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ORIGINAL ARTICLE

Water storage gap in the Tana-Beles sub-basin, Upper Blue Nile, Ethiopia

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Abstract

Water demand is rising globally due to population growth, rapid urbanization, climate change, and the need for economic development. The need for additional water storage is therefore increasing to meet these demands. Water storage, both natural and built infrastructure, offers a way to manage the availability of water resources. Properly planning and optimizing diverse water storage options for increasing water demand requires an assessment framework. We developed a framework for assessing water storage gaps under current and future scenarios. It is applied in an African setting in the Tana-Beles sub-basin of the Blue Nile basin, one of Ethiopia's economic growth corridors, where irrigation and hydropower development are planned. The volume of usable water storage in Lake Tana, groundwater, and built reservoirs was estimated and compared with irrigation, energy, domestic, livestock, and industrial water demands for the current and future periods. Results showed that the current annual water storage gap is 613 MCM. The storage gap increases to 3663 MCM by 2040s, about five times higher than in the current period. Besides, spatial disparity exists between where most water storage is available and where the water demand occurs. Particularly, demands for irrigation, domestic use, and livestock are spread throughout the sub-basin while there is a strong reliance on surface water sources, which are located in the upstream part of the basin. Given that these sources are subject to spatial and temporal limitations, diversifying natural and built water storage sources is recommended to address the increasing gap between supply and demand.

Keywords Water demand · Water storage · Storage gap · Tana-Beles · Upper Blue Nile · Ethiopia

Introduction

Globally, many regions, including Africa, are grappling with the intensifying water crisis driven by a complex interplay of factors. This includes rapid population growth, economic development, and the intensifying impacts of climate change. With an average annual population increase of 2.5% (Kaba 2020) and accelerated urbanization (Dos Santos et al. 2017), the existing water scarcity across the continent is set to worsen in Africa. Besides, Veldkamp et al. (2015) reported that socio-economic shifts and the increasing variability of hydroclimates are key contributors to the escalating water scarcity in the continent. Adding to the complexity, the availability and distribution of water resources remain critical challenges (Wandiga 2015). The combination of these factors strongly suggests a significant surge in current water demand, aggravating the already pressing issue of water scarcity.

Ethiopia, the second most populous country in Africa, is experiencing rapid urbanization and an associated increase in water demand (Abraha et al. 2022). This demand is further driven by the nation's socio-economic development, which has led to a steady growth in water consumption across various sectors (Tassew 2017). On the other hand, water availability is being hampered by climate change and its increasing variability (Taye et al. 2018). In addition, Ethiopia faces significant water management challenges, resulting in substantial water loss and accelerated water scarcity (Meaza et al. 2022).

Tana-Beles sub-basin, a vital economic growth corridor in Ethiopia, is facing escalating water demand driven by a combination of factors. A growing population necessitates

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expanded irrigation to ensure food security. The demand for electricity generation and broader socio-economic development further intensifies water needs within the sub-basin. Concurrently, water availability in the region is increasingly threatened by the adverse impacts of climate change, sedimentation of water bodies, the spread of invasive water hyacinth, and the degradation of crucial wetland ecosystems (Assefa et al. 2023). Consequently, a thorough assessment of the evolving storage gap is indispensable for implementing sustainable water resource management strategies.

Given the need for a storage gap assessment and the complexity of conducting it at the basin level, the absence of an existing framework represents a significant knowledge gap. To address this knowledge gap, we developed a framework for storage gap assessment and applied it to the Tana Beles sub-basin to quantify the storage gap for the baseline, current, and future water demand scenarios.

This study addresses the following key questions:

- What are the current and future water demand in volumes?
- How much is the volume of usable water storage from natural and built sources?
- Is there a storage gap at present and in the near future?

This paper builds on existing evidence generated on the types of natural and built storage in the basin (Taye et al. 2025) and it provides insights to support the development of integrated policies and strategies for addressing water scarcity through diversifying water sources and efficient water use.

Study area description

Tana-Beles sub-basin of the Blue Nile lies between 35.1 to 38.2 °E and 10.5 to 12.8 °N (Fig. 1). It has a drainage area of 29,254 km^2, of which Lake Tana covers about 3000 km^2, accounting for about 10% of the sub-basin area. Lake Tana

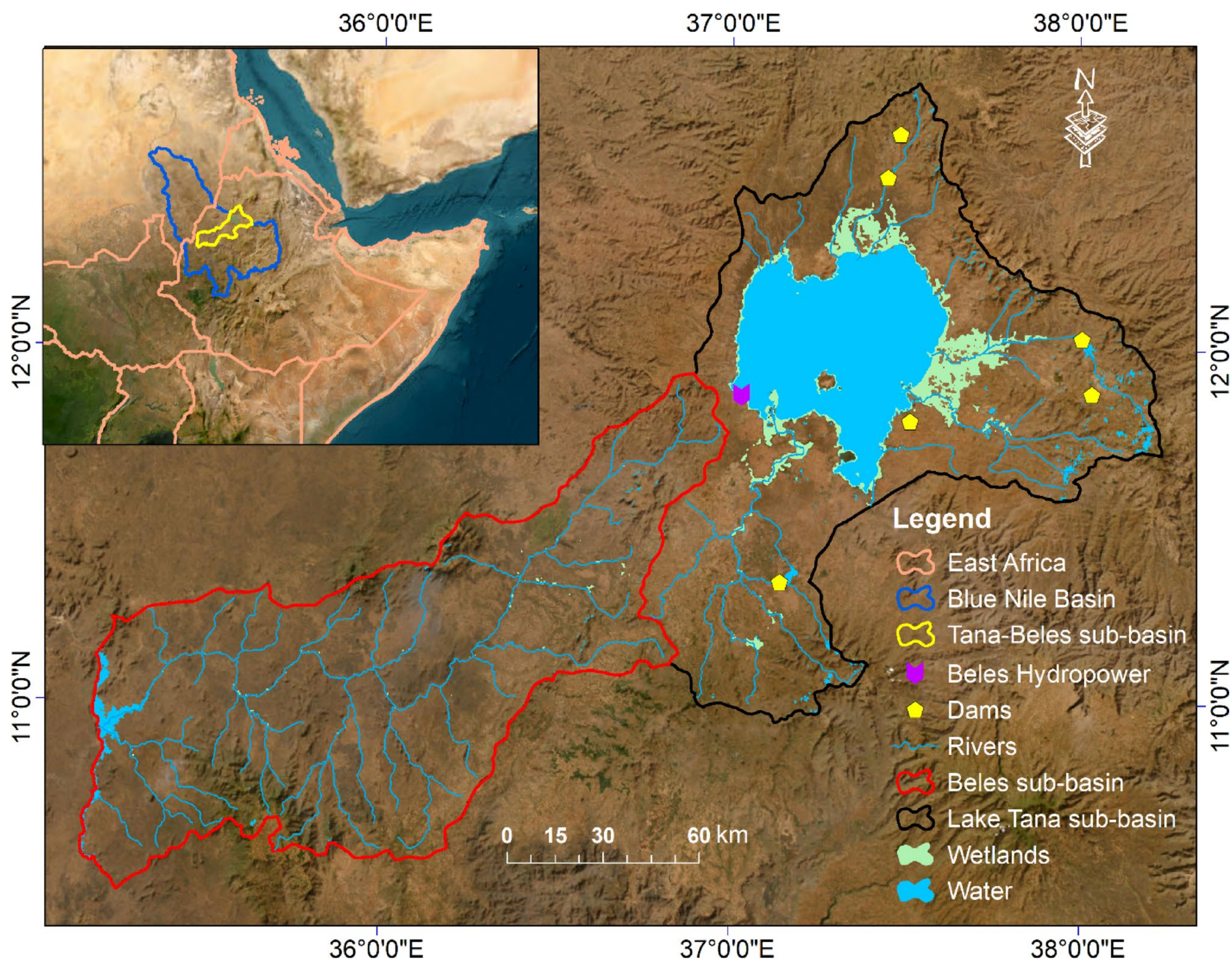

Fig. 1 Location of Tana-Beles sub-basin in the Blue Nile Basin, Ethiopia

is the largest lake in Ethiopia and serves as a major natural water storage reservoir for the region. The wetlands within the sub-basin provide essential ecosystem services and act as a buffer, protecting Lake Tana's ecological integrity. The sub-basin also substantially contributes to the Grand Ethiopian Renaissance Dam, GERD.

The sub-basin's elevation ranges from 513 m above sea level (asl) in the southwestern Beles region to 4094 m asl in the eastern Lake Tana area. Rainfall distribution varies significantly within the sub-basin, ranging from 951 mm in lower Beles and Upper Lake Tana regions to 2217 mm in the lower Lake Tana and Upper Beles areas (Fig. 2A). Temporal analysis from 2014 to 2023 revealed that the highest mean monthly rainfall occurs in July (341 mm), while January records the lowest (2.5 mm). The main rainy season, spanning June to September, contributes 77% (1070 mm) of the mean annual rainfall, which averages 1388 mm. The sub-basin's mean annual temperature from 1979 to 2015 was 19.3 °C (Weldegerima et al. 2023).

