# Unveiling Hydrological Dynamics in Data-Scarce Regions: Experiences from the Ethiopian Rift Valley Lakes Basin

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**Abstract:** The hydrological system of Rift Valley Lakes in Ethiopia has recently experienced changes since the past two decades. Potential causes for these changes include anthropogenic, hydro-climatic and geological factors. The main objective of this study was to utilize an integrated methodology to gain a comprehensive understanding of the hydrological systems and potential driving factors within a complex and data-scarce region. To this end, we integrated a hydrologic model, change point analysis, indicators of hydrological alteration (IHA), and bathymetry survey to investigate hydrological dynamics and potential causes. A hydrologic model (SWAT+) was parameterized for the gauged watersheds and extended to the ungauged watersheds using multisite regionalization techniques. The SWAT+ model performed very good to satisfactory for daily streamflow in all watersheds with respect to the objective functions, Kling–Gupta efficiency (KGE), the Nash–Sutcliffe efficiency (NSE), Percent bias (PBIAS). The findings reveal notable changes of lake inflows and lake levels over the past two decades. Chamo Lake experienced an increase in area by 30.1 km² (9.5%), in depth by 4.4 m (30.9%), and in volume by 7.8 x 108 m³ (27.2%). In contrast, Lake Abijata witnessed an extraordinary 68% decrease in area and a depth decrease of 1.6 m (37.2%). During the impact period, the mean annual rainfall experienced a decrease of 6.5% and 2.7% over the Abijata Lake and the Chamo Lake, respectively. Actual evapotranspiration decreased by 2.9% in Abijata Lake but increased by up to 4.5% in Chamo Lake. Surface inflow to Abijata Lake decreased by 12.5%, while Lake Chamo experienced an 80.5% increase in surface inflow. Sediment depth in Chamo Lake also increased by 0.6 m (4.2%). The results highlight that the changing hydrological regime in Chamo Lake is driven by increased surface runoff and sediment intrusion associated with anthropogenic influences. The hydrological regime of Abijata Lake is affected by water abstraction from feeding rivers and lakes for industrial and irrigation purposes. This integrated methodology provides a holistic understanding of complex data scarce hydrological systems and potential driving factors in the Rift Valley Lakes in Ethiopia, which could have global applicability.

**Keywords Hydrological change; IHA; Bathymetry; Lake Chamo; Lake Abijata; SWAT+; Rift Valley; Lake level.**

# Introduction

Continuous anthropogenic and natural activities are adversely altering the water resources from local to global scales (Flörke et al., 2018, Sivapalan et al., 2003). Changes of lake levels influence ecosystem services worldwide (Gownaris et al., 2015, Kolding and van Zwieten, 2012). In Eastern Africa, the Rift Valley Lakes are supporting eco-regions of great biodiversity, considered amongst the global 200 freshwater eco-regions of the world (O'Brien et al., 2018, Olson and Dinerstein, 2002). In this region, water resources play a crucial role for economic development through use of water for domestic supply, irrigation and industry, fishery, recreation and tourism (Cowx and Ogutu-Owhayo, 2019, Minale, 2020, White et al., 2002).

The Ethiopian Rift Valley Lake basin is known as the Lakes District, containing a chain of eight main lakes situated at the Rift floor. The total surface area of open waters, including wetlands of the Rift valley was 3413 km2 in 2019 which is 46% of total area of open waters resources of Ethiopia (Ayalew et al., 2022a). Most of these lakes are highly productive, contain indigenous populations of edible fish, and support a variety of aquatic and terrestrial wildlife (Tudorancea and Taylor, 2002). Currently, the hydrology of the Rift Valley Lakes is changing, i.e. water levels, areal extent, and volumes are altered, affecting ecosystem services and the communities. The situation has been aggravated recently due to increasing population density, excessive water abstraction and catchment land use changes (Billi and Caparrini, 2006, Legesse and Ayenew, 2006). Because of high water abstraction for irrigation and industry, as well as climate change, the open water surface area has decreased by 2.1% in three decades (Ayalew et al., 2022a). The problem is getting worse since water abstractions is often carried out without a basic understanding of the complex hydrogeological system, and the fragile nature of the Rift ecosystem (Zinabu et al., 2002, Ayenew, 2002). The basin has become economically significant because of the development of flower and horticultural production, soda ash factory, tourism, and other human activities around the shores of the lakes. Despite the basin's significance as a vital component of the country's economy and ecological balance, the major challenge lies in the limited availability of accurate hydrological data. Previous hydrological studies conducted in the Rift Valley Lakes have predominantly focused on analyzing the impact of single drivers and have failed to provide a quantitative assessment of the respective contributions of land use and climate change on streamflow. For instance, some studies have primarily investigated the effects of high water abstraction for irrigation and industries (Kebede et al., 1994, Zinabu and Elias, 1989, Legesse and Ayenew, 2006, Ayenew, 2002) , environmental degradation (Ayalew et al., 2004, Meshesha et al., 2012, Ayenew, 2004), volcano-tectonics, and sedimentation (Le Turdu et al., 1999, Street and Grove, 1979), bathymetry analysis (Awulachew, 1999) as well as the occurrence of frequent earthquakes and faults (Ayalew et al., 2004, Ayenew, 2002, Belay, 2009). However, the hydrological system of the Rift Valley is very complex and processes within a basin are driven by the interplay of climate, LULC, topography, soil and human activities. Evaluating hydrological change typically involves assessing changes in the flow regime and water balance of a river, a lake or a reservoir. Therefore, to understand the hydrological system and driving forces that control the hydrological processes requires an integration approach. Flow regime analysis, trend analysis, time series analysis, and hydrological modelling are common methods used for hydrological change analysis (Wagener and Montanari, 2011, Hargreaves and Samani, 1985, Jain and Singh, 2019); and in regions with limited available hydrological data, the application of regionalization techniques is a commonly employed approach (Viglione et al., 2013, Pool et al., 2021, Pagliero et al., 2019).

The study aims to understand the changing hydrological systems and driving factors by integrating hydrological modelling, indicators of hydrological alteration (IHA), change point/break, and bathymetry survey analysis. We hypothesize that the changes in the hydrological regimes are associated with changes in high water abstraction, climate change and land use.

# Materials and methods

## 2.1. Study Area Discerption

The Ethiopian Rift Valley Lakes Basin is located between 36° and 40°E and 4° and 9°N. It extends from the Afar depression southwards to Kenya across the broad basins of Abijata-Ziway, Abaya-Chamo, and Segen (Fig. 1). It is 55,050 km² large and one of the most important basins in Ethiopia. The basin is characterized by diverse landscape features and climate conditions. It has a complex hydrological system and encompasses numerous lakes, springs, wetlands, and rivers.

The climate of the basin is dominated by semi-arid climate (BSh) and tropical wet and dry climate (Aw/As) climate, which is characterized by low rainfall, high temperature, and high evapotranspiration. Three climate regions can be found in the basin (Ayalew et al., 2022a). The Abijata-Ziway subbasin which is characterized by low annual average rainfall ranging from 400 mm to 860 mm with one peak in August. The second basin, Abaya-Chamo subbasin, is receives higher annual precipitation ranging from 704 mm to 1200 mm with a bimodal climate pattern with peaks in April and August. The third subbasin, Segen subbasin, is characterized by a bimodal rainfall pattern with peaks in April and October and receives an average annual precipitation ranging from 500 to 1100 mm. Temperatures within the basin exhibit a wide range, from 10°C to 36°C, with the warmest temperatures measured on the Rift Valley floor and frost-prone conditions in the Afro-alpine zone. The southern region of the Rift Valley is both lower in elevation and warmer and drier than the other areas of the basin.

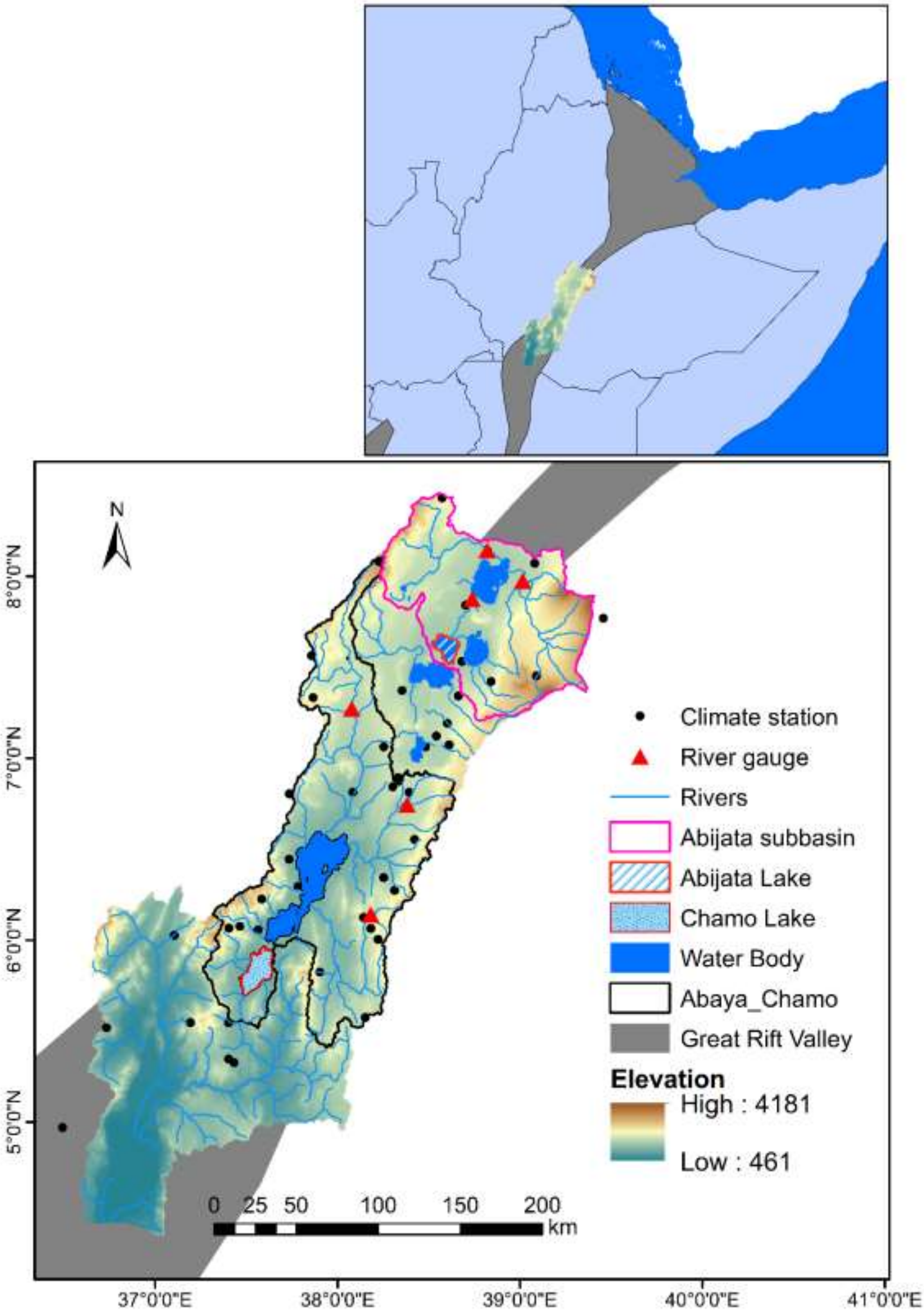

Figure 1: Topography of the Rift Valley Lakes basin as well as the river network, river and climate stations used for modelling.

The basin is also characterized by a complex and rugged topography with active faults, volcanoes and hot springs (Stamps et al., 2008). Based on the digital elevation model (USGS, 2023) data, the slope ranges from 0 to 161 %. Agricultural land is the most dominant land use followed by semi-natural vegetation and water bodies. Two lakes were chosen from the basin as representative examples of its hydrological system, based on their degree of impact. Lake Abijata was selected as an example of a monomodal climate regime, while Chamo Lake was chosen to represent a bimodal climate regime. Lake Abijata is a terminal lake of the Ziway-Abijata subbasin and linked to Lake Ziway via the Bulbula River and to Lake Lugano via the Hurakolo River. Lake Chamo is a terminal lake for the Abaya-Chamo subbasin and linked with Lake Abaya via the Kulfo River.

