IMPACT OF WATER ABSTRACTION ON THE WATER LEVEL OF LAKE ZIWAY, ETHIOPIA

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ABSTRACT

Significant change has been observed in the water level of Lake Ziway in Ethiopia which hinders its services for a wide variety of ecosystems. However, the contribution of water withdrawal and its impact on the lake water level variation has not been quantified yet. In this study, we conducted a water abstraction survey (WAS) to estimate actual water withdrawal from the lake. Then, we applied a water balance model coupling with simulated river inflow from rainfall-runoff model output data to evaluate the isolated impact of water withdrawal on the lake water level from 1986–2000 at monthly time steps. The amount of water withdrawal from the lake for irrigation water use is 37×10^6 m^3 per year. This led to 0.36 m drop in the lake level which corresponded to 18 km^2 reductions in the lake surface area. This consequently resulted in a reduction of mean annual lake volume by 162×10^6 m^3 from 1986–2000, which accounts for 23% of the total lake inflow from rivers.The results indicate that abstraction from the lake is a significant contributor to the drop in water level of Lake Ziway. This calls for serious action on the management of water abstraction from the lake.

Keywords: Lake Ziway, water level, irrigation water abstraction, impact, surface area.

1 INTRODUCTION

Lake Ziway provides a wide variety of ecosystem services with significant contributions in the livelihoods of many people in the area. The lake is a vital source of water for irrigation, domestic, and fish supply for market in the country. Furthermore, the lake and its basin are the focus of the Ethiopian government to stimulate large scale export-oriented irrigated floriculture and a number of irrigation schemes. However, recent expansion of intensive water abstraction activities from the lake are leading water level drops. Hence, this will consequently damage the hydrological and ecological integrity of the lake [1].

Significant change has been observed in the water level of different Rift Valley Lakes in Ethiopia, as a result of natural processes and human activities over the past decades. For instance, Seyoum et al. [2] showed that water level of Lake Abiyata significantly changed as a result of human activities. They reported 70% (4.5 m) reduction in lake height between 1985 and 2006. A rise in the size and water level of Lake Awassa and Beseka was also reported in literature with the main cause of its variation is uncertain [3]. Jansen et al. [1] indicated annual average water level of Lake Ziway approximately decreased by 0.5 m as a result of recent expansion of irrigation activities around the lake and its tributaries. The authors also showed that this drop result in a tremendous decrease in the discharge of Bulbula River which in turn result in a reduction in size of Lake Abiyata by more than 40% of its size in 1999.

The reduction in water level of Lake Ziway is mainly attributed to both natural and anthropogenic factors. Ayenew [4] estimated annual water abstraction for irrigation from the lake to be 28×10^6 m^3. However, recent studies reported that dramatic increase in water abstraction for horticulture and floriculture even doubles this value [1], [5]. The estimate of these studies was only from a dominant crop in the study area and results vary among

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/WS190071

different studies. However, site-specific water abstraction surveys need to be performed to estimate actual water withdrawal. Desta et al. [5] assessed water abstraction of Lake Ziway by considering pump capacity and operation hour for all users. Then, they multiply these values by the number of pump to estimate the amount of water abstraction. However, it is unlikely to assume constant pump capacity and daily working hour for all water users in the study area. Therefore, a systematic study that takes in to account the spatial and temporal water abstraction is required to estimate actual irrigation water abstraction.

Irrigation water abstraction for flower farm, diversion schemes and smallholder farmers are the major water user of Lake Ziway. However, much of the water abstractions from the lakes have not been quantified, as a record of water abstraction rates are not available. Furthermore, water users abstract free of charge from the lake without awareness on water conservation. This consequently may result in overexploitation of the lake water resources, which in turn result in partial or complete loss of the lake storage over time.

