
		Short-term	38.45	21.44	17.02	44
		Long-term	55.94	28.72	27.72	50
3	Lake Ziway	Recent	37.13	37.13	0.00	0
		Short-term	56.13	56.13	0.00	0
		Long-term	89.74	89.74	0.00	0
4	Bulbula	Recent	13.01	12.50	0.5	4
		Short-term	17.32	15.26	2.06	12
		Long-term	20.38	17.79	2.58	13
5	Langano	Recent	11.12	7.41	3.71	33
		Short-term	14.22	8.87	5.34	38
		Long-term	20.87	11.58	9.30	45
6	Lake Abiyata	Recent	3.63	3.63	0.00	0.0
		Short-term	7.06	7.06	0.00	0.0
		Long-term	10.5	10.5	0.00	0.0

May) is relatively small compared to the dry season. The total annual unmet demand under the recent development was about 15.8 Mm^3, which accounts for 15% of the total water demand. This amount increases by a factor of 1.85 (i.e., 29.2 Mm^3) for the short-term development. At the end of the long-term development pathway, the annual unmet water demand will increase by a factor of 3.0–47.9 Mm^3 as compared to the recent development.

5.3. Impact of water resources development

For accurate estimation of water resources development it is crucial to determine respective water balance components. Estimates of annual water balance components for the recent development pathway (1986–2000) for the three interconnected lakes are shown in Table 8. Estimates are comparable to estimates shown in the various studies (Vallet-Coulomb et al., 2001; Ayenew, 2004; Legesse and Ayenew, 2006; Desta et al., 2017). Findings indicate that lake evaporation is the largest component of the water balance for all lakes whereas surface outflow is the smallest component. Note that the amount of water abstraction was estimated from the recent (2018) water abstraction survey being field survey period. The amount of water abstraction from Lake Ziway was significantly larger than the abstraction from Lake Langano and Abiyata. In Table 8, the net volume change (ΔV) is estimated as the difference of lake inflows (rainfall and streamflow) and outflows (streamflow, evaporation and abstraction). For the baseline period (1986–2000), the net volume change and water abstraction for Lake Ziway is comparable to Lake Langano and Abiyata. This will result in minimum closure term for Lake Ziway when water abstraction is considered and the vice-versa for other two lakes.

Fig. 8 shows observed water levels of the three CRV lakes for the period 1986–2014 with reference to the mean lake bottom depth. The overall pattern with seasonal variations of water levels of Lake Langano and Lake Ziway appears to be similar, but the pattern of Lake Abiyata shows some deviation. In particular, a noticeable reduction in water level is observed from 2002 to 2006 which is a dry period of the study area (Fig. 8). That may be attributed to the cumulative effect of reduced water level of Lake Abiyata by reduced lake rainfall, but also by the propagated effect of the reduced water level of Lake Ziway and Lake Langano. Also, Lake Abiyata is relatively small (148 km^2) and nearly three times smaller than Lake Ziway (435 km^2) with surface outflow that does not exhibit a large seasonal variation (Ayenew and Becht, 2008).

Lake Langano showed relatively small seasonal and inter-annual water level variations as compared to the other lakes (Ayenew, 2001; Vilalta, 2010). This phenomenon mainly can be attributed to relatively smaller irrigation water abstraction around the lake and its tributaries. Overall, for all interconnected lakes a notable decrease of the water level after 2000 is observed. Very low water levels were recorded from 2002 to 2005, which coincides with climatic drought years. Since June 2016, the outflow of upstream Lake Ziway is regulated by a barrage constructed at Bulbula River near Lake Ziway.

Fig. 9 shows result of lake level simulation for baseline period and the three development pathways. Findings indicate that the simulated lake levels for the three development pathways were lower than the water levels that apply to the baseline period. Lake Ziway shows a water level reduction because of water resources development in feeding rivers as well as direct pumping from the lake. We note that for respective years a maximum of up to 3 m water level reduction will occur during long-term development pathway. Results of water level simulation of Lake Ziway indicate that the level will drop below the water scarcity level in most years of the short-term and long-term development pathways.

