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An integrated modeling framework for water accounting assessment in the Lake Tana Sub-Basin, Ethiopia: Impacts of interbasin water transfer

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ABSTRACT

Study Region: Lake Tana Sub-Basin, Ethiopia
Study Focus: The Lake Tana sub-basin plays a vital role in Ethiopia's hydropower generation and irrigation development. However, the recent operation of an interbasin water transfer has intensified competition for water resources, raising concerns about long-term hydrological sustainability and downstream ecological flows. To evaluate these impacts, this study developed an integrated modeling framework that couples the HBV Light rainfall-runoff model, a lake water balance model, and the Water Accounting Plus (WA+) approach to assess water availability, consumption patterns, and downstream ecological flow conditions for 2010–2020.
New hydrological insights for the Region: The HBV Light model was unable to accurately simulate the natural lake outflow, but its coupling with the lake water balance model significantly improved model performance, resulting in NSE of 0.79 and R^2 of 0.92. The mean annual inflow to the lake was estimated at 6.9 km^3 , with 55% contributed by the Gilgel Abbay catchment. The rainfall and evaporation over the lake was estimated at 4.1 km^3 yr^{-1} and 5.1 km^3 yr^{-1} , respectively. Total annual outflow averaged 5.8 km^3 , with 3.1 km^3 yr^{-1} diverted through the interbasin water transfer and 2.7 km^3 yr^{-1} outflow at the natural outlet. The interbasin water transfer now exceeds lake's natural outflow and has increased the frequency of unmet environmental flow requirements from 6% (pre-transfer period) to 27% during 2010–2020. In terms of consumption, rainfed agriculture dominates water consumption at 5.7 km^3 yr^{-1} , while irrigation accounts for only 0.4 km^3 yr^{-1} . Green evapotranspiration (ET) constitutes 68% of total water consumption, with blue ET making up the remaining 32%. These results demonstrate the hydrological implications of interbasin water transfer on lake outflow and downstream ecological conditions. The

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integrated modeling framework offers a scalable approach for hydrological assessment and water allocation in data-scarce basins.

1. Introduction

Effective water resource management is essential for sustaining economic growth, food security, and ecosystem health, particularly in regions facing increasing pressure from population growth, climate variability, and expanding infrastructure. Ethiopia faces many of these pressures, making improved management of its major river basins increasingly important. The Lake Tana sub-basin, located in the upper Blue Nile Basin, is one of the country's most important freshwater systems, supporting hydropower generation, irrigation, and domestic water supply. Despite its hydrological and socio-economic importance, sustainable management of the basin is constrained by persistent data gaps (Dile et al., 2018; Haile et al., 2023; Wale et al., 2009). For example, lake outflow data, which are crucial for understanding lake hydrology and downstream flow dynamics, have been unavailable since 2014, hindering effective water management.

Increased development efforts in the Lake Tana sub-basin have further intensified competition for water among irrigation, hydropower, and ecosystem services, leading to growing water scarcity and environmental challenges (McCartney et al., 2010; Taye et al., 2021). To address these issues, effective water management strategies and informed decision-making are crucial, both of which rely on accurate data on water supply, demand, and use (Dembélé et al., 2023; Karimi et al., 2013). Regarding this, the Water Accounting Plus (WA+) framework is a valuable decision-making tool, providing spatially explicit evidence on water supply, demand, accessibility, and use (FAO, 2012; Karimi and Bastiaanssen, 2015; Molden and Sakthivadivel, 1999).

The WA+ framework is a standardized methodology that provides a comprehensive assessment of water resources and management practices within a river basin (Owusu et al., 2025). It offers critical insights into the total available water, landscape-specific water consumption, irrigation use, ecological water requirements, and the volume of water potentially available for future allocation (Delavar et al., 2025; Dembélé et al., 2023; Karimi et al., 2013; Liu et al., 2018; Nkiaka et al., 2021). The framework distinguishes between green and blue water consumption and quantifies utilizable outflows to support informed water allocation decisions. Moreover, WA+ presents results through a user-friendly "sheet" format, enabling clear visualization for planners and policymakers. Such detailed information is often lacking in many basins, even where hydrological monitoring networks are in place.

The WA+ framework has been successfully applied in various river basins worldwide, including the Volta River Basin (Dembélé et al., 2023b), the Awash River Basin (Dost et al., 2013), the Indus River Basin (Karimi et al., 2013), and the Tashk-Bakhtegan River Basin (Delavar et al., 2020). Despite its usefulness, a major drawback of the WA+ framework is its inability to account for storage dynamics, like changes in lake and reservoir volumes. Moreover, the WaterPix hydrologic model embedded within WA+ doesn't include river routing or explicit storage processes (Delavar et al., 2020), which limits its applicability in basins where flows are heavily regulated by reservoirs or altered by human interventions. To overcome these limitations, recent studies have coupled WA+ with hydrological models to improve representation of runoff generation and routing (Dembélé et al., 2023; Delavar et al., 2020; Patle and Sharma, 2025). However, storage dynamics, particularly in lake-dominated systems, remain insufficiently addressed. This gap is especially critical in the Lake Tana sub-basin, where regulated outflows, interbasin water transfers, and limited inflow–outflow measurements complicate basin-scale water accounting.

Numerous studies have examined the hydrological processes and water balance of the Lake Tana sub-basin (Alemu et al., 2020; Kebede et al., 2006; Rientjes et al., 2011; Wale et al., 2009); however, most were conducted before the operation of the interbasin water transfer,[1] which diverts water from Lake Tana to the neighboring Tana-Beles sub-basin. Following the transfer, Dessie et al. (2015) evaluated the lake's water balance, but their analysis covered only two years, providing limited insight into the long-term hydrological impacts of the transfer. More recent assessments often oversimplify the diversion by treating it as constant flow, thereby neglecting the substantial temporal variability in diverted volumes and introducing uncertainty in the evaluation of the lake's hydrology. Moreover, the long-term impacts of the transfer on Lake Tana's natural outflow to the Blue Nile River and on downstream environmental flow requirements remain poorly understood.

The novelty of this study lies in its integrated modelling approach to analyze the water balance of the lake, particularly in the context of a lack of lake inflow data, interbasin water transfer, and the use of in situ and remote sensing datasets to address data scarcity. Beyond methodological integration, the present study also advances the policy relevance of water-accounting research in the upper Blue Nile basin by translating physically based indicators into actionable management triggers and by generating a wide range of water availability and use indicators for the basin. Moreover, this study presents a scalable approach, transitioning from a basin-specific case study to a transferable decision-support template for data-scarce African basins and lakes. Therefore, the present study addresses the following research questions: 1) What are the lake's inflows and outflows, and which catchments contribute most to these inflows? 2) How much of the outflow is diverted for hydropower, and what impact does this have on the lake's natural outflow? 3) What is the state of water availability and scarcity in the basin, and how much water is used for irrigation and rainfed agriculture? and 4) How does the lake's natural outflow impact the downstream environmental water requirements?

[1] The transfer is technically intra-basin (both rivers are upper Blue Nile tributaries) but is conventionally labelled 'inter-basin' in Ethiopian water resource planning documents; we retain that usage for consistency

2. Study area and data

2.1. Study area

This study was conducted in the Lake Tana sub-basin, located in the upper Blue Nile basin of Ethiopia (Fig. 1). The sub-basin covers

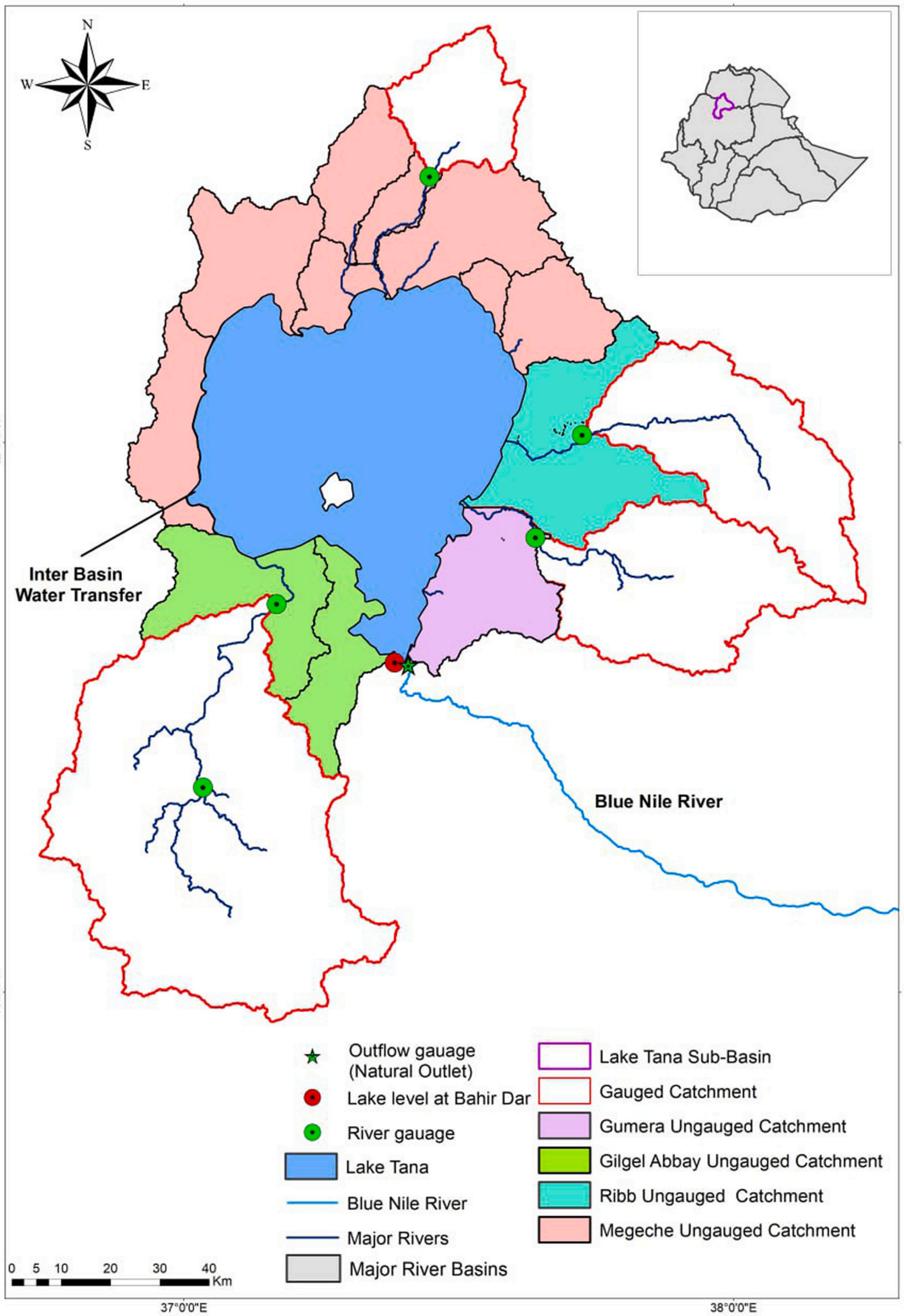

Fig. 1. Location map of the study area, gauged (white) and ungauged catchments (coloured) in the Lake Tana sub-basin.

a total drainage area of 15,077 km^2, with Lake Tana itself accounting for 3062 km^2. The lake is a vital water source for domestic use, irrigation, and hydropower generation. It is fed by over 40 rivers, primarily the Gilgel Abay River from the south, the Ribb and Gumara Rivers from the east, and the Megeche River from the north. Despite its hydrological significance, more than 50% of the basin remains ungauged, posing substantial challenges for accurate water balance assessments and informed water resource management.