## 2.2. Spatial and hydroclimatic data

The main hydrological characteristics of the basin have been acquired from the climate data, topography, land use, soil properties, streamflow, lake level and bathymetry survey. Time series of climate data for 44 stations (1981- 2018), a georeferenced Landsat image (1999), bathymetry of Lake Chamo (1998 and 2021), streamflow of rivers (1987 – 2006), Lake level (1987-2015) the Shuttle Radar Topography Mission digital elevation model (SRTM DEM) (30x30) and soil data were used for this study. The SRTM DEM has been used, from which slope, river network, and watershed boundaries are obtained. Selected soil physical properties and the area coverage of each soil type were classified based on the requirements of the hydrologic model. The bathymetry survey data was used to calculate the change in volume, area and depth of a lake. It was also used to obtain information about sediment deposition in the lake.

*Table 1. List of data and source used in this study*

| Data | Resolution(m) | Access Date | Sources |
|---|---|---|---|
| Landsat 5, Thematic Mapper | 30 | Feb 25,1999 | http://earthexplorer.usgs.gov |
| STRM DEM | 30 | 2014-09-23 | |
| Soil | 30 | 2016 | Ministry of water irrigation and electricity |
| Stream flow | - | 1987-2006 | |

| | | | |
|---|---|---|---|
| Lake level | - | 1987-2015 | |
| Climate ( rainfall and temperature) | - | 1987-2018 | Ethiopian National Meteorological Agency |
| Lake extent shape file | | 1999 | http://earthexplorer.usgs.gov |
| Bathymetry survey | - | 1998 & 2021 | AMU-VLIR-IUC |

## 2.3. Methodology

### Hydrological regime change analysis

In this study, a common approach for analyzing hydrological regime change is utilized by combining a change point analysis and Indicators of Hydrological Alteration (IHA). The IHA can be used to assess and quantify changes in the natural flow regimes of rivers and streams. It provides a systematic way to analyze the impacts of human activities, e.g. dam construction and water withdrawals, on hydrology. A set of indicators are used to evaluate alterations in flow magnitude, frequency, duration, timing, and rate of change. Combining a change point analysis and IHA allows for a more robust and comprehensive analysis of hydrological regime change (Zhang et al., 2016, Vieceli et al., 2015, Vu et al., 2019). Change point analysis is a statistical method that is used to detect changes in the mean or variance of a time series. We used it to identify breakpoints of the Lake level. Once the break points have been identified, IHA were used to evaluate the degree of alteration of the natural flow regime. The Range of Variability Approach (RVA), Environmental Flow Components (EFC), Flow Duration Curve (FDC), Box-and-Whisker (BAW), and Percentile analysis of the IHA were used to evaluate the alteration of the hydrological regime (Gunawardana et al., 2021, Song et al., 2020).

The Range of Variability Approach (RVA) evaluates hydrological alterations by analyzing 33 hydrological parameters, which are categorized into five groups which evaluate the magnitude, timing, frequency, duration, and rate of change (Richter et al., 1998, Shieh et al., 2007) (Table 2). Group 1: The 12-monthly mean flows were computed to determine the water level. Group 2: twelve parameters were used to explain the range of changes in annual extreme flows in magnitude and duration in daily, weekly, monthly, and seasonal cycles. Group 3: Julian dates for 1-day annual maximum and minimum were computed to determine the variation of timing of annual extreme flows that can be associated with extreme conditions. Group 4: four parameters are categorized in this group that refers to the frequency and duration of high and low pulses. The high pulses refer to periods within a year when the daily flows are above the 75th percentile of the data. The low pulses are periods within a year when the daily flows are below the 25th percentile of the data. Group 5: three parameters are also categorized in this group to understand the direction and magnitude of hydrological regime changes, including both positive and negative changes. These parameters are important because they capture the variability of hydrological flow over short periods, as high flow can cause erosion and sediment transport, while low flow pulses can lead to habitat degradation and changes in water quality.

Table 2| Hydrologic parameters used in the RVA, and their features

| General group | Regime features | Streamflow parameters used in the RVA |
|---|---|---|
| Group 1: Median of monthly water condition indices | Magnitude, timing | The median monthly value for each month |
| Group 2: Yearly extreme water conditions indices | Magnitude, duration | 1-day minimum<br>3-day minimum<br>7-day minimum<br>30-day minimum<br>90-day minimum<br>1-day maximum<br>3-day maximum<br>7-day maximum<br>30-day maximum<br>90-day maximum<br>Number of zero days<br>Base flow index |
| Group 3: Yearly extreme water conditions indices | timing | Date of minimum<br>Date of maximum |
| Group 4: High and Low pulses indices | frequency and duration | Low pulse count<br>Low pulse duration<br>High pulse count<br>High pulse duration |
| Group 5: Water condition changes indices | rate and frequency | Rise rate<br>Fall rate<br>Number of reversals |

The calculation of pulse count and pulse duration was carried out through the utilization of the Indicators of Hydrological Alteration (IHA). A threshold for both high and low pulses is used. Pulse count represents the number of pulses exceeding the established threshold (here the median), while pulse duration indicates the time from the start to the end of a high or low pulse.

The uncertainty concerning pulse counts, determined by the threshold, stems from potential overcounting and undercounting of low and high pulses. This occurs due to the computation of the median for the data series, which includes both flood and drought years. The presence of flood and drought years in the data series influences the median value, consequently affecting the counted number of high and low pulses. Another threshold definition or other climate data will lead to different results.

In the annual average water balance, the flow signals are averaged and it is difficult to distinguish which flow signals affect the annual water balance. To avoid this limitation, we used FDC to evaluate the variation of streamflow for the pre-impacted and impacted periods. The shape of the curve is an index of the natural storage in the watershed, including the groundwater. Since the dry season flow consists entirely of return flow from the groundwater, i.e., the lower end of the FDC indicates the general characteristics of shallow aquifers. Therefore, flow signals were determined from the FDC based on the exceedance probability threshold. Here, low flow signals are defined as >= 75% of the exceedance probability, while higher flow signals are defined as <= 20% of the exceedance probability and the rest are mid flows. The choices of thresholds for disaggregation were based on earlier studies (Pfannerstill et al., 2014, Smakhtin, 2001).

### 2.3.1. Hydrologic model

The Soil and Water Assessment Tool Plus (SWAT+), a completely revised version of the SWAT model (Arnold et al., 1998) was built to simulate water balance fluxes in a watershed. It is more flexible than SWAT in terms of the spatial representation of interactions and processes within a watershed (Bieger et al., 2017). It simulates the hydrological processes from precipitation to streamflow using the water balance equation. There are two methods for channel routing currently implemented in SWAT+ (Muskingum and Variable Storage Routing (VSR)). In this study, the VSR, that is the standard method in SWAT+, was used for river routing. It provides a flexible representation of channel routing behavior using storage coefficients for each reach that depend on travel time and length of the time step (USDA-ARS 2024). It also considers the storage-discharge relationship for each reach, allowing for a better representation of channel routing processes (Pati et al., 2018). The Soil Conservation Service (SCS) Curve Number (CN) method was employed to estimate surface runoff. The Hargraves equation was used to calculate the potential evapotranspiration, which is commonly used in data scarce regions (de Sousa Lima et al., 2013, Moeletsi et al., 2013).

Currently, SWAT+ is tested in few watersheds across the world, where the results from SWAT+ are favorable compared to the previous model version (Wagner et al., 2022)  It can simulate the quantity and quality of water resources from a hydrological response unit to basin scale. SWAT is also suitable to assess the impact of climate change (Mahmoodi et al., 2021a), land cover change (Tigabu et al., 2019) and  land use change (McGinn et al., 2021, Wagner et al., 2023), and watershed management practices on water resources (Mahmoodi et al., 2021b) Moreover, it has been proven capable of modeling in data scarce regions (Tigabu et al., 2023, Wagner et al., 2012). To depict the spatial heterogeneity of a watershed, each watershed is divided into multiple homogenous hydrological response units based on a unique combination of land-use, slope and soil characteristics (HRU).

### 2.2.1. Model parameterization, calibration, and validation

Sensitive parameters were adopted from previous research (Ayalew et al., 2023) for streamflow simulation in two subbasins (Table 3). Lakes, which are located on the main channel network of the subbasin, are accounted for during modelling. The lakes areal extent are used as input for the SWAT+ model. The default model parameters for the reservoirs are used, e.g. SWAT+ assumes an average depth of 10 m to calculate the volume of the lake. During the calibration process, the lake depth was modified using bathymetric data obtained from Ethiopian ministry of water and energy.

*Table 3* | Calibration parameters and the upper and lower boundaries used for calibration

| Parameters | Description | Limit | | Change | Fitted range & value | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Min | Max | | Lake Abijata | | | Lake Chamo | | |
| | | | | | Min | Max | Value | Min | Max | Value |
| CN2 | Condition II curve number | -15 | +15 | abschg [a] | -15 | -5 | -1.8 | -15 | -10 | -11.8 |
| Sol-Awc | Available water capacity of the soil layer (mm H2O/mm soil) | -0.25 | +0.25 | abschg | -0.16 | +0.15 | -0.05 | -0.16 | +0.15 | -0.12 |
| ESCO | Soil evaporation compensation coefficient | 0 | 1 | absval [b] | 0.01 | 0.5 | 0.34 | 0.01 | 0.5 | 0.21 |
| SURLAG | Surface runoff lag Coefficient(days) | 0 | 24 | absval | 0.1 | 10 | 6.7 | 0.1 | 10 | 8.4 |
| PERCO | Percolation coefficient (mm H2O) | 0 | 1 | absval | 0.01 | 0.95 | 0.91 | 0.01 | 0.3 | 0.17 |
| LATQ_CO | Lateral flow contribution to reach (mm H2O) | 0 | 1 | absval | 0.01 | 0.95 | 0.63 | 0.01 | 0.3 | 0.10 |
| ALPHA_BF | Baseflow recession constant fast aquifer (days) | 0 | 1 | absval | 0.01 | 0.6 | 0.27 | 0.01 | 0.3 | 0.07 |
| k | Saturated hydraulic conductivity (mm $h^{-1}$ ) | -45 | +45 | pctchg [c] | -10 | +15 | 1.86 | -10 | +15 | -3.7 |
| EPCO | Plant uptake compensation factor | 0 | 1 | absval | 0.6 | 0.9 | 0.8 | 0.6 | 0.9 | 0.85 |
| z | Soil depth (mm) | -45 | +45 | pctchg | -15 | +0 | -3.7 | -15 | +0 | -7.5 |
| Lake depth | Average depth of a Lake (m) | 10 (default) | | absval | 2.5 | 9 | 5.5 | 5 | 13 | 9.7 |

Where, a abschg [a] adds an absolute value to the initial parameter value; b absval[b] replaces the initial parameter value with an absolute value; c pctchg[c] increases or decreases of the initial parameter value by the given percentage of the value.