In contrast, the water level of Lake Langano is unlikely to decrease below the water scarcity level for all pathways but for extended period in the long-term pathway, but with a possible exception for drought periods that in the assessments were not considered. This indicates that irrigation water abstraction from Langano Lake and its tributary rivers do not directly affect water availability by lake storage. The projected water level fluctuations in Lake Abiyata follow the same pattern as simulated for Lake Ziway. Findings show that

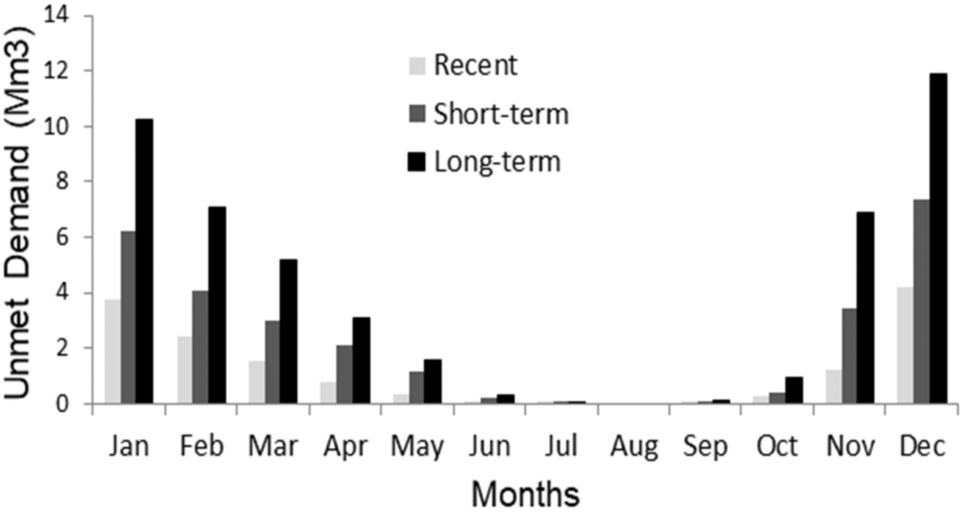

Fig. 7. Monthly temporal unmet demands for the three development pathways.

Table 8

Estimated mean annual water balance of CRV lakes from 1986 to 2000 (all unit in Mm^3 per year).

	Water Inflow			Water Outflow			Net volume
Lake	R_i	Q_{in}	Q_{un}	Evap	Qout	Abstraction	ΔV
Ziway	338	614	81	832	171	37	30
Langano	196	232	67	467	53	12	-25
Abiyata	115	225	–	362	–	11	-23

Note: R_i, rainfall on the lake surface; Q_{in}, river inflow; Q_{un}, inflow from ungauged catchment; Evap, evaporation from the lake surfaces, Q_{out}, lake outflow in the river outlet, and ΔV, net volume change.

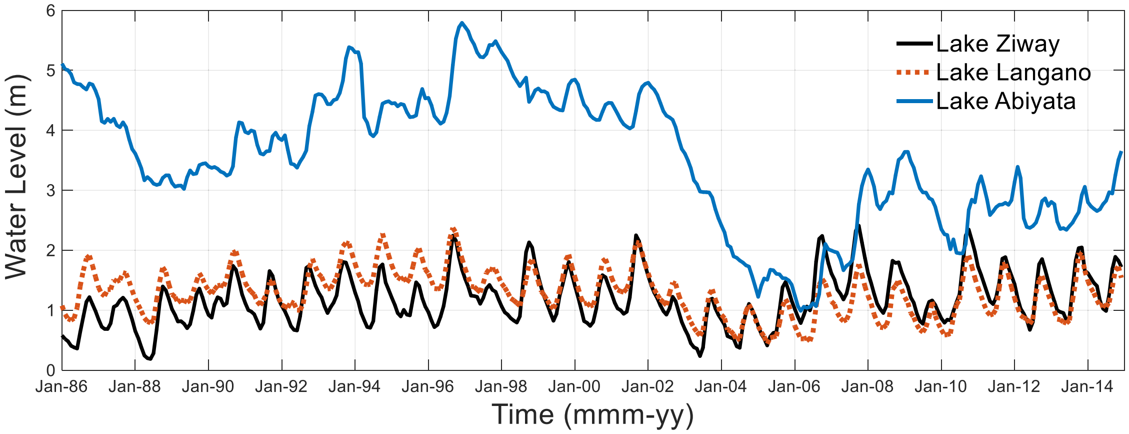

Fig. 8. Observed water level fluctuation of the three interconnected lakes (1986–2014).

the lake level notably reduces below the water scarcity level for all development pathways including the recent development pathway. For instance up to a maximum of 4.2 m water level reduction in Lake Abiyata as attributed to long- term water resources development.