Currently, the lake has been managed as a reservoir with two outlets: a natural outlet and a hydropower outlet. The natural outlet, located on the southeastern side of the lake (Fig. 1), directs water into the Blue Nile River. About 30 kilometers downstream, the river forms the Tiss Issat Waterfall, also known as the Blue Nile Falls, one of Ethiopia's most prominent tourist attractions. The hydropower outlet, situated on the western side of the lake, diverts water to the Tana Beles hydropower plant through a 12-kilometer headrace tunnel with an approximate diameter of 7.1 m (Salini and Mid-day, 2006). This outlet serves as the point of interbasin water transfer, connecting Lake Tana sub-basin with the Tana-Beles sub-basin, both located within the upper Blue Nile Basin. The Tana Beles Hydropower Plant, commissioned in 2010, has four turbines with a total installed capacity of 460 MW (SMEC, 2007). It is designed to operate at an average discharge of 77 m^3/s, with a maximum capacity of 160 m^3/s (Salini and Mid-day, 2006). After power generation, the diverted water is released into the Tana Beles River.

2.2. Hydro-meteorological and ancillary datasets

A range of in-situ and remotely sensed datasets were collected from multiple sources for this study. The datasets used for the HBV-light model, Lake Water Balance Model (LWBM), and the WA+ framework are summarized in Table 1.

2.3. Validation of remotely sensed rainfall and ET products

Given that precipitation and actual evapotranspiration (ETa) are the dominant components of the basin water balance, four remotely sensed actual evapotranspiration and eight rainfall products were evaluated prior to their integration into the modeling framework. The ETa products were assessed against water balance derived ETa estimates, and the validation results are presented in Supplementary Figure S1. The selected ETa product was then used to estimate consumptive water use across multiple spatial and temporal scales. Among the rainfall datasets, MSWEP was selected because of its performance in reproducing observed rainfall variability and magnitude (Mekonnen et al., 2023).

3. An integrated modelling framework

This study utilizes an integrated modeling framework to estimate water accounts for the Lake Tana sub-basin from 2010 to 2020

Table 1
Input data used for this study.

Variable	Dataset/Source	Spatial (°)/Temporal resolution	Purpose	Reference
Rainfall	MSWEP v2.8*	0.1/Daily	HBV, LWBM and WA+	Beck et al. (2019)
Reference evapotranspiration	WaPOR v2.1	0.001/Decadal	HBV and WA+	FAO (2022)
Elevation	SRTM DEM	0.003/Static	HBV and WA+	NASA (2013)
Temperature	ERA 5	0.25/Hourly	HBV	Hersbach et al. (2020)
Observed discharge	In situ	Point/Daily	HBV	Ministry of Water and Energy (MoWE)
Lake level	In situ and remotely sensed	Point/Daily	LWBM	MoWE, and Hydroweb
Bathymetric survey for the lake (Volume-area-Elevation)	In situ	Point/One-time measurement	LWBM	MoWE
Lake outflow	In situ	Point/Daily	LWBM	MoWE
Inter-basin water transfer	In situ	Point/Hourly	LWBM	Ethiopian Electric cooperation
Actual evapotranspiration	SSEBop v.5.0*	0.001/Monthly	WA+	Senay et al. (2013)
Land cover	WaPOR v2.1	0.001/Annual	WA+	FAO (2022)
Leaf area index	MODIS 15	0.005/8-day	WA+	Myneni et al. (2002)
Population	Worldpop	0.002/Static	WA+	Lloyd et al. (2019)
lake outflow data derived from HM and LWMB	In situ and model results	Point data/Monthly	WA+	This study
Interception	Computed*	0.001/Monthly	WA+	This study
Saturated soil water content	-	0.0025/Static	WA+	Simons et al. (2020)
The world database on protected areas	FAO	Shapefile/Static	WA+	WDPA (2022)
The global reservoir and dam database	GRanDv1 -NASA	Shapefile/Static	WA+	Lehner et al. (2011)
Number of rainy days	Computed*	0.1/Daily	WA+	This study
Net primary production (NPP)	MODIS 17	0.005/8-day	WA+	Zhao et al. (2005)
Gross primary production (GPP)	MODIS 17	0.005/8-day	WA+	Zhao et al. (2005)
Net dry matter (NDM)	Computed*	0.005/8-day	WA+	This study

* Rainfall and actual evapotranspiration products were selected based on validation results. The equations used to estimate the number of rainy days, interception, and net dry matter are provided in Table S1.

following the inter basin water transfer. The methodology combines hydrological modeling (HBV-light), lake water balance analysis (LWBM), and a comprehensive water accounting framework (WA +) (Fig. 2). A detailed description of the methodology is provided in the following sections.

3.1. HBV-light runoff modelling

The HBV (Hydrologiska Byråns Vattenbalansavdelning) light model (Seibert and Vis, 2012) was used to estimate lake inflow from both gauged and ungauged catchments for the period 2010–2020 (Fig. 2). This model was chosen for this study due to its proven effectiveness in simulating streamflow within the Lake Tana sub-basin (Rientjes et al., 2011; Wale et al., 2009; Worqlul et al., 2017; Wubneh et al., 2024).

The HBV-light model comprises three core subroutines: the snow routine, the soil moisture routine, and the river routing routine. Given the absence of snow in the study basin, the snow routine was excluded from this analysis. The soil moisture routine represents the storage and movement of water in the soil. It is typically divided into several layers to account for different soil properties and depths. The river routing represents the flow of water through the river network and uses a linear reservoir routing model to simulate the time lag and attenuation of flow. These subroutines are characterized by several parameters that define the catchment's properties (Table 2).

The input data used for the HBV-light model are daily average basin temperature from ERA 5, potential evapotranspiration from WaPOR (monthly climatology), and rainfall from MSWEP v2.8 (selected through validation). Calibration and validation of the model were conducted for the gauged catchments using observed streamflow data provided by the Ethiopian Ministry of Water and Energy (MoWE). The calibration was performed on a daily timescale for varying periods: 2001–2005 for the gauged Gilgel Abbay and Gumara catchments, 2004–2008 for the Ribb catchment, and 2001–2008 for the Megeche catchment. A Monte Carlo-based calibration procedure was applied to calibrate model parameters, with the Nash-Sutcliffe Efficiency (NSE) as the objective function. The optimal parameter set was identified from 10,000 Monte Carlo simulations. The overall model performance was assessed using both the NSE and the coefficient of determination (R^2).

Following the calibration and validation process, the lake inflow from the gauged catchments was simulated for 2010–2020. To estimate lake inflows from ungauged catchments, a spatial proximity regionalization approach was employed, whereby calibrated parameters from gauged catchments were transferred to neighboring ungauged catchments based on geographic proximity (Merz and Blöschl, 2004). This approach was selected because neighboring catchments experience similar hydro-climatic conditions, which strongly control runoff generation and therefore support more reliable parameter transfer than physical-based similarity approach (Dessie et al., 2015). The resulting inflow estimates from both gauged and ungauged catchments were then used as inputs for the LWBM.

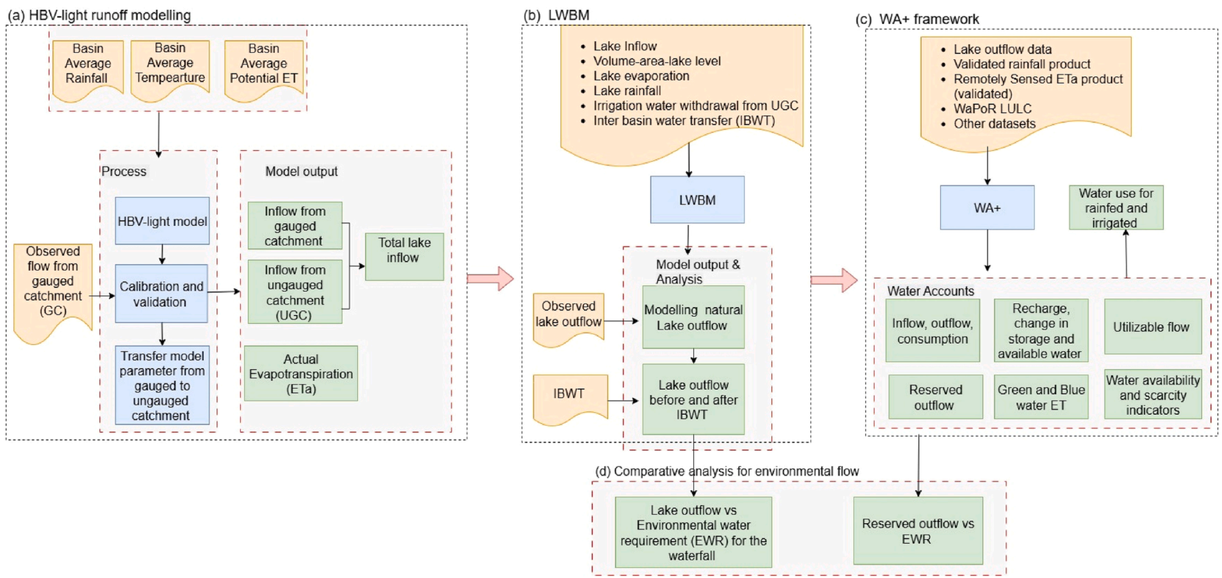

Fig. 2. Workflow illustrating: (a) estimation of lake inflows from both gauged and ungauged catchments using the HBV-Light model; (b) estimation of lake outflows at the natural outlet through LWBM following interbasin water transfer (IBWT); (c) assessment of water accounts for the Lake Tana sub-basin, including water use across rainfed, irrigated, and other land cover types, as well as water availability indicators, using WA+ framework; and (d) comparison of natural lake outflows and reserved outflows (derived from WA+) with the downstream environmental water requirements for the Tis Issat waterfall, estimated before the inter basin water transfer.

Table 2
List of the HBV-light model parameters.

Model parameters	Definition	Minimum	Maximum	Unit
Soil Moisture Routine				
FC	Maximum soil moisture storage	100	1000	mm
LP	Threshold for reduction of evapotranspiration	0.3	1	-
BETA	Shape Coefficient	1	5	-
Response Routine				
PERC	Maximum flow from upper to lower box	0	4	mm/d
UZL	Upper Zone Limit	0	70	
K0	Recession coefficient upper box	0.1	0.5	d^{-1}
K1	Recession coefficient upper box	0.01	0.2	d^{-1}
K2	Recession coefficient lower box	0.00005	0.1	d^{-1}
Routing Routine				
MAXBAS	Routing, transformation of run-off	1	2.5	d^{-1}

3.2. Lake water-balance model

Hydrological models applied in the Lake Tana basin have frequently struggled to accurately estimate the lake's outflow at its natural outlet because they do not explicitly represent lake storage dynamics (Setegn et al., 2011). Accounting for these dynamics is essential, as the storage–outflow relationship regulates seasonal water availability, buffers short-term fluctuations, and influences downstream flow regimes (Dessie et al., 2015). In this study, we employed the LWBM that explicitly incorporates lake storage dynamics to improve the estimation of lake outflow at monthly time step.