Based on land cover data in 2021 from the European Space Agency, ESA, with 10 m resolution, the Tana-Beles sub-basin is characterized by diverse land use (Fig. 2B). Cropland accounts for 44% of the total area, followed by forests (22%) and shrub land (14.7%). The Lake Tana region is dominated by extensive cropland. In contrast, forests largely cover the Beles region. Water bodies make up 10.7% of the sub-basin and grasslands cover 7.4% of the sub-basin area. Agriculture is the main livelihood in the region, dominated by smallholder subsistence farming and livestock husbandry. Water demand in the sub-basin is tied to the livelihoods of its communities, driven primarily by agriculture, hydropower, domestic use, livestock, industries, tourism, and the ecosystem. Rainfed farming dominates crop production, with limited irrigation despite its significant potential. Major rainfed crops include cereals such as maize, rice, teff, millet, wheat, and barley, along with pulses, oilseeds, and vegetables (Weldegerima et al. 2023). Irrigated agriculture focuses mainly on wheat, sugarcane, and vegetables (Mebrie et al. 2023; Abshiro and Singh 2018).

Methods

Framework for storage gap assessment

A storage gap assessment framework was developed to evaluate current (2021–2023) and future (2040s) storage gaps (Fig. 3). The framework compares total annual water demand with annual usable storage as a benchmark, which is a planning-level diagnostic tool rather than a sub-annual operational model. Besides, sectoral analysis in the sub-basin indicated that irrigation is inherently storage-limited

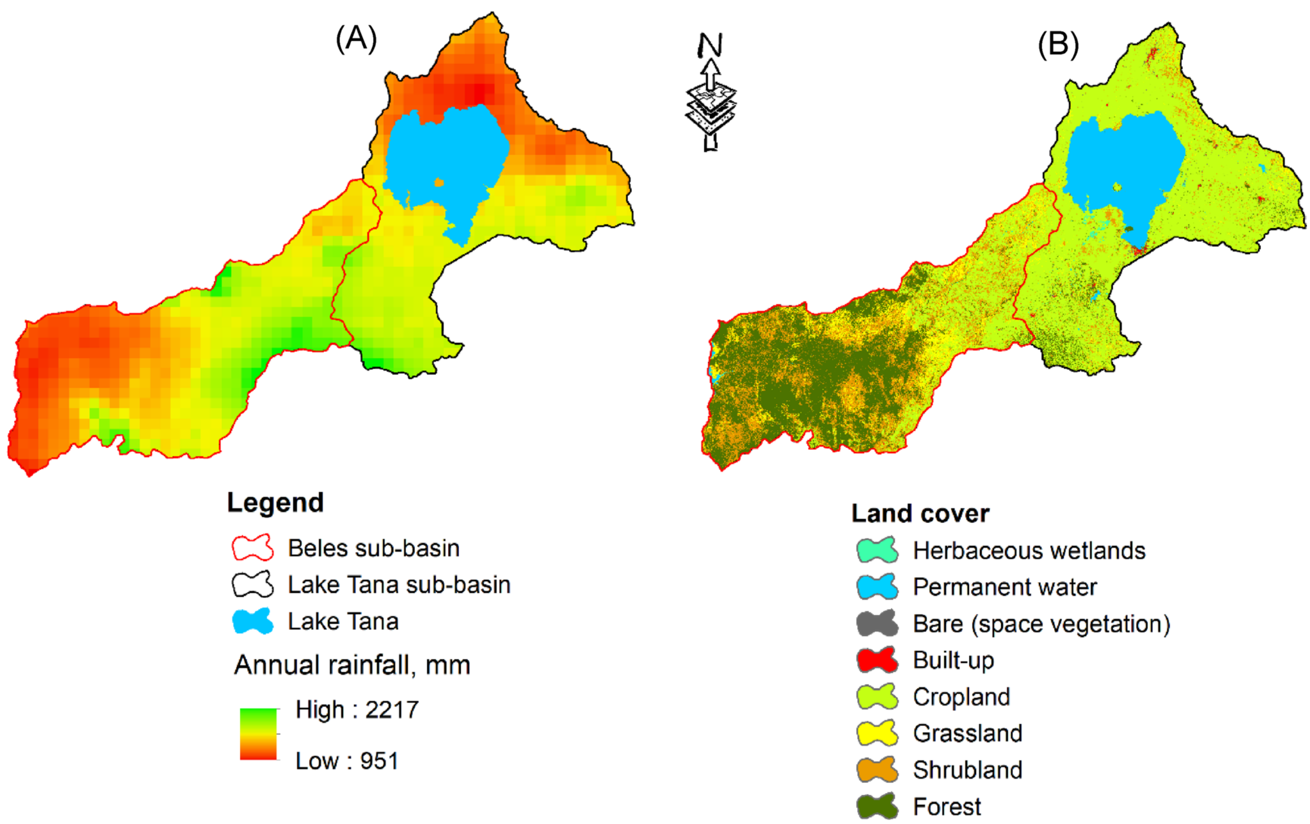

Fig. 2 Mean annual rainfall for the period 2014 to 2023 from CHRIPS (**A**), and land cover map of 2021 from European Space Agency (**B**)

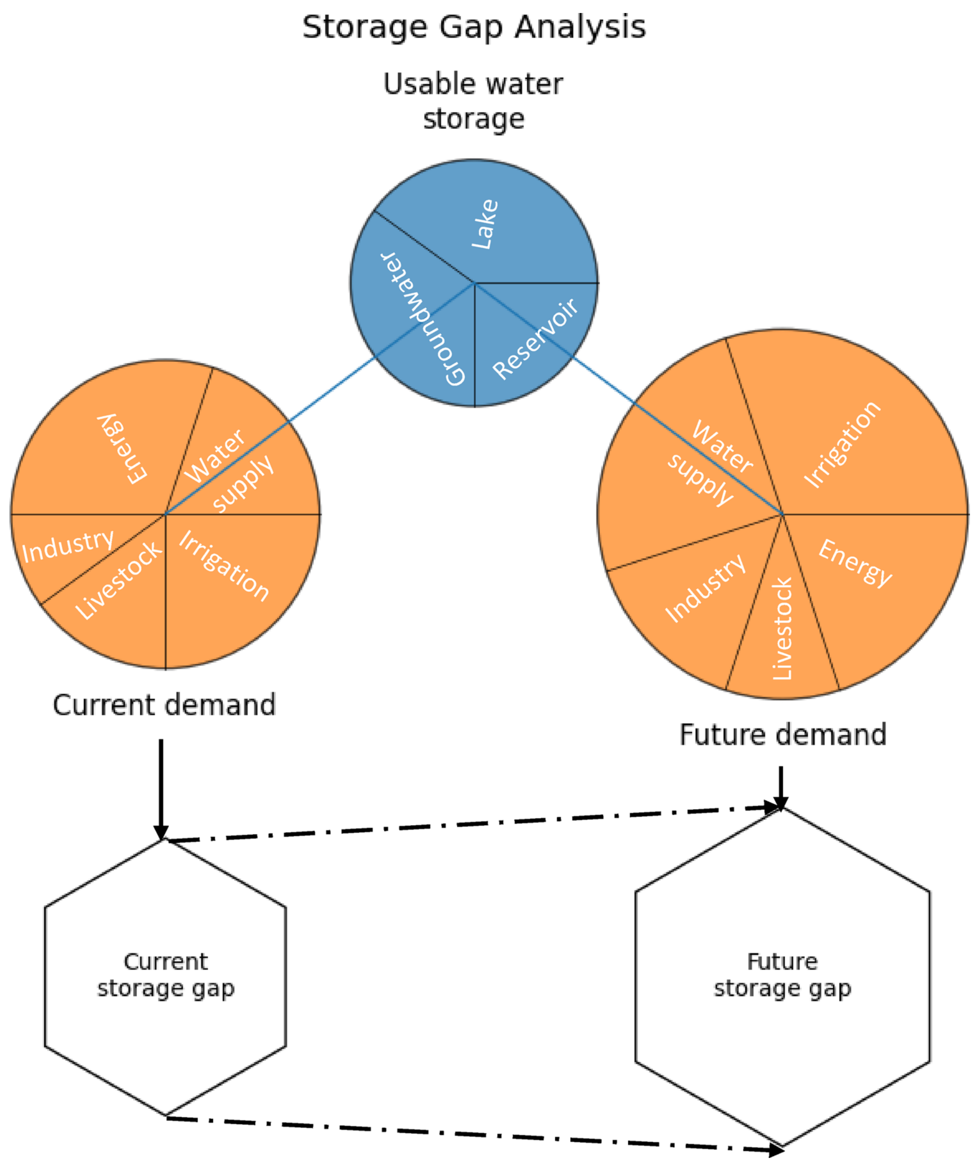

Fig. 3 Water storage gap assessment framework. All data sources used in the analysis are presented in supplementary material (Table S1)

and other uses (domestic, livestock, and industry) are distributed throughout the year. Hydropower, in conventional in-basin or runoff-river systems, the use is largely non-consumptive and more appropriate to characterize as flow-limited rather than storage limited. However, for the Tana-Beles hydropower, water is diverted from Lake Tana, and nearly all the discharge exits the sub-basin via the Beles River. In this configuration, the hydropower diversion is neither pure flow-limited nor a non-consumptive use from the sub-basin storage perspective: it is a net, largely non-recoverable depletion of Lake Tana storage. The annual storage benchmark is therefore a reasonable benchmark from a sectoral demand perspective.

Water demand was evaluated across the various sectors: agriculture, energy, domestic use, livestock, and industries. For the agriculture sector, we focused on irrigation. Irrigation demand was estimated based on consumptive crop water use, irrigated area, and irrigation efficiency. Energy demand focused on hydropower. The estimate was focused on the operational Tana-Beles hydropower plant. Domestic water demand was estimated based on the population and per capita water demand differentiated for urban and rural settings. The water demand for livestock was estimated based on the number of livestock, and per capita livestock water demand. Estimates of current industrial water demand were taken from literature on major industries' water consumption.