Several studies at global and local scales have indicated lack of data as a major challenge in the estimation of actual water abstracted for irrigation [6]. As such most of previous studies estimate irrigation water demand from a crop that requires the highest amount of water using national statistics, reports and climatic database [7]–[9]. However, recently remote sensing and field survey techniques are commonly applied by researcher to estimate irrigation water abstraction. The spatial and temporal coverage obtained from remote sensing data provides improvement in estimating water requirements. Note that field survey provides actual amount as it is based on actual measurement at field level.

The hydrology of many lakes has been relatively well documented, for instance that of, Lake Victoria [10], Lake Malawi [11], Lake Tana [12]–[15]. However, the hydrology of Lake Ziway is not well documented in scientific literature as compared to other lakes. Among the literature, on the hydrology of Lake Ziway [2], [3], [16]–[18] most of them focused on the water budget of the lake under the natural conditions. However, there is no study that quantitatively estimated actual water abstraction from the lake and its impact on the water level based on WAS.

The actual magnitude of water withdrawal and its impact on the water level from available studies are uncertain. The absence of such knowledge in the study area will hinder effective water management of the lake. Therefore, the objective of the present study is to estimate actual water withdrawal from the lake and evaluate its impact on water level using water balance modelling approach. Therefore, this study will provide information on the contribution is water abstraction to the observed drop in water level. Such information can be used by decision-makers, planner and water sectors for better management of water abstraction around the lake. Results of such analysis are of relevance to the scientific community to show the potential use of WAS to improve estimation of actual water withdrawal.

2 STUDY AREA

Lake Ziway is located in the Central Rift Valley (CRV) lakes basin of Ethiopia with a lake surface area covering 450 km^2. It is situated between 7.43°–8.58°N latitudes and 38.2°–39.25°E longitudes. Lake Ziway receives most of its water from Meki and Katar rivers, which drain the western and eastern plateaus, respectively. The two rivers account a total catchment area of 7020 km^2. The outflow from Lake Ziway water is discharged into Bulbula River, which in turn flows to Lake Abiyata.

The climate in Lake Ziway is sub-humid to humid climatic, with mean annual temperature ranges from 13 to 27.5°C. The mean annual rainfall varies from 454 to 995 mm, with the highest rainfall occurring from June to September and lowest from October to January. Water abstractions from the lake for agricultural and domestic water demand account for the major water uses in the lake. The dominant land covers around the lake include agricultural cultivation, wetlands and water bodies (Fig. 1). Fig. 1 shows the location of Lake Ziway including contributing catchments.

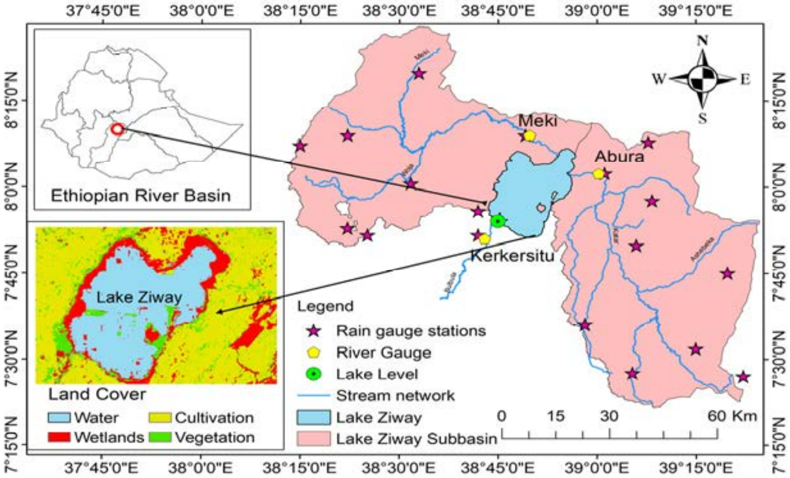

Figure 1: Location of Lake Ziway showing its catchment, major feeding rivers (Meki and Katar), rain gauge stations, and land cover classification around the lake from Google Earth image.