The LWBM requires various input datasets, including total lake inflow, lake volume, lake area, lake level, lake evaporation, over-lake rainfall, and inter-basin water transfer. Lake inflows from both gauged and ungauged catchments were estimated using a combination of the HBV-light hydrological model and a regionalization approach (Section 3.1). Lake volume and area were estimated from bathymetric survey data obtained from MoWE. For lake level data, bias-corrected remotely sensed measurements were used due to the absence of continuous in-situ records. Specifically, satellite-derived lake levels from Hydroweb (http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/) were incorporated into the LWBM. To enhance the accuracy of these data, monthly bias corrections were applied using available in-situ lake level measurements from MoWE for the periods 1993–2009 and 2016–2019. The resulting bias-corrected remotely sensed lake level data were then used as inputs for the LWBM for the period 2010–2020.

Lake evaporation was determined using the Penman-combination equation (Maidment, 1993), and lake areal rainfall was estimated from the MSWEP rainfall product. Hourly interbasin water transfer data were collected from the Ethiopian Electric and Power Corporation. We also included irrigation water withdrawals from ungauged catchments in the LWBM. For this purpose, irrigated areas were identified from WaPOR land cover classifications, and irrigation water use estimates was estimated using SSEBop ETa product.

Lake outflow at the natural outlet was modeled using the LWBM with Eqs. 1–5. All water balance terms are expressed in Mm^3 per month.

$$Q_{Nout} + Q_{Hout} = P_{lake} + Q_{Inflow} - E_{lake} - \frac{\Delta S}{\Delta t} \quad (1)$$

$$Q_{out} = Q_{Nout} + Q_{Hout} \quad (2)$$

$$Q_{Inflow} = Q_{Ungauged} + Q_{Gauged} \quad (3)$$

$$\frac{\Delta S}{\Delta t} = P_{lake} + Q_{Ungauged} + Q_{Gauged} - E_{lake} - Q_{Hout} - Q_{Nout} \quad (4)$$

$$\mathrm{V}_{\mathrm{lake(t)}} = \mathrm{V}_{\mathrm{lake(t-1)}} + \frac{\Delta \mathrm{S}}{\Delta \mathrm{t}} \quad (5)$$

Where Q_{out} is the sum of the lake outflow through the natural outlet (Q_{Nout}) and the hydropower outlet (Q_{Hout}), P_{lake} represents the rainfall over the lake,Q_{Inflow} is the sum of the lake inflow from the ungauged catchment ($Q_{Ungauged}$), and gauged catchment (Q_{Gauged}), E_{lake} is the evaporation over the lake, $\frac{\Delta S}{\Delta t}$ is the change in storage over time, which is derived from the bathymetric survey data, $V_{lake(t)}$ is the lake volume at the current time step, *and* $V_{lake(t-1)}$ is the lake volume at the previous time step.

3.3. Water accounting assessment

A Python-based WA+ framework was used to analyze water use across landscapes at a monthly time step and a 100-meter spatial resolution for the period 2010–2020 (Fig. 2). The input data used for this framework is presented in Table 1. Since the WA+ framework requires lake outflow as an input, we used lake outflow data derived from the LWBM. This integration enabled us to estimate several key water accounts for the study basin, including water availability, water consumed by different landscapes, managed water use (water currently used for irrigation and other uses), reserved flows for maintaining ecosystems, and utilizable flow (water available for further use).

The WA+ framework requires land use and land cover (LULC) data to estimate water use across different landscapes. For this purpose, the WaPOR v2.0 LULC dataset was used. To align the dataset with the WA+ classification system, we grouped the WaPOR LULC categories into four broader water management classes: protected land use, utilized land use, modified land use, and managed water use. Definitions of these classes are provided in Table S1. Table 3 presents the distribution of these LULC classes within the Lake Tana sub-basin. Our analysis identified three main water management classes in the study area: modified land use (72.9%), managed water use (23.3%), and utilized land use (3.8%). Rainfed cropland (72.9%), classified as modified land use , is the dominant LULC, followed by water bodies (20.1%).

Moreover, in the WA+ framework, the total actual evapotranspiration (ETa) was further separated into green evapotranspiration (green ET or rainfall ET) and blue evapotranspiration (blue ET or incremental ET) to provide a more nuanced understanding of water use and supply across various landscapes. Green ET represents the portion of precipitation that is used by plants through transpiration and evaporated from soil and plant surfaces – ET primarily driven by rainfall. In contrast, blue ET refers to the evapotranspiration of water sourced from surface and groundwater, typically through irrigation or storage. To ensure the reliability of these data products, we established specific checks and criteria. For example, green ET cannot exceed rainfall. We also confirmed that in natural landscapes like grasslands and shrublands, green ET equals total ET when blue ET is zero. Blue ET is considered to occur when total ET exceeds rainfall based soil moisture. The monthly values for both green ET and blue ET were calculated using Eqs. 6–8.

$$ET_{blue} = \begin{cases} 0, & if(SM_t \geq 0) \\ (SM_t \times -1), & if(SM_t < 0) \end{cases} \tag{6}$$

$$ET_{green} = \begin{cases} ET_a \, if(SM_t > ET_a) \\ ET_a - \quad ET_{blue} \, if(SM_t < ET_a) \end{cases} \tag{7}$$

$$SM_t = \quad SM_{t-1} + (P-I)_t - (ET_a - I)_t - \quad QP_t - \quad QS_r \tag{8}$$

where, SM_{t-1} is soil moisture from the previous month, (P-I) represents the effective precipitation calculated using MSWEP rainfall data and I is the interception losses grid obtained from FAO WaPOR; QP and QS are percolation and surface runoff parameters, respectively; QP is derived as an exponential function of the soil moisture and QS is derived using an adjusted version of the Soil Conservation Service runoff method; subscript r indicates rainfall-based parameter and subscripts t and t–1 indicate current and previous time steps, respectively. The value of SMt will be zero or positive in landscapes where rainfall exceeds the actual evapotranspiration at monthly timestep. In contrast, SMt becomes negative when actual evapotranspiration (ETa) exceeds the available water from rainfall, indicating the presence of additional water sources such as irrigation or groundwater abstraction (blue ET or incremental ET). The key WA+ terminology and water availability indicators utilized in this study are provided in Tables 4 and 5.

3.4. Environmental flow analysis

To evaluate the impact of the inter-basin water transfer on downstream environmental flow, we compared flow conditions across two periods: the pre-transfer period (1999–2009) and the post-transfer period (2010–2020). Monthly environmental flow requirements for the 30-km river reach between Lake Tana's natural outlet and the Tis Issat waterfalls were used as the benchmark. These requirements were previously estimated for the pre-transfer period by Alemayehu et al. (2010) using the Desktop Reserve Model (Hughes and Hannart, 2002).

For the post-transfer assessment, reserved outflow derived from WA+ were compared against the benchmark. Moreover, modeled outflow at the natural outlet was evaluated against the environmental flow requirements after accounting for tributary inflows along the river reach. This comprehensive analysis allowed us to identify specific months when the environmental flow requirements were not met, thereby quantifying the magnitude and timing of the impact of the inter-basin water transfer.

Table 3
Distribution of WaPOR LULC in the Lake Tana basin and the corresponding water management classes required for WA+ .

Water Management Class for WA+	WaPOR LULC	Area (Km2)	Area (%)
Utilized Land use	Shrubland	233.2	1.55
	Grassland	85.8	0.57
	Bare/Sparse Vegetation	4.4	0.03
	Shurb or herbaceous cover, flooded	29.0	0.19
	Tree cover: closed evergreen broadleaved	3.0	0.02
	Tree cover: closed deciduous broadleaved	31.6	0.21
	Tree cover: closed unknown type	4.0	0.03
	Tree cover: open deciduous broadleaved	31.8	0.21
	Tree cover: open unknown	144.9	0.96
Modified Land use	Cropland, rainfed	10992.4	72.90
Managed water use	Water Bodies	3023.6	20.05
	Cropland, irrigated	452.6	3.00
	Built-up	41.6	0.28
Total		15077.8	100.0

Table 4
List of key hydrological variables in the WA+ frameworks.

Water accounts	Definition	Calculation procedure/data used
P	Rainfall	Evaluation of eight gridded rainfall products
Gross Inflow	Total inflow into the basin	P + any additional water sources
Net Inflow	Total inflow minus the change in storage, where ΔS is estimated using Eq. 4.	*Gross Inflow* − ΔS
Incremental ET (ET_{blue})	The actual evaporation from blue water sources (e.g. lakes, streams, reservoirs, deep-root water uptake from groundwater, irrigation water).	Determined based on the soil water balance model using Eq.6
Rainfall ET (ET_{green})	The actual evaporation from green water sources (e.g. precipitation, unsaturated soil).	Eq.7
Total Actual ET (ETa)	The actual evapotranspiration	Selecting an appropriate ETa product
Landscape ET (ET_{land})	The actual evapotranspiration from natural landscapes (not including the MWU class)	Overlay the WA+ water management classes with the ET map and then calculate zonal statistics.
Exploitable water (E_{water})	The amount of water that can potentially be used within the basin	Net Inflow − ET_{land}
Available water	The water that is left after meeting ET and reserve flow requirements	Exploitable - Reserved flows - non-utilizable
Utilized flow (U_{flow})	Incremental ET from managed water uses classes (irrigated crops, managed reservoirs).	ETblue estimated from the managed water use
Reserved outflow (Routflow)	Surface water allocated for navigation and environmental needs. It can be calculated considering the environmental flow requirement fraction (EWRf, Smakhtin et al.,2004) and *mean* Q_{Nout}	EWRf X Q_{Nout}
Utilizable outflow (Uoutflow)	The physical water available for furthers use after satisfying current demand	Ewater – Routflow-Uflow-non utilizable outflow
Non-recoverable flow	Non-consumed water that is lost to further use by pollution	*grey water fraction* × Q_{Nout}
Non-consumed water	Water remaining after consumption	Uoutflow + Routflow + Non utilzable outflow
Consumed water (C_{water})	Water withdrawn from the basin in the form of evaporation and pollution	Landscape ET+ Managed water use
Q_{sw}^{outlet}	The lake outflow at the natural outlet	Estimated by combining the HBV-light model with LWBM
Q_{sw}^{out}	The lake outflow at the hydropower outlet	It was determined from in situ hourly inter-basin water transfer data
Outflow	Total lake outflow	Qswoutlet + Qswout

Table 5
Water availability indicators derived in this study.

Indicators	Description	Formula
Water Yield (mm)	Water that is available after meeting landscape water requirements (landscape ET). This is the amount of water that can be exploited for human needs	$P - ET$
Water Availability Per Capita (m3/per capita)	The amount of freshwater resources available for each person in a specific domain	$\frac{available\ water}{Population}$
Environmental Water Stress (EWS)	It is also known as ecosystem water stress or ecological water stress/scarcity, refers to a situation in which the demand for freshwater by the ecosystems and environment exceeds the available supply of freshwater for a given domain. A value close to 100 indicates extreme pressure on renewable freshwater resources, and very little water is left available in the environment, while a value closer to 0 indicates less pressure on the environment	$\frac{utilized\ flow}{exploitable - reserved\ flow}$
Basin Closure	The total amount of water available that is utilized within a basin. Any basin with estimates closer to 100% indicates basin closure – indicating most to all water availability in the basin is currently consumed within the basin. A smaller value indicates that water is available in the basin.	$\frac{Utilized + Reserved}{Exploitable\ water}$
Evaporative stress index (ESI)	The Evaporative Stress Index (ESI) describes temporal anomalies in evapotranspiration (ET), highlighting areas with anomalously high or low rates of water use across the land surface. PET refers to potential evapotranspiration	$1 - \frac{ET}{PET}$
Beneficial fraction	Beneficial ET: This is the amount of water transpired by plants or evaporated from surfaces that contribute to a productive purpose. In agriculture, this would be the water used by crops for growth. T refers to transpiration	$\frac{T}{ET}$

4. Results

4.1. Observed lake outflow and lake level analysis

Table 6 summarizes the observed lake outflow at the natural outlet (Bahir Dar) for three periods. The average daily outflow was 147.4 m^3/s from 1995 to 2000, before the inter-basin water transfer. This value dropped to 129.3 m^3/s between 2001 and 2009. Following the transfer in 2010, the outflow declined further to 73.1 m^3/s. Overall, a significant decreasing trend ($p < 0.01$) in lake outflow at the natural outlet was observed from 1995 to 2014 as shown in Fig. 3a.

