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Hydro Systems Analysis of Tana Basin for the Lake Ecosystem Resilience

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Abstracts

Lake Tana Basin (LTB), part of the Afro-Tropical wetland system, is Ethiopia's primary freshwater resource, providing significant socioeconomic, ecological, and religious benefits to the community. However, the region is facing major ecological and social changes due to soil degradation and shifts in water resource supply, demand, and quality. There is a lack of coordinated efforts to regulate land and water use by the government and NGOs, leading to competing interests. This study assessed stakeholder perspectives on upstream and downstream relations using both qualitative and quantitative methods. Water balance analysis revealed that Lake Tana has a storage capacity of 29.175 BCM, with 65% as dead storage. Around 50% of the basin's water is lost to evaporation, and 36% of annual inflow (3,740 MCM) is discharged. The environmental flow over the Chara-Chara weir is 9.6% of the annual inflow, while 898.4 MCM is used for irrigation and 3,310.8 MCM (33%) for hydropower. The lake's estimated residence time is 2.8 years, with depth variations from 1.5 to 3.0 meters.

Keywords: LTB, Water balance, water quality, lake volume, irrigation, hydropower

1.Introduction

Water and energy resources are interlinked, as water is essential for energy production and vice versa. Inefficient management of either can exacerbate shortages of the other. Upstream water withdrawals and operating policies affect downstream availability, creating conflicts between reservoir objectives during extreme conditions (Swain, 2008). Setting operational policies can balance upstream activities and maintain discharge for downstream needs like navigation, tourism, and fishing (Giuliani et al., 2014; Giuliani *et al.*, 2014). The Lake Tana basin, part of

Ethiopia's Upper Blue Nile, has been a focus of irrigation and hydropower development since the 1930s. Projects like Tis Isat I & II and Tana Beles Tunnel are operational, while large dams such as Rib, Megech, and Mugechit are under construction (Studio Peterngeli, 1990; BCEOM & Associates, 1999; Geremew, 2020). Competition for water among agriculture, hydropower, navigation, and tourism is intensifying, driven by growing energy and food demands. Balancing water storage in wet seasons for dry-season agriculture and hydropower needs poses a critical challenge, requiring trade-offs between sectors.

Studies on the Lake Tana basin reveal increased water management challenges with growing development and population demands. Addressing these challenges requires reservoir operation rules based on the basin's water balance, despite complexities in measuring parameters across sub-basins. Estimating lake inflows from gauged and ungauged watersheds remains a key challenge, tackled by models like the HBV (Wale, 2008) and regionalization methods (Studio Pietrangeli, 1990). Annual inflow estimates vary, with figures ranging from 9,380 to 10,452 MCM (Wale, 2008, Tekleab *et al.*, 2011). Research on the impact of current and future upstream irrigation withdrawals in the Lake Tana basin is limited but essential to understanding changes in inflow, lake levels, and outflows. This study analyzes the lake's water balance and level variations under different irrigation scenarios.

2. Materials And Methods

2.1 Descriptions of the study area

Lake Tana is located at the Northwest of Ethiopia adjacent to Bahir Dar City at the coordinates of 11°36′ N, 37° 23′ E (Figure 1). It occupies a wide depression in the Ethiopian western plateau and was formed by volcanic blocking of the Blue Nile, probably in the early Pleistocene period (Mesfin, 1972).

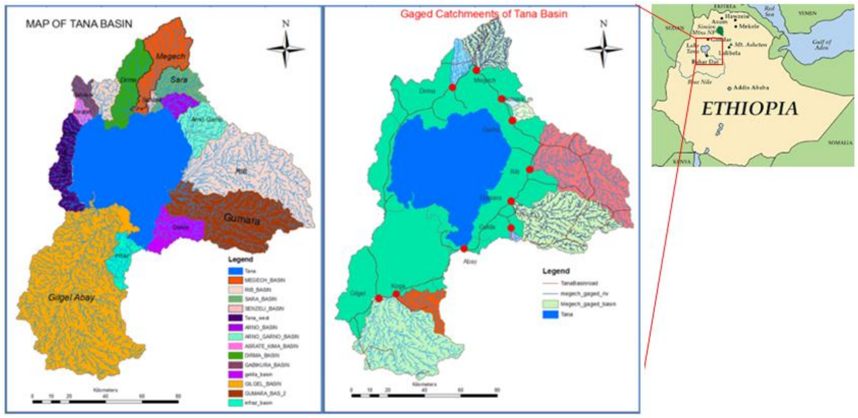

Figure 1. Location map of LTB and the sub-watersheds

2.2 Method and software used in the study

a) Literature review

Lake Tana watershed is the most researched and studied area (Aynalem *et al.*, 2017) where extensive numbers of literature and project reports are available. Under this phase, more than 90 relevant project reports, empirical studies and databases were reviewed and synthesized. Analysis focused on impacts, challenges, and risks to future water use and resilience.

b) ArcGIS, WATBAL and AutoCAD civil 3D Models

We have intensively used these models for our study to accomplish spatial and non-spatial analysis. AutoCAD civil 3D was used for lake elevation - volume analysis for the updated lake level information.