The streamflow data at each outlet (at each gauge from 1987 to 2006 splatted in to three periods for model warm-up (one year), model calibration (1987 to 1995) and validation (1995 to 2006). For calibration, 5000 parameter sets were generated with Latin Hypercube Sampling (Soetaert and Petzoldt, 2010) using the parameter ranges given in Table 3. The model configurations were evaluated for the same 5000-parameter sets. For each parameter set a model run was performed and the final parameter fitted range was selected based on the best combined 0.6<=KGE<=1 (Gupta et al., 2009), 0.5<= NSE<=1(Nash and Sutcliff, 1970), and percent Bias -25<= (PBIAS) <= 25, and 0<= RMSE-observations standard deviation ratio (RSR)<= 1 values, so that the KGE , NSE , PBIAS and RSR were filtered within this range and the model runs were accepted within these range. The best optimal value (fitted value) has selected among the best value of KGE. During calibration and validation, the water balance (total amount, distribution through time), storm sequence (time lag or shift), and shape of hydrograph (rising limp, peak, recession) are considered as key components. Calibration and validation were carried out in R using the packages FME for Latin Hypercube Sampling (Soetaert and Petzoldt, 2010), hydroGOF for model evaluation (Zambrano-Bigiarini, 2018), and the packages zoo (Zeileis and Grothendieck, 2005) and xts (Ryan and Ulrich, 2011) for data processing.

In addition to statistical performance evaluation, visual inspection of the hydrography and flow duration curve (FDC) provide information about the overall qualitative match between measured and modeled streamflow.

### 2.2.2. Regionalization

A multisite (stepwise and pooled) regionalization method was applied to ensure that the model accurately represents the hydrological behavior of multiple locations and that the model can be used to make predictions for other locations. It improves the accuracy of the model by calibrating it with data from multiple sites (Hundecha et al., 2016). The method can also help to reduce uncertainty and improve the robustness of the model by taking into account the variability of hydrological conditions across different sites.

Hydrological processes are primarily controlled by rainfall, topography, soil characteristics, and land use, similarity between watersheds has been demonstrated prior to regionalization. The stepwise calibration carried out on a nested class of sub-basins for the corresponding multiple gauging stations in the sub-basin (Tsegaw et al., 2019). Multi-gauge calibration strategy involves calibrating all parameters of the model domain simultaneously against multiple streamflow gauges within the subbasin (Wi et al., 2014). This approach aims to look for suitable parameters that are able to produce satisfactory model results at all neighboring gauging stations in a single implementation of optimization. Therefore, pooled regionalization technique has been chosen for this study based on its ability to predict streamflow and calibration uncertainties. To do so, Bulbula assumed to be gauged watershed and Katar at Abura and Meki were assumed ungauged watersheds for validation (Figure 2). Likewise, Kulfo at Abaya has considered as gauged watershed and Bilate, Gidabo and Upper Gelana considered as ungauged watershed (Figure 2). The gauged stations are considered as the “donor” watershed, and the ungauged stations are considered as the ‘pseudo’ watersheds. The donor watersheds are used to parameterize and calibrate the SWAT+ model parameters. The pseudo-ungauged watersheds are used to test the calibrated model. In testing the model on the pseudo ungauged watersheds, the model was run with calibrated parameters for the same period and the model performance for donor and pseudo watersheds were evaluated using the objective functions KGE, NSE, PBIAS and RSR. If the developed model for the donor watershed performed sufficiently (KGE> =0.5, NSE=0.5, -25 <= PBIAS <= and 0 <= RSR <= 1) for the pseudo watershed, the model is considered robust and was used for regionalization. The optimal values of parameters of each catchment were transferred to the nearest ungauged catchments and reach.

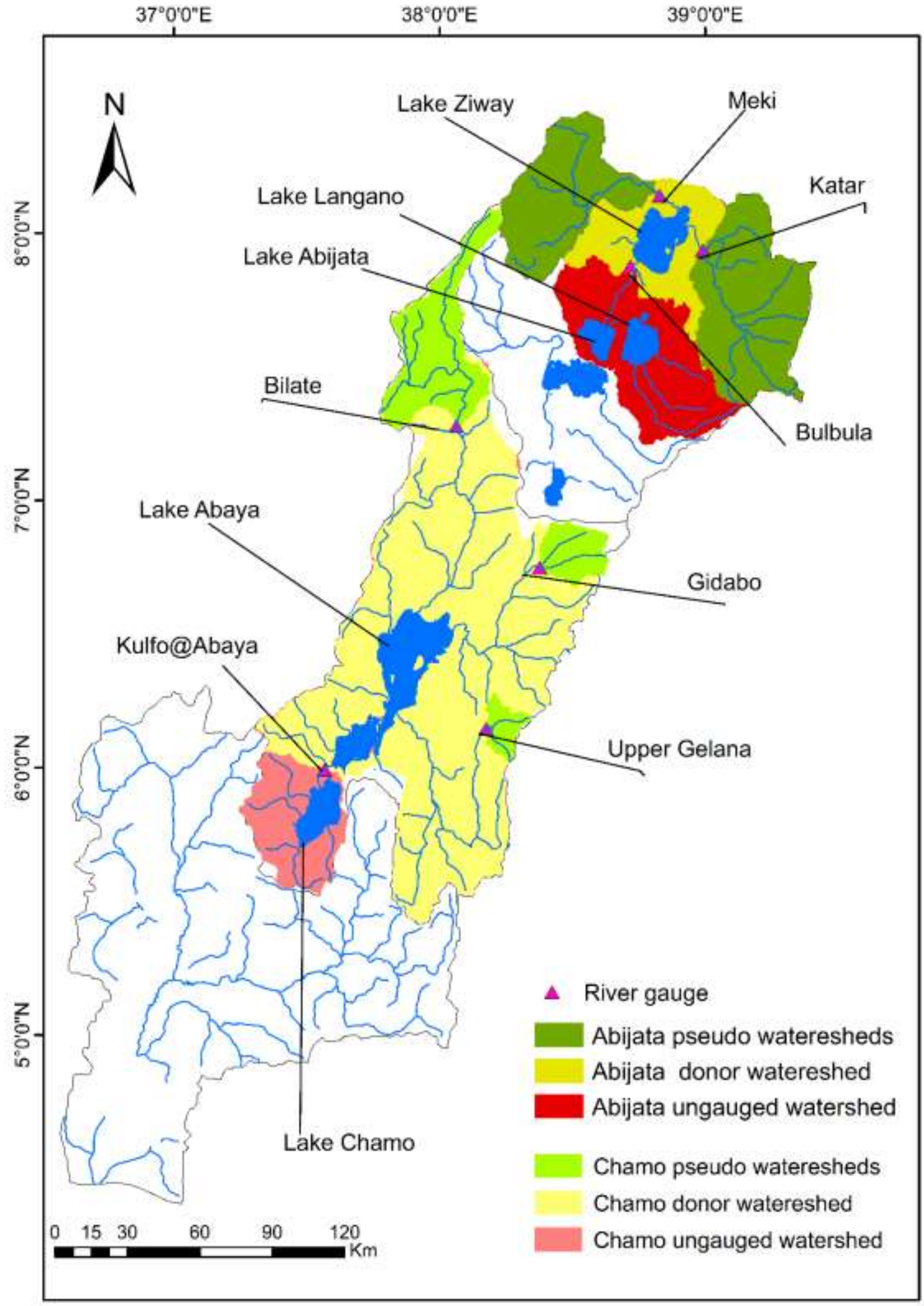

Figure 2| Multisite-pooled calibration technique to estimate flow of ungauged watersheds

### 2.2.3. Bathymetry analysis

The Lake Chamo was surveyed using Multibeam echosounder (MBES). It is sonar technology that uses a band of multiple beams to create a high-resolution 3D map of the lake bed. It is based on the principle of emitting a series of acoustic pulses and measuring the time it takes for the sound to travel to the lake bed and back. Although our hydrologic model was developed on two terminal lakes, Abijata and Chamo, we conducted a bathymetry survey only for Chamo Lake.

The survey was conducted during the dry season from 1 to 21 July 2021. Before the survey began, the surface elevation of the lake level was measured with a handheld GPS, which was at a level of 1110 m and used as the reference level. Following that, a continuous record of lake floor topography was measured with an MBES mounted on a motor boat at a constant speed of 5 km/h along predefined average traverse lines at 450 m spacing along a north-south direction.  A crossing and recrossing survey was also performed in the same area to correct errors caused by potentially misleading reflections and variations in the speed of sound moving through the lake (Figure 3). To supplement the dataset produced by the echo sounder, zero depth coordinates were taken simultaneously with hand-held GPS along the lake's shoreline at shorter distances. Because there were no other obstacles, the true size of the lake was preserved during mapping using these border coordinates. The bathymetry data typically in the form of point data (XYZ) that represent the depth measurements at various locations within the lake was imported into Surfer20 to analyze the lake floor morphology in 2D and 3D, as well as depth, area, and volume.

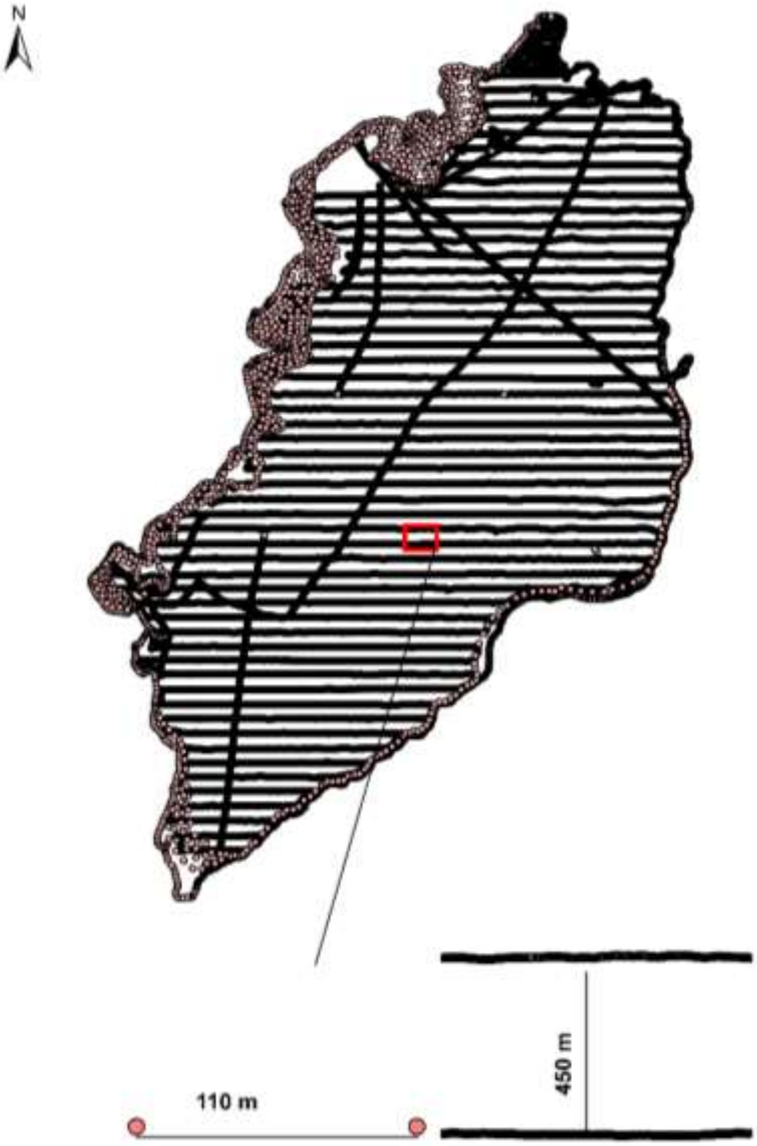

Figure 3: Bathymetry survey using multibeam echosounder (MBES) along predefined average traverse lines at 450 m spacing along a north-south direction and 110 m along east-west direction.

# Results and Discussions

## 3.1. Lake water balance analysis

### Hydrological modelling and model performance

The hydrographs shown in Fig. 4 indicate that the SWAT+ model was successfully calibrated and validated for each ‘donor watershed’. Similarly, the hydrograph depicted in Fig. 5 signifies the model's success within each respective 'pseudo' watershed. The relationship between the simulated and observed streamflow based on the model is statistically summarized in Table 4. The values of the objective functions indicate a strong goodness-of-fit for both ‘donor and pseudo watersheds.