The long-term average inter-basin water transfer was 97.9 m^3/s between 2010 and 2020. The highest transfer occurred in April at

106.5 m^3/s, while the lowest was in September at 85 m^3/s (Fig. 3b). This transfer follows a clear seasonal pattern: peak transfers occur during the dry season (October–March) and lower transfers during the main rainy season (June–September). The lake outflow at the hydropower outlet consistently surpasses the outflow at the natural outlet.

Additionally, lake level measurements derived from remotely sensed data were validated against in-situ observations (Fig. 3c). Although the two datasets showed a high correlation ($r = 0.96$), the remotely sensed lake levels were consistently higher than the in-situ measurements, with average values of 1787.9 m and 1786.7 m, respectively. After applying bias correction, the agreement between remotely sensed and in situ lake level observations improved substantially, with the RMSE reducing from 1.1 m to 0.1 m and the percent bias reduced from 0.1% to 0%. The bias corrected dataset was subsequently used as input to the LWBM.

4.2. Model calibration and validation

We performed 10,000 Monte Carlo simulations to identify optimal parameter sets for each gauged catchment (Fig. 4). The results showed considerable variability in parameter values across catchments, reflecting differences in their hydrological characteristics.

Calibration of the HBV-light model for the four gauged catchments (Megeche, Ribb, Gilgel Abbay, and Gumera) demonstrated reasonable agreement between the observed and simulated discharge (Fig. 5). The time series plots (left panel) reveal that the model effectively captures the flow patterns. However, some discrepancies existed in the magnitude and timing of peak flows across certain years and catchments. The corresponding scatter plots (right panel) further illustrate this relationship, providing additional insight into the model's accuracy. The model demonstrated reasonable performance in explaining the variance in observed data, with Nash-Sutcliffe Efficiency (NSE) values ranging from 0.56 to 0.82 and R^2 values from 0.56 to 0.85. During the calibration period, the model performed better in the Ribb and Gilgel Abbay catchments compared to Megeche and Gumera catchments. Although the Ribb and Gumera catchments have similar drainage areas, differences in rainfall distribution, soil characteristics, land use, evapotranspiration, and groundwater contribution result in different runoff responses. These variations are reflected in the basin-specific HBV calibration parameters (Fig. 4), which produce higher simulated flows in the Gumera catchment compared to the Rib catchment.

During the validation period, the model's performance remained strong, yielding NSE values of 0.54 for Megeche, 0.81 for Ribb, 0.76 for Gumera, and 0.81 for Upper Gilgel Abbay. Following calibration and validation, lake inflows from the gauged and ungauged catchments were simulated, and the results are summarized in Table 7.

4.3. Estimating lake outflow at the natural outlet

Initial simulations of natural lake outflow were performed using the HBV Light model configured at the basin outlet. However, the model failed to adequately reproduce the observed lake outflow (Figure S2), yielding a NSE of –0.29 and an R^2 of 0.20. This poor performance is primarily attributed to the influence of lake storage dynamics, which are not explicitly represented in the HBV-Light model. After coupling the model with the LWBM, the simulation of lake outflow improved substantially. Fig. 6 illustrates the simulated and observed lake outflows at the natural outlet following the interbasin water transfer. The coupled model reproduced the monthly observed outflows from 2011 to 2014 with an NSE of 0.79 and an R^2 of 0.92 (Fig. 6a). The simulated results also indicated that lake outflows in 2016 and 2017 were substantially lower than in other years, corresponding with a significant decline in lake levels (Fig. 6b). The relationship between lake levels and outflow shows a strong non-linear pattern, with outflows increasing exponentially as lake levels rise (Fig. 6c). The fitted exponential relationship ($R^2 = 0.77$) highlights the pronounced sensitivity of lake outflow to variations in lake level.

4.4. Post-transfer lake water balance

Table 7 presents the long-term average lake water balance following the inter-basin water transfer. Lake areal rainfall was estimated at 4148 $Mm^3\ yr^{-1}$, representing direct precipitation over the lake surface. In contrast, lake evaporation, a major loss component, was estimated at 5146 $Mm^3\ yr^{-1}$, indicating that evaporation from the lake exceeds rainfall over the lake. The total lake inflow was estimated to be 6911 $Mm^3\ yr^{-1}$, with 3843 $Mm^3\ yr^{-1}$ from gauged catchments and 3068 $Mm^3\ yr^{-1}$ from ungauged catchments. The Gilgel Abbay catchment contributed the largest inflow (55 %) to Lake Tana, followed by the Gumera and Ribb catchments. In terms of outflow, the water leaving the lake through the hydropower outlet was reported as 3087 $Mm^3\ yr^{-1}$. Additionally, the natural lake outflow at Bahir Dar was estimated as 2663 $Mm^3\ yr^{-1}$. Combined, these components resulted in a total outflow of 5750 $Mm^3\ yr^{-1}$.

The water balance closes with a closure error of 162 Mm^3 (53 mm yr^{-1}), which reflects the residual between the total inflows and the combined total of outflows and evaporation. This error may stem from uncertainties in remote sensing data products (Velpuri et al., 2012), limitations in the model structure (Mekonnen et al., 2022), or groundwater exchange between the lake and surrounding aquifers (Chebud and Melesse, 2009; Kebede et al., 2006). Nevertheless, the relatively small closure error suggests that the water

Table 6
Analysis of observed lake outflow at the natural outlet (at Bahir Dar) before and after the interbasin water transfer (IBWT).

Period	Mean Daily Flow (m^3/s)	Developmental activities on the Lake Tana
1995–2000	147.4	Chara Chara weir was functional in 1996 with two gates- Before IBWT
2001–2009	129.3	5 additional gates were added to the weir- Before IBWT
2010–2014	73.1	The Tana Beles hydropower plant has been operational since 2010-After IBWT

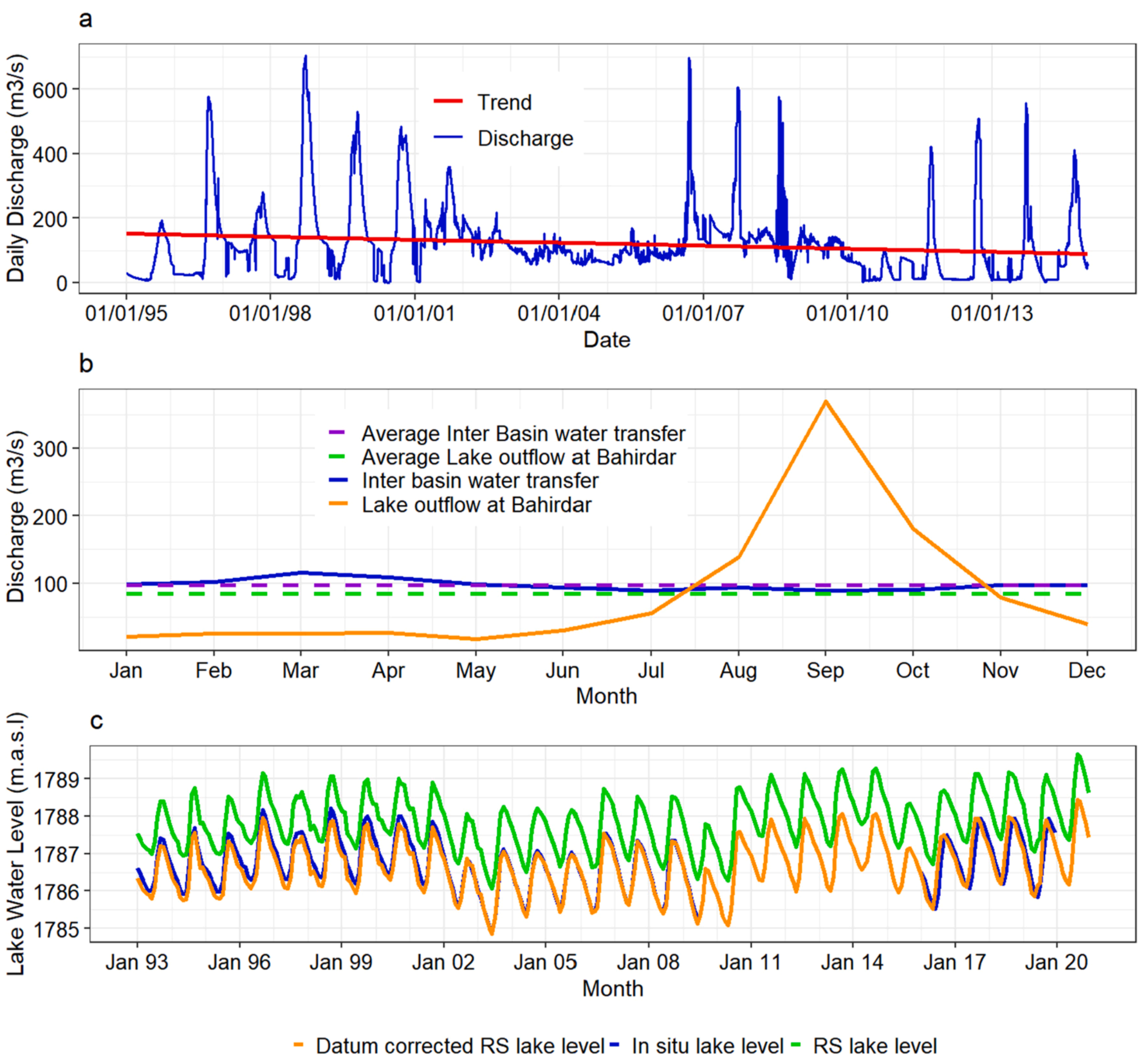

Fig. 3. Daily observed lake outflow at the natural outlet (at Bahir Dar) for the period 1995–2014 (a), long-term average monthly lake outflow at the natural and hydropower outlets after the interbasin water transfer for the period 2010–2014 (b) and lake water level measurements derived from in situ and datum-corrected remotely sensed datasets from 1993 to 2019 (c). Please note that in situ lake water level measurements were unavailable from 2009 to 2016.

balance is well constrained, with minimal discrepancies among the estimated components of the lake's water balance.

4.5. Basin water accounts and availability indicators

Following the lake water balance analysis, the basin water accounts were translated into valuable insights for facilitating informed decisions for effective water management. As indicated in the resource base sheet (Fig. 7), the basin's gross inflow was assessed at 19.4 $km^3\ yr^{-1}$, representing the total water entering the system, primarily rainfall. A significant portion of this inflow, 12.7 $km^3\ yr^{-1}$ (65%), was lost through total evapotranspiration , which includes water used by vegetation, agricultural crops, and natural landscapes. The net inflow was estimated at 18.4 $km^3\ yr^{-1}$ of which 9.4 $km^3\ yr^{-1}$ was consumed through landscape ET, with rainfed agriculture (classified as modified land use) accounting for the largest share at 5.7 $km^3\ yr^{-1}$, and irrigated agriculture contributing 0.4 $km^3\ yr^{-1}$. The remaining portion of the net inflow constitutes the exploitable water, which was approximately 9.0 $km^3\ yr^{-1}$. Of this exploitable water, about 94%, or 8.5 $km^3\ yr^{-1}$, was available for consumption purposes within the basin.