2.3 Basin Data Availability

2.3.1 Climate data

There are 36 meteorological stations in and around the Tana basin, where 26 located within the basin and the remaining outside. 32 stations were used for rainfall-runoff analysis, with rainfall data being the most heavily relied upon. Missing data were estimated using a method from the U.S. Environmental Data Service(Walker, 2001), either through arithmetic averages or a normal-ratio approach (Linsely R.K *et al.*, 1982). Rainfall data profiles for 5 major meteorological stations are summarized in Table 1.

Table 1. Profiles of major stations in the Tana basin (MoWIE, 2011).

No	Station	Station	No of years >50%	Data	Remark

Name	profile	missing	Adopted
Bahir Dar	1961-2010	*	1976-2010
Gondar	1952-2010	6	1980-2010
Debre Tabor	1951-2010	3	1976-2010
Dangila	1954-2010	7	1993-2010

**3 months missing during the 1991 war.*

2.3.2 Hydrometric data

This study was delinated the gauged portion of the Tana basin, covering 5,881.94 km² (38.99% of the catchment). Rainfall-runoff simulations utilized data from 11 hydrometric stations, including lake level measurements. Bahir Dar station data, with records since 1964, was preferred for analysis due to its long history and data quality. As an open lake, outflow data was collected at the Abbay River near Bahir Dar. Bathymetric surveys, conducted in 1937, 1990, 2007, and 2011, assessed sedimentation (Morandini et al., 1940, Studio Peterngeli1990, Kaba *et al.*, 2014). Details of key hydrometric stations are summarized in Table 2.

Table 2. River flow and lake level monitoring stations in Tana basin (MoWIE, 2011).

No	Station Name	Station profile	>50% missing years	Data Adopted	Remark
1	Abay Bahir Dar	1973-2010	1	1973-2010	Outflow
2	Gilgel Abay	1973-2010	1	1973-2010	Inflow
3	Rib	1959-2010	6	1978-2010	“
4	Gumara	1975-2010	2	1992-2010	“
5	Megech	1980-2010	3	1980-2010	“
6	Dirma	1997-2010	2	1997-2010	“
7	Gelda	1985-2010	1	1985-2010	“
8	Kilty	1973-2010	3	1990-2010	“
9	Gumara-Maksegnit	1985-2010	3	1985-2010	“
10	Garno	1987-2010	2	1987-2010	“
11	Tana Lake Level	1959-2010	4	1980-2010	level

2.4 Selections of major catchments for analysis

Coordinate points were collected by hand GPS at each inlet point into the lake for 18 selected sub-catchments including established gauging stations in the basin (Figure 1). All watersheds were delineated using 30m x 30m resolution SRTM data and ArcGIS-SWAT software model. Watershed areas and other proximity aerial parameters were also computed for further processing.

As shown in Table 3, four major rivers namely Gilgel Abay, Rib, Gumara and Megech constituted 56.95% of the total basin area and 70.91% of the land drainage area (when lake area is excluded). Lake Tana's surface area accounts for 20% of the watershed (3,040 km²), while the total basin area is 6,489 km² gauged (43%) and 5,557 km² ungauged (37%). Despite being Ethiopia's largest lake, covering over 50% of the nation's lake area, it has the country's lowest drainage ratio (CA:LA ≈ 4).

Table 3. Area proportion of gauged & ungauged Tana sub-basins

No	**Sub-basin Name**	**Gauged Area (Km^2)**	**Ungauged Area (Km^2)**	**Total Area (Km^2)**	**Area (%)**
1	Rib	1,592.00	419.79	2,011.79	13.34
2	Gumara	1,394.00	247.53	1,641.53	10.88
3	Gelda+	32.00	405.48	437.48	2.90
4	Koga	244.00	-	244.00	1.62
5	Dek+	-	28.43	28.43	0.19
6	Gilgel Abay	1,664.00	1,698.24	3,362.24	22.29
7	Kilty	606.60	-	606.60	4.02
8	Infraze+	-	307.64	307.64	2.04
9	Tana_west+	-	511.33	511.33	3.39
10	Megech	514.74	209.93	724.67	4.80
11	Sara-Gumara	174.00	252.33	426.33	2.83
12	Dirma	173.20	400.53	573.73	3.80
13	Abagenen	-	417.35	417.35	2.77
14	Asrate-delgi+	-	94.04	94.04	0.62
15	Arno-Garno	94.00	564.49	658.49	4.37
16	Lake Tana	-	-	3,039.87	20.15
	Total	6,488.54	5,557.11	15,085.52	100.00
	Percent	43.01	36.84	20.15*	100.00