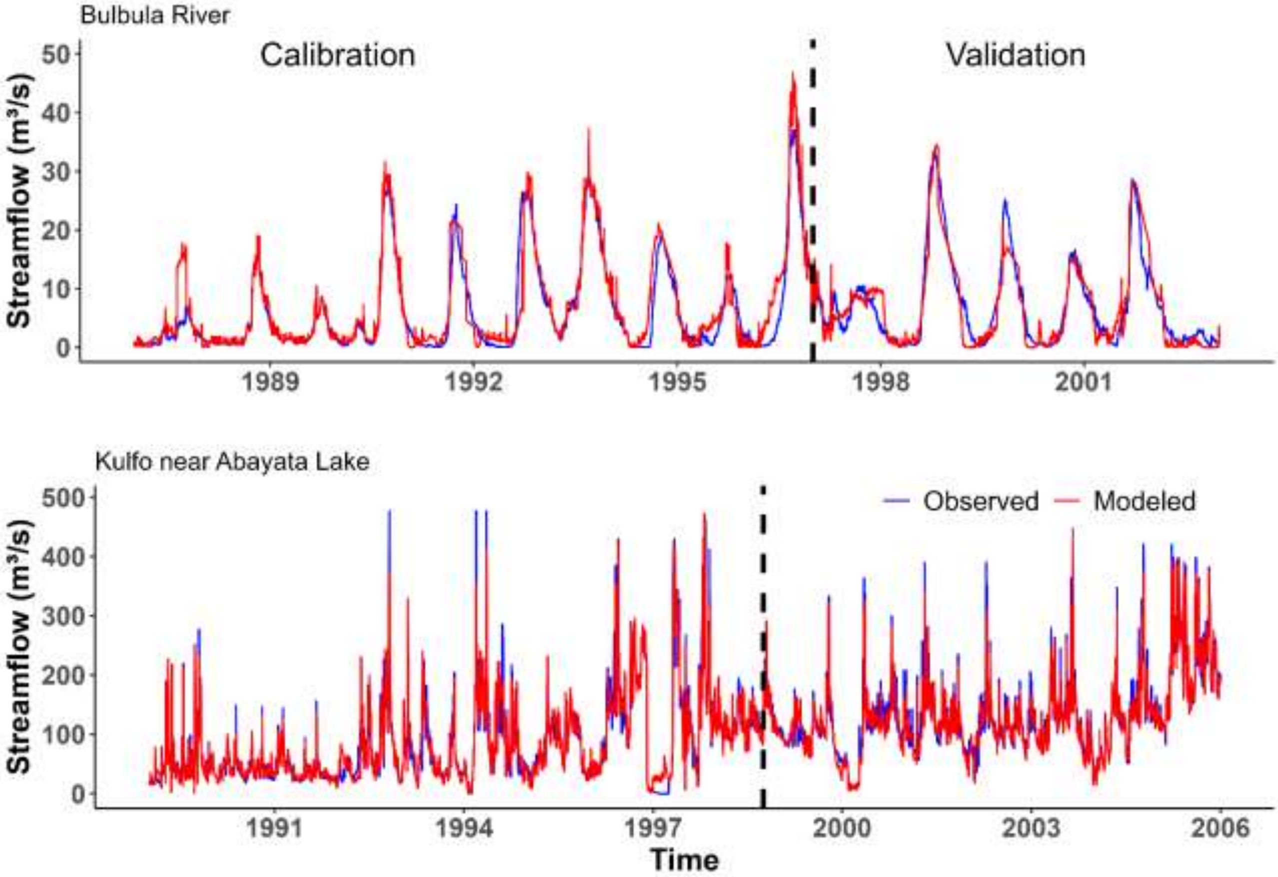

Figure 4 | Hydrograph of modeled and observed daily streamflow for calibration and validation period of the donor watersheds.

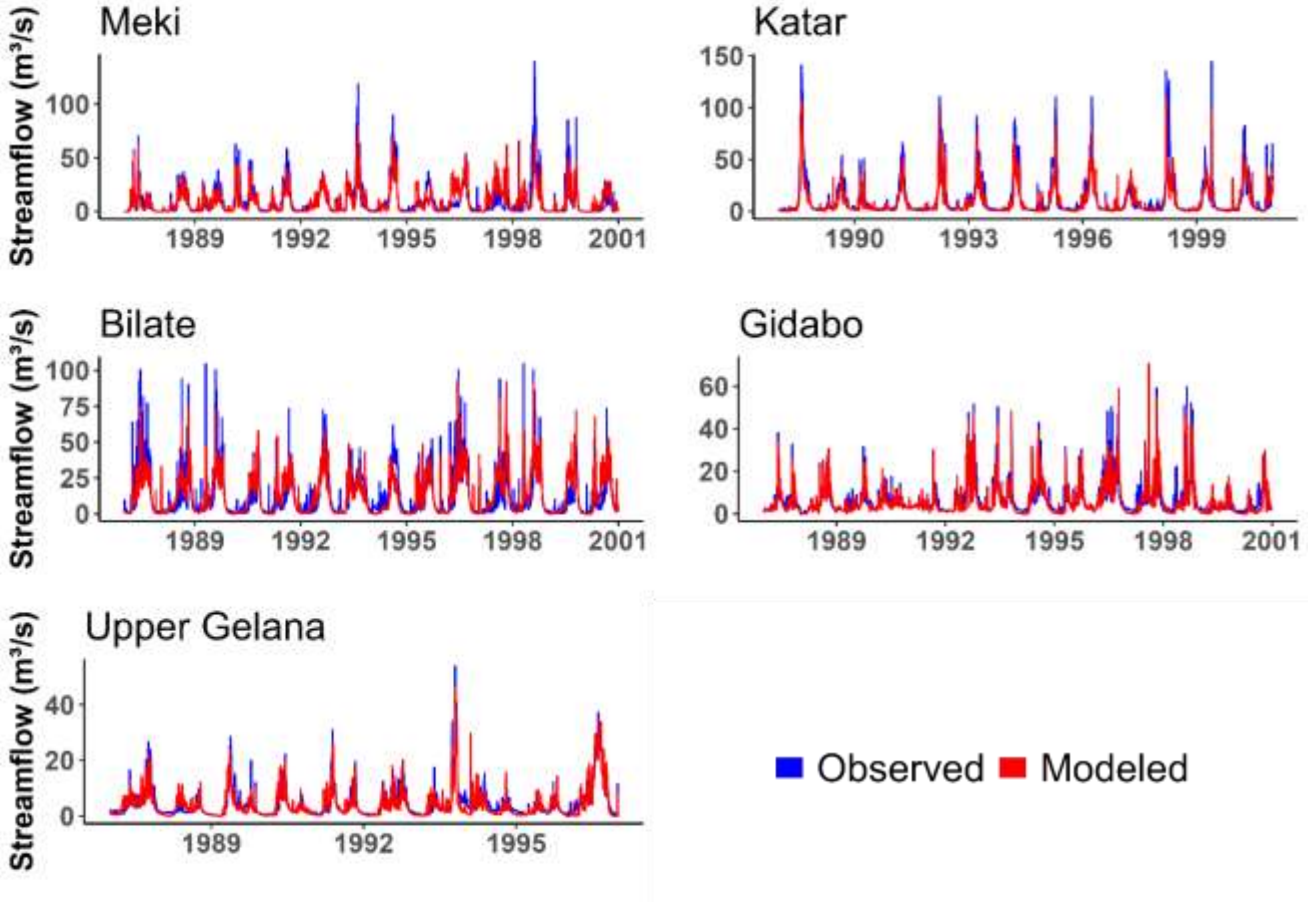

Figure 5 | Hydrograph of modeled and observed daily streamflow of the ‘pseudo’ watersheds

Similarly, the FDC in Fig. 6 & 7 show that there is a good agreement between observed and the modeled discharge in both ‘donor and pseudo’ watersheds. Throughout the calibration and validation period, the model shows a slight overestimation of high, middle and low flows in Bulbul River. However, at Kulfo, high and low flows are slightly underestimated. The test of the regionalization approach shows that high flows were underestimated in all ‘pseudo’ watersheds.

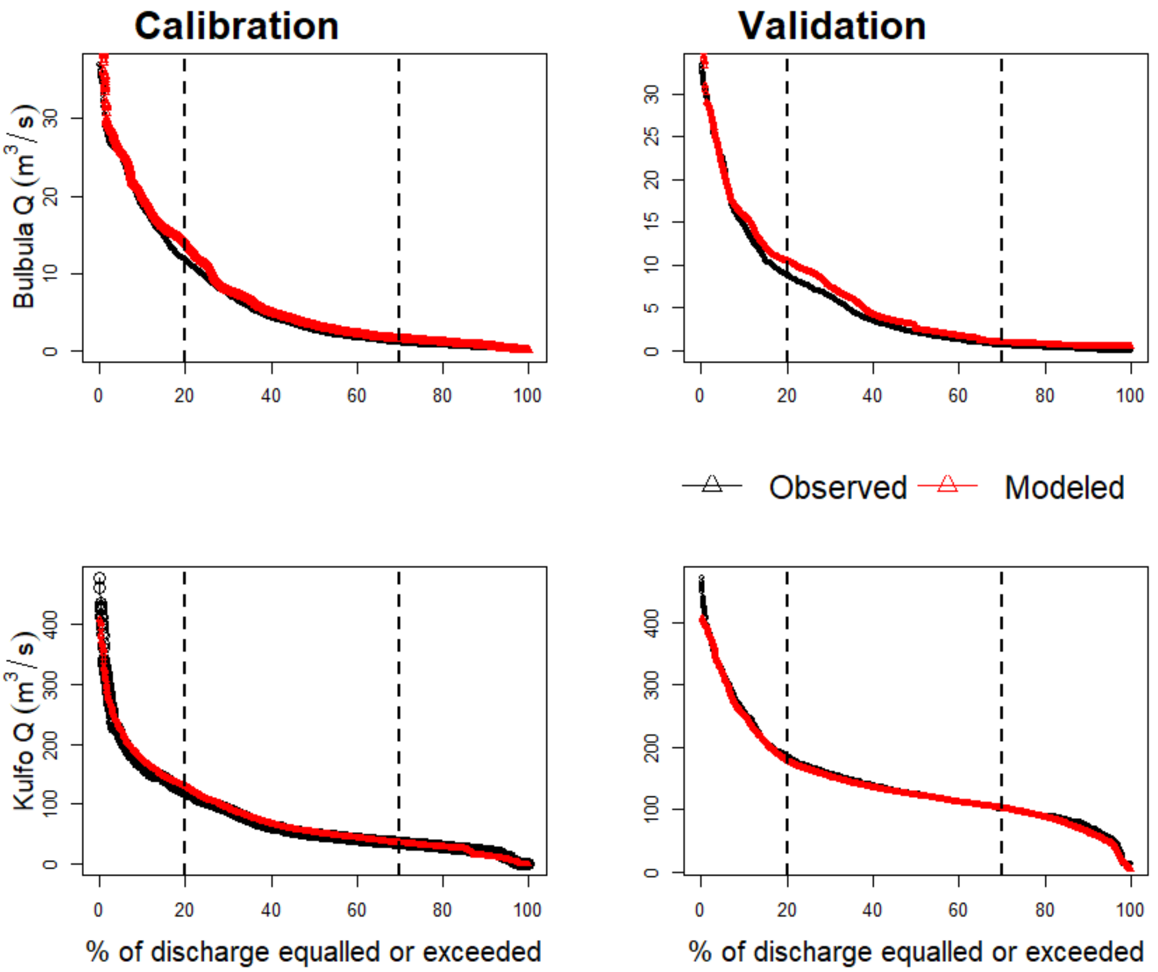

**Figure 6 |** Flow duration curves of observed and modeled daily streamflow for the calibration and validation period of the 'donor watersheds.