There is significant difference between the patterns of the natural simulated water level and that for short-term and long-term development pathways of the three interconnected lakes. Hence, the results of this study show that the influence of water resources development on the lake water levels and thus lake water balance is substantial. There is large difference between the water level under the recent development and base line period. The shift from recent to short-term development will aggravate the reduction of the water level. However, simulation on the lake water level indicates the largest reduction applies to long-term development pathway. During this period, the water levels significantly reduce below the water scarcity level for most of the time for Lake Ziway and Abiyata. This is mainly related to increasing cumulative water abstractions from the lakes and tributaries. This likely would have a significant impact on shipping and fishing of Lake Ziway and ecology of both Abiyata and Ziway lakes.

Table 9 shows volume, water level and surface area relationships for each development pathway for CRV lakes. As expected when water resources development in the sub-basin increases, then water storage of the lake will decline. For instance, the mean annual water level of Lake Ziway drops by 0.72 m for recent development, which results in reduction by 21% and 7.6% of the storage volume and surface area of the lake from the baseline period, respectively. The long-term development pathway further aggravates the drop in the water level, volume, and surface area of the lake. During this development, the average lake water level of Lake Ziway declines by 1.76 m from the natural recent condition. This would result in 40% and 20% reduction of the lake volume and surface area of the lake, respectively (Table 9).

For Lake Langano, the impact of water resources developments follows nearly similar pattern for both volume and surface area of the lake. The recent development pathway indicated a 0.5 m reduction in water level, which transforms to a reduction of 3.5% storage volume and 4.2% in surface area of the lake. For long-term development, the lake water level decreases by 0.97 m, this yields 7.4% reduction in surface area of the lake. This transforms to 8.5% reduction in the volume of the lake.

For Lake Abiyata, during recent development, the mean annual water level and volume of Lake Abiyata reduces by 1.13 m and 11%, respectively, as compared to baseline period that represent the natural condition. This will result in reduction of lake surface area by 9.4% (Table 9). The short-term development causes further reduction of the water level of Lake Abiyata. The impact of the water resource developments for the long-term pathway notably reduced the average water level by 2.1 m. This will yield 27.6% reduction in lake surface area and 46.7% reduction in volume of the lake. These findings indicate that any intervention in the upstream catchments results in further reduction in the water level of Lake Abiyata. Overall, the impact of water resources developments from the CRV lakes results in significant impact on the water level, volume and surface area of the lake.