3 DATASETS

In this study, we used climate, hydrological and water abstraction data sets. The observed climate data sets were obtained from the National Meteorological Agency of Ethiopia and Climate Hazards Group Infrared Precipitation (CHIRP) satellite-only product at (daily temporal and 5.5 km spatial resolutions) extracted from http://chg.geog.ucsb.edu/data/. CHIRP covers regions that are situated between 50°S –50°N latitude and all longitudes [19], [20].

Lake Ziway water level, outflow (at Kerkersitu) and river discharge (at Meki and Katar Rivers) data were obtained from the Ethiopian Ministry of Water, Irrigation and Electricity of Ethiopia. The lake level–area–volume bathymetric survey conducted by the Ministry of Water, Irrigation and Electricity of Ethiopia in 1984 and 2013 were used for water level simulation, with a reference datum level of 1,635 m above sea level.

Water abstraction data around Lake Ziway was collected from water abstraction survey at field level for 15 days from 20 October 2018 to 5 November 2018. This period was selected because the problem associated with water resources in the area usually occur in the dry season. This is mainly water user start to irrigate more water during this period and feasible for field measurement. Although, the field survey was conducted during dry season we interviewed the user there seasonal water use for accurate water abstraction estimation.

The field survey was performed with a GPS device, bucket, measurement tape, current meter, and stopwatch. In addition, the data was upgraded by additional data obtained from water and agricultural offices of the localities in the study area. The facilities for water abstraction include individual farmers pumping points, water diversion schemes, flower farms, and domestic water supply owned by individuals, community and private sectors. We also surveyed seasonal pump and/or scheme operation, crop types, command area and irrigation scheduling for season irrigation pattern throughout the year.

4 METHODS

This study is based on the assessment of existing and satellite hydro-meteorological dataset, water abstraction survey, and review of published studies. We applied the hydrological model output coupling with water balance modelling and field surveys. The hydrological model output was based on calibrated and validated results from Goshime et al. [21].

The methodologies followed in this study are: First, we estimated water abstraction for all abstraction points based on Water Abstraction Survey (WAS). Next, we evaluated the water balance components of the lake under the natural condition on a monthly time steps. Then, the implication of existing water abstraction on the water level was evaluated using a water balance modelling approach. The simulated lake level for the natural condition was used as a reference to evaluate the impact of water abstraction on the water level and volume. The natural period run from 1986 to 2000 as major water abstraction was insignificant around the lake and at upstream catchments during this period. Furthermore, this period also represents a year before construction of Lake Ziway outflow regulation at the head of Bulbula River.

4.1 Impact of water abstraction

A record of water abstraction volume is not available at abstraction points in the study area. Hence, we measured the amount of water abstraction for selected abstraction points and managers were interviewed based on our data collection format. The amount of water abstracted was measured using a bucket with a known size. The time which is elapsed to fill the bucket was recorded and was used to estimate the capacity of the pump in volume per unit time. The equation reads

$$Q_{abs} = Qd \times n \times h, \tag{1}$$

where Q_{abs} is the amount of water abstracted (m^3), n is a number of pumps used by the user, Qd is the diverted discharge of the pump (m^{3}s^{-1}), and h is abstraction operation duration (s).

We measured the water abstraction for the pumps which were under operation during our field survey. However, the characteristics of all pumps were recorded and used to extrapolate using the sampled abstraction rates, pump type and size. The rate of water abstraction was assumed to be constant throughout the year. However, we estimated the monthly seasonal water abstraction based on irrigation pattern and pump operation condition. Hence, this monthly estimated water abstraction amount was used constantly throughout the simulation period.

4.2 Lake water level simulation

The inflow and outflow water balance components of the lake were expressed using the following relationships at monthly time steps including water abstraction

$$\Delta V = R(t) - E(t) + Q_{in}(t) - Q_{out}(t) - Q_{abs}, \tag{2}$$

where ΔV is the change in lake water volume, R is rainfall over the lake surface and E is evaporation from the lake surface, Q_{in} is surface water inflow to the lake, Q_{out} is surface water outflow from the lake, and Q_{abs} is water abstraction from the lake. All terms are in m^3 month^{-1} unit.