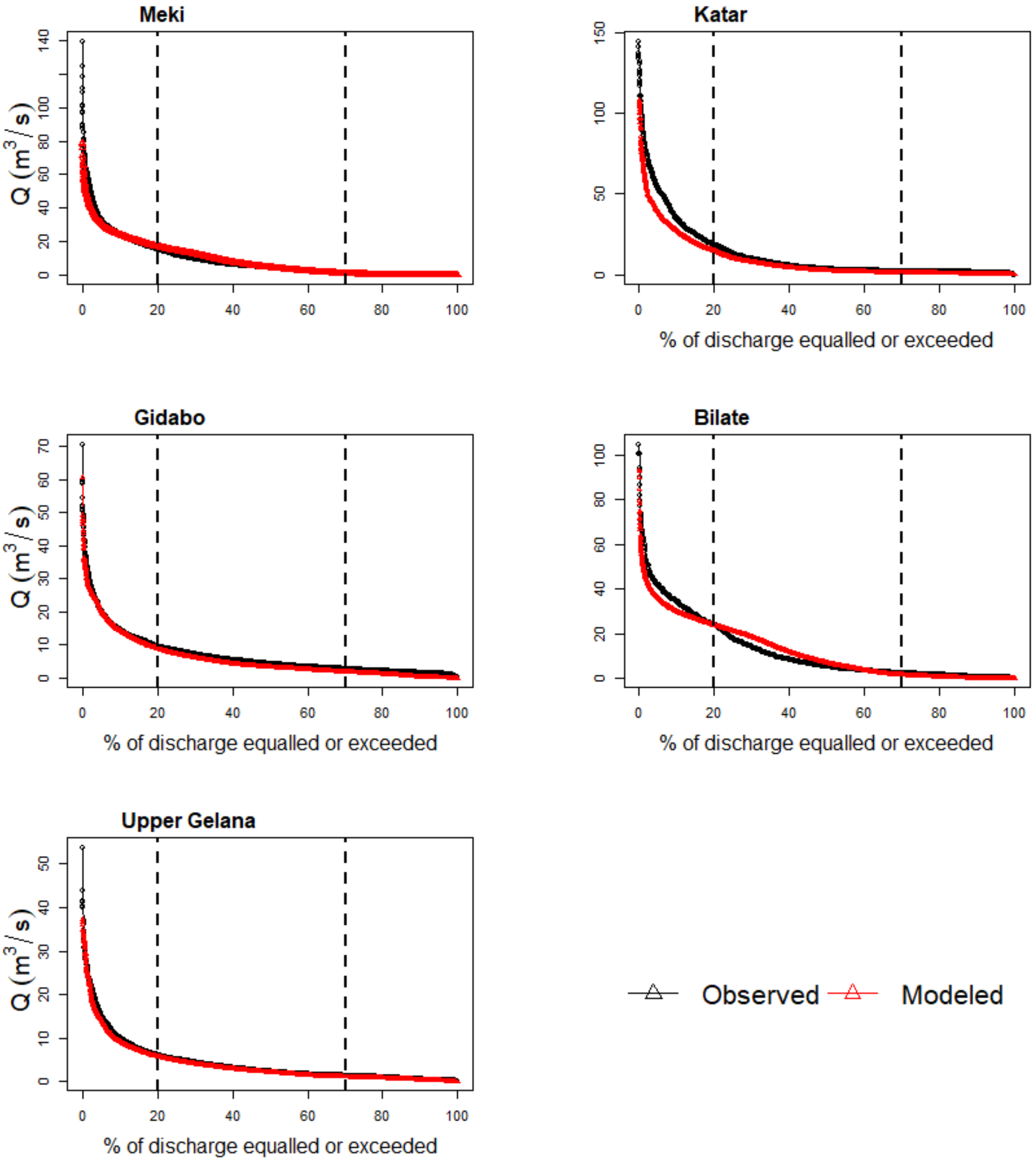

Figure 7 | Flow duration curves of observed and modeled daily streamflow of the ‘pseudo watersheds.

Table 4 | Model evaluation statistics of the daily SWAT+ for the calibration, validation and regionalization (1987-2000)

| **Watershed** | **Method** | **Objective functions** | | | |
|---|---|---|---|---|---|
| | | KGE | NSE | PBIAS | **RSR** |
| **Bulbula (Donor)** | Cal. | 0.84 | 0.76 | -2.1 | **0.51** |
| | Val. | 0.80 | 0.72 | -5.4 | **0.53** |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| **Meki (Pseudo)** | Test | 0.71 | 0.63 | 9.2 | **0.69** |
| **Katar (Pseudo)** | Test | 0.75 | 0.64 | 10.7 | **0.67** |
| **Kulfo@ Abayata (Donor)** | Cal. | 0.81 | 0.68 | 3.7 | **0.56** |
|  | Val. | 0.78 | 0.63 | 7.6 | **0.68** |
| **Gidabo (Pseudo)** | Test | 0.70 | 0.59 | +9.3 | **0.75** |
| **Upper Gelana (Pseudo)** | Test | 0.67 | 0.61 | +11.8 | **0.73** |
| **Bilate (Pseudo)** | **Test** | **0.59** | **0.53** | **+14.3** | **0.78** |

## Lake water balance change

The water balance of Lake Abijata is controlled by rainfall and evaporation, water abstraction from the lake by the soda ash factory, inflow from Bulbula and Horakelo Rivers, and inflow from ungauged watersheds. The water balance of Lake Chamo is primarily controlled by evaporation and rainfall on the lake, inflow from Kulfo River, 40 springs, and inflow from ungauged watersheds (Sile and Elgo) (Table 5). We assumed that the groundwater flow and movement influence is negligible, following findings by Ayenew (2004). The result depicted that the surface runoff and evaporation increased in the impact period in both lakes. Abstraction increased in the Abijata Lake (Table 5). Changes in lake level and volume reflect variations in the inputs from rainfall, evaporation, abstraction and surface flow. Trends in the lake water levels in both lakes are highly variable. The Abijata Lake level decreased by 2 m due to large-scale water use for irrigation and soda abstraction in the catchment, significant changes have been recorded in the past few decades, and by 2021, the area of Lake Abijata had been reduced by about 68% as compared to year 1989 (Ayalew et. al, 2022) and 60% as compared to the year 2016 (Wagaw et al., 2019). Because irrigation is highly expanding and abstraction of water from Meki, Katar and Bulbula Rivers, and Lake Ziway for irrigation takes place year-round, its effect on water levels is increased during dry season (Getnet et al., 2014, Jansen et al., 2007, Wagaw et al., 2019). The water balance of the lakes in Table 5 was determined by combining model output, including lake areal rainfall, evaporation, and inflow from both gauged and ungauged watersheds, with recorded data such as abstraction, depth, and spring inflow.

Table 5: Changes of the annual water balance components in million $m^3$

| Water Balance Components | Lake Abijata |  |  | Lake Chamo |  |  |
|---|---|---|---|---|---|---|
|  | Pre-impact period | Impact period | ΔV, million $m^3/y$ | Pre-impact period | Impact period | ΔV, million $m^3/y$ |

| | | | | | | |
|---|---|---|---|---|---|---|
| Lake areal rainfall | 103.3 | 96.6 | -6.7 | 338.4 | 329.4 | -9.0 |
| Lake evaporation | 240.7 | 233.9 | -6.9 | 496.2 | 518.3 | 2.2 |
| Gauged river inflow | 238.3 | 208.4 | -29.8 | 2184.3 | 3943.0 | 1758.7 |
| Inflow from springs | - | - | - | 5.3 | 4.1 | -1.2 |
| Ungauged river inflow | 14.7 | 16.3 | 2.4 | 171.6 | 312.1 | 140.5 |
| Lake outflow | - | - | - | - | - | - |
| Abstraction | 5 | 13 | 8 | - | - | - |
| Enclosure term* | 110.6 | 74.4 | -35.2 | 2203.4 | 4070.3 | 1886.8 |
| Change in depth (m) | 4.3 | 2.7 | -1.6 | 14.2 | 18.6 | 4.4 |

* *The enclosure term in this case is the water balance on the lake, which is determined by the difference between the input and output. The magnitude of this term depends on the amount of loss and gain.*

## 3.2. Hydrological alteration

The analysis of hydrological alterations was carried out on both Lake Abijata and Lake Abaya. The change point analysis presented in Fig. 8 shows that there is an abrupt shift in lake level over the Rift Valley Lake Basin. The change point analysis results revealed that the lake level has decreased after the year 2003. Abaya Lake has experienced a decrease after a change point from the 2000s until 2009 and more recently, a large increase was observed. Based on the change point analysis, three periods have identified, the pre-impact period (1985-2003), impact period (2003 to 2009) and post-impact period (2010 to 2015).

The environmental flow analysis in Fig. 8 depicted that the natural flow pattern has been disrupted. The magnitude and timing, duration, seasonality and frequency of high and low flows of the impacted periods have changed compared to the pre-impact period. The extreme low flow, low flow, small floods and large flood values for the impacted period have decreased in Abijata Lake, while they have increased in the Abaya Lake.

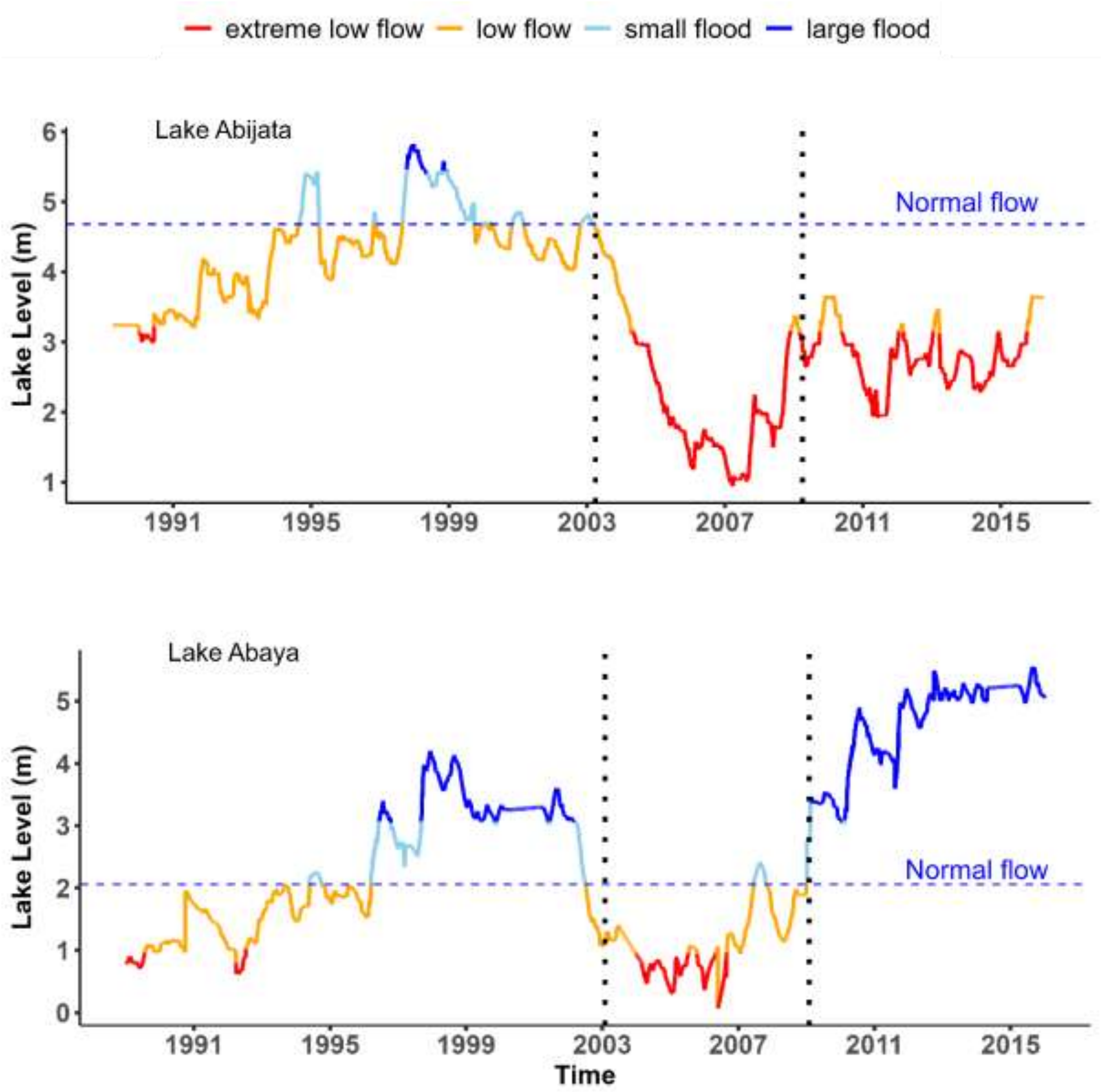

Figure 8 | Environmental flow analysis of Lake Abijata and Abaya based on observed data

Fig. 9 depicts the monthly median and FDC plot of Lake Abijata and Abaya in the pre-impacted and impacted period. It is observed that the lake level and the natural regime have altered after the year 2002/2003 in both lakes. The Abijata lake level exhibited a significant decrease during the pre-impacted period for all months, while the Abaya Lake level showed a significant increase during the impacted period in all months. The FDC showed an increase in the Abaya Lake level across all flow regimes (low, middle, and high) and a decrease in the Abijata Lake level. A high degree of alteration is observed in both lakes; but the hydrological regime of Lake Abaya has undergone a complete change, especially during the dry season (May to September). This is associated with a change of the rainfall pattern (Ayalew et al., 2022a).

