Research

Water storages in Tana-Beles sub-basin of Ethiopia: what do we know, and where should we go?

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Abstract

The Tana-Beles sub-basin, a strategic economic growth corridor in Ethiopia, relies on water storage to provide a suite of key services to agriculture, drinking water supply, energy, and ecosystems. While there are a range of storage options (e.g., from large dams to subsurface aquifers) that can be utilized to provide these services, a systematic stock-take of literature on water storage in the Tana-Beles has not been undertaken. This knowledge gap constrains the identification of the relative contribution of different storage types in the Tana-Beles. Accordingly, in this study, we conducted a systematic review of literature on the surface and sub-surface storages to examine key issues of the different storage types and their linkages in the Tana-Beles sub-basin. Peer-reviewed and grey publications from various databases were considered for the systematic review. The results indicate that literature in the Tana-Beles sub-basin is more focused on natural storage like wetlands and Lake Tana than built storage types like human-made reservoirs. Overall, the analysis revealed three key points. First, storage volume and water quality in those storages are declining. Second, the causal factors for storage loss and water quality deterioration are agricultural expansion, land degradation, sedimentation, and increasing water withdrawals. Third, the storage gap will increase because of climate change, population, and economic growth while current management options are fragmented. Therefore, the need for more integrated nexus approaches is paramount to optimize storage resources in water, food, energy, and ecosystems in light of population-driven growth in demand and the ongoing global climate crisis.

Article Highlights

- Water storage volume and water quality in the Tana-Beles sub-basin declined over time.
- Expansion of agriculture, land degradation, and sedimentation are factors for water storage decline.
- Water storage gaps are expected to rise due to climate change, population, and economic growth.

Keywords Water storage · Tana-Beles sub-basin · Nexus approach · Storage gap

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1 Introduction

Water storages have essential functions in societal, economic, and ecosystem dimensions, which assist in managing uncertainties and variabilities that can enhance adaptive capacity and resilience [1]. Storages can be natural or built, and water can be stored on the surface or underground. Around the globe water storage needs are increasing to meet the demands of the ever-increasing population, resulting in storage gaps (i.e., the gap between required and available storage) that need to be addressed [1–3]. The concept of integrated storage is introduced, which considers all storage facilities, surface and sub-surface, as part of a larger integrated system, instead of individual storage, for improved resilience in water management and services [1, 4]. Such management addresses the competing water demands for food and energy production while sustaining healthy ecosystems and promoting nexus thinking.

The Tana-Beles sub-basin of Ethiopia can serve as a representative example for implementing the nexus approach due to its complex interconnection of water, food, energy, and the ecosystem. It has substantial potential for hydropower and irrigation with several dams and weirs constructed or planned to support the livelihood of local communities. Both natural and built storage is being used to provide services to human needs and the ecosystem. The sub-basin is also the home to the Blue Nile River, a major tributary to the Nile River that crosses Sudan and Egypt to reach the Mediterranean Sea. On the other hand, the changes in climate such as rainfall variability, frequency of drought and flood, and temperature rise would affect the availability and quality of water resources, agricultural and energy productivity, and consumption [5, 6]. Understanding key issues in the different types of storage and their linkage is essential to effectively utilize integrated storage management. Given the presence of various sectors in the sub-basin the benefits of integrated storage management will be important for water-energy-food-ecosystem (WEFE) nexus thinking and management.

In addition, the Tana-Beles sub-basin constitutes one of the country's economic growth corridors, particularly for irrigation and energy development [7]. To support these developments and drinking water supply, the sub-basin has six dams that are currently operational and more than five that are planned to serve for irrigation and drinking water supply. The Tana-Beles hydroelectric power plant, fed by water transfer from Lake Tana, provides a key energy service in the sub-basin. Small-scale irrigation activities are expanding in the sub-basin mainly from surface water sources, where nearly 50% of the dry season flows are being used for small-scale irrigation in the Lake Tana sub-basin alone [8]. Agricultural expansion in the Tana part of the sub-basin is evidenced by the increase in farmlands as shown by Getachew and Manjunatha [9] with an increase of 35% from 1989 to 2019. The Beles part of the sub-basin is also expected to host large irrigation schemes to irrigate more than 135,000 ha command area [10] signifying the importance of the sub-basin.