Future demands for irrigation and industries were estimated considering irrigation area and industrial expansion, respectively. Future domestic use and livestock water demand were estimated based on population and livestock projections for the 2040s. Usable water storage in the sub-basin was derived from the live water storage estimate by Taye et al. (2025), accounting for navigation requirements and Blue Nile Waterfall needs from Lake Tana and considering an estimate for sustainable use for groundwater. Storage gaps at present and in the future were computed by deducting current and future water demands from existing usable water storage, respectively.

Characterization of different water demand sectors

Irrigation water demand

The current irrigation water demand, IWD, was calculated based on existing irrigated areas, using reference evapotranspiration (ETo), effective rainfall (ER) and crop coefficients (Kc) for the dominant crops (Eq. 1). Irrigated area estimate for Lake Tana sub-basin was based on (Taye et al. 2022), while for the Beles sub-basin the data was obtained from Metekel Zone Agricultural Office. Climate Hazard Group Infrared Precipitation with Station, CHIRPS, (Funk et al. 2015) and the Food and Agricultural Organization, FAO, Water Productivity Open Access Portal, WaPOR v3 were used as the sources of rainfall and reference evapotranspiration, respectively. The FAO Irrigation and Drainage Paper 56 was used for the crop coefficients of wheat, maize, small vegetables, and sugarcane considered in this study. The analysis utilized time-variable crop coefficients. A 60% irrigation inefficiency for furrow irrigation was assumed based on Worqlul et al. (2017). This calculation assumed conventional furrow irrigation efficiency, with ER derived as a function of precipitation, P, (Eq. 2) based on Patwardhan et al. (1990). Current demand includes existing small- to medium-size irrigation schemes, Koga, Ribb, Megech Seraba, and 26% of the Beles irrigation schemes as these are operational or equipped (Table 1 and Fig. 4).

Table 1 Planned and constructed large scale irrigation schemes and their consideration for current and future demand (Mequanent and Mingist 2019)

Scheme (project)	Command area for current demand (ha)	Command area for future demand (ha)
Megech Dam	–	7300
Megech Seraba	4995	4995
Megech (Robit)	–	6532
Ribb	19,925	19,925
Gumara	–	13,980
Gilgel Abay	–	10,310
Gilgel Abay Diversion	–	3264
North East Tana	–	5750
North West Tana	–	6720
South West Tana	–	5130
Tana Wonjeta	–	4848
Tana Asrate	–	1333
Tana Mekonta	–	1139
Koga	6118	6118
Upper Beles	16,400	53,700
Lower Beles (50% assumed)	–	42,500

Large-scale current and planned irrigation schemes alongside with a 5% annual expansion of small to medium-sized schemes (Bojago and Abrham 2023) were considered as a proxy for future irrigation demand by 2040. The planned large-scale schemes were incorporated based on their intended command areas rather than their operational status. For the lower Beles irrigation scheme, 50% of its command area was included in future irrigated areas since the GERD reservoir partly overlaps with it (above 20% in February 2025). The main irrigation season runs from January to May while supplemental irrigation occurs from October to December. Climate change studies in the region presented evapotranspiration projections that increase between 6 and 15% (Eshetie et al. 2026; Ayele et al. 2016), while minimal rainfall changes were reported for mean rainfall (Tigabu et al. 2020). An average 10% increase in future evapotranspiration was assumed in this study, representing a mid-range of projected values.

$$IWD = 1.6KcETo - ER \tag{1}$$

$$ER = \frac{P\,(125 - 0.2 * 3P)}{125}\ for\ P \le \frac{250}{3}, \frac{125}{3} + 0.1P\ for\ P > \frac{250}{3} \tag{2}$$

where, IWD, Kc, ETo, ER, and P refer to irrigation water demand, crop coefficient, reference evapotranspiration, effective rainfall, and precipitation. All units are in mm except Kc (unit less).

The ratio of effective rainfall (ER) to crop water requirement (ETc) during the main irrigation season depicted that the contribution of ER to crop water needs is small, less than 16%, (Table 2). This indicates that during the main irrigation season, January to April, irrigation water demand should be met from different water storages. During June to September, ER meets or exceeds crop water requirement, allowing storage replenishment. This seasonal pattern confirmed that irrigation in the sub-basin is fundamentally storage dependent.

Given that irrigation demand is the major component of total basin demands, and sensitive to assumed increases in evapotranspiration, we conducted a sensitivity analysis to evaluate the robustness of the projected storage gap to alternative ET scenarios. Three scenarios were considered; 5%, 10%, and 15% ET increment, while all other demand parameters were held constant across scenarios.

Energy water demand

The Tana-Beles hydropower plant operates via an inter-basin water transfer where water is diverted from Lake Tana through a tunnel and discharged into the Beles River

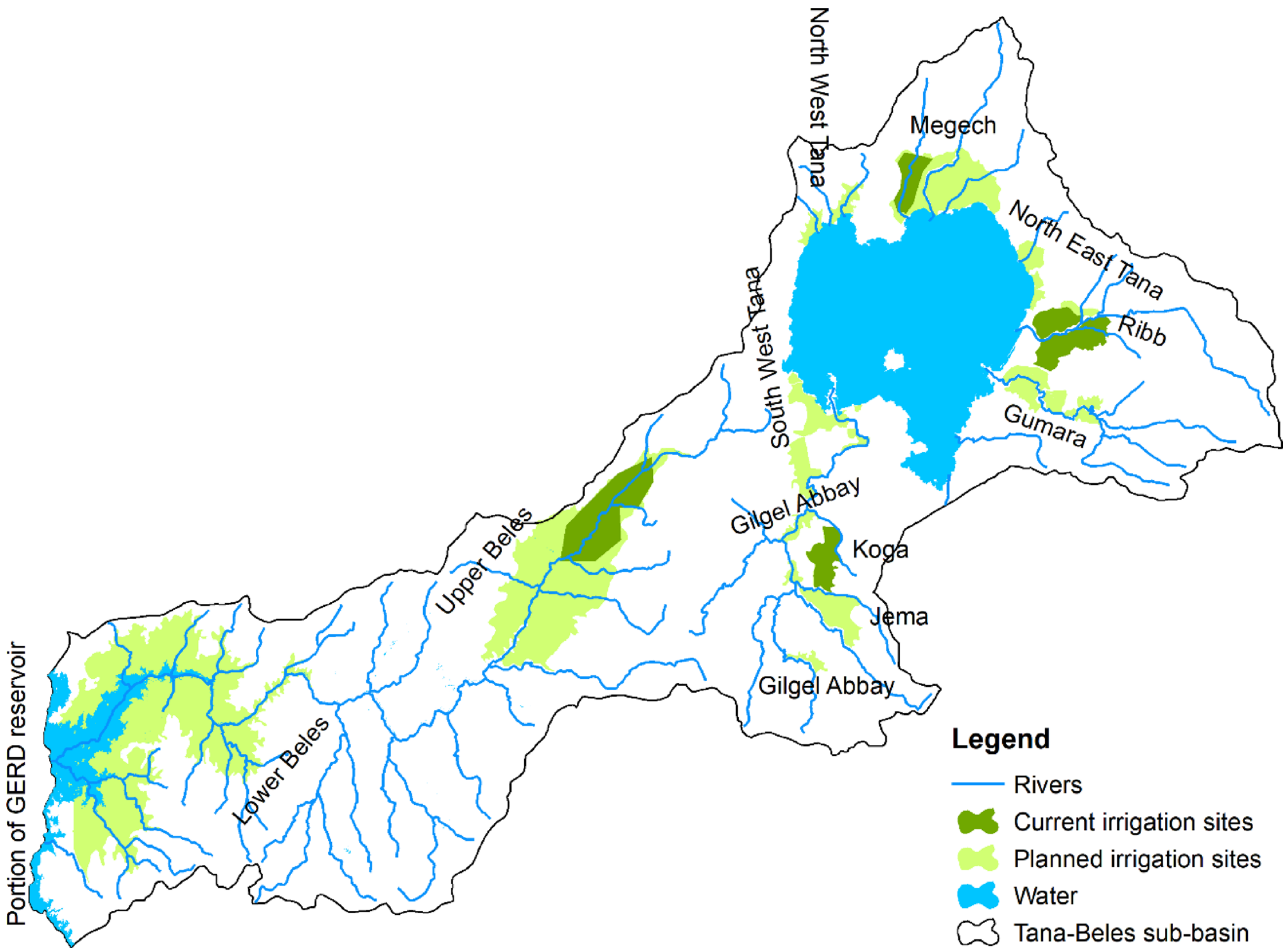

Fig. 4 Current and planned large-scale irrigation schemes in the Tana-Beles sub-basin

Table 2 Effective rainfall to crop water requirement (ETc) fraction during main irrigation season

Month	Mean rainfall (mm)	Effective rainfall, ER, (mm)	ETo (mm)	ETc (mm)	ER as % of ETc
January	2.5	2.5	150	45.1	5.5
February	7.8	7.6	159	47.6	15.9
March	13.5	12.6	188	131.8	9.6
April	37.8	31	188	216.3	14.3

following power generation. This diversion occurs continuously, including wet periods when rainfall is sufficient to satisfy crop water demand. The outflow largely leaves the sub-basin with the Beles River, as existing irrigation infrastructure remains incomplete and additional storage would be required to capture and utilize the return flow. As a result, the hydropower diversion constitutes a near-complete net loss from the Lake Tana storage system at the sub-basin scale and is therefore considered in the storage gap assessment.