The long-term mean annual utilizable outflow is estimated at 4.5 $km^3\ yr^{-1}$. This value represents the volume of water available for further allocation after meeting all basin demands. This significant amount highlights a high potential for expanding agriculture in the Lake Tana sub-basin. Green and blue water accounts for 68% and 32% of the total evapotranspiration, respectively.

Fig. 8 illustrates the interannual variability of water accounts for the Lake Tana sub-basin over the period 2010–2020, providing a clear picture of the interplay among gross inflows, storage dynamics, and consumptive losses. The analysis reveals that gross inflows,

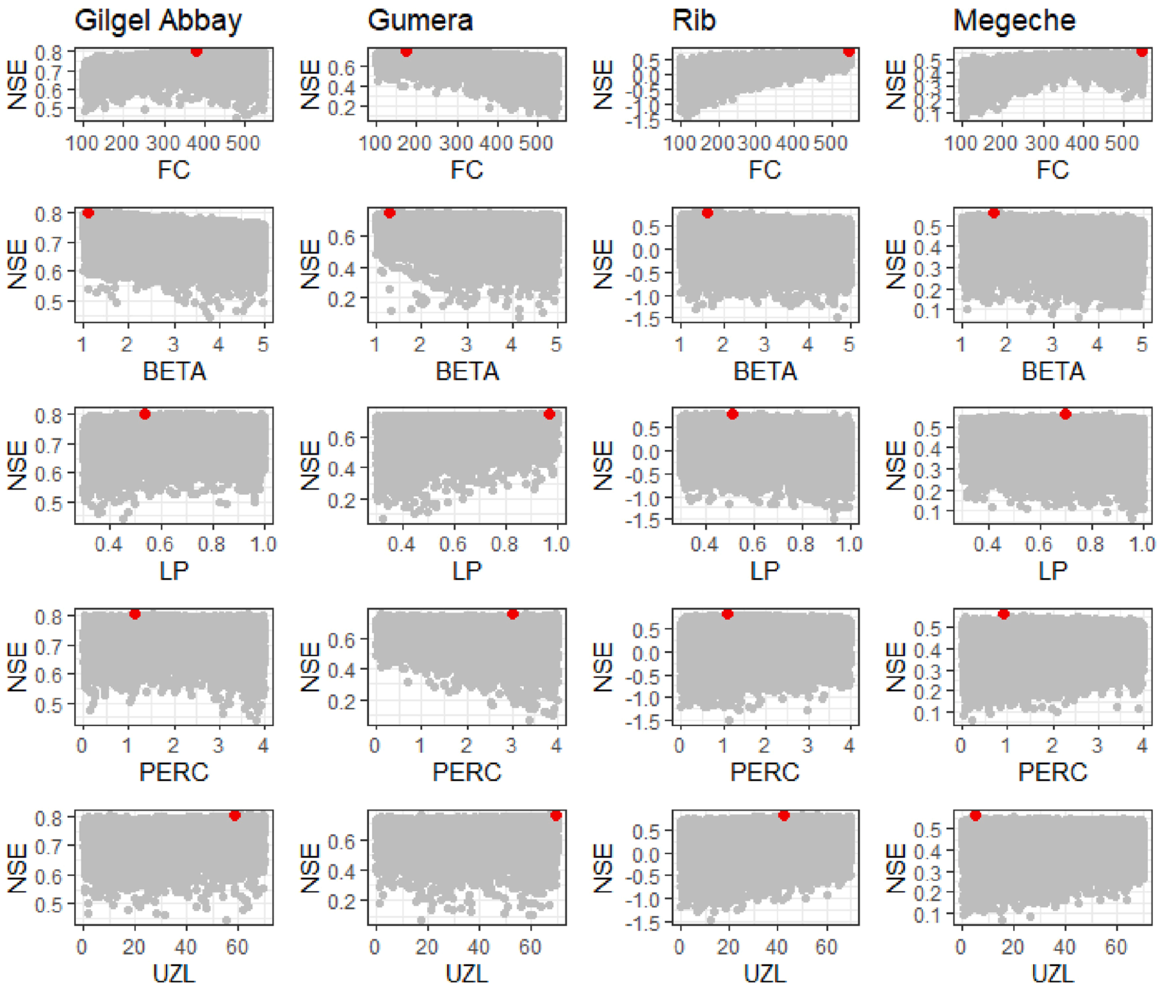

Fig. 4. Parameter identifiability of the HBV-light model for gauged catchments using 10,000 run Monte Carlo simulations, considering NSE as the objective function. Red dots are the optimal model parameter values.

ranges from 17–20 km^3 yr^{-1} , constitute the total water entering the basin primarily through precipitation. Evapotranspiration (ET) stands out as the dominant outflow, with landscape ET alone accounting for approximately 8–10 km^3 annually. Meanwhile, changes in storage hover close to zero, indicating years with modest increases or reductions in water held within lakes and reservoirs, and suggesting that the system has maintained a relatively stable storage balance throughout the decade. These hydrological patterns shape the volume of water effectively available in the basin.

The spatial and temporal variability of water yield, blue ET, and green ET in the Lake Tana sub-basin is presented in Fig. 9. The analysis reveals significant spatial and seasonal variations in water yield and evapotranspiration, driven primarily by the region's distinct wet and dry seasons.

During the main wet season (Kiremt, June to September), abundant rainfall results in high green ET across the sub-basin, reflecting robust water availability (Fig. 9). In contrast, the dry season (October to May) is characterized by pronounced water scarcity, with a substantial decline in green ET due to reduced soil moisture and minimal rainfall. However, blue ET is higher during the dry season, largely due to irrigation practices. The short-wet season (Belg) exhibits moderate levels of both green ET and blue ET, with variations depending on the amount and distribution of rainfall. Spatially, the Gilgel Abbay catchment in the southern part of the sub-basin stands out as the area with the highest water yield and blue ET. Such quantification helps decision-makers better understand total consumptive water use in the study region.

The water availability and scarcity indicator result for the study basin is presented in Fig. 10. Results show that the long-term average water availability per capita in the Lake Tana sub-basin was 3096 m^3 yr^{-1} . This estimate varied over time, with the highest values recorded in September and the lowest in June. Significant variability was observed both from year to year and from month to month. Both environmental water stress and basin closure show significant year-to-year fluctuations rather than a steady increase or decrease over the decade. This suggests that annual climatic variability plays a crucial role in the basin's water status. Environmental water stress appears to be highest in 2010 (~ 60%), 2012 (~58–59%), and 2015 (~ 58%). These years have likely experienced conditions where environmental flows were significantly reduced due to high water abstraction. In contrast, years such as 2011

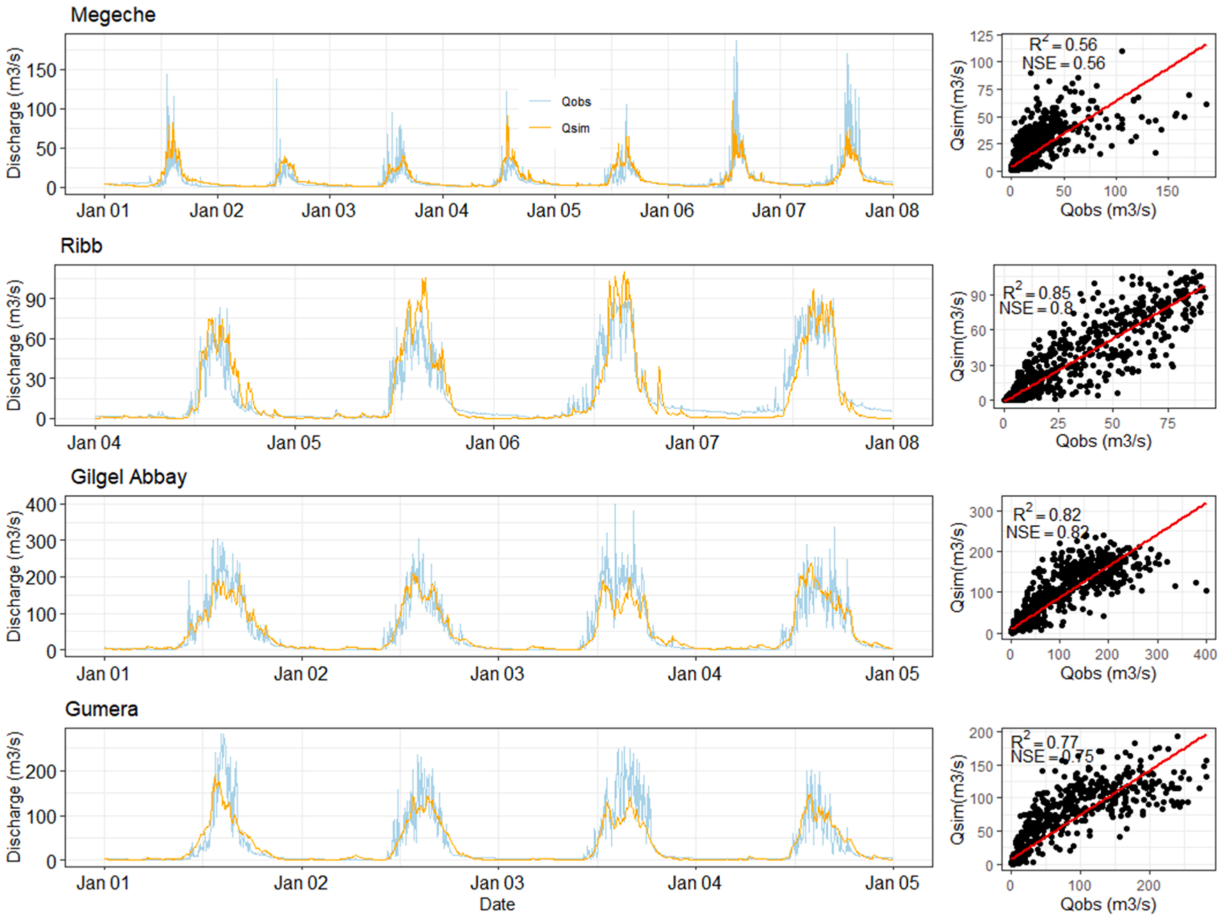

Fig. 5. Model calibration results for the Gilgel Abbay, Ribb, Gumera, and Megeche catchments at a daily timescale. The left panel shows time series plots of observed and simulated discharge, while the right panel displays corresponding scatter plots.

Table 7
Long-term average annual water balance components after the interbasin water transfer.

Water Balance Terms	Long-term average	
	Mm^3	mm
Lake Areal Rainfall	4148	1355
Lake Evaporation	5146	1681
Total Inflow	6911	2257
Lake outflow hydropower outlet	3087	1008
Lake Outflow Bahir Dar	2663	870
Total outflow	5750	1878
Closure error	162	53

(~45%), 2013 (~ 48%), and 2016 (~ 45%) showed lower environmental water stress. Consistent periods of high environmental water stress can lead to degraded aquatic ecosystems, loss of biodiversity, reduced water quality, and impaired ecosystem services.