Other than irrigation and hydropower, the Tana-Beles sub-basin is rich in biodiversity, fishery, tourist industry, and bird habitats mainly because of the lake and the presence of wetlands in the area [11]. Livelihood in the sub-basin is mainly dependent on agriculture; crop production, to a lesser extent, livestock, and fishery [12]. Other livelihoods in the sub-basin include navigation for transport and tourism [12], blacksmithing, and carpentry.

Despite the current and growing role of storage to support the economic activities of the Tana-Beles storage, no comprehensive analysis has been conducted to understand the available data and the knowledge gaps on the topic. For instance, previous studies investigated the ecological status and threats of wetlands, and the role of wetlands in food security [13–15]. Similarly, others investigated the water quality deterioration of Lake Tana and the impacts of pump irrigation from the Lake [16–18]. Groundwater and soil moisture storage changes from excessive water extraction and landscape interventions were also investigated [19–21]. On the other hand, built storage was examined by some studies; reservoirs [22–24], and water harvesting ponds [25–27]. Compiling and understanding past studies can provide important insights into key areas of research to focus on going forward using nexus thinking. To date, there is no such effort found in the literature that provides key insights into the different storages in the Tana-Beles sub-basin with the aim of understanding proper usage and finding solutions for current challenges as it is an important tool for climate change adaptation.

There are several ways to conduct a literature review depending on the focus of the review [28] which include systematic, narrative, descriptive, and critical reviews [29, 30]. A systematic review is a commonly used approach to analyze a wide range of data and literature on a specific topic with pre-defined criteria [31]. Machine learning (ML) and artificial intelligence (AI) can be used to reinforce human findings to support human-derived systematic review [32] but can introduce bias including non-existent publications and language biases [33, 34], which warrants caution in using them. The systematic review employs an explicit technique to monitor bias in the selection and evaluation of studies by searching multiple databases including grey and unpublished studies [35, 36].

The main objectives of this paper are, therefore, to conduct a systematic review analysis of the literature and provide key insights about surface and sub-surface storage in the Lake Tana and Beles sub-basin. Achieving this objective requires identification and analysis of (1) storage considerations and services, (2) storage critical issues and performance indicators, and (3) suggested storage management options. The findings from this systematic review provide evidence on key storage issues, knowledge gaps, and research direction for researchers and decision-makers in light of the water, energy, food, and ecosystems (WEFE) nexus approach.

2 Methods

2.1 Study area

Tana-Beles sub-basin is located between 35 to 38.2° E and 10.3 to 12.8° N, covering a total area of about 29,200 km^2 and elevation ranging from 515 to 4000 m asl (Fig. 1). The sub-basin contains the largest lake in Ethiopia, Lake Tana [37], and wetlands surrounding the Lake and on the sides of rivers. The mean annual rainfall of Lake Tana and Beles parts of the sub-basin is 1400 mm [38] and 1490 mm [39], respectively. Tana-Beles sub-basin is dominated by a tropical highland monsoon climate and receives most of its annual rainfall from June to September; 70 to 90% [40] and 70 to 80% [41] of the annual rainfall in Lake Tana and Beles parts, respectively. The temperature of the Lake Tana part ranges from 9 to 28 °C [42] and the temperature in the Beles part ranges from 16 to 33 °C [43]. The climate in the Beles ranges from near desert-like in the far southwest region at low elevations to tropical monsoon in the higher elevations near the Tana border [44]. The sub-basin is rich in biodiversity [39, 45].

2.2 Literature search and selection criteria

First, we defined keywords for water storage based on systematic review procedures described in Pickering and Byrne [46]. The literature search used the following keywords "Lake Tana", "wetlands", "ponds", "reservoir", "weirs", "groundwater", "soil moisture", "hydrology", "water quantity", and "water quality". These keywords were combined one by one with the study's geographical location ("Lake Tana sub-basin", "Lake Tana basin", "Beles sub-basin) using the conjunctive "and" during the search. In addition, the snowball approach was used if a keyword search did not satisfy the search. The snowball approach refers to tracking literature from the citation of other target papers. In the second stage, we identified or selected the search database. Publications were collected from Google Scholar (https://scholar.google.com/), Science Direct (https://www.sciencedirect.com/), Springer (https://link.springer.com/), and Tayler and Francis (https://www.tandfonline.com/) as shown in Fig. 2. The types of publications