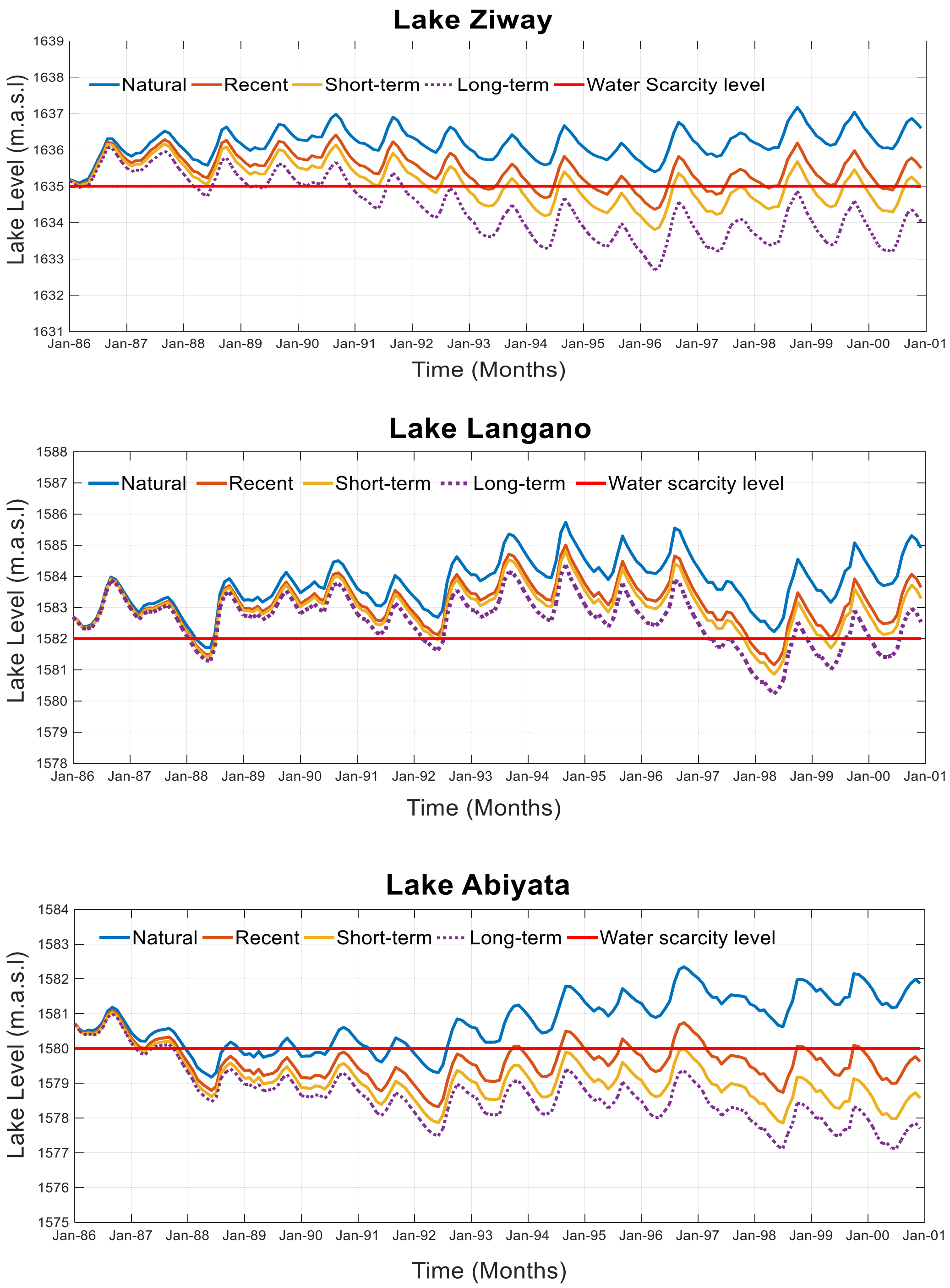

Fig. 9. Comparison of the natural and simulated lake levels for the three development pathways for Lake Ziway, Langano and Abiyata.

6. Discussions

In this study, in-situ, satellite and survey datasets were used and combined in rainfall-runoff, water balance, crop water modeling, and water resources planning models. Streamflow from Lake Ziway gauged catchments is simulated by use of a HBV conceptual rainfall-runoff model. The contributions of streamflow from ungauged catchments are estimated by use of area-ratio methods. The lake open water evaporation was estimated from the air temperature data of the eastern and western shore of the lake whereas previous studies only used one station. Lake area rainfall estimation used the bias-corrected CHIRP satellite rainfall on the lake surface. This study extended on previous studies on the CRV Lakes sub-basin by considering effects of water abstractions on the water balance over

Table 9
Summary of mean annual water balance simulation results for each development pathways.