In this study, lake areal rainfall is estimated from bias-corrected CHIRP rainfall estimate using rain gauge dataset as a reference. For a more detailed analysis of a bias correction approaches refer Goshime et al. [21]. Lake open water evaporation was estimated from three representative stations (i.e. Ziway, Ogolcho and Arata) which are located close to the lake using Penman [22] method.

The surface inflow to the lake from Meki and Katar river gauge stations simulated using Hydrologiska Byråns Vattenbalansavdelning (HBV) hydrological modelling output based on our prevouis studies, see Goshime et al. [21]. The ungauged inflow contribution was estimated using the area–ratio method. Lake Outflow discharge available at the Kerkersitu station was directly used in the water balance.

After all water balance terms estimated a spread sheet water balance model is developed to simulate lake volume as follows:

$$V_{lake}(t) = V_{lake}(t-1) + \Delta V, \tag{3}$$

where V_{lake} (t) is the lake volume at time t, V_{lake} is lake volume at a previous time (t-1), and ΔV represents a change in lake volume as estimated using eqn (2). The lake volume was then converted to lake level using the bathymetric relationships.

4.3 Impact of water abstraction

To evaluate the impact of water abstraction, two scenarios were built: the baseline natural (BS) and existing development (ED). The BS is the natural simulated water level from 1986–2000 without water abstraction whereas ED represent the existing water abstraction to irrigate a total of 2,000 ha withdrawing water from the lake. For this, first we assessed the lake water balance without and with water abstraction component (Q_{abs}) included in eqn (2). Then, we simulated the lake volume (corresponding lake level) for the baseline natural condition and existing development using eqn (3). The isolated impact of water withdrawal from the lake on the water level will be estimated from the net difference between the simulated for natural and existing condition. Further, we applied a steady state threshold water level below which the lake water might not satisfy the water need of all users. This level is assumed to represent the level at which the impact of water abstraction is minimal and hence all water use including fishing and shipping water requirement will be fulfilled.

In this study, we also assessed the effect of water level change on the lake water quality variation based on temporal lake water chemical characteristics from published articles [23]–[25]. We selected to use different anions (Cl^-, F^-, $SO4^{2-}$) and cations (Na^+, Ca^{2+} and Mg^{2+}) including salinity level [23]. We compared the range of minimum and maximum water quality parameters and the corresponding temporal water level variation. The sampled points were considered to represent both the dry (October–March) and wet (July–September) seasons of the years to consider for low and high water level, respectively.

5 RESULTS AND DISCUSSION

5.1 Water abstraction

The estimated amounts of annual water abstraction for surveyed water sectors are given in Fig. 2. The water uses from individual smallholder farmers were summed up into three administrative districts. The figure shows that Sher Ethiopia flower farm, Meki–Ziway pump irrigation and smallholder individual farmers at three districts were the major water users from the lake. The survey shows that water abstraction for irrigation accounts for 97% and only 3% accounts for domestic water use. We surveyed a total of 856 pumping stations of the individual farmers, seven flower farms, four irrigation schemes, and one water supply facility. The domestic water supply in Ziway town was estimated to be 1.26 × 10^6 m^3 per year over the study period (personal office communication).

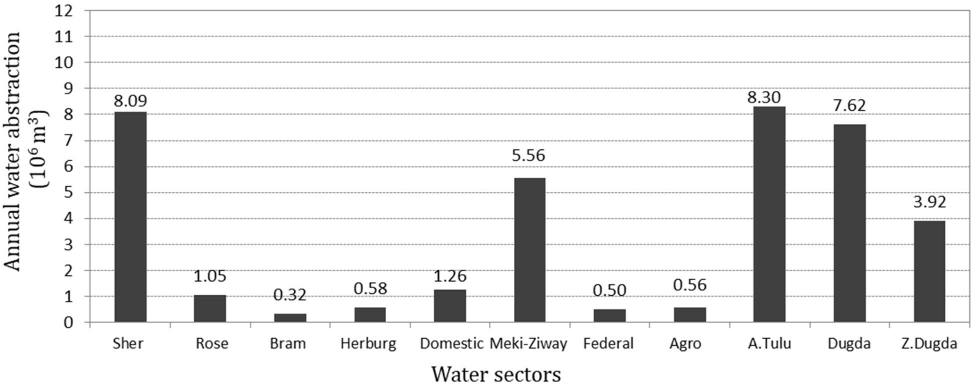

Figure 2: Annual water abstraction amount for the existing situation for all considered water sectors. The total annual water withdrawal makes 38 x 10^6 m^3 per year.