The Tana-Beles hydropower is the only active energy facility in the sub-basin. Tis Abbay I and Tis Abbay II hydropower power plants became non-functional after the Tana-Beles power plant is operational (Mulat et al. 2018). For the current energy water demand we used actual water withdrawal data of the Tana-Beles power plant for the period 2017 to 2020, obtained from the Environmental Protection Agency, EPA. We considered this power plant to be the only hydropower facility available in the sub-basin up to 2040 for the future analysis. Hence, the energy water demand remains the same in the current and future scenarios.

Industrial water demand

The current industrial water demand, in 2023, was calculated considering only major industries such as the Tana-Beles Sugar Factory, Dashen Brewery, Moha Soft Drinks, Tana-Flora Horticulture, and major hotels in main towns. In addition, estimates of other industries by ADSWE (2015) were considered. To estimate future industrial water demand, we utilized the Newman et al. (2016) study that estimated 10% annual industrial expansion rate in Ethiopia.

Domestic water demand

The current domestic water demand was estimated based on population size and per-capita water demand. District level population data for 2014 was extracted from the CSA district-level data (CSA 2014). The population within the sub-basin was then projected for the base year, 2023, using national average growth rates.[1] To estimate current domestic water demand, a standard per-capita demand of 60 l/c/day for urban areas and 25 l/c/day for rural areas was applied, aligning with Ethiopia's Growth and Transformation Plan II (GTP II). Domestic water was computed at the district level as a product of per-capita demand and population size, separately for urban and rural areas. The district-level water demand was aggregated to the sub-basin. The future domestic water demand was estimated by projecting the population from the base year to 2040. An assumed increase of about 30% per capita water demand by 2040, 80 l/c/day for urban and 35 l/c/day for rural areas was used, due to expected improvements in living standards (Tefera et al. 2023).

Livestock water demand

Livestock water demand was estimated based on the per capita water demand and the number of livestock. We considered cattle, sheep, goats, horses, mules, donkeys, and poultry to determine the livestock population and associated water uses. The livestock population data and per capita water use were obtained from CSA (2022) and Sileshi et al. (2003), respectively. We converted each livestock category into a common metric known as the tropical livestock unit, TLU. To compute current and future livestock water demand, we used a daily consumption rate of 25 liters per day per TLU (l/d/TLU). Livestock population projections to 2040 were made considering annual average growth rates of each animal. Cattle, sheep, goats, and poultry were increased per annum by 4.2%, 5.9%, 11.6%, and 6.6%, respectively (Begna et al. 2024). The populations of horses and donkeys were assumed to increase by 3.3%, and 4.6%, respectively (Fitsum and Ahmed 2015). Following Begna and Masho (2024), a 6.3% annual increase in mule population was used.

Storage gap assessment

We considered the basin's usable water storage to compare with the annual water demand for usable water storage assessment. Usable water storage here refers to the available water within Lake Tana after accounting for various constraints including requirements for navigation, downstream water requirements to sustain the Blue Nile Falls and its ecosystem, and sustainable limits for groundwater extraction. In addition, the live storage of built reservoirs is considered as part of the usable water storage from reservoirs. In this study, we capitalize on Taye et al. (2025) estimate of the total and active water storages. Built-in reservoirs in this context refer to dams for water supply and irrigation. Water requirements for navigation and the Blue Nile Falls were considered as constraints for Lake Tana based on McCartney et al. (2010) to estimate usable storage. The water level of the lake needed for these is 1785.85 m asl. Considering the need for sustainable groundwater extraction, 50% of recharge was assumed as usable aquifer storage. The storage gap was estimated by subtracting the total annual water demand from the available usable water storage for current and future scenarios.

[1] https://www.macrotrends.net/global-metrics/countries/ETH/ethiopia/population-growth-rate

Results

Current and future water demand

Irrigation demand

The current annual irrigation water demand is 1.4 BCM and the future water demand is projected to be 4.4 BCM, an increase of 208%. The sub-basin's current and projected irrigated area is 100,143 ha and 296, 919 ha, respectively, exhibiting significant spatial variation. District level variations of current and future irrigated areas are presented in supplementary material (Table S2 and Fig.S1). Similarly, current (Fig. 5A) and future (Fig. 5B) irrigation water demand varies significantly across the districts corresponding to the irrigated area. Analysis of current demand shows that Fogera district has the largest irrigation water demand with 424 MCM, followed by Jawi (321 MCM), and Dembia (151 MCM) districts. In the future, Jawi district will have the largest water demand, associated with Upper Beles irrigation scheme. Detailed district level current and future irrigated area found in the supplementary material (Table S3).

The temporal irrigation water demand estimated at the monthly level in Fig. 6 shows that the highest current demand occurs in March, reaching 282 MCM, followed by April (257 MCM), and May with (226 MCM). A similar temporal pattern is projected for the future, with peak values in March at about 855 MCM (Fig. 6).

Energy water demand

The Tana-Beles hydropower plant is a key energy facility in the region, leveraging water diverted from Lake Tana to

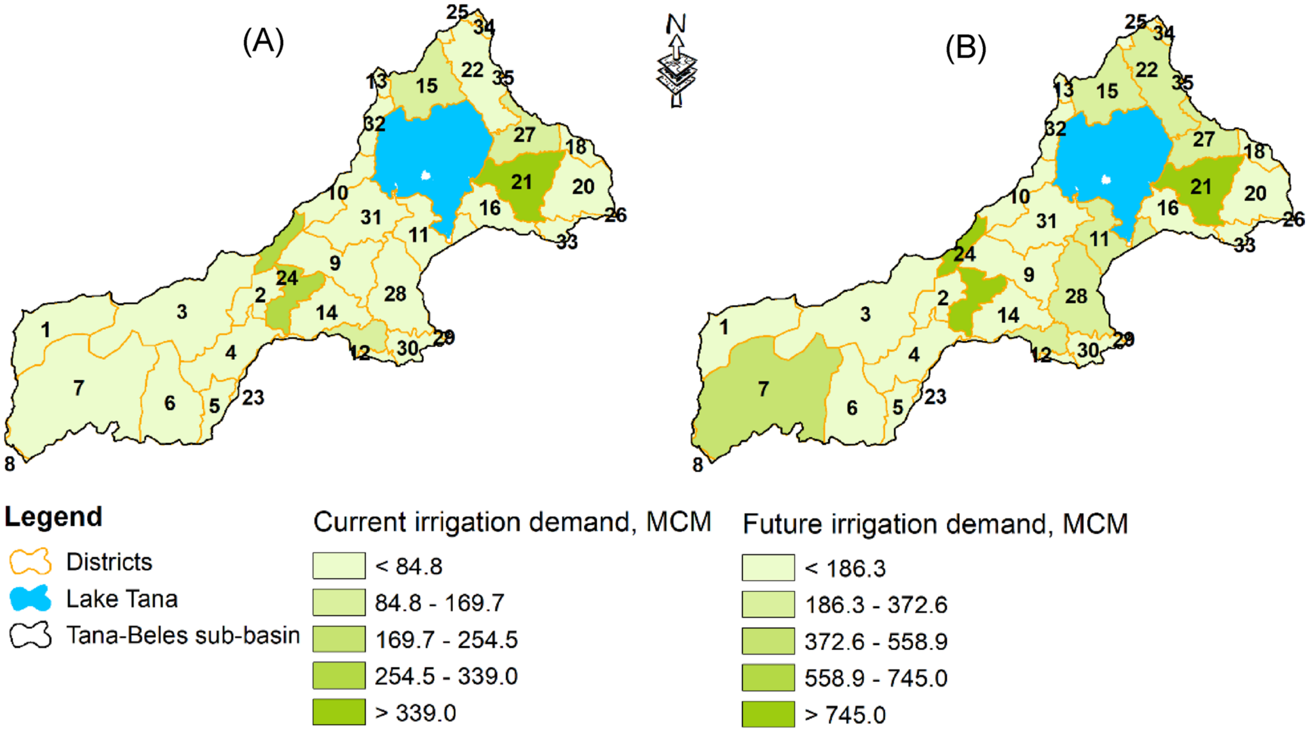

Fig. 5 Current (**A**), and future (**B**) irrigation water demand in the Tana-Beles sub-basin. Refer supplementary material, Table S3, for the district map labels description