	Mean Water level	Area	Volume	Water level Change	Area Change	Volume change
Lake Ziway	m.a.s.l	km^2	Mm^3	m	%	%
Baseline	1636.18	442.24	1529.50			
Current	1635.46	408.53	1211.21	-0.72	-7.6	-20.8
Short-term	1635.08	389.20	1059.39	-1.10	-12.0	-30.7
Long-term	1634.42	352.33	914.28	-1.76	-20.3	-40.2
Lake Langano						
Baseline	1583.78	225.37	5339.28			
Current	1583.28	217.48	5115.03	-0.50	-3.50	-4.2
Short-term	1582.96	213.65	4976.21	-0.82	-5.20	-6.8
Long-term	1582.81	206.69	4885.44	-0.97	-7.40	-8.5
Lake Abiyata						
Baseline	1580.76	135.5	1058.74			
Current	1579.63	122.8	947.82	-1.13	-9.4	-10.5
Short-term	1579.10	115.4	789.56	-1.65	-14.8	-25.4
Long-term	1578.66	98.1	564.32	-2.10	-27.6	-46.7

the lakes and its tributaries. Findings of this study on lake water balance are affected by various sources of error and uncertainty, each of which cannot be quantified directly by lack of sound data. This study assumed that lake-groundwater interaction is negligible. Given pronounced, long-term, erosion and sedimentation in the lakes, we assume that fine grain lake bottom materials largely obstruct flow of water. For estimation of lake evaporation, the Penman method was used and meteorological data from only two stations was available. Rainfall estimates to serve rainfall-runoff modeling and to estimate lake-rainfall were from bias-corrected CHIRP satellite rainfall. Since runoff from ungauged catchments was related to runoff from gauged catchment though area-ratio conversions, this implies that errors in HBV model simulation results propagate to ungauged basins as well.

Crop water requirements for irrigation were estimated by the CROPWAT model. By lack of field data on crop yield or bio-mass production, results on water requirements could not be explicitly verified and thus results must, somewhat, be exercised with care. Time series data from twelve meteorological stations that were located close to the demand sites were used for rainfall and for potential evapotranspiration input estimation. As such estimates on irrigation demands for each development pathway relied on the same meteorological data. We suggest that future studies consider detailed uncertainty analysis to indicate how uncertainties affect the water balance and findings in this study on lake sustainability.

In Table 10 findings on water balance components of CRV Lakes sub-basins in this study are compared to findings in (Vallet-Coloumb et al., 2001; Ayenew, 2004; Legesse et al., 2004; Jansen et al., 2007; Ayenew and Legesse, 2007; Seyoum et al., 2015; Desta et al., 2017; Goshime et al., 2020). Causes of differences not only relate to the methodological approach in this study but also to the selected data sources and utilized models, and length of the simulation periods. In this study, we estimated lake rainfall from bias-corrected CHIRP satellite rainfall whereas previous studies only used observed data with limited rain gauge network coverage. We also used the bias-corrected CHIRP product to estimate Lake Ziway catchment streamflow discharges as time series from rain gauges were incomplete hampering water resource assessments.

Open water evaporation estimates (832 Mm^3) in this study from Lake Ziway are lower than estimates by Ayenew (2004) (890 Mm^3) but higher than that by Jansen et al. (2007) (774 Mm^3). For Lake Langano and Abiyata, estimates in this study are quite similar to estimates by Ayenew (2004) and Ayenew and Becht (2008) (467 and 372 Mm^3, respectively). Any difference may arise from the number of stations and length of the time series of the meteorological data used to estimate the lake evaporation. The volume of streamflow outflow (171 Mm^3) for Lake Ziway in this study is lower than the volumes by Ayenew (2004) (184 Mm^3) and Jansen et al. (2007) (185 Mm^3) but higher than Vallet-Coulomb et al. (2001) (157 Mm^3). Water abstraction from Lake Ziway as estimated by

Table 10
Comparison of water balance components of CRV lakes among different studies in Mm^3 (1986–2000).

	Inflow			Outflow		
Water Balance Components	R	Q_{in}	Q_{ung}	Evap	Q_{out}	Q_{abs}
Lake Ziway						
Vallet-Coulomb et al. (2001)	335	691	50	832	157	–
Ayenew (2004)	323	657	48	890	184	28
Desta et al. (2017)	356	656	–	854	–	41
This study (2020)	338	613	81	832	171	37.3
Lake Langnao						
Ayenew (2004)	186	212	–	463	46	–
This study (2020)	196	232	27.2	467	53	11.1
Lake Abiyata						
Ayalew (2003)	97.2	180	–	291	0	0
Ayenew (2004)	113	230	15	372	0	13
This study (2020)	115	219.5	–	328	0	15

Ayenew (2004) (28 Mm^3) is lower than estimates in this study but match estimates in Desta et al. (2017) (41 Mm^3). This is due to the difference in time period for which the abstraction was estimated and the method applied. The amount of Lake Abiyata water abstraction estimated in this study (11 Mm^3) is relatively close to Ayenew and Legesse (2007) (13 Mm^3). Overall, there is some disagreement in reported outflow and water abstraction findings by different studies for all lakes.