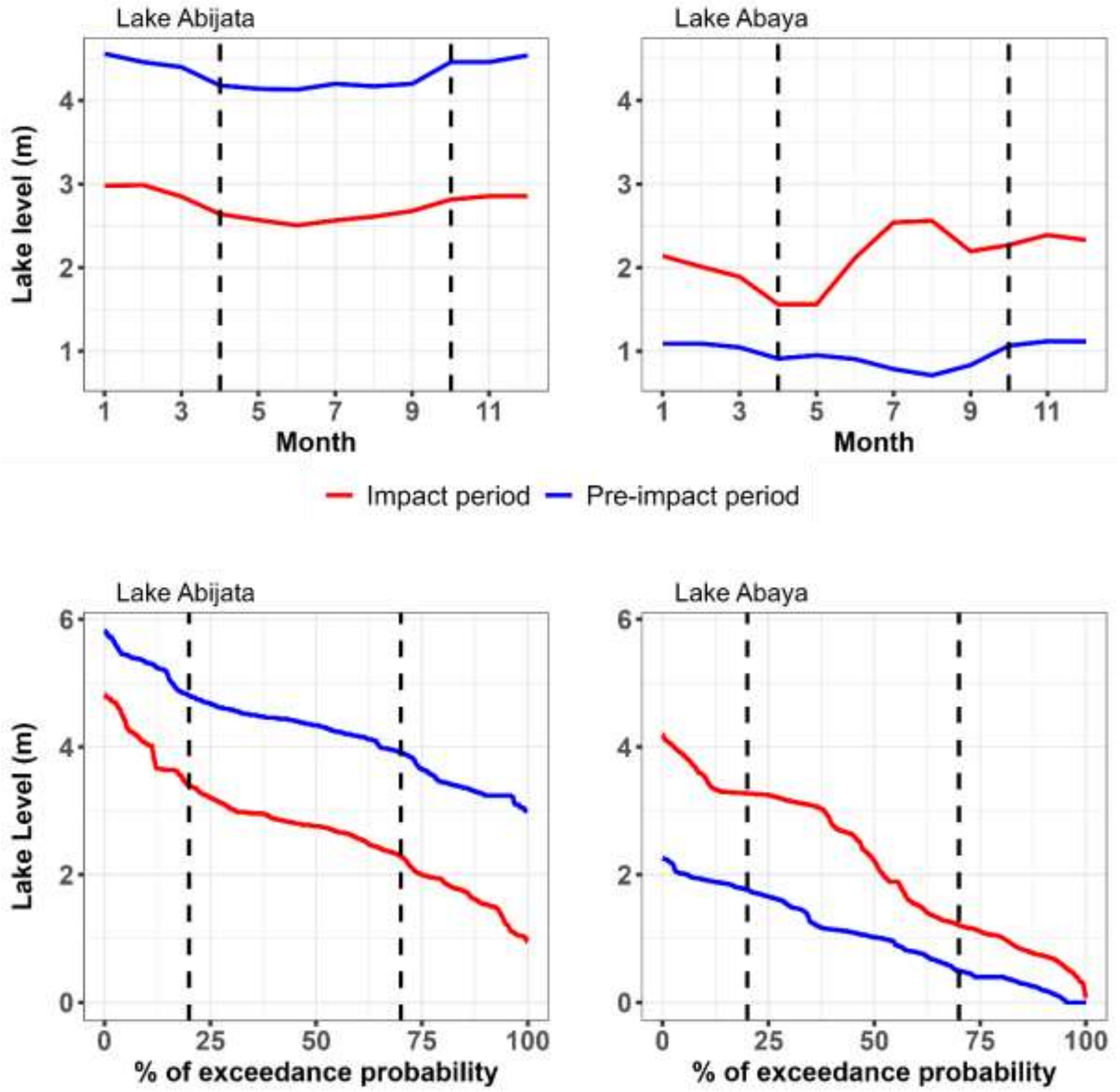

Figure 9 | Monthly median and FDC analysis of pre-impacted and impacted period

Median of monthly flow (RVA Group 1) throughout the impact period indicates a decreasing trend compared with the pre-impact period in the Abijata Lake. The dispersion coefficients for the pre-impact period (ranging from 0.21 to 0.33) are mostly lower than those for the impact period (ranging from 0.3 to 0.49), indicating the higher flow fluctuations in the impacted period due to the irrigation expansion and soda ash factory. Whereas in Abaya Lake, median of monthly flow depicted an increasing trend compared with the pre-impact period. The dispersion coefficients for the pre-impact period (ranging from 1.18 to 1.68) are mostly lower than those for the impact period (ranging from 0.80 to 1.5), indicating that the higher flow fluctuations in the impacted period due high runoff are associated with high deforestation

(Ayalew et al., 2022b, Dessie and Kleman, 2007, Garedew et al., 2009). The medians of annual 1-, 3-, 7-, 30-, 90-day minimum and 1-, 3-, 7-, 30- and 90-day maximum for the impact period decrease significantly for Abijata Lake and significantly increase in the case of Abaya Lake. These results indicate that the daily, weekly, monthly and seasonal maxi-mum/minimum flow cycles are negatively influenced by water abstraction for irrigation and factory in the case of Abijata Lake; and positively influenced by runoff increasing the case of Lake Abaya.

The median Julian dates for the annual 1-day minimum have shifted forward in the impacted period, moving from the 137th and 91st day in the pre-impact period to the 130th and 113th day in Lake Abijata and Abaya, respectively. Likewise, the median Julian dates for the annual 1-day maximum have also moved forward in the impact period, shifting from the 309th and 320th day to the 327th and 311st day in Lake Abijata and Abaya, respectively. The result also showed that there is no significant change on the medians of low, high pulse counts and base flow index in the impact period and in the pre-impact period, in both lakes (Figure 10).

The medians of low pulse durations (increased from 2 to 47) and high pulse durations (increased from 64 to 140) in the impacted period are higher than those in the pre-impact period in Abijata Lake. However, the medians of low pulse durations (decreased from 125 to 36) and high pulse durations (increased from 208 to 223) in the impact period in Abaya Lake which indicates a high hydrologic alteration of low and high pulse durations. Median of high pulse durations have increased in both lakes, which is associated with increasing runoff during wet season.

The medians of rise rate and fall rate are the same as those in the pre-impact period in both Lakes except the number of reversals. The number of reversals are higher than in the pre-impacted period (decreased from 41 to 23) in Abaya lake; and (decreased from 88 to 78) in Abijata lake.

Considering all 33 parameters (Figure 10), the highest hydrologic alteration factors has occurred in low RVA category (ranging from 1 to 2.7) except fail rate and high pulse duration, which indicates annual parameter values more often fell inside the RVA target window than expected in Abijata Lake. Likewise, in this lake the second highest hydrologic alteration factors have occurred in high RVA category (ranging from -1 to -0.1) except low pulse count, which indicates annual parameter values less often fell inside the RVA target window than expected. High hydrologic alteration factor has also been observed in Abaya Lake which in the low RVA category (ranging from -1 to -0.1) except fail rate and low pulse duration, which indicates annual parameter values less often fell inside the RVA target window than expected. In this lake also the second highest hydrologic alteration factor has occurred in high RVA category in group one and group two (ranging from 0.6 to 1.5), which indicates annual parameter values more often fell inside the RVA target window than expected.

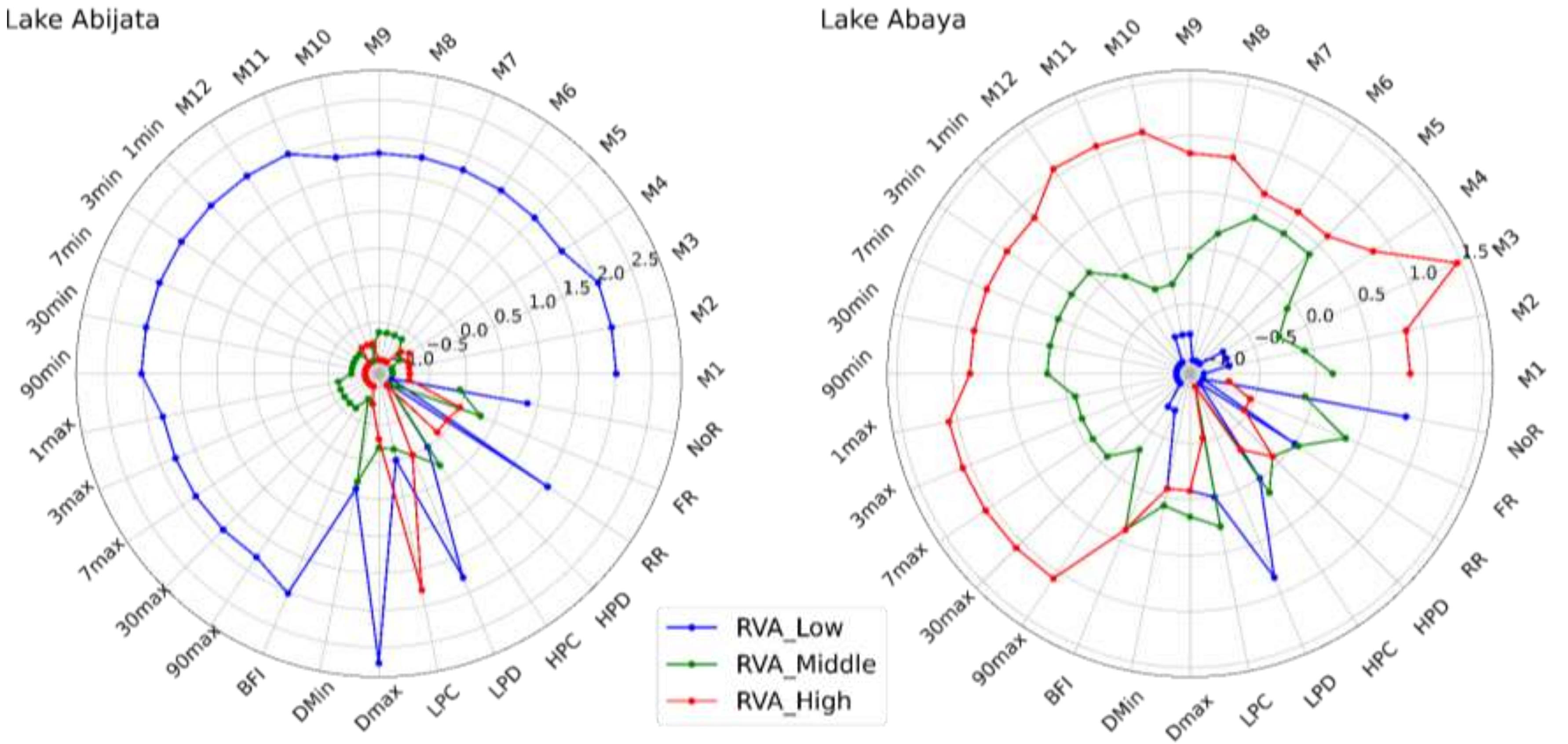

Figure 10 | Hydrological alteration analysis using RVA

Where, 'M1', 'M2', 'M3', 'M4', 'M5', 'M6', 'M7', 'M8', 'M9', 'M10', 'M11', 'M12', '1min', '3min', '7min', '30min', '90min', '1max', '3max', '7max', '30max', '90max', 'BFI', 'DMin', 'Dmax', 'LPC', 'LPD', 'HPC', 'HPD', 'RR', 'FR', 'NoR' are 'January', 'February', 'March', 'April', 'May', 'June', 'July', 'August', 'September', 'October', 'November', 'December', '1_day_min', '3_day_min', '7_day_min', '30_day_min', '90_day_min', '1_day_max', '3_day_max', '7_day_max', '30_day_max', '90_day_max', 'Base_flow_index', 'Date_of_min', 'Date_of_max', 'Low_pulse_count', 'Low_pulse_duration', 'High_pulse_count', 'High_pulse_duration', 'Rise_rate', 'Fall_rate', 'Number_of_reversals'.