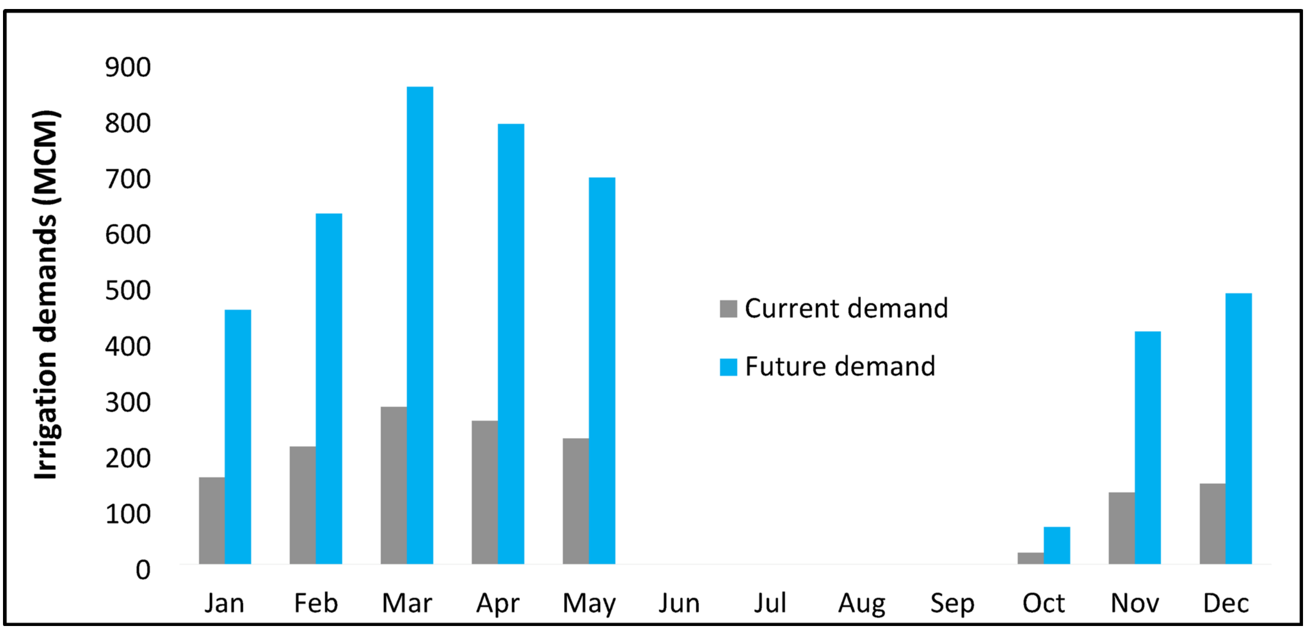

Fig. 6 Current and future monthly irrigation water demand in the Tana-Beles sub-basin

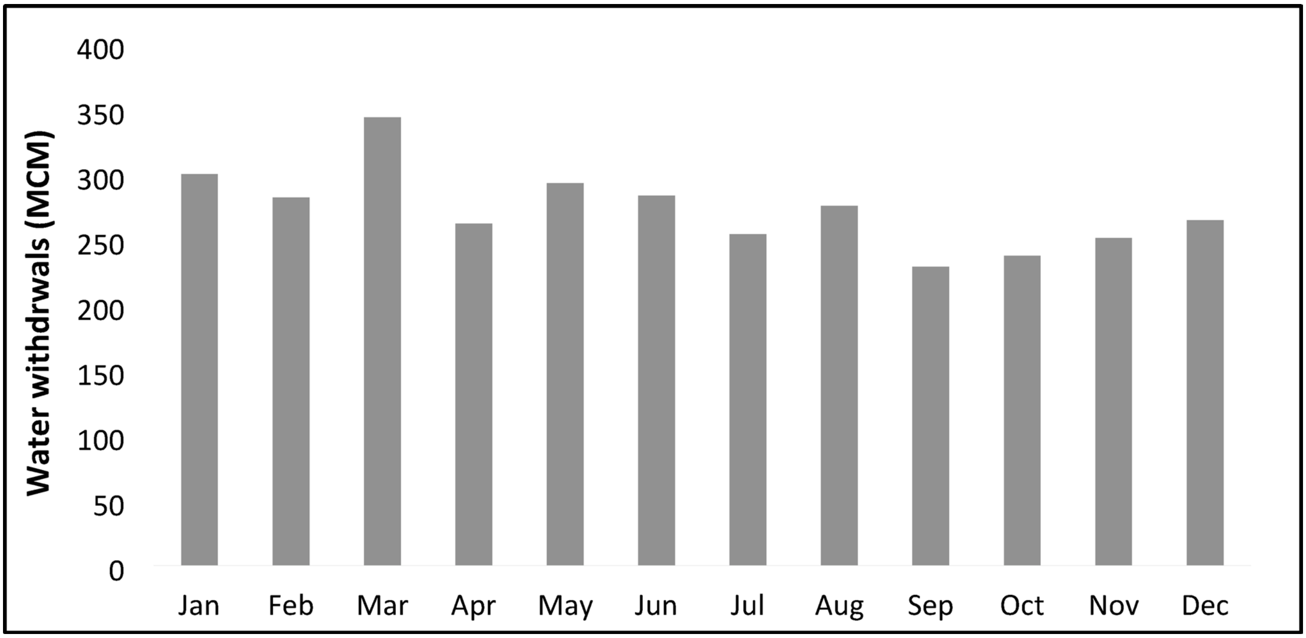

Fig. 7 Mean monthly water withdrawal for the Tana-Beles hydropower plant for the current period (based on 2017 to 2020) and future scenario, which is a similar value

Table 3 Population size and annual domestic water demand in the current and future scenario

Rural/ Urban area	Estimated population in 2023	Population projection by 2040	Current water demand (MCM)	Future water demand (MCM)
Rural	3,311,818	4,801,534	30.2	61.3
Urban	959,057	1,433,940	21.0	41.9
Total	4,270,875	6,235,477	51.2	103.2

generate an average energy production of 2356 Gigawatt-hour, GWh (Tesfaw 2016). Recent data by Hamza and Getahun (2022) indicated a slightly lower average annual energy production of 2051 GWh. According to EPA's energy withdrawal data, the mean monthly water withdrawals from the lake for the Tana-Beles hydropower vary significantly throughout the year (Fig. 7), ranging from 254 MCM in July to 344 MCM in March. The current annual water demand for energy production is 3277 MCM.

Domestic water demand

The total current population in the sub-basin was 4,270,875 (Table 3) with significant population variation across districts (Fig. S1A). The Gondar Zuria district is the most populous, accounting for 14.5% of the total, followed by Farta and Dembia, each representing 9%. The majority of the population, 77.5%, lives in rural areas. In the future, the population in the sub-basin is projected to reach 6,235,477, which is a 46% increase. The current annual domestic water demand in the sub-basin is 51.2 MCM. Annual water demand per district varies significantly (Fig. 8A), ranging from less than 1 MCM to over 10 MCM per district. Detailed district level current and future population and associated water demands can be found in the supplementary material, Table S4 and Table S5, respectively. By 2040, annual water demand is projected to rise by 87%, reaching 103 MCM in total with significant variation across district (Fig. 8B).

Livestock water demand

The Tana-Beles sub-basin hosts a diverse range of livestock including cattle, sheep, goats, horses, mules, donkeys, and poultry. In 2022, the total livestock population in the sub-basin exceeded 7 million animals (Table 4). Among these, poultry represents the largest share, accounting for 32% of the total population. Cattle follow closely with 31%, and sheep make up 25.5%. The total livestock population in the sub-basin was found to be 1,975,922 TLU. The spatial distribution of current (Fig. S3A) and future (Fig. S3B) livestock population varies significantly across districts. By 2040, the livestock population in the sub-basin is projected to double.

The current annual livestock water demand is 18 MCM with significant spatial distribution across sub-basin, ranging from less than 0.1 MCM to over 2 MCM per district (Fig. 9A). Detailed district level current and future livestock population and associated water demands can be found in the supplementary material Table S6 and Table S7, respectively. Cattle are the largest consumer, accounting for 76% of the total water demand. By 2040, the annual livestock

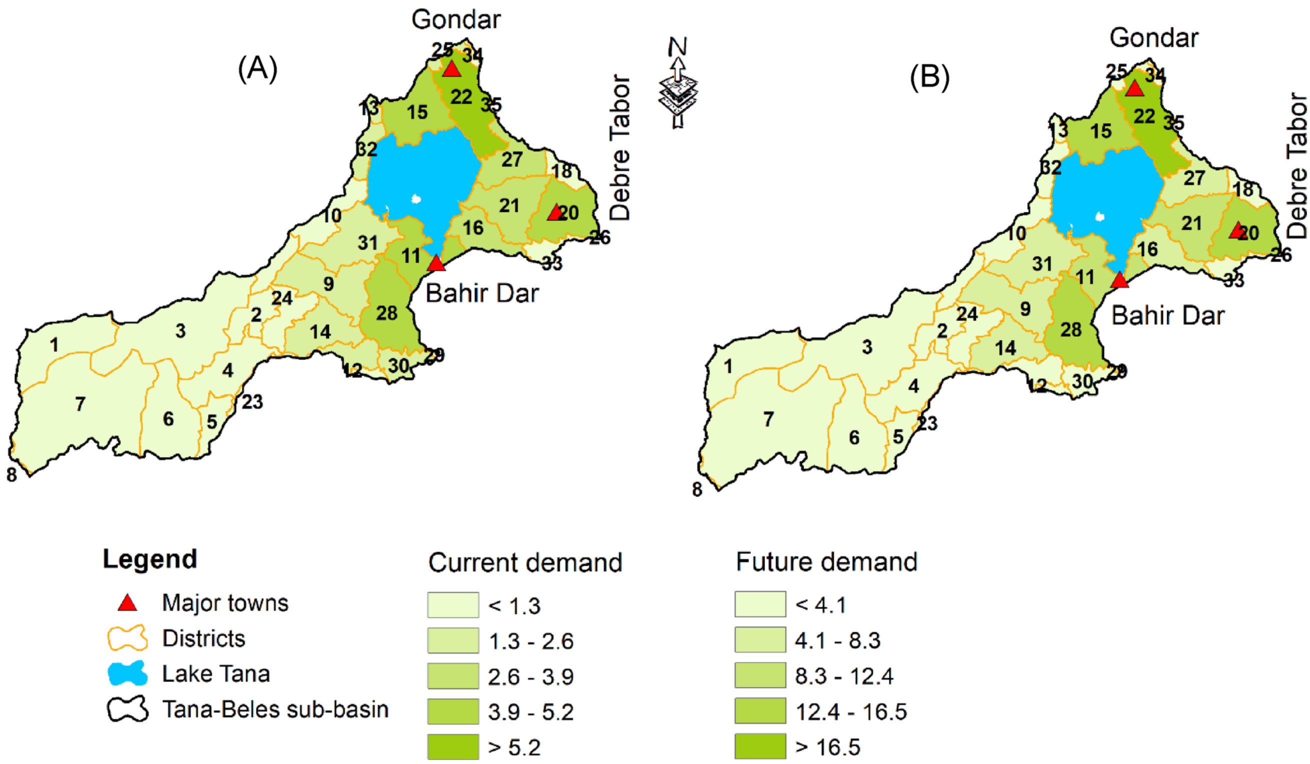

Fig. 8 Current (**A**), and future (**B**) domestic water demand in the Tana-Beles sub-basin. Refer to the supplementary material, Table S5, for the district map labels description