*** Lake area %*

2.5 Simulation of runoff from ungauged catchments

Runoff from ungauged catchments was estimated using regionalization, parameter transfer from neighboring catchments, and previous modeling methods like HBV, SCS, and regionalization (Merz and Blöschl, 2004, Strzepek *et al.*, 1999, Yates, 1996). These approaches linked catchment characteristics to model parameters for runoff simulation. Various studies have applied these models to estimate ungauged catchment contributions to Lake Tana inflow (Wale, 2008, Melkamu, 2005, Pietrangeli, 1990). The monthly water balance (WATBAL) model was found to be practical for simulating runoff in 15 ungauged sub-watersheds, as it improves conclusions about watershed responses (Strzepek *et al.*, 1999). The model effectively estimates potential evapotranspiration in rainfall-runoff simulations and is widely accepted for basin runoff estimation using physically sound assumptions (Yates, 1996). It operates on mass balance systems within the soil moisture zone (Yates, 1996).

$$S_{max}\frac{dz}{dt} = P_{eff}[1-\beta] - R_s - R_{ss} - E_v - R_b$$

Where S_{max} stands for maximum catchment water-holding capacity, Rd represents direct runoff , Rs indicates the surface runoff, R_{SS} is the sub-surface runoff, R_b base flow, E_v is evaporation and P_{eff} is effective rainfall.

2.6 Calibration and Validation of Model Parameters

Observed runoff data from selected hydrometric stations were split into two-thirds for calibration and one-third for validation. The WatBal model was used for rainfall-runoff simulation, calibrating parameters such as alpha (α), epsilon (ε), and the ratio of actual to potential evaporation (z), with other parameters calibrated manually. Model performance was evaluated using R², Nash-Sutcliffe (NS), and Relative Volume Error (RVE) (Moriasi et al., 2012).

3. Results and Discussion

3.1 Calibration and validation Result

As shown in Table 4, The Gumara Maksegnit catchment failed to meet NS and RVE model performance criteria, excluding its parameters from rainfall-runoff simulations for ungauged watersheds. NS values of 0.6–0.8, 0.8–0.9, and 0.9–1 indicate reasonable, very good, and excellent performance (Nash and Sutcliff, 1970), while an RVE of 0 is ideal, with ±5% considered good and ±10% reasonable (Janssen and Heuberger, 1995). Calibrated parameters were used to estimate runoff for ungauged areas based on proximity. Parameters from gauged upstream catchments were assigned to downstream ungauged ones, while ungauged areas without simulations used nearby gauged catchment parameters (Wale, 2008) (Table 5).

Table 4. calibration and validation results of six major gauged basins

No	Name of Basin	Values of Calibration objective functions			Calibration period	Values of Validation objective functions			Validation period
		RVE	NS	R2		RVE	NS	R2	
1	Rib	-0.003	0.80	0.87	1976-1999	-0.97	0.68	0.88	2000-2007
2	Gilgel A.	-2.22	0.88	0.91	1993-2002	-8.41	0.85	0.87	2003-2007
3	Gumara	4.93	0.77	0.83	1976-1997	-5.5	0.50	0.84	2001-2005
4	Megech	7.74	0.81	0.80	1980-1999	-8.23	0.71	0.88	2000-2005

5	GumaraMaks	**-29.01**	**0.30**	0.79	1985-1999	**-48.72**	**0.19**	0.62	2000-2005
6	Dirma	-5.82	0.68	0.84	1980-1993	-12.5	0.77	0.92	1994-2004

Table 5. Calibrated parameters used for ungauged catchments

No	Basin Name	(γ)**	(ε)	(bf)	(α)	(β)	Remark
1	Rib	1.85	1.64	0.09	0.65	0.24	NE ,E
2	Gilgel	2.00	1.56	0.28	2.62	0.42	S
3	Gumara	2.00	1.15	0.23	0.16	0.63	E
4	Megech	1.80	0.18	1.71	2.56	0.01	N, NW
5	Dirma	2.00	3.60	0.04	2.50	0.02	W,SW

** Subsurface runoff parameter (γ), Surface runoff (ε), Base flow parameter (bf), Subsurface runoff parameter (α), Direct runoff parameter (β), *N=parameter used for ungauged watersheds drained from North, E=from East, S=from South, W=from West*

3.2 State of Water Resources in LTB

3.1.1 Water Balance inputs

a) Rainfall

The watershed's mean annual rainfall ranges from 800 to 1957 mm, with the highest rainfall (1957 mm) in the west, 1398 mm in the southeast, lower precipitation in the west (807 mm) and north (1134 mm), and Lake Tana receiving 1000–1375 mm annually (IFAD, 2007; Shimeles et al., 2008).