Fig. 10 shows annual water level change of Lake Ziway and that of downstream Lake Abiyata for the baseline period 1986–2000. The comparison illustrates a direct relationship between water level changes of both lakes. For instance, for 1990 a 0.5 m reduction in water level of Lake Ziway can be associated to a 1.8 m reduction in Lake Abiyata, and a 3 m reduction in Lake Ziway water level for 2000 can be associated to a 4.5 m reduction in Lake Abiyata. Similar findings were reported in (Vallet-Coulomb et al., 2001; Seyoum et al., 2015). For instance, Seyoum et al. (2015) reported that approximately up to 4.5 m reduction in water level of Lake Abiyata was observed between 1986 and 2006. Overall, in this study the simulated water level reduction in the downstream Lake Abiyata is considerable. Moreover, any water level reduction in Lake Ziway will result in larger reduction in the downstream Lake Abiyata. The water balance of Lake Abiyata depends on seasonal rainfall, and river inflow mainly from Bulbula and Horakelo rivers, which are the largest inflowing river into the lake. Hence, any intervention either from Lake Ziway or Bulbula River contributes to changes in the water inflow and propagates to affect lake storage of Lake Abiyata.

Further, intensive irrigation water abstraction is on-going from Lake Ziway and its tributaries, and Bulbula rivers for the production of horticulture, vegetables, and flowers. As a result, the water level of Lake Ziway and water flow into Bulbula River is reduced by water withdrawal. This phenomenon might be related to regulation of Lake Ziway through a recently constructed barrage that causes reduced lake outflow. This consequently will result in significant water level decline of Lake Abiyata. In addition, Abiyata soda ash production could be the other possible anthropogenic cause for the water level reduction. Since the water withdrawal from the lake for soda ash production does not return to the lake, the shore of Lake Abiyata has receded each year (personal communication). Fetahi (2016) reported that Lake Abiyata shore receded by 3 km from its pumping station and soda ash production has reduced because of the loss of water in Lake Abiyata at recent time. Therefore, this study suggests appropriate measures should be taken by decision makers and any concerned stakeholders for improved water management of the CRV lakes.

In this study, water resources and water balance assessment were based on climatic data for recent time periods. For assessment on future development pathways the same climate data was used and as such aspects of climate change have been ignored. We consider this an omission and recommend climate change assessments to better project on available water resources. Therefore, future studies should consider projected future climate by global and regional climate circulation models as employed in various studies (Setegn et al., 2011; Haile et al., 2017; Bekele et al., 2021). Also, future studies can explore approaches supported by field survey and stakeholder consultation to fix the environmental flows of the rivers. The environmental flows can be estimated using various approaches such as Tennant (1976) or hydrological variability based on the original flow time series and its corresponding Flow Duration Curve (FDC) as a cumulative distribution function of flows. Following Mersha et al. (2021) a range of Environmental Management Classes (EMC), from "natural" to "severely modified" cane be used to calculate flow duration curve with a corresponding progressively reducing environmental flows resulting in a decreasing level of ecosystem protection.

7. Conclusions

In this study, impacts of water resources development on the water balance of CRV lakes and their contributing catchment was assessed. Three development pathways covering for recent and future water demands were considered. As a benchmark to simulation results for respective pathways, a baseline period with minimum of water abstractions was considered to best represent natural conditions. This study is distinctive as it considers the spatial and temporal water resources developments of the sub-basin using a combination of modeling approaches, and since up-to-date datasets are used considering ground observations, satellite rainfall