The amount of annual water withdrawal from the lake for irrigation and domestic purpose revealed 38 × 10^6 m^3 volume of water to irrigate 2,000 ha of agricultural lands for three seasons each year. This value is slightly lower than estimated in Desta et al. [5] (41 × 10^6 m^3) but higher than in Ayenew [4] (28 × 10^6 m^3). The difference on the amount of estimated water abstraction among the studies arise from the methods and assumptions applied to estimate. In this study, we used more precise data from water abstraction survey whereas previous studies simply applied from a highest crop water requirement in the area.

5.2 Lake water balance

The monthly average simulated water balance components of Lake Ziway from 1986 to 2000 for the natural condition are presented in Fig. 3. The figure illustrates that lake inflows mostly occur during the wet season (i.e. June–September). Lowest contribution to the inflow occurs from November to March. The lake outflow due to evaporation was greater than the river outflow. The larger outflow through Bulbula River occurs from September to January while lower river outflow occurs from February to July. Overall, our result revealed that rainfall, river inflow and evaporation constitute 33, 60 and 83% of the annual water balance of the lake, respectively. This indicates that the river inflow contributes the major Lake inflow and evaporation over the lake surface accounts the major lake water loss.

The results of annual lake water balance for the natural condition (1986–2000) for Lake Ziway are given in Table 1. The finding of this study was compared with other previous studies [1], [4], [5], [18]. We note that our estimates of the annual water balance components are comparable with most of the studies. Results of this study revealed that water balance closure error of Lake Ziway is 67 mm from 1986–2000, which accounts for 2.9% of the total lake inflow from rainfall and river inflow. The source of this error can be attributed to uncertainty in the estimation of any of the water balance component in addition to our assumption of negligible groundwater components.

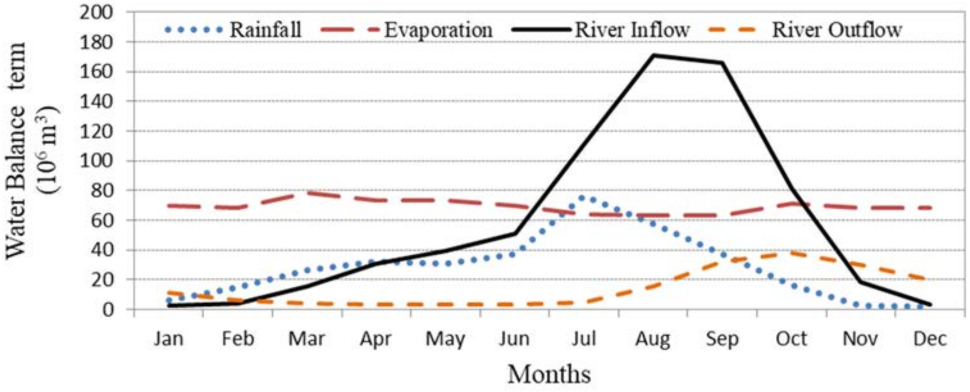

Figure 3: Mean monthly water balance of Lake Ziway from 1986 to 2000.

Table 1: Annual water balance terms of Lake Ziway for the natural condition for 1986–2000 (all unit expressed in 106 m^3).