b) Evaporation and inflow into the Lake

The average evaporation from Lake Tana and nearby water bodies ranges between 1478 mm (Kebede et al., 2005) and 1690 mm (Wale, 2008). From October to June, evaporation exceeds rainfall, causing many inflowing streams to dry up. Accordig to this study annual evaporation volumes of 5133.28, 17.55, and 0.84 MCM were found for Tana, Koga, and Angereb water surfaces, totaling approximately to 5152 MCM/year (1670 mm). This value is lower than estimates by Wale (5242 MCM), Giezke (5180 MCM), and Studio Pietrangeli (6000 MCM. Over 40 years, the highest inflowing discharge into Lake Tana was 412 m^3/s (1964), the lowest 218 m^3/s (1972). Annual inflow, including rainfall, was 378.8 m^3/s (10,391.13 MCM) (Table 6), corresponding to a lake level of 1787.15 m asl, with a 0.02% deviation from actual levels. Gilgel Abay, Gumara, Rib, and Megech Rivers contribute 46% (165 m^3/s or 4,780 MCM), while direct rainfall accounts for 34.9% and other watersheds 19%. Annual outflow via the Abay River is about 36% (3,700 MCM) of total inflow (Teshale, 2003).

Table 6. Tana basin annual inflows (MCM) into the Lake

No	Basin name	Gauged	Un-gauged	Total Inflow	Percentage Inflows
1	Rib	448.74	94.21	542.95	5.23
2	Gumara	1,164.68	123.18	1,287.86	12.39
3	Gelda	45.07	245.17	290.24	2.79
4	Koga	164.42	0.19	164.61	1.58
5	Dek	-	19.36	19.36	0.19
6	Gilgel Abay	1,735.85	955.06	2,690.91	25.90
7	Kilty	283.80	-	283.80	2.73
8	Infraze	-	197.85	197.85	1.90
9	Tana_west	-	299.49	299.49	2.88
10	Megech	190.59	67.21	257.80	2.48
11	Sara-Gumara	39.41	104.36	143.77	1.38
12	Dirma	116.17	140.63	256.80	2.47
13	Abagene	-	119.68	119.68	1.15
14	Asrate-Delgi	-	26.80	26.80	0.26
15	Arno-Garno	23.60	154.61	178.21	1.72
16	Lake Tana	-	3,630.99	3,630.99	34.94
	Total	4,212.33	6,178.80	10,391.13	100.00

*MCM= Million Cubic Meter

c) Groundwater recharge and Environmental flows

Drilling data revealed that up to 80 m of stiff clay at the lake floor, preventing substantial vertical flow due to the piezometric head in the underlying aquifer (SMEC, 2008). Hence, the vertical leakage through the 80m thick clay layer, with an assumed vertical hydraulic conductivity of say 0.0001 m/day, would suggest a leakage rate of 7 mm/yr which is so negligible (Kebede et al 2005).

d) Environmental flows

Lake Tana with a storage capacity of 29.175 BCM (This study analysis) of water and an average depth of 9m, feeds Abay river (Howell and Allan, 1994). The state of all downstream uses and other reservoir losses determine the waters that would outflow from the Lake Tana. An environmental impact assessment for the Tana Beles transfer scheme recommended maintaining an average annual release of 17 m^3/s (536 MCM) from Chara Chara, with a minimum of 10 m^3/s, to support the Abbay River ecosystem (Salini & Mid-day, 2006). Variable environmental flows (VEF) were proposed, averaging 864 MCM/year, with a guaranteed flow of 997 MCM (35 m^3/s on average), ranging from 60 m^3/s in December to 10 m^3/s in January (Humphrey & Associates, 1996). Including environmental flows, total outflows from Lake Tana are 4,304.37 MCM/year, supporting hydropower and irrigation flow (60–166 m^3/s).

e) Current irrigation and water supply abstractions

The Tana Basin, a densely populated agricultural zone in Ethiopia's northern highlands, is transitioning to sustainable irrigated farming with numerous irrigation and hydropower projects. Currently, over 70 modern irrigation schemes exist, with an average base flow of 25.8 m³/s (811.5 MCM/year) (Amhara Water Resource Bureau, 2013). Key reservoirs include the Koga Dam, irrigating 7,000 ha with 81.51 MCM annually, and Angereb Dam, supplying Gondar's drinking water with 5.3 MCM/year but reduced by 50% due to sedimentation(Nigusie, 2010). Selamko and Shina micro-dams abstract 2.5 MCM/year combined.