Like the environmental water stress, basin closure is notably higher in 2010 and 2012 (~55%) and 2015 (~ 53%). In contrast, years such as 2011 (~ 42–43%), 2013 (~ 45%), and 2016 (~ 40%) show lower basin closure percentages. These findings indicate significant water utilization pressure within the basin. Furthermore, there is a clear positive correlation between environmental water stress and basin closure: when basin closure is high, indicating greater water use, environmental water stress also tends to increase. This relationship is expected, as higher human water abstraction reduces water availability for environmental flows, thereby contributing to ecological degradation.

Moreover, the beneficial fraction, a key indicator of plant water use efficiency, is highest in the northern and eastern catchments of the basin (Fig. 11). This suggests that crops and natural vegetation in these regions are utilizing the available water more effectively to support productive transpiration. Such high efficiency may be attributed to targeted irrigation practices, favorable soil properties, or

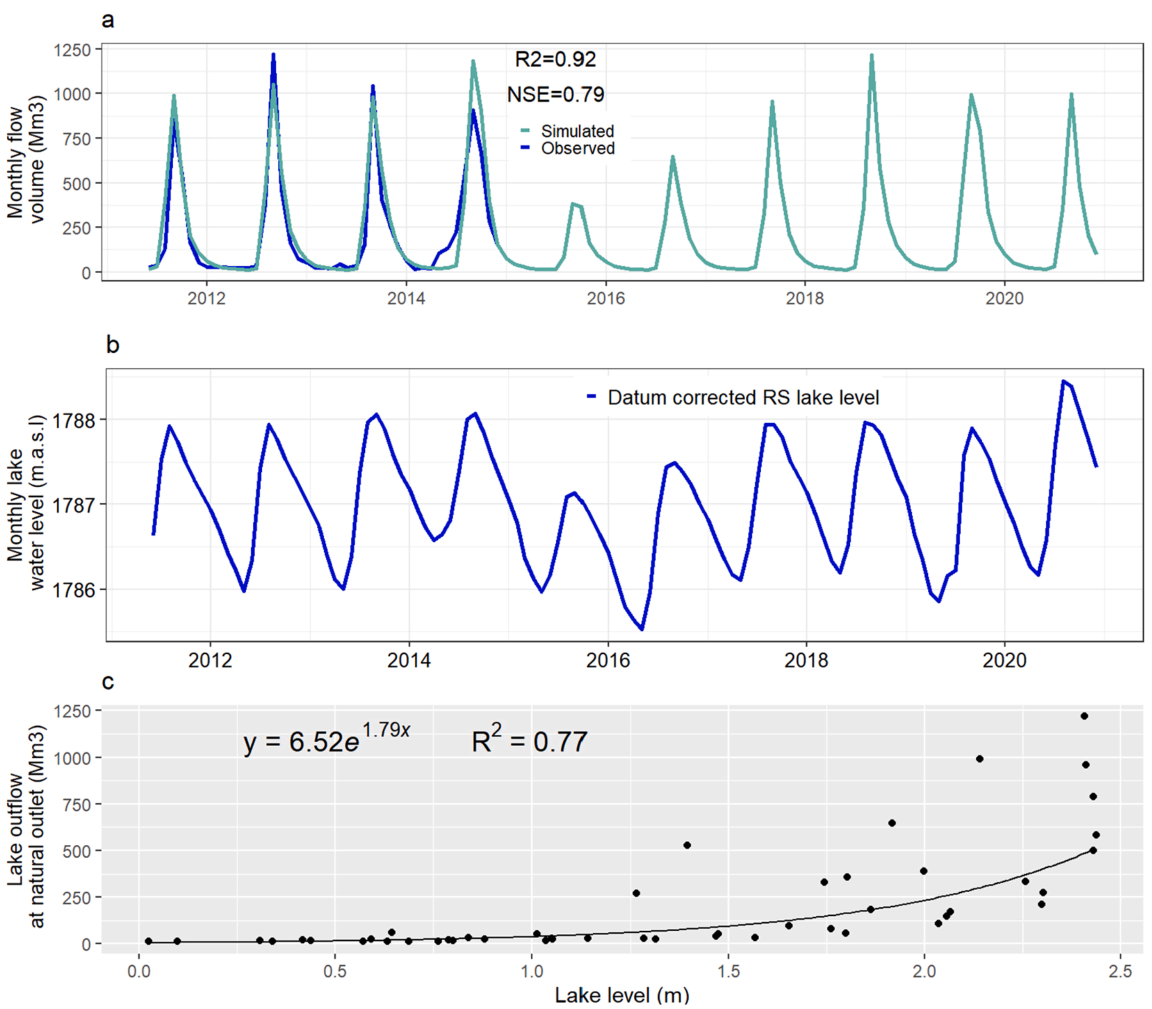

Fig. 6. (a) Observed vs simulated lake outflow at a monthly timescale, (b) datum corrected remotely sensed lake level, and (c) the relation between observed lake level and lake outflow at the natural outlet at monthly timescale.

crop types that are well-adapted to local climatic conditions. However, when considering the evaporative stress index (ESI), a different pattern emerges. The results show that the eastern and northern parts of the basin experience higher levels of water stress compared to the southern regions. This implies that despite their higher water use efficiency, these areas are more vulnerable to periods of limited water availability, which could constrain plant growth and reduce yields during critical stages. In contrast, the southern parts of the basin appear to face lower evaporative stress, benefiting from relatively more stable water supplies. Together, these findings underscore the complex spatial dynamics of water availability and use across the basin, emphasizing the need for tailored water management strategies that address both efficiency and resilience to stress.

4.6. Impact of interbasin water transfer on environmental flows

Fig. 11 presents a comparison between the monthly observed lake outflows and the downstream environmental flow requirements for the 30-kilometer river reach between Lake Tana's natural outlet and the Tis Issat waterfalls. Results from the Desktop Reserve Model suggest that maintaining the Tis Issat waterfalls ecosystem requires an average environmental flow of 0.86 $km^3\ yr^{-1}$ (Alemayehu et al., 2010). While average outflows generally satisfy these requirements across most months, they fall short in December and January (Fig. 11, left panel). This shortfall coincides with the peak tourist season and may negatively impact visitor experience, as the falls are among the most popular tourist attractions in Ethiopia. In addition, reduced flows may also have ecological consequences for riparian vegetation, which warrants further investigation in future studies. From 2010–2020, monthly outflows failed to meet the environmental requirements in 27% of the months, a significant increase compared to only 6% during the 1999–2009 period (Fig. 11, right panel). This increased shortfall is largely driven by the substantial interbasin water transfer from Lake Tana to the Tana-Beles hydropower plant, which reduces the lake's natural outflow and subsequently affects downstream environmental flow requirements. The reserved outflow derived from the WA+ framework was estimated to be 0.6 $km^3\ yr^{-1}$ (Fig. 7), falling

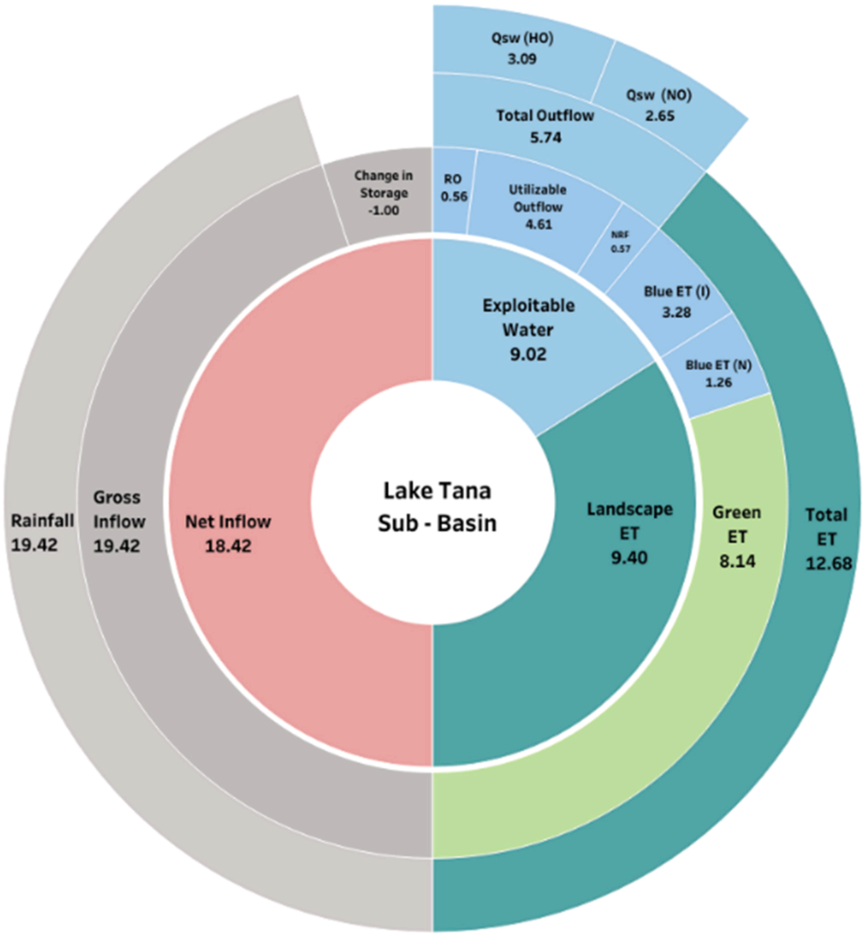

Fig. 7. Sunburst diagram showing the long-term average resource base sheet for the Lake Tana sub-basin (km^3 yr^{-1}) for the period 2010–2020. Qsw (NO) is lake outflow at the natural outlet, and Qsw (HO) is lake outflow at the hydropower outlet.

below the threshold defined by the desktop reserve model and reinforcing the need for more integrated water resource planning. These findings underscore the critical need to balance hydropower demands with environmental flow requirements to ensure the sustainable management of Lake Tana's water resources.

5. Discussion

5.1. Lake water balance vs previous studies

The estimated total lake inflow, evaporation, and aerial rainfall over the lake (Table 8) are consistent with the findings of Dessie et al. (2015). However, some differences are observed in the overall water balance components. The water balance closure in the present study is 53 mm, which is considerably lower than the 82 mm reported by Dessie et al. (2015). In addition, the total lake outflow estimated in this study (5750 Mm^3/year), is slightly higher than the 5023 Mm^3/year reported by Dessie et al. (2015). These differences may partly reflect differences in the representation of the inter-basin transfer in the respective water balance analyses. Dessie et al. (2015) may have used a design transfer discharge value of 77 m^3 s^{-1} , whereas the present study relies on observed hourly diversion records provided by Ethiopian Electric Power Cooperation. Moreover, the analysis periods differ substantially: the present study covers a longer and more recent period (2010–2020), whereas Dessie et al. (2015) focused on 2012–2013. Given the pronounced interannual variability in lake inflow, rainfall, and operational diversion volumes, differences in the study period are likely a key factor contributing to the variation in the estimated water balance components.