Table 4 Livestock population and annual water demand in the current and future scenario

Animals	Livestock population in 2022	Livestock population in 2040	Current water demand, MCM	Future (2040) water demand, MCM
Cattle	2,150,981	3,764,217	13.7	24.0
Sheep	1,786,821	3,680,851	1.6	3.4
Goats	393,842	1,216,972	0.4	1.1
Horses	54,564	99,306	0.4	0.7
Mules	41,648	87,461	0.2	0.4
Donkey	333,355	740,048	1.5	3.4
Poultry	2,238,872	4,880,741	0.2	0.4
Total	7,000,083	14,469,596	18.0	33.5

water demand is projected to increase by 86%, reaching 33.5 MCM with significant variation per district (Fig. 9B). Surface water serves as the primary source for livestock water consumption, as highlighted by Taye et al. (2022).

Industrial demands

According to Taye et al. (2022), most industries in the Tana-Beles sub-basin are concentrated in large towns, and their water demands have not been systematically documented. Annual water demand for hotels in the major towns is estimated to be 5.21 MCM. Dashen Brewery's water demand was estimated to be 0.72 MCM, while Moha Soft Drinks requires 0.47 MCM. Tana-Flora, another significant industry, has a water demand of 3.57 MCM. The Tana-Beles Sugar Factory, one of the largest industries in the sub-basin, needs 2.76 MCM of water. In addition, five other industries; Hileta Flour Factory, Asharf Agro-Industry, Gudar Agro-Industry, Amhara Plastic Factory, and Bahir Dar Edible Oil collectively demand 0.1 MCM per annum (ADSWE 2015). The total current industrial water demand in the sub-basin is estimated to be 12.8 MCM, with groundwater sources supplying 85% of the water used for processing (ADSWE 2015). By 2040, industrial water demand is projected to increase by 170%, reaching 34.6 MCM.

Total water demand

The total annual current and future water demands are 4.8 BCM and 7.8 BCM, respectively (Table 5). The monthly current total water demand fluctuation, Fig. 10A, showed that water demand peaks in March with 633 MCM and reaches its lowest point in July (261 MCM). A similar total water demand monthly pattern is observed in the future (Fig. 10B). Sectoral analysis revealed that energy and irrigation water demand constitute the vast majority, accounting for 98% of this demand in the current and future scenarios. Energy production dominates the current water demand, representing about 68% of the total, while irrigation accounts

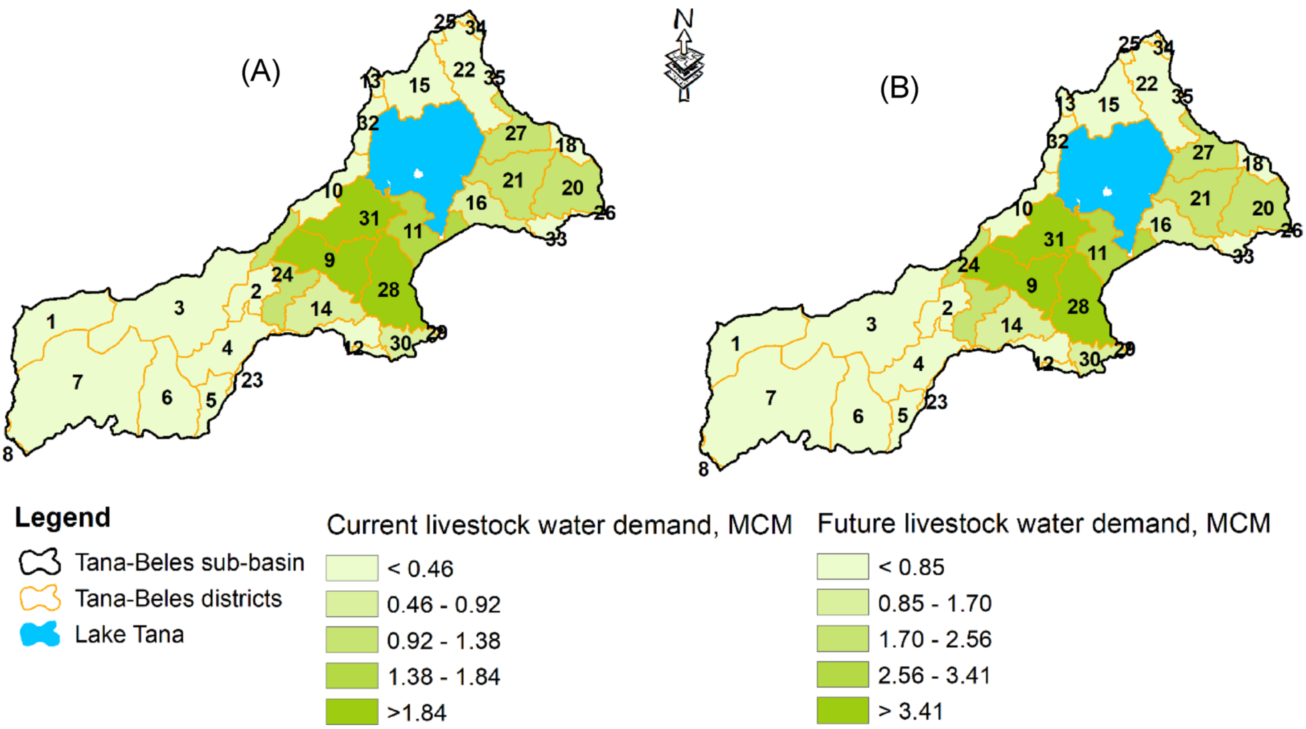

Fig. 9 Current (**A**), and future (**B**) livestock water demand in the Tana-Beles sub-basin. Refer to the supplementary material, Table S7, for the district map labels description

Table 5 Current and future annual water demands across various sectors in Tana-Beles sub-basin

Sector	Energy	Irrigation	Domestic	Livestock	Industries	Total
Current (MCM)	3277	1426	51.2	18	12.8	4785
Future (MCM)	3277	4387	103	33.4	34.6	7836
Change (%)	0	208	101	86	170	64

for 30% of the total. In the future, irrigation water demand will be dominant, accounting for 56% of the total, while energy accounts for 42% of the total. The combined water demands for domestic use, livestock, and industrial activities account for less than 2% of the total water demand in the current and future scenarios.

Usable water storage in the sub-basin

The usable water storage within the sub-basin exhibits significant temporal variation (Fig. 11A). The total water storage fluctuates from low (0.4 BCM) in May to peak value of 4.9 BCM in September. The annual usable water storage is derived from three primary sources: Lake Tana (2.1 BCM), groundwater (1.8 BCM), and reservoirs (0.3 BCM), which make up 4.2 BCM in total (Fig. 11B). The total annual usable water storage remains constant at 4.2 BCM for current and future scenarios. This assumes no additional planned water storage dams in the future. This stored water is meant to serve various demands, including irrigation, energy production, industries, domestic and livestock use.

Storage gap analysis

The current storage gap in the sub-basin is 613 MCM and projected to exhibit significant increase, reaching 3.7 BCM by 2040 (Fig. 12), an increase by five folds. Besides, it is vital to note the presence of geospatial constraints, which limit water availability for the spatially distributed demands within the sub-basin. Water withdrawals for energy and irrigation are the main contributors to the current storage gap , while irrigation expansion is the primary contributor to future storage gap. The larger percentage of expected expansion of irrigation areas are in the drier part of the basin (in Beles) requiring additional built storage. The irrigation expansion closer to Lake Tana is expected to use water from the lake requiring careful withdrawal not to impact the environment and ecosystems. Groundwater sources are not expected to be used for the potentially large-scale irrigation expansion. However, small-scale irrigation in parts of the basin is expected to intensify the use of groundwater.