3.1.2 Tana basin annual water balance (MCM) Results from 1984-2010

Reservoir analysis (Table 7) indicates that the minimum flowable storage at the end of June was 595.38 MCM, which increased to a maximum of 5,805.38 MCM by September, representing the total dynamic storage utilized by all users. The net maximum annual release, calculated as 5,210.0 MCM, is the difference between these values and is distributed via the Chara Chara weir and Tana-Beles tunnel. The recorded average annual outflow (1960–2001) through Chara Chara weir was 4,304.37 MCM, 906 MCM less than the dynamic storage. A volume of 1,501 MCM maintains water depths of 0.54 m at the 1784.5 m elevation contour area and 0.53 m at 1785 m, ensuring navigation and wetland sustainability.

Table 7. Tana basin Monthly water balance components (MCM) from 1984-2010

Month	Total Inflow	Irrigation/supply uses	Environmental flows	Tana-Beles hydropower	Total Evaporation	Total outflow	Basin Balance
Jan	78.9	129	160.7	105	485.7	880.4	**-801.6**
Feb	61.7	117.9	145.2	62.3	560.1	885.4	**-823.7**
Mar	105.5	114.7	26.8	202.5	657.3	1001.3	**-895.8**
Apr	130.6	102.1	25.9	201.2	634.9	964.1	**-833.5**
May	394.3	104	26.8	148.6	594.8	874.2	**-479.9**
Jun	1133.2	0.5	25.9	144.4	367.1	537.9	**595.4**
Jul	2460.6	0.5	53.6	207.5	190.8	452.3	**2008.2**
Aug	3109	0.5	53.6	357.1	191	602.1	**2506.9**
Sep	1747.6	0.5	103.7	670.3	278.3	1052.7	**694.8**
Oct	827.3	104	107.1	613.8	369.7	1194.6	**-367.4**
Nov	223.9	103.2	103.7	400.7	394.9	1002.4	**-778.5**
Dec	118.6	121.6	160.7	197.5	427.2	907	**-788.3**
Total	**10391.1**	**898.4**	**993.6**	**3310.8**	**5151.7**	**10354.4**	**36.7**

The basin average runoff from the perfect no-loss catchment (15,092 km^2) yield would be 20,273 MCM (no-evapotranspiration, no-infiltration). This shows that a runoff generation efficiency of the watershed was 10,391/20273 MCM = 0.50 which indicated that the rest water is used for evapotranspiration of 8,110 MCM (40%) and infiltration of 2,026 MCM (10%). Results of common water balance environmental flow simulation results on Lake Tana watershed have been made at different times as shown in Table 8.

Table 8. Annual averaged Lake Tana water balance terms from literature (1995–2001).

Water Balance Terms	**This study**	**Wale (2008)**	**Gieske et al. (2008)**	**Kebede (2005)**
	MCM	MCM	MCM	MCM
Lake areal rainfall	3631	3784	3891	3906
Gauged river inflows	4212	3970	4021	5028
Un-gauged river inflows	6179	2729	1466	nd
Lake evaporation	-5152	-5242	-5180	-5115
Blue Nile outflows	-4304	-4714	-4179	-3816
Current Upstream uses	+898	nd	nd	nd
Balance	+36.7	527.00	19.00	3.00

nd*=No data, negative signs indicate reservoir losses and positive signs indicate inflows or gains; This study included the contribution of small-scale irrigation abstraction (898.35 MCM) to Lake Tana water balance.

3.2 Lake Tana Water Level and Implications on Water Uses

a) Historical lake level and fluctuation

The zero level of the staff gauge in Bahir Dar is at 1783.515 m asl, and care must be taken when comparing water levels from different reports, as local measurements may differ by 1 m. In 2002, the staff gauge readings at Gorgora were increased by 1 m compared to Bahir Dar and Kunzila, with a better correlation between Bahir Dar and Gorgora. The Chara Chara weir regulates water levels in Lake Tana between 1784 and 1787 m asl, with active storage of 9,100 Mm³, about 2.4 times the annual outflow. Before construction, water level fluctuations ranged from 1785.75 to 1786.36 m asl, with natural discharge linked to rainfall and variability over 6-7 year cycles. The minimum bed level of Lake Tana outlet, set by the Ethiopian Mapping Agency in 1998, is 1785 m asl.

The complex water inflow and loss patterns in Lake Tana lead to significant daily and seasonal fluctuations in water levels, with the highest levels occurring at the end of the rainy season, and the lowest around the end of the dry season. The difference between the minimum (May-June) and maximum (September-October) water levels before the weir's construction was typically 1-1.5 m (Figure 2). In recent years, water levels have decreased significantly, affecting access to the islands by ferryboats. The highest recorded water level was 1787.53 m asl in 1964, and the lowest was 1784.66 m asl in 2003. At the natural water level of 1785 m asl, the lake's volume is about 21,820 MCM, but the ecological systems have been impacted by disturbances in the hydrological regime, wetland drainage and water abstractions. Recent fluctuations in water depth range from 1.44 to 3.08 meters, with a marked increase in fluctuation to 3.0 meters after 1995, and the lowest level recorded in June 2003 (Figure 2).