As shown in Table 8, notable differences exsist between the water balance components estimated for the pre-transfer period (Gieske and De Vries, 1990; SMEC, 2007; Wale et al., 2009) and those estimated for the post-transfer period (this study and Dessie et al., 2015). The inflow estimates in the present study are in close agreement with those reported by Dessie et al. (2015) and Wale et al. (2009), likely reflecting the use of direct hydrological observations in these analyses. In contrast, earlier studies such as Gieske et al. (2008) and SMEC, (2007) employed stage-discharge rating curves, which may introduce greater uncertainty in inflow estimation due to inherent

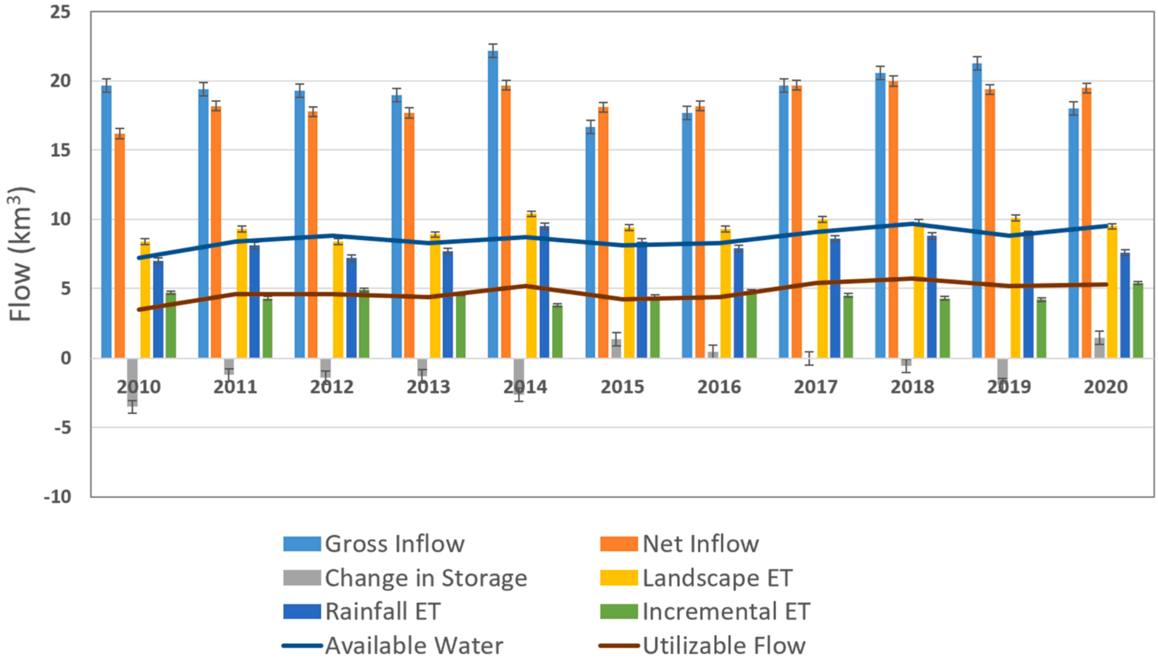

Fig. 8. The inter-annual variability of water accounts for Lake Tana basin for the period 2010–2020. The error bars show the standard deviation range.

limitations in rating curve accuracy (Haile et al.,2023). Furthermore, our results indicate that the interbasin water transfer has substantially reduced the lake's natural outflow at Bahir Dar, potentially affecting the ability to meet downstream environmental flow requirements. While the transferred water provides significant hydropower and irrigation benefits to the Tana–Beles sub-basin (Annys et al., 2019), the diversion reduces the volume of water released through the lake's natural outlet, potentially creating challenges for downstream water management.

As a result of the diversion from the lake to the hydropower plant, the mean annual lake outflow at the natural outlet was reduced from 4.1 km^3 (131 m^3/s) over 1999–2009 to 2.7 km^3 (82 m^3/s) for 2010–2020. Since 2010, an interbasin water transfer has diverted 3.1 km^3 yr^{-1} to the Tana–Beles hydropower scheme. During the same period, discharge through the natural outlet at Bahir Dar averaged 2.7 km^3 yr^{-1} , which was 1.4 km^3 yr^{-1} lower than the 1999–2009 average. As can been seen in Table 8, rainfall over the lake during 2010–2020 was slightly higher than in earlier periods, which may have increased inflows and partially offset the diversion impact. However, further analysis is needed to quantify the relative contribution of these factors and to analyze water balance terms for the pre- and post-transfer periods.

5.2. *Water-availability indicators & management options*

Significant spatial and temporal variability in blue and green water use was observed across the sub-basin (Fig. 9). The southern regions exhibited the highest levels of green ET and water yield, largely driven by relatively high rainfall. Rainfall plays a fundamental role in controlling the partitioning of evapotranspiration into green and blue components. Rainfall replenishes soil moisture and increases the contribution of green evapotranspiration by satisfying part or all of crop water requirements directly from precipitation. During periods of higher or well-distributed rainfall, irrigation demand is reduced, leading to a lower contribution of blue ET derived from surface or groundwater abstractions. In contrast, during dry periods or years with low or poorly distributed rainfall, soil moisture deficits increase and irrigation is required to maintain crop growth, resulting in higher blue ET. The timing, intensity, and effectiveness of rainfall are therefore critical, as intense rainfall events may generate runoff rather than contribute to soil moisture, limiting their effect on green ET. Consequently, seasonal and interannual rainfall variability strongly influences consumptive water use patterns, irrigation dependence, and the relative shares of green and blue ET at both field and basin scales

Irrigation is prevalent in the eastern and southern parts of the basin, as reflected by significantly higher blue ET values in the dry season (Fig. 9). To support sustainable water management under growing pressures from climate change, population growth, and urbanization (Setegn et al., 2011; Taye et al., 2011), integrating green and gray water storage infrastructure is therefore essential in these regions. Such infrastructure can help buffer seasonal variability, improve water availability during dry periods, and enhance overall water security in the basin. Moreover, reliable estimates of water availability indicators are also essential for the planning and implementation of innovative water management technologies across diverse agricultural landscapes. Recognizing this need, the present study quantified various water availability indicators (Fig. 10). The per capita water availability within the basin is estimated to be about 3096 m3 per year (Fig. 10a). According to the Falkenmark water stress index (Falkenmark, 1989), which defines water

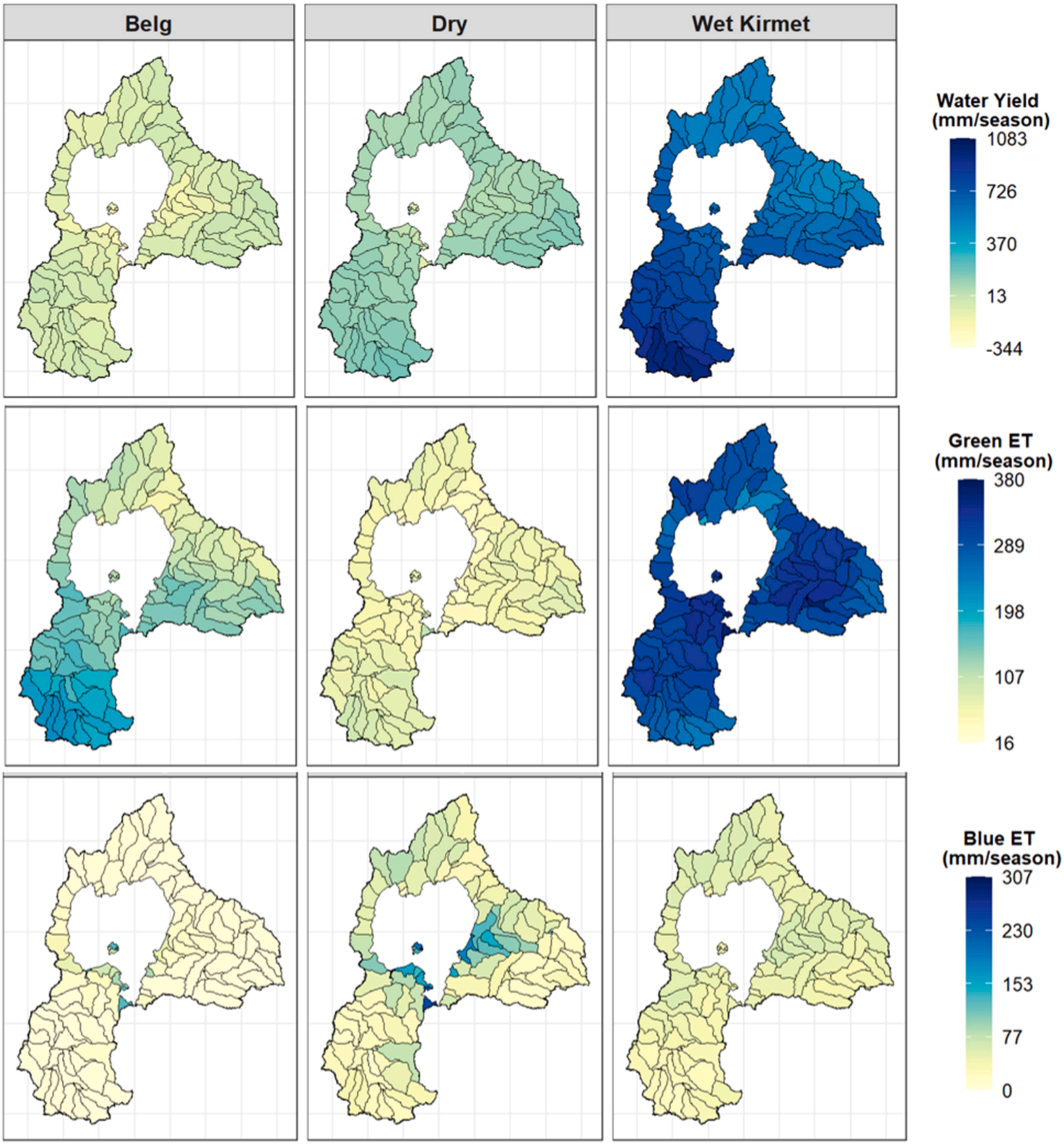

Fig. 9. Spatiotemporal variability of major water fluxes across the Lake Tana sub-basin, illustrating the seasonal distribution of Water Yield, Green Evapotranspiration (green ET), and Blue Evapotranspiration (blue ET) over the land surface.

stress as below 1700 m^3/person/year, water scarcity as below 1000 m^3/person/year, and absolute scarcity as below 500 m^3/person/year, the basin is not classified as water-stressed, as the estimated value exceeds the 1700 m^3 threshold. Furthermore, the sub-basin's per capita water availability is significantly higher than the national average of 1162 m^3/year, as reported by USAID/USAID/Sustainable Water Partnership (SWP) (2021).