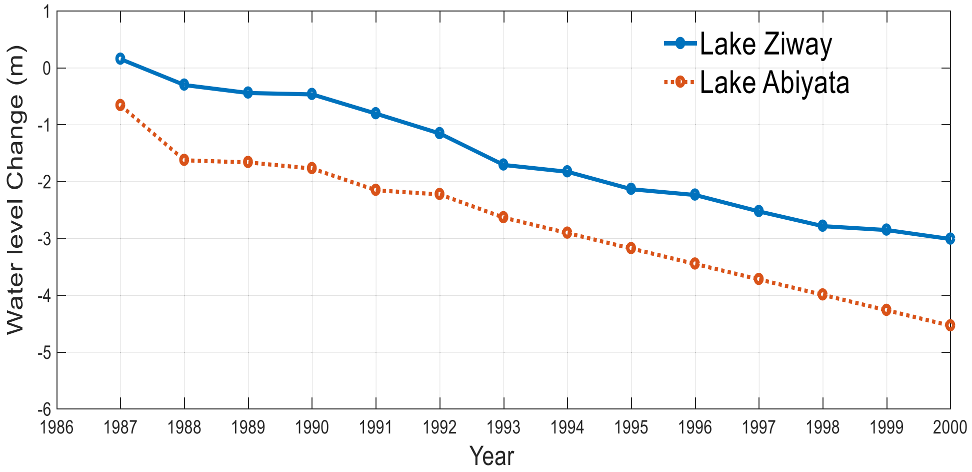

Fig. 10. Estimated annual water level change of Lake Ziway and Abiyata from 1987 to 2000 with 1986 as a reference.

estimates and field survey datasets. The Water Evaluation and Planning (WEAP) model was used to assess existing and future water demand and thereby to evaluate the likely impact of three water resources development pathways on the water balance of Lake Ziway, Langano and Abiyata.

Simulated streamflow resulted from the HBV model that well captured volumes of observed hydrographs for most of the gauge stations. Volumetric errors by RVE model performance indicator in general only were small (<5%). Crop water requirements for irrigation were estimated by CROPWAT model.

Findings of this study indicate severe implications of water resources development pathways around the lake and its feeding rivers. For increasing time periods from recent to long-term development, the water balance of the three interconnected lakes shows substantial impacts with water shortage that only further increases. The WEAP simulation results revealed that in the long-term development, the water demand in the CRV will be twice the present water demand. Under long-term development pathways, the water demand of the sub-basin is estimated to be 222.9 Mm^3. Compared to the recent development; this will reduce the mean annual lake water level by 1.76 m, 0.97 m and 2.1 m for Lake Ziway, Langano and Abiyata, respectively. This will cause reduction in the lake volumes by 615 Mm^3 of Lake Ziway, 454 Mm^3 of Lake Langano and 494 Mm^3 of Lake Abiyata. The largest unmet water demand occurs from November-February that marks the dry season. Findings also indicate that the demand sites at Katar, Meki and Langano catchments have highest unmet demands for all development pathways.

Our findings indicate that for long-term and short-term development the water levels of Lake Ziway expectedly will reduce below a water level that indicates water scarcity. Finding show that any reduction will propagate to the downstream Lake Abiyata with even further increased reduction of water storage. Water levels are expected to fall below the critical water level that indicates water scarcity for all development pathways mainly due to intensive upstream water abstraction and barrage outflow regulations. The result also suggests that the newly constructed barrage can be used to regulate the lake level of Lake Ziway. This study shows that, to prevent further desiccation of CRV lakes, it will be necessary to reduce irrigation water abstractions, and to adapt water resources development pathways. More efficient irrigation techniques and scheduling could be considered, crops could be introduced that consume less water, but also improved planning and redistribution of available water resources at national scale should be considered. Hence, we suggest future studies to assess and evaluate various water management scenarios that will reduce impacts of water withdrawal, climate change and inform integrated water resources management among all stakeholders.

CRediT authorship contribution statement

Demelash Wondimagegnehu Goshime: Conceptualization, data acquisition, model set-up, calibration, & draft manuscript. **Alemseged Haile Tamiru:** Conceptualization, validation, editing, & supervision. **Tom Rientjes:** Editing, validation & supervision. **Rafik Absi:** Editing & supervision. Béatrice Ledésert: Editing & supervision. **Tobias Siegfried:** review & editing.

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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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2021.100969.

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