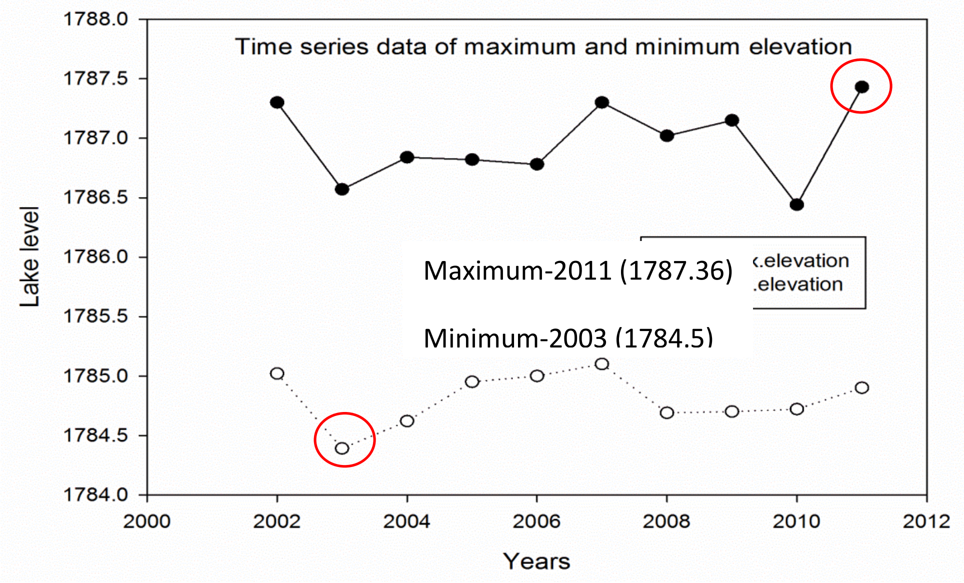

Figure 2. Trends in minimum and maximum Tana lake level

3.3 Lake Tana reservoir area -volume analysis

3.3.1 Lake Tana reservoir area -volume and elevation analysis

The bathymetric survey by Morandino (1940) found Lake Tana to have a regular bottom with a low bed slope of 0.01% to 0.09%, and a maximum depth of 16.0 m. The lake’s water surface area is 2,929 km² at a reservoir level of 1786 m asl, with a maximum capacity of 29,186 MCM at 1787.5 m asl. The dead storage capacity at the minimum operating level of 1784 m asl is 19,045 MCM (Figure 3).

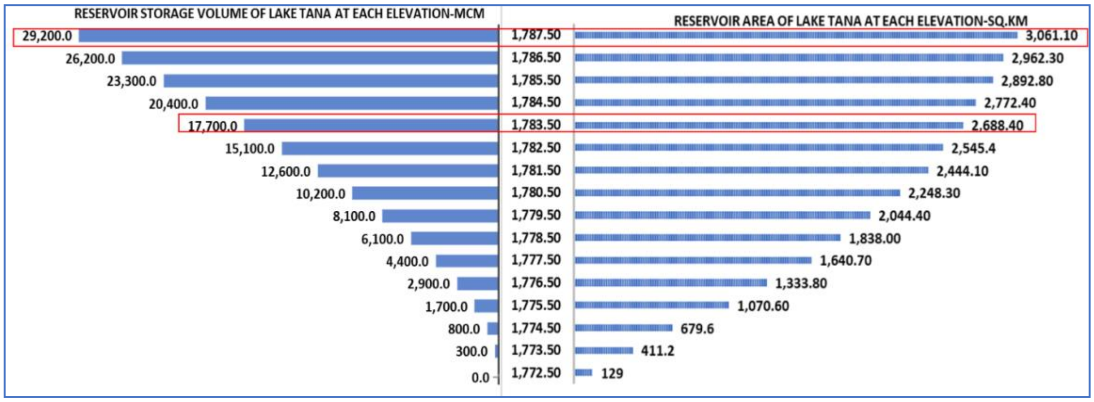

Figure 3. Lake Tana elevation and reservoir volume and area bar graph

The lake volume – area- elevation curve (Figure 4a) was developed using bathymetric data conducted by Kaba et al. (2007). The intersection point of the graphs shows the crest elevation of the outlet point from the lake water. Reservoir volume versus inundated area of the lake is shown in Figure 4b.