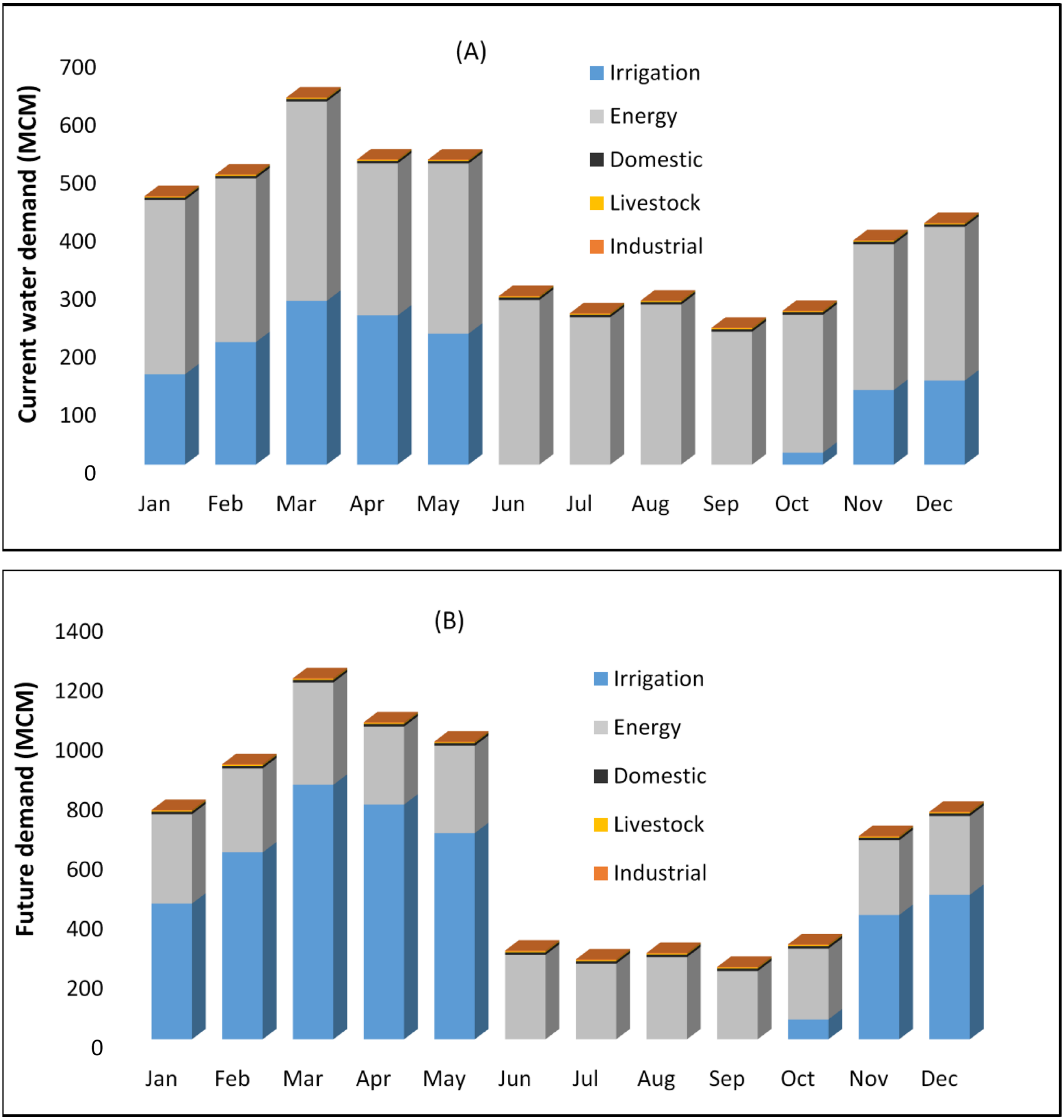

Fig. 10 Current (**A**) and future (**B**) monthly water demands for Tana-Beles sub-basin

Discussion

Current water storage gap

The reported current storage gap should be interpreted within the context of how water demands were estimated in this study. Demands across sectors, except for hydropower, were estimated based on standard service requirements and design capacities. The storage gap quantifies the structural deficit between the storage needed to meet all sectoral demands at standard service levels and the usable storage currently available. However, this gap is not merely a volumetric shortfall; it also reflects a spatial mismatch between where storage is located and where water is needed. The existing storage is mainly around the Lake Tana area and upstream of the sub-basin, whereas planned irrigation schemes, particularly lower Beles scheme; are located

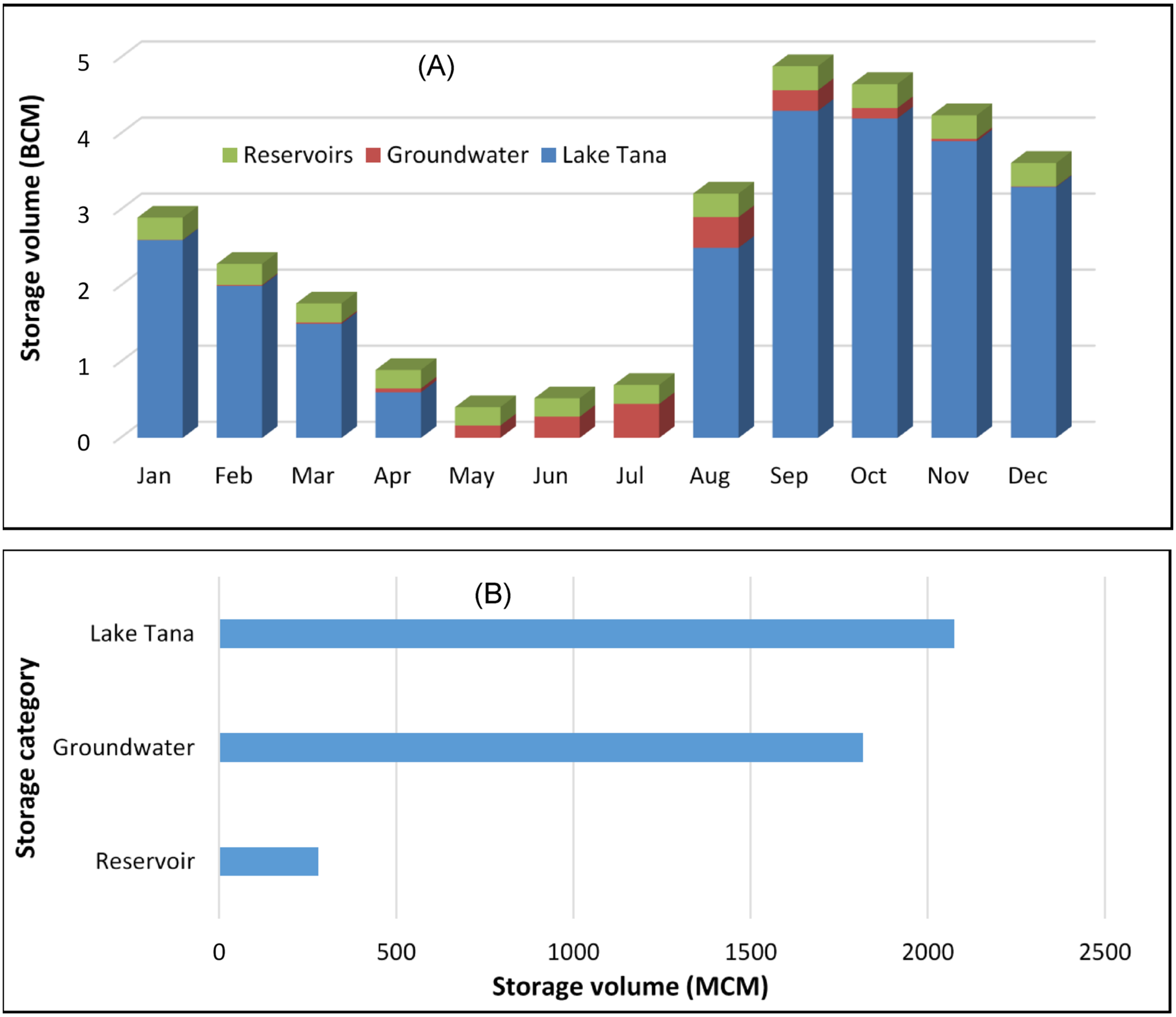

Fig. 11 Monthly usable storage variation (**A**), and annual usable storage (**B**) in the Tana-Beles sub-basin

downstream. This spatial disconnect means that even if sufficient storage volume existed, water would still need additional infrastructure and energy for pumping. The apparent ability of the system to function under this reported gap is largely explained by the fact that actual consumption remains below standard requirements, for example domestic water delivery is below the standard 60 l/day/capita for urban settings. The storage gap of 613 MCM therefore captures the scale of the planning and investment deficit, that is, the additional storage required to elevate service delivery to standard levels across all sectors.

While the current storage gap is modest in total volume, its uneven spatial distribution creates a significant challenge. This geographical mismatch between available storage and actual water needs in diverse locations underscores the need for spatially distributed storage options and strategic planning to ensure reliable access to water storage across all areas in the sub-basin. This can be done in various ways: i) placing water storage options such as small reservoirs across the basin, and ii) considering the use of groundwater where it is feasible. Given its distributed nature, groundwater offers a significant advantage by providing accessible water resources across the basin in a decentralized manner, thereby playing a crucial role in securing water availability for various needs; and iii) using water transfer schemes. A notable example exists in the basin, where an inter-basin transfer strategically diverts water from lake Tana to the Beles sub-basin. This transfer primarily supports the Tana-Beles hydropower project, and subsequently, the water discharge from this hydropower plant serves as a water source for the upper Beles irrigation scheme. It is worth noting that though the current storage gap volume is manageable, there