	Inflow				Outflow		Water Abstraction	
Water Balance	R	Q_M	Q_K	Q_U	Evap	Q_{out}	Irrigation	Domestic
This study	338	233	380	81	832	171	37	1.26
Vallet-Coulomb et al. [18]	335	273	418	50	832	157	–	–
Ayenew [4]	323	265	392	48	890	184	28	–
Jansen et al. [1]	327	274	411	–	774	185	27	1.31
Desta et al. [5]	356	262	394	–	854	–	41	–

Note: R = rainfall on the lake; Q_M = Meki river inflow; Q_K = Katar river inflow; Q_U = inflow from ungauged catchment; Evap = evaporation from the lake surface, Q_{out} = lake outflow in the river outlet.

5.3 Lake water level simulation

After all water balance components estimated, we developed a water balance model to simulate the lake water volume using eqn (3). The simulated lake volume was then transformed into a lake water level using area–elevation–storage bathymetric relationships. The simulated lake levels were compared with observed lake levels. Fig. 4 shows the simulated and observed lake levels for 1986–2014 on a monthly time step. The simulated monthly lake levels reasonably fit the pattern of observed water level up to 2000. However, for a recent period (after 2000) the simulated lake level significantly deviated from the observed counterparts. The deviation between the simulated and observed levels beginning from the end of 2000 attributed to an error in any of the water balance terms and human activities such as pumping water abstraction for irrigation, which are not incorporated in our model simulation.

We also refer to previous studies that indicated increased irrigation water abstraction during recent periods in the Central Rift Valley lakes basin [5], [26]. Additionally, future climate change projections such as increased air temperatures and decreased precipitation might also lead to decline in lake water levels as well as severe water scarcity problems. Hence, the time series prior to the year of the deviation (i.e. 1986–2000) was considered as

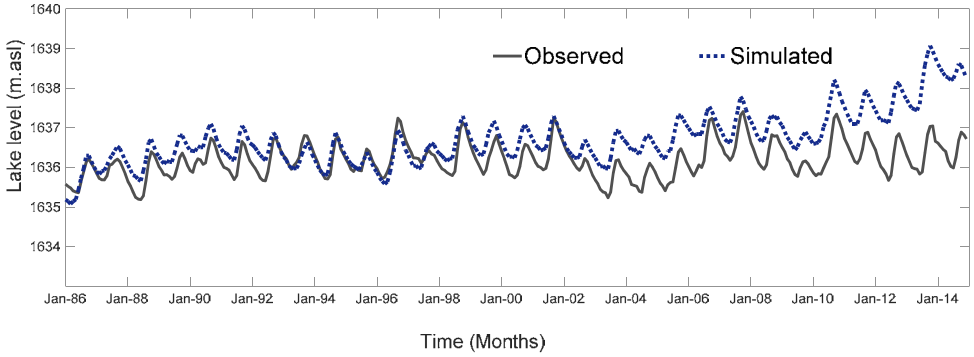

Figure 4: Comparison of observed and simulated lake level for the period 1986 to 2014.

the baseline natural period to evaluate the impact of water abstraction on the water level due to it represents natural flow condition to occur with minimum human influences in the lake and its tributaries.

The comparison of simulated lake water level for natural condition (BS) and the simulated including water abstraction for existing development (ED) from 1986 to 2000 are shown in Fig. 5. The constant line represents the steady state restriction water level (1,636 m.asl). The figure shows that the simulated lake level for existing water abstraction was below the natural baseline water level over the simulation period. This clearly indicates that the influence of water abstraction on the water level of Lake Ziway is substantial. The disagreement was significant after 1990 onwards, which possible due the cumulative effect of water abstraction and variation of climatic regions over the study area. This is especially significant when expressed by the periods of time when the lake levels below the restriction water level. For the existing water abstraction, the lake water level drops below the steady state at about 67% of the time.