5.3. Balancing hydropower, irrigation and ecosystem needs

Balancing the competing demands of hydropower, irrigation, and ecosystem sustainability presents an increasingly complex challenge in many river basins (McCartney et al., 2010), where limited water resources often result in trade-offs. In the Lake Tana sub-basin, the interbasin water transfer has resulted in unmet downstream environmental flow requirements during certain months, as a substantial portion of water is diverted to the Tana-Beles hydropower scheme, reducing natural lake outflows. However, coordinated reservoir operation at the basin scale may offer opportunities to better balance competing water demands. For example, the future

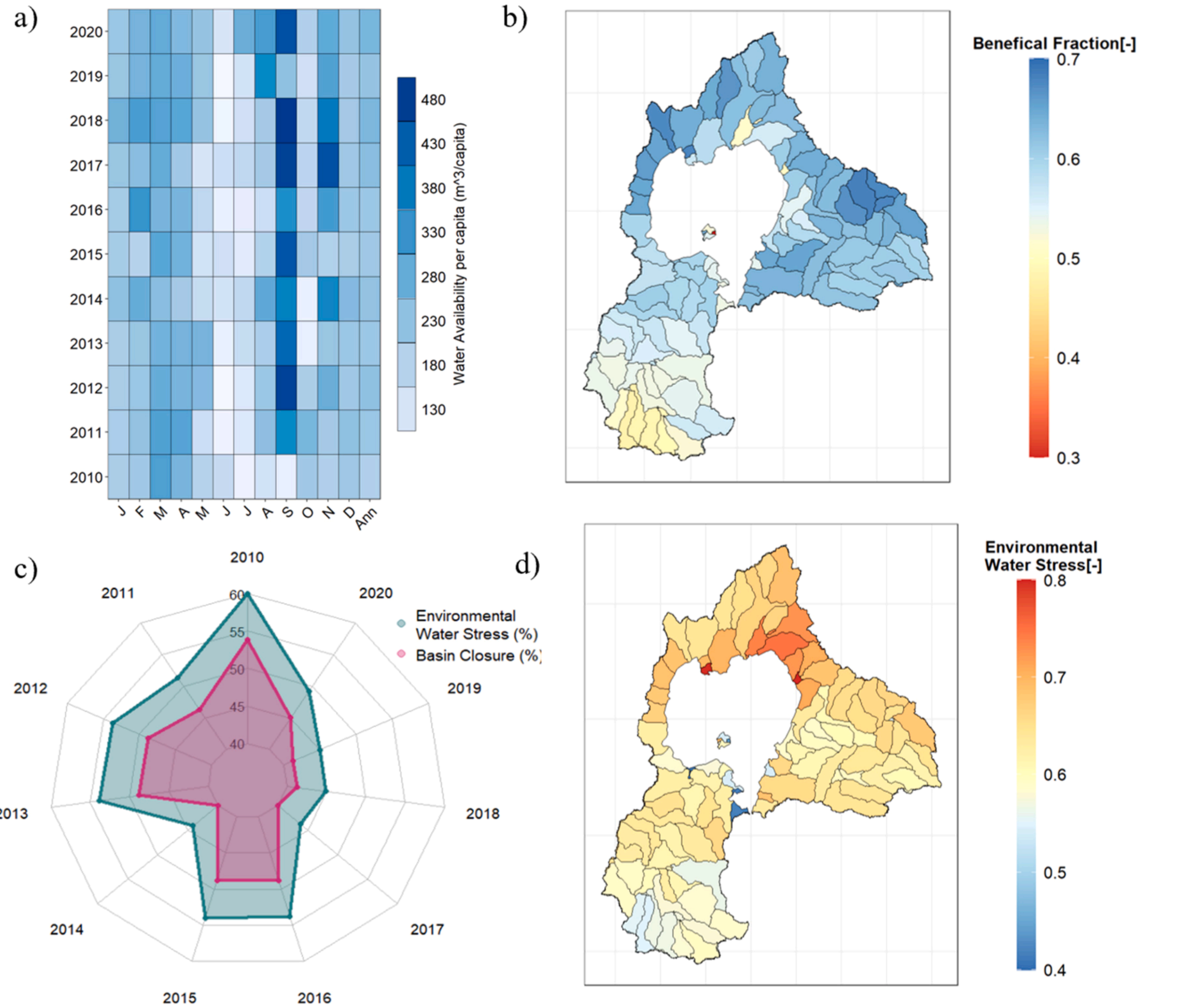

Fig. 10. Water availability indicators: A) Water availability per capita at monthly timescale for 2010–2020, B) long-term average beneficial fraction, C) environmental water stress and basin closure for 2010–2020 and D) long-term average Evaporative Stress Index (ESI).

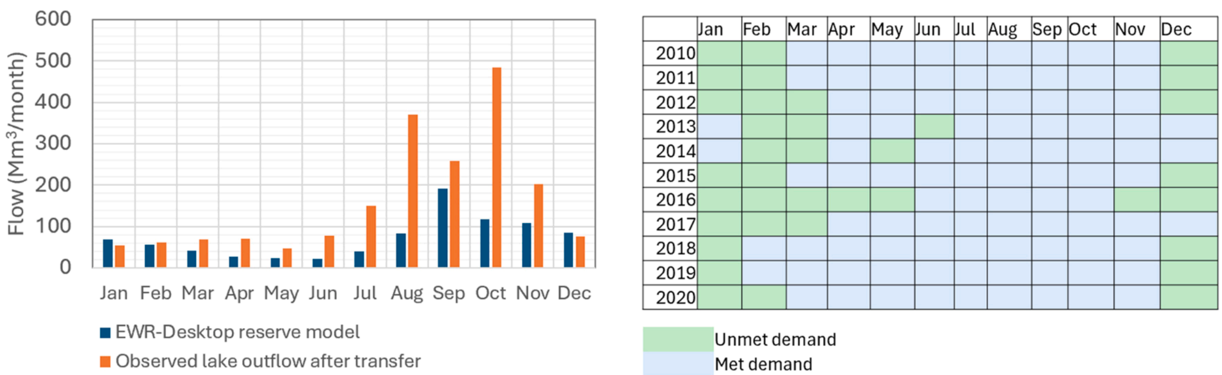

Fig. 11. Comparison of lake outflow at the natural outlet with the downstream environmental flow requirements (EWR) from Lake Tana at natural outlet (Bahirdar) to Tiss Issat Falls, derived from the desktop reserve model (Alemayehu et al., 2010) (left), and assessment of periods when EWR demand is met or unmet (right).

Table 8
Comparison of the Lake Tana water balance terms estimated by the present and previous studies.

	This paper*		Dessie et al. (2015)*		Gieske et al.(2008)**		Wale et al.(2009)**		SMEC, (2007)**	
	(2010–2020)		(2012–2013)		(1992–2003)		(1992–2003)		(1960–1995)	
Water Balance Terms	Mm^3	mm	Mm^3	mm	Mm^3	mm	Mm^3	mm	Mm^3	mm
Lake Areal Rainfall	4148	1355	4129	1331	3891	1255	3784	1220	3906	1206
Lake Evaporation	5146	1681	5547	1789	5180	1671	5242	1690	5115	1650
Total Inflow	6911	2257	6892	2201	5487	1770	6699	2160	5028	1622
Interbasin water transfer	3087	1008	-	-	-	-	-	-	-	-
Natural lake outflow	2663	870	-	-	4179	1348	4714	1520	3816	1231
Total outflow	5750	1878	5023	1480	4179	1348	4714	1520	3816	1231
Closure term	162	53	256	82	19	6	-527	170	1	-

* After the inter-basin water transfer (after the operation of hydropower plant)
** Before the inter-basin water transfer

operation of the Grand Ethiopian Renaissance Dam (GERD) could potentially reduce reliance on interbasin transfers to the Tana–Beles hydropower scheme. Although this scenario was not explicitly evaluated in the present study, such coordinated management could lessen pressure on ecological flows downstream of Lake Tana's natural outlet. In turn, this may support improved aquatic ecosystem functioning and contribute to more sustainable regional water resource management. Moreover, improved regulation of flows at the Chara Chara weir could contribute to meeting minimum ecological flow requirements downstream. Ecosystem health depends heavily on maintaining adequate environmental flows in terms of volume, timing, and quality of water needed to sustain aquatic ecosystems (Mulatu et al., 2024; Zhang et al., 2024). Yet in many regions, especially arid and semi-arid areas, ecological needs are often deprioritized in favor of agriculture and domestic water use. Our findings highlight the need for policy frameworks that safeguard ecological water requirements, ensuring that environmental services. Achieving a sustainable balance requires coordinated planning across sectors, strong governance, and a recognition of the interconnectedness of water, energy, and ecosystem systems. In addition, sediment concentration should also be considered, as sedimentation has significantly altered river morphology and can further influence ecological conditions and flow regimes (Lemma et al., 2017).

5.4. Uncertainties and limitations

The findings of this study may be limited by the unavailability of recent bathymetric data for Lake Tana. Without up-to-date bathymetric surveys, there may be uncertainties in estimating the lake's storage capacity and understanding how changes in water levels affect the lake's hydrological balance. Moreover, the uncertainty of input remotely sensed datasets may limit the findings of this study.

6. Summary and conclusion

We applied an integrated modeling framework that couples a hydrological model, a lake water balance model, and the Water Accounting Plus (WA+) framework to generate water accounts for the Lake Tana sub-basin by integrating both in situ and remotely sensed datasets. Lake inflows from gauged and ungauged catchments were estimated using the HBV-light model, combined with a regionalization approach. The lake outflow at the natural outlet to the Blue Nile River was modeled using a lake water balance model, while the reported lake outflow data at the hydropower outlet (interbasin transfer) were used directly in the analysis. WA+ was coupled with the outputs of HBV-light and LWBM models to estimate water use across different landscapes for the period 2010–2020. The key findings of this study are as follows:

- The lake water balance model performs well in reproducing the observed monthly lake outflow at the natural outlet, achieving an NSE of 0.79 and an R^2 of 0.92. The resulting simulated lake outflow data provides valuable input for a wide range of hydrological analyses and applications as lake outflow data at the natural outlet has been unavailable since 2014.
- The water balance closes with a residual of 0.16 km^3 yr^{-1} . Mean annual inflow to the lake totals 6.9 km^3 , precipitation over the lake is 4.1 km^3 , and evaporation accounts for 5.1 km^3 . Since 2010, the Tana–Beles diversion conveys 3.1 km^3 yr^{-1} to the hydropower plant, exceeding the current 2.7 km^3 yr^{-1} that exits via the natural outlet and reducing natural outflow by about 1.4 km^3 yr^{-1} relative to the 1999–2009 average.
- The interbasin water transfer from the lake to the hydropower plant has significantly reduced the lake outflow at the natural outlet, adversely affecting downstream environmental flow requirements between the lake at the natural outlet and Tis Issat waterfalls. As a result, environmental flow requirements for the waterfall were not met in 27% of the months during the post-transfer period (2010–2020), compared to 6% during the pre-transfer period (1999–2009).
- The water accounts for the basin varies in space and time. The southern part of the basin (Gilgel Abbay catchment) produces the highest green ET and water yield. The eastern and northern parts of the basin are relatively water stressed compared to the southern part of the basin

- The Lake Tana basin is not water-stressed, with an average per capita water availability of 3096 m^3 /yr. Rainfed cropland consumes 5.7 km^3 yr^{-1} , while current irrigation uses only 0.4 km^3 yr^{-1} . The utilizable outflow is estimated at 4.5 km^3 per year, available for sustainable irrigation expansion.

Overall, this study offers valuable insights into sustainable water management in the Lake Tana sub-basin. The water balance analysis reveals that the inter-basin water transfer to the hydropower plant reduces the lake's natural outflow and increases the risk of failing to meet downstream environmental flow requirements. Identifying an optimal balance between environmental flow and inter-basin water transfer for hydropower production therefore remains an important area for future research. Additionally, the potential impacts of climate change on key lake water balance components should be considered in future studies to ensure the long-term sustainability of water resources in the basin.

CRediT authorship contribution statement

Kirubel Mekonnen: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Naga Manohar Velpuri:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Mansoor Leh:** Writing – review & editing, Supervision, Conceptualization. **Komlavi Akpoti:** Writing – review & editing, Software, Methodology. **Afua Owusu:** Writing – review & editing. **Smaranika Mahapatra:** Writing – review & editing. **Primrose Tinonetsana:** Writing – review & editing. **Lahiru Madushanka:** Writing – review & editing, Software. **Tharindu Perera:** Software. **Hailay Zeray Tedla:** Writing – review & editing. **Mamaru Talema:** Data curation. **Abdulkarim Seid:** Writing – review & editing, Resources.

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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2026.103318.

Data availability

Data will be made available on request.

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