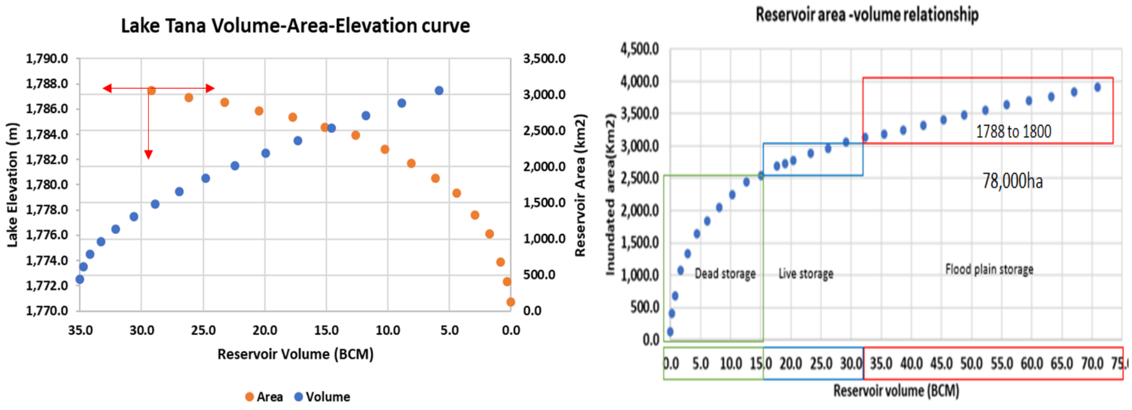

Figure 4. Reservoir Volume-Area-Elevation Curves Reservoir volume versus area plot

3.3.2 Lake level change implications to water use

It is possible to discuss what quantity of lake water is potentially useful between each elevation of the lake. Using the absolute minimum elevation of 1783.5, the dynamic lake volume and the corresponding inundated reservoir area have been computed (Table 10). This provides very important implication on forms of water uses that for what quantity of water and reservoir area and between what elevations are the conflicting demands occurring within the lake context (Table 9).

Table 9. Reservoir volume and area at the elevation over the minimum level (1783.50).

Elveation, m	1782.5	1783.5	1784.5	1785.5	1786.5	1787.5
Volume, BCM	15.07	17.69	20.42	23.25	26.18	29.189
Live volume	0.00	0.00	2.73	5.56	8.49	11.50
>95% of the year stored between contours -the potential for navigation and EIA flows			2.83			
70% of the year stored between contours /Jul to Feb/ -Potential for hydropower, wetland, and irrigation				2.93		
<30% of the year stored between contours /Aug to Nov/ hydropower					3.01	
Area, km^2	2545.42	2688.45	2772.39	2892.83	2962.30	3061.07
Live area, km^2	0.00	0.00	83.94	204.38	273.86	372.63
>95% of the year water-covered area - potential for navigation and EIA but less potential for wetland			12,044 ha			
70% of the year water-covered area- high potential wetland				6,947 ha		

(fish and bird), hydropower, and irrigation		
<30% of the year water-covered area - the potential for temporary wetland, recession agriculture, paddy rice but probability of flood occurrence	9,877 ha	

3.3.3 Reservoir sedimentation and water resident time

Regarding sedimentation of the reservoir, the volume at two bathymetric studies Morandino (1940) and Kaba et al. (2007) had been compared and the change in reservoir bed level variation was reported. Therefore, the accumulation of 0.5 m depth sediment was estimated over the reservoir area for the past 70 years (1940-2007). It means that about 1.5BCM lake volume has been occupied by sedimentation in 70 years time. The mean water residence time (WRT) of Lake Tana has significantly decreased due to natural factors like silt buildup and human activities causing erosion. Rzoska (1976) reported a WRT of 6.5 years, while recent models suggest it has dropped to 1.6 years. Our analysis, based on a reservoir volume of 27.15 BCM and an annual inflow of 10.39 BCM, estimates a WRT of about 2.7 years.

3.4 Current Water Uses and Interacting Impacts

The Lake Tana Basin (LTB) is a key growth corridor for irrigation and hydropower investments, and understanding current and future water demands is essential. The basin has a high population density due to its cultural, historical, and socio-economic significance. Approximately 89% of the population lives in rural areas and is engaged in agriculture (CSA, 2018). In 2019, the population within the watershed was 2.95 million, with an average family size of 4.9 and a population density of 245 people/km², indicating significant pressure on the basin's natural resources.