Generally, results indicate that the hydrological system is changing in both lake basins but responding differently to the changes. Changes in hydrology are mainly associated with human activity and climate change. Apparently, the changing hydrology for the impacted period (2003-2009) was worsen in the Abijata Lake and linked with frequent droughts and water abstraction. Despite the fact that the Abijata Lake's level increased during the post-impacted period, it remained lower than the lake level observed in the pre-impacted period. In contrast to the pre-impacted period, the water level of Lake Abaya increased during the post-impacted period.

## Bathymetry analysis, Bathymetric characteristics of Lakes

### Morphometric characteristics and contour maps

Morphological parameters used to characterize the morphometry of the Lake Chamo, including area (A), Volume(V), maximum effective length (Lme), maximum width (Wme), mean width (W), maximum depth($_{dmax}$) and mean depth ($d_{mean}$), are summarized in Table 6. The values are presented with respect to the reference datum discussed in the methodology. The result is also compared with the bathymetry analysis of Awulachew (2001) conducted in 1998. The maximum depth increased by 4.4 m in the middle of the lake , the sediment thickness increased by about 0.6 m, the area increased by 30 km$^2$ and the volume increased by 7.8 x 10$^8$ m$^3$ within two decades (Figure 8).

Table 6 | Morphometric characteristics of Lake Chamo

| **Parameter** | **Chamo Lake** | |
|---|---|---|
| | This study (2021) | Awulachew (1998) |
| Altitude (m) | 1110 (GPS) | 1107(EMA 1: 50 000 maps) |
| Basin area, including lakes (km$^2$) | 18 599.8 (with Lake Abaya contribution) | 18 599.8 (with Lake Abaya contribution) |
| A, including islands (km$^2$) | 346.76 | 316.72 |
| Volume (m$^3$) | $4.12\times 10^9$ | $3.24 \times 10^9$ |
| $L_{me}$ (km) | 33.93<br>between 5°41′36″N and 37°28′40″E to 5°58′24″N and 37°35′56″E | 33.50<br>between 5°42′00″N and 37°39′00″E to 5°58′00″N and 37°36′00″E |
| $W_{me}$ (km) | 16.07 | 15.5, perpendicular to L |
| W (km) | 10.17 | 10.1 |
| $d_{max}$ (m) | 18.6 | 14.2, near the middle |
| dmean (m) | 11.38 | 10.23 |

The water depth distribution obtained using Kriging interpolation method in surfer20 is shown in Figure 9. A grid size of 110 m x 450 m bathymetric data was used to interpolate the depth distribution of the lake. The resulting depth estimates were plotted on a contour map to visualize the underwater topography of the lake; and we observed that the central region of the lake had the deepest parts.

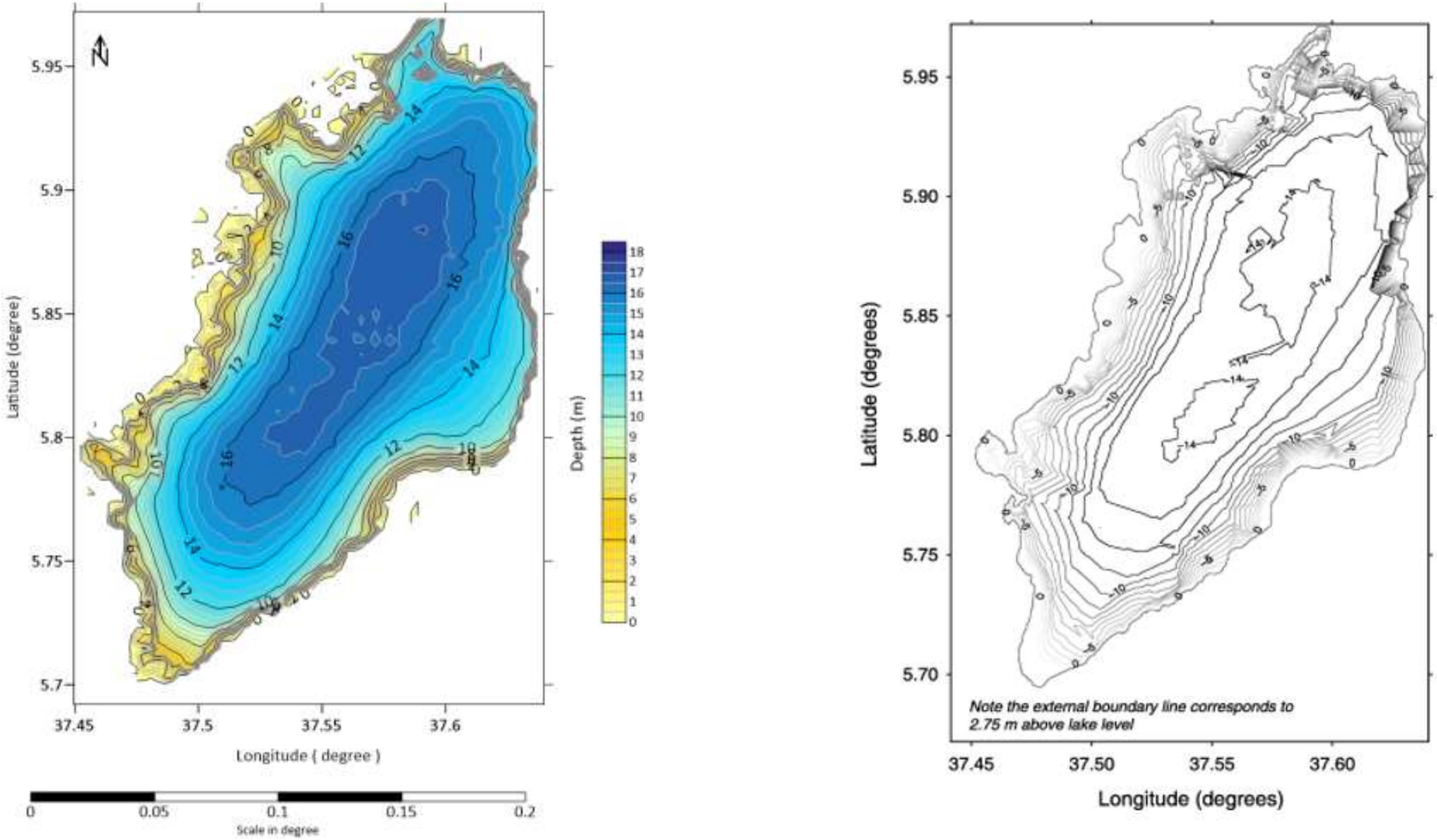

*Figure 11* | *Bathymetric maps of Lake Chamo (a) bathymetry of this study (2021); (b) Bathymetry of Awulachew (1998)*

## Water level and storage change analysis

Fig. 12 a & b illustrates the changes in spatio-temporal patterns of Lake Chamo depth, area and storage over a span of 20 years (1998-2021), as indicated by the depth-area and storage analysis. Specifically, the lake has experienced an expansion, gaining an area of 30 km$^2$ (9.5%), and its volume has increased by 7.8 x 108 m$^3$ (27.2%) over the same period. As the maximum depth increased by 4.4 m (31%) and the lakebed level increased by 0.6 m (4.5%) possible factors that could contribute to such changes in lake size and volume are increased runoff and sedimentation from rivers or streams that flow into the lake due to land use change, deforestation. Another reason may be changes in the underlying geology of the area, such as changes in the flow of underground water and springs, that can contribute to changes in a lake's size and volume. These changes in size and volume could have significant ecological and environmental impacts on the lake and its surrounding area.

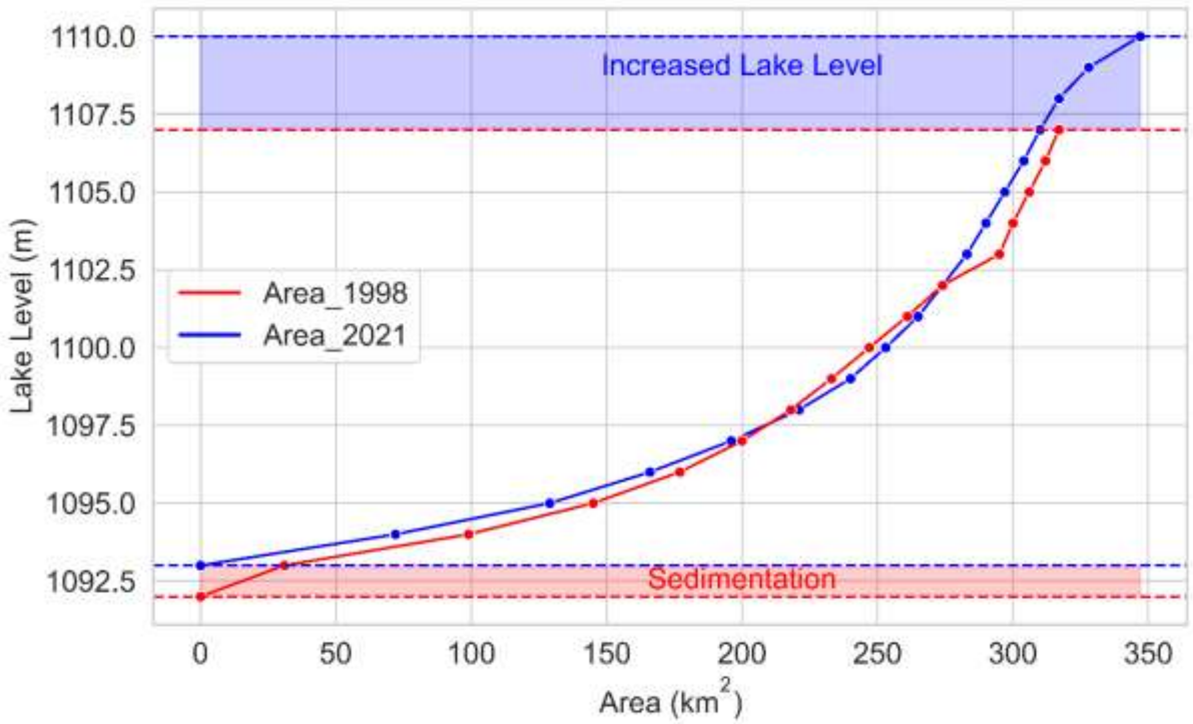

Figure 12 a | Area-depth change analysis: blue color for the 2021; red color for 1998 (Awulachew (1998)