The summary of the average annual water level, surface area and volume for natural level and with existing water abstraction condition are presented in Table 2. The result indicates the mean annual lake level, volume and surface area decreased during water abstraction for existing development. For existing water abstraction, the average annual water level of the

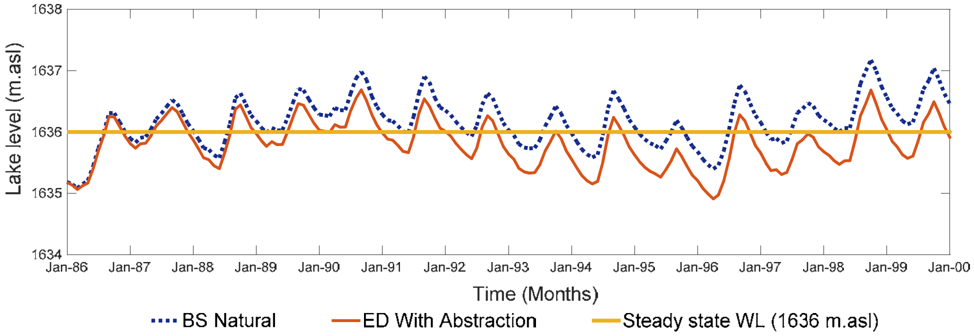

Figure 5: Comparison of simulated lake level for natural condition and existing development around Lake Ziway from 1986 to 2000.

lake lowered by 0.36 m from the baseline natural condition, with result reduction of 18 km^2 of the lake surface area (Table 2). This consequently will result in 162 × 10^6 m^3 reductions in the volume of the lake from 1986–2000, which accounts for 11% of the average lake volume from the baseline (Table 2). The decrease in water level of the lake in some dry years even drops up to 1.08 m from the natural water level. Hence, this will likely to have significant impact on the ecology of the lake and reduce its services for a wide variety of ecosystems. Lake Ziway supports the largest fish stock in the CRV basin and serve as a principal source of commercial fishing in Ethiopia [27], [28]. Hence, the reduction in water volume will hinder its potential as a freshwater fishery which in turn reduces the main economic income of the country. The impact also goes to reduce its service for food and shelter for a wide variety of endemic birds and wild animals [28].

Table 2: Summary of lake level simulation result for natural and existing development for 1986 to 2000.

Scenario	Water level (m.asl)	Area (km^2)	Volume (10^6 m^3)	WL change (m)	Area change (%)	Volume change (%)
BS	1636.18	442.24	1529.50			
ED	1635.82	424.35	1367.49	-0.36	-4.0	-10.6

Note: BS = baseline natural; ED = existing development.

To further evaluate the effect of water level change on water quality of the lake, we reviewed Vallet-Coulomb et al. [18] and Legesse and Ayenew [23], which they compiled from different sources [25] (Table 3). We assessed the variation of chemical characteristics and the corresponding mean annual water level for natural condition for dry and wet seasons. We note that the lake chemical characteristics values obtained during wet season increased than dry season mainly as a result of inflow from rain that might carry high concentration of solutes. Atmospheric deposition, which includes wet rain and dry dust are the main sources of chloride and sodium concentration in the water system. Table 3 shows the concentration of chloride water ranges from a minimum of 0.26 mmol l^{-1} to a maximum of 0.51 mmol l^{-1}, with mean annual water level of 0.58 m fluctuation. The variation in the concentration of chloride will affect the quality of the lake water for drinking, treatment and irrigation water use. The concentration of fluoride and SO4^{2-} showed slight temporal variation as compare to chloride ion (Table 3).

The sodium concentration of the lake water also increased from 2.4 to 4.2 mmol l^{-1} for dry and wet season, respectively. This mainly indicate that rain contribute to the formation of this chemical. The sodium concentration combined with Mg^{2+} and Ca^{2+} determines the suitability of the lake water for irrigation water. Therefore, any variation in the concentration of these cations due to water level change will likely to affect its vital source for irrigation water. Furthermore, for 1988 to 1994 the salinity level fluctuated from 311 to 618 mmol l^{-1} and pH varied from between 7.3 and 8.7 for approximately 0.2 m average water level change. The salinity content of the water plays important role in the usability of the lake water for irrigation and drinking purpose. Overall, this study showed that water level change clearly reflected in the temporal variations of the chemical concentration of the lake water (Table 3). This is especially significant with increasing flower farm activities around Lake Ziway due to the fertilizer used in the farm like nitrate, sulfate, and organic waste. Similar findings were also reported in other studies [24], [29]–[31].