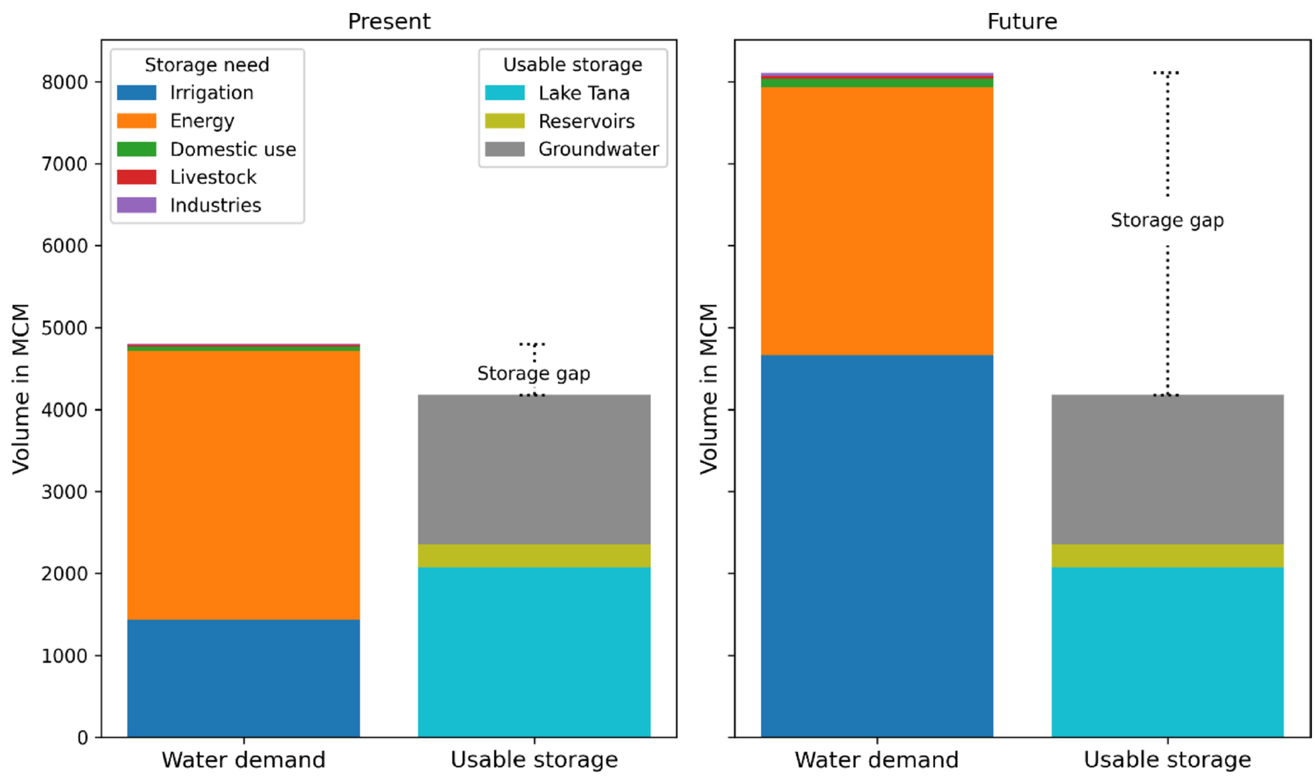

Fig. 12 Current and future water storage gaps in the Tana-Beles sub-basin

is spatial disparity between where demands (Figs. 4, 5, 8, and 9), and water storages (Fig. 1) are located.

Future water storage gap

The future projection shows a significant increase in the water storage gap. This is concerning given the increasing rate of sedimentation, proliferation of invasive water hyacinth, further reducing the lake storage volume, and the impact of climate change. Decreasing water storage coupled with increasing future demand will significantly increase storage gaps. Several studies in the sub-basin indicated that water storage volume is threatened by decline due to various reasons. Particularly, studies highlight threats to Lake Tana's water volume from invasive water hyacinth (Damtie et al. 2021), and sedimentation (Gebrekidan et al. 2020) due to poor agricultural practices and land degradation. Built-up reservoirs also exhibit similar threats to their storage volume due to sedimentation. Besides, global studies indicate that the availability of surface water storage is being further compromised by climate change (Yao et al. 2023). Consistent with this global pattern, Nigatu et al. (2022) reported soil moisture and groundwater depletion within the Tana-Beles sub-basin, attributing it to climate and land cover changes. This converging evidence of storage decline highlights a concerning and potentially worsening storage gap in the near future.

The sensitivity analysis reveals that the projected future storage gap varies between 3.4 BCM under a 5% evapotranspiration increase and 3.9 BCM under a 15% increase scenario compared to 3.7 BCM associated with our assumption (i.e., 10% increment). While evapotranspiration assumption introduces quantitative uncertainty, with a range of nearly 0.5 BCM across the three scenarios, the core finding is robust. Under all ET scenarios, the projected storage gap represents a five-fold or greater increase over the current gap and constitutes a critical water security challenge for the sub-basin by the 2040s. Refinement of demand projections using higher-resolution regional climate model outputs would further reduce this uncertainty and strengthen the precision of storage gap estimates.

Mechanisms to bridge water storage gap

Several effective strategies can help bridge the water storage gap. First, augmenting water availability by developing new sources such as constructing dams, drilling new wells, and implementing inter-basin transfers. Second, managing water demand plays a vital role. This includes implementing efficient irrigation systems, adopting water-saving technologies, and water reuse. In addition, Nouri et al. (2019) highlighted the need to shift towards improved cropping patterns and cultivating drought-tolerant crops to reduce the strain on existing water resources. Similarly, Assefa et al. (2018)

demonstrated the potential of conservation agriculture coupled with efficient irrigation systems to optimize irrigation water use.

Third, enhancing resources by increasing groundwater availability is paramount. Managed Aquifer Recharge (MAR) offers a promising path to replenish aquifers and maximize groundwater potential (Zhang et al. 2020). While groundwater presents substantial opportunities, its sustainable use hinges on a supportive environment and solutions to key challenges. This includes access to affordable and efficient water-lifting technology. Fourth, to enhance soil moisture storage, Yimam et al. (2020) revealed that conservation agriculture practice could enhance soil moisture by 4% to 10%, compared to traditional farming, depending on the specific crop.

Fifth, conjunctive management and use of both surface and groundwater resources represent another vital strategy for addressing the storage gap and improving water availability both spatially and temporally (Lautze et al. 2023). The sixth approach involves tackling reservoir volume decline by reducing reservoir sedimentation through watershed management and the implementation of effective soil conservation practices.

Limitations of this study

- Storage gap assessment is a complex task demanding a multitude of spatial and temporal datasets from multiple sources. Consequently, this study faced limitations primarily due to restricted access to certain datasets. The specific limitations are:
- *Static water storage assumption*: The analysis assumed consistent water storage capacities between the current and future scenarios. This assumption is grounded in recent empirical evidence specific to the Lake Tana region. While sedimentation-driven storage decline has been claimed in some contexts (Assefa et al. 2023), a comprehensive national-level quantitative water storage trend analysis from 1985 to 2023 found no consistent trend around the Lake Tana area (Getaneh et al. 2024). In addition, a detailed surface and sub-surface storage assessment in the Tana-Beles sub-basin for the period of 2013–2022 revealed no significant storage change over the decade (Taye et al. 2025). On the other hand, the construction of new storage infrastructure for future scenarios, such as the addition of reservoirs, expanded groundwater development, or wetland restoration represents a fundamentally different modeling scenario. Evaluating the water security implications of new water storage options require a separate scenario framework that explicitly models infrastructure expansion, investment timelines, and policy decisions that are beyond the scope of this analysis. Therefore, the constant storage assumption was maintained to ensure analytical clarity while acknowledging that any prospective storage development would require detailed scenario investigation.
- *Irrigation demand projections*: Future irrigation water demand was projected based on anticipated expansion of both small-scale and planned large-scale irrigation schemes. A key assumption was that all planned irrigation projects would be fully operational by the year 2040.
- *Industrial water demand estimation*: Due to a lack of specific data on water consumption across various industries, the estimation of industrial water demand relied on literature.

Conclusion and recommendations

This study quantifies potential water storage gaps in the Tana-Beles sub-basin by comparing current and future water demands across sectors with integrated usable water storages under climate change scenarios. Our findings reveal a critical and escalating water security crisis that demands urgent action. We conclude and recommend the following points:

- *Critical storage deficit*: the Tana-Beles sub-basin faces an alarming and widening water storage gap. This deficit is driven primarily by demands for irrigation expansion, far outpacing available usable water storage.
- *Sectoral demand imbalance*: energy production and irrigation collectively account for 98% of total demand. Notably, irrigation alone is projected to increase by 208%, creating the primary driver of the storage gap, highlighting that these are critical areas for water management intervention and optimization.
- *Dynamic Optimization and Water Allocation*: Implement a dynamic optimization and water allocation framework that can adapt to changing environmental conditions, sectoral demands, and climate variability, ensuring efficient and equitable water distribution.
- *Storage accessibility*: usable water storage is not evenly distributed, creating spatial accessibility challenges that limit its effectiveness in meeting demands across the entire sub-basin. This suggests the need for built storage in areas with limited groundwater and dry conditions.
- *Implementing integrated storage*: surface water, particularly Lake Tana, is the primary service provider in the sub-basin, with groundwater utilization mainly confined to domestic use, indicating a substantial potential for groundwater integration in irrigated agriculture.

- *Necessity of hydrological data monitoring*: estimating water storage gap is complex, requiring integration of diverse datasets and modeling, which highlights the need for robust data monitoring systems that include water availability and water use both spatially and temporally.
- *Action needed*: projected water storage deficits necessitate strategic interventions to ensure sustainable water resource management in the sub-basin through both natural and built water storage options.
- *Collaborative efforts:* collaborative efforts among government agencies, local communities, and other stakeholders would create a more sustainable and resilient future, enhance water availability and conserving the ecosystem simultaneously.

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Data availability All data used in this study are listed in the manuscript.

Declarations

Conflict of 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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