3.4.1 Irrigation and hydropower

Current developments in the Lake Tana watershed could increase irrigable area to more than 134,670 ha (Sileshi et al., 2007). The types of structures found under traditional irrigation were diversion, shallow wells, and ponds. While under modern schemes diversion, dam, pump, pond, and hand-dug wells were employed. Diversion is the dominant structure used for both traditional and modern irrigation development in the watershed. The details of large-scale projects are discussed (Table 10) in terms of opportunities and negative effects and the required mitigation measures. Hydropower projects have been implemented at Chara Chara near Bahir Dar and the Tana-Beles tunnel near Kunzila. The first, Tis Abay I, was built in the early 1960s with a 12 MW capacity, utilizing a 46 m head and 29 m³/s discharge. It operated until 1996, when Tis Abay II was introduced with a 72 MW capacity, and a weir with seven gates was installed to regulate water levels between 1784 and 1787.5 m. In 2007, the Tana-Beles tunnel hydropower plant began operations, with a 380 MW capacity and a 200 m head, transforming the lake's water management system for irrigation.

Table 10. Opportunity and associated impacts attributed to four large scale developed irrigation schemes in Tana basin (Koga, Rib, Megech and Serava and Tana-Beles)

Opportunity	**Negative effect**	**Mitigation measures**
- Securing food and nutrition security in the region - increase youth employment - employ more agro-processing industries - reduce the pressure of sediment to Lake Tana - employ fishery industry in the area - reduce sudden flooding along the river to Lake Tana when it joins Gilgel Abay river - reduce the irrigation pressure near the lake by employing more labor on upstream irrigation - Reducing the water supply deficit of nearby cities	- Reduction of land for the reservoir - Environmental biodiversity disturbance during and after construction - High agrochemical loading to the lake and groundwater - Reservoir May be affected by water hyacinth - High sediment storage before fulfilling its objective - High seepage of canals and drains affected the community - Failure of irrigating while power interruption (in 2019 a block was seriously dried) and users requested compensation.	- use of water-saving technologies in the upstream of the lake - use of proper chemical usage and zoning and appropriation - using drainage ponds drain and reuse planting at the irrigable land buffer - Cautious management of the watershed, reservoir, irrigated area, and the community.

3.4.2 Cities, industries and Water supply

The expansion of cities like Bahir Dar, Gondar, and Gorgora in the Amhara Region is straining natural resources, compromising biodiversity, and food security. Urban growth has led to the development of agro-industries, hotels, and factories around Lake Tana, often neglecting environmental considerations. According to an inventory by ABAY Engineering (2005), there are 1,946 potable water sources in the Lake Tana watershed, with 58.32% hand-dug wells, 37.77% springs, 3.24% shallow wells, and 0.67% boreholes. Currently, 85.110 MCM/year is used for drinking water, with Bahir Dar, Gondar, and Debre Tabor consuming 25 MCM, expected to grow by 30% in the next 20 years. Water supply for industries, including Bahir Dar textile, Dashen brewery, and Tana Flora, has reached over 12 MCM. Additionally, over 10 licensed water bottling companies in the basin use significant amounts of water, with Wahaha, Gion, and Choice consuming 0.4 MCM, 0.25 MCM, and 0.05 MCM, respectively.

3.4.3 Navigation, wetlands and Environmental flow

Lake Tana's water levels often fall below the minimum required for shipping navigation (1785 m masl), particularly during dry seasons, impacting both navigation and the lake's ecology. In the full development scenario, water levels exceed 1785 masl only 78% of the time, which could significantly affect shipping, as seen in 2003 when the Lake Tana Transport Enterprise lost around 4 million Ethiopian Birr due to low water levels. The introduction of Variable Environmental Flow (VEF) further reduces lake levels by 0.37 m and its surface area by 26 km², exacerbating environmental and social impacts. This creates a trade-off between preserving the lake ecosystem and supporting the Abay River ecosystem, requiring careful management of water use to balance both ecological and human needs (SMEC 2009).

Currently, approximately 4200 Mm³/year of water is diverted for hydropower and irrigation in the Lake Tana sub-basin, lowering the annual water level by 0.33 m and reducing the lake's surface area by 289 km². This will significantly affect the ecology, particularly in the littoral zones and wetlands, leading to the loss of aquatic vegetation like papyrus reeds. Consequently, the breeding habitat for fish and other aquatic fauna will be reduced, impacting the lake's fisheries. Lower water levels also encourage land cultivation and grazing on the dried lakebed, increasing sedimentation and further harming the ecosystem.

4. Conclusion

In conclusion, the analysis highlights the n2.5 cm (1 inch) margins in all sides.eed for improved water management to support upstream abstractions, which can enhance crop productivity. Future water abstractions in the Tana basin should be supported by advanced infrastructure to ensure the continued success of the Tana Beles project, given its multipurpose economic benefits. The study also showed that abstractions in the upper Tana basin significantly affect the outflows from the two hydropower plants, Tis Abbay I & II, and Tana-Beles. It concluded that for optimal economic use, Tis Abbay I & II should be reserved for emergency operations, while the available outflows from Lake Tana should prioritize the Tana-Beles hydropower plant and irrigation projects.

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