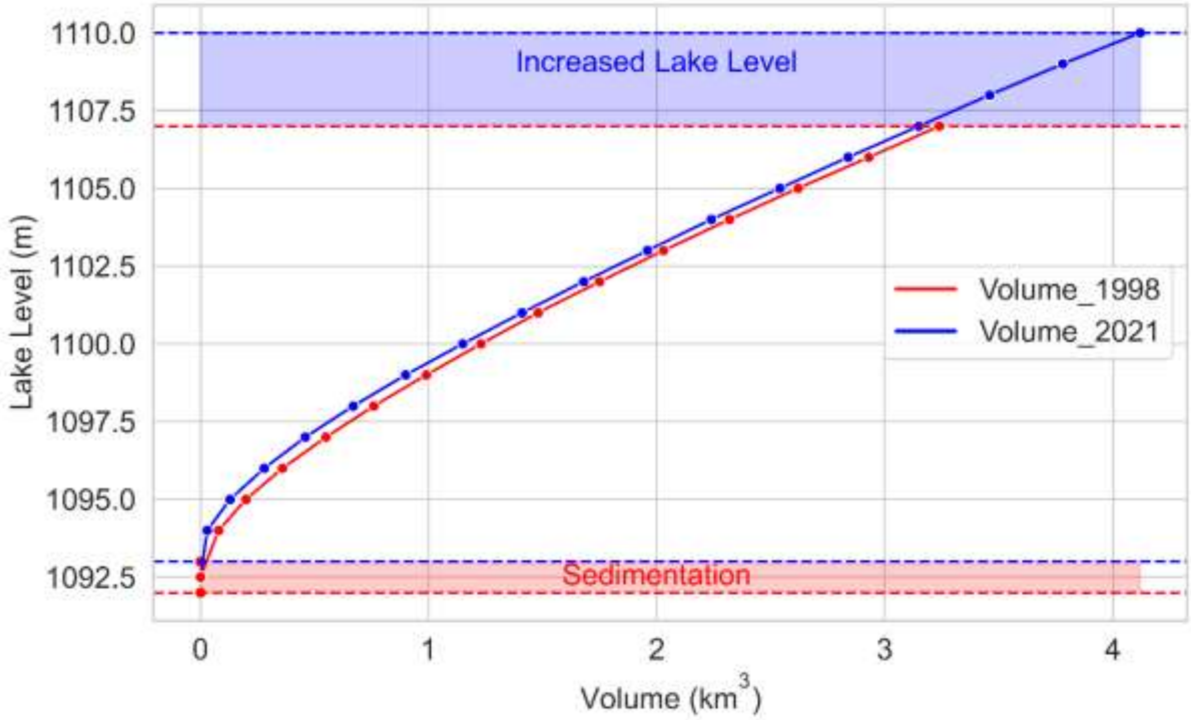

Figure 13 b | Volume-depth change analysis: blue color for the 2021; red color for 1998 (Awulachew (1998)

## Discussion

In the context of regionalization of model parameters, our hydrological model exhibited a performance level that aligns closely with the findings documented in the literature (Seibert, 1999, Beldring, 2002, Merz and Blöschl, 2004). Based on the evaluation using the objective functions NSE, KGE, PBIAS and RSR, the pooled calibration technique showed a good performance. It exhibited a remarkable ability to accurately represent observed hydrological behavior, particularly for the closest pseudo watersheds (Gidabo, Upper Gelana, Meki, Katar, and Bilate). This phenomenon of varying performance across spatially related watersheds has also been noted by Merz and BlÖschl (2004), who attributed it to the interplay of spatial hydrologic variability and poor data quality. Seibert (1999) observed a decline in NSE runoff efficiency from 0.81 to 0.79 when transitioning from calibrated to regionalized parameters across 11 catchments and a decrease to 0.67 for a separate set of 7 catchments. Beldring (2002) also found a NSE of 0.68 for 141 gauged catchments and 43 catchments treated as ungauged, though approximately 20% of the latter group exhibited efficiencies below 0.3. Compared to this the maximum decline in model performance due to regionalization in our study is observed in the Bilate watershed with a decreased of the NSE from 0.68 (cal) /0.63 (val) in the donor watershed to 0.53 in the pseudo watershed (Table 4). In this case the donor watershed (Chamo) is dominated by semi-natural vegetation, whereas, the pseudo watershed (Bilate) has a larger share of agricultural land. It is evident that while regionalization allows for broader model applicability, the accuracy of predictions can vary significantly depending on contextual factors and the specific characteristics of the studied watersheds.

The study revealed significant changes in lake levels and inflows over the past two decades in the Rift Valley Lakes. Notably, Chamo Lake experienced substantial increases in area, depth, and volume, while Lake Abijata witnessed an extraordinary decrease in area and depth. The resuly revealed that significant shifts in the hydrological system of Lake Abijata and Lake Abaya after the year 2003. Substantial decreases in lake levels were observed in both lakes from 2003 to 2009. The lake levels recovered after 2009. In the post-impact period (2010-2015), the lake level of Abaya Lake showed an increase compared to both the pre-impact (1987-2003) and impact period (2003-2009). On the contrary, during the same period, the lake level of Abijata Lake showed a noticeable decreasing trend compared to the pre-impact period. According to Ayalew et al. (2022), the significant decline in water level during the impact period (2003-2009) was primarily attributed to prolonged drought affecting both lakes. A study by Street (1979) also investigated that many of the rift lake's water level fluctuations were associated with climate conditions rather than anthropogenic factors. However, recently the changing water level is also associated with anthropogenic activities (Alemayehu et al., 2006).

The Range Variable Approach (RVA) analysis also revealed that the river's flow regime has deviated significantly from its natural or historical patterns. The High-RVA and Middle-RVA values are negative in Lake Abijata, which indicates that the river's flow conditions are lower than what would be expected based on historical data. The negative value of high andmiddle and the positive value of low level of Lake Abijata coincides with the time of high-water abstraction for soda production and water abstraction for irrigation from the upstream Lake Ziway. In the wet season, the time between May to September is a refilling period of the lake from large inflows from the Katar and Meki rivers. During the dry season (November to June), Ziway shows a net loss of storage due to high abstraction of water for irrigation. This high abstraction of water leads to shifts in the flow regime, and a positive value of low-RVA as observed. In Abaya Lake, the hydrological system responded reversely. The High-RVA and Middle-RVA values are positive, and the low-RVA value is negative. This indicates that the peak flow increased in the impact period during the wet season. Our previous work, Ayalew et al. (2023), showed an increasing surface runoff and decreasing infiltration and evaporation after 2000, which is associated with deforestation and agricultural expansion.

Lake Abijata is a terminal lake; it lacks any surface or groundwater outflow, making its water level and volume subject to changes in hydrological budget components such as rainfall, river inflow, and evaporation. However, recent development schemes in soda ash extraction and irrigation have also contributed to the drastic reduction of the lake level (Alemayehu et al., 2006). The main inflow is from the discharge from the Horakelo and Bulbula rivers, which are the outflows of lakes Langano and Ziway, respectively, and direct rainfall. The total river inflow decreased by 12.5%, which is associated with water abstraction for irrigation. As it is a terminal lake, the ways of water loss from the lake are evaporation and abstraction. Therefore, the main reason for hydrological regime change was water abstraction of feeding rivers for irrigation and water abstraction for industrial purposes from the lake followed by evaporation. Alemayehu et al. (2006) also state that abstraction of Lake Ziway for irrigation also has an influence on the level of Lake Abijata. Conversely, Lake Chamo experienced an increase in its water level during the post-impact period. The lake level increased by 4.4 m, and the lake bottom elevation increased by 0.6 m. This significant water level rise is mainly due to high surface runoff and sediment transportation. The total surface inflow increased by 80.5%, which is influenced by changes in Land Use and Land Cover, particularly deforestation and agricultural expansion, which resulted in higher runoff (Ayalew et al., 2023) and enhanced sediment transportation. In contrast to many East African terminal lakes, lake Chamo has shown significant water level rise. These changes can be explained by change in Land Use and Land Cover (LULC) and climate change (Ayalew et al. 2023). Influence of human activities exerted a more significant impact compared to climate change. The hydrological regime of the lakes is affected by human-induced factors (mainly abstraction, urbanization, and deforestation) associated with rapid population growth. In the Northern part of the study area high water abstraction for irrigation and industry was the main driving factor for the changes hydrology. However, in the Southern part of the study area, high runoff and sedimentation associated with high deforestation are the main driving factors for the hydrological alterations (Ayalew et al. 2023). Even though further investigation is required, the changing hydrological system in the Rift Valley also might be linked to the geological setting. The Rift Valley is formed due to the divergent movement of tectonic plates, leading to the creation of a rift or crack in the Earth's crust. This tectonic activity results in the formation of grabens and horsts, additionally influencing the hydrological characteristics of the region (Scoon, 2018, Chorowicz, 2005).

# Summary and conclusions

The Rift Valley Lakes in Ethiopia have experienced changes in their hydrological regime, due to anthropogenic and climate change. Integrating a physical based hydrologic model, break point analysis, indicators of hydrologic alteration (IHA) and bathymetry survey is a better approach to understand a dynamic and complex hydrological system and the potential diving factors. Indicators of hydrological alteration (IHA) were derived from lake level data that clearly showed the alterations of hydrological regime. Main water balance components were simulated using a semi-distributed Soil and Water Assessment Tool plus (SWAT+) model. Multisite regionalization techniques represent the hydrological behavior of multiple locations and that the model can be used to make predictions for other locations. The SWAT+ model performed well for daily stream flow during calibration and validation period. The pooled calibration approach showed a satisfactory performance in capturing observed hydrological behavior, both in 'donor' and 'pseudo' watersheds. The applied calibration technique was suitable for regionalization of model parameters as the rather small decrease of model performance in the pseudo ungauged watersheds showed.

The findings reveal notable changes over the past two decades. Chamo Lake experienced an increase in area by 11.86 km$^2$, depth by 4.4 meters, and volume by 7.8 x 10$^8$ cubic meters. In contrast, Lake Abijata witnessed an extraordinary 68% decrease in area and a depth decrease of -1.6 meters. Mean annual rainfall decreased by 6.5% in Abijata Lake and 2.7% in Chamo Lake during the impacted period. Actual evapotranspiration decreased by 2.9% in Abijata Lake but increased by up to 0.5% in Chamo Lake. Surface inflow to Abijata Lake decreased by 12.5%, while Lake Chamo experienced an 80.5% increase in surface inflow. Sediment depth in Chamo Lake also increased by 0.6 meters.

The results of this study highlight on the changing hydrological regime in Chamo Lake, emphasizing the role of anthropogenic influences in increasing surface runoff and sediment intrusion. Conversely, the hydrological dynamics of Abijata Lake are primarily affected by water abstraction from the rivers and lakes that serve as its water sources, driven by industrial and irrigation demands. By examining these factors, this research offers valuable insights into the evolving hydrological systems of the Rift Valley Lakes in Ethiopia, contributing to a better understanding of the driving forces behind these changes.

The hydrological regime of Chamo Lake has experienced changes characterized by increased area, depth, and volume, primarily influenced by heightened surface runoff and sediment intrusion.

Abijata Lake has undergone significant changes in its hydrological regime, marked by a substantial decrease in area and depth, resulting from water abstraction for industrial and irrigation purposes from feeding rivers and lakes.

The findings emphasize the importance of understanding the driving factors behind hydrological changes in Rift Valley Lakes, particularly the influence of anthropogenic activities and climatic variations. Lake level changes, whether declining or increasing, have resulted from a combination of natural and human-induced factors. These changes can have significant impacts on ecosystems, human communities, and water availability. Mitigating the impacts of these changes requires sustainable water management practices, climate change adaptation strategies, and a holistic understanding of the interconnection of ecosystems and human activities.

Further research and monitoring efforts are necessary to deepen our understanding of the hydrological processes and identify effective management strategies to ensure the sustainable use and conservation of the Rift Valley Lakes in Ethiopia.

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