In this study, we focused on the impacts of direct water abstraction from Lake Ziway on the water level. Desta et al. [5] reported that a number of human-induced impacts, such as

Table 3: Temporal chemical characteristics of Lake Ziway, data from various sources.

	Anions (mmol l^{-1})			Cations (mmol l^{-1})			Water level (m.asl)	Salinity	pH
Period	Cl^-	F^-	$SO4^{2-}$	Na^+	Ca^{2+}	Mg^{2+}	BS	mg L^{-1}	(-)
Dry season									
Mar 1991	0.32	–	0.16	2.87	1.12	1.3	1636.18	400	8.5
Dec 1992	0.34	0.07	0.03	2.39	2.00	1.2	1635.15	311	8.7
Nov 1994	0.31	0.07	0.02	3.18	1.28	1.1	1636.38	618	–
Dec 1998	0.26	0.05	0.03	2.35	1.72	1.2	1636.42	–	7.9
Oct 2001	0.27	0.04	0.07	2.42	1.92	1.2	1636.56	–	7.9
Wet season									
Aug 1988	0.51	0.11	0.06	4.18	1.72	1.4	1636.13	579	7.3
Jul 1993	0.35	0.07	0.03	3.96	2.00	1.3	1635.87	439	8.2
Sep 1995	0.37	0.10	0.14	3.04	1.68	1.4	1636.74	–	–
Aug 1999	0.32	0.07	0.04	2.96	1.72	1.4	1636.87	–	9.1

Note: Cl^- = chloride; F^- = floride; $SO4^{2-}$ = sulfate; Na^+ = sodium; Ca^{2+} = calcium; Mg^{2+} = magnesium.

sediment loads due to deforestation, soil erosion, uncontrolled water abstractions from the lake and its feeding rivers are main causes for the lake water level reduction. Our result also share the view of their studies that water abstraction contributed to the observed drops in Lake water level. Hence, if the current water abstraction situations continue without intervention, the lake will lead to vulnerable to excessive water scarcity problem as that has been observed in Lake Alemaya [32]. Therefore, consideration should be given to determine how the water is appropriately utilized. This requires integrated management of water abstraction among all water sectors in the study area.

6 CONCLUSION

In this study, we evaluated the actual water withdrawal from the lake and its impact on the water level using a water balance modelling approach. The study was unique as we applied field water abstraction survey coupling calibrated hydrological model output and water balance model. The bias-corrected CHIRP rainfall dataset was used as input in a rainfall-runoff simulation where the simulated river inflow served as input to the water balance model. A water abstraction survey (WAS) was conducted to estimate actual water withdrawal from the lake.

This study indicated that an accurate estimate of actual water withdrawal and its impact on the water level can be estimated using WAS and water balancing approach, respectively. As a result of 37×10^6 m^3 annual water withdrawals from the lake for irrigation, the mean water level and volume of Lake Ziway drop by 0.36 m and 162×10^6 m^3, respectively. This will cause the water level to be lower than the steady state level over 67% of the time and the mean lake area to reduce from 442 to 424 km^2 (i.e. 18 km^2). Hence, this study indicates that water abstraction directly from the lake has a significant impact on the water level, volume and surface area of the lake. The water level change also further reflected in the temporal variation on the water quality of the lake. Therefore, we suggest the need for integrated water abstraction management among all sectors towards achieving sustainable water use around the lake including future climate change condition.

ACKNOWLEDGEMENTS

This study is part of the first author's PhD thesis, supported by Ethio-France sandwich program. We gratefully acknowledge the financial support from Water, Irrigation and

Electricity of Ethiopia and EBI school of Engineering. We also acknowledge Central Rift Valley lakes basin authority field office and data collector for their help during data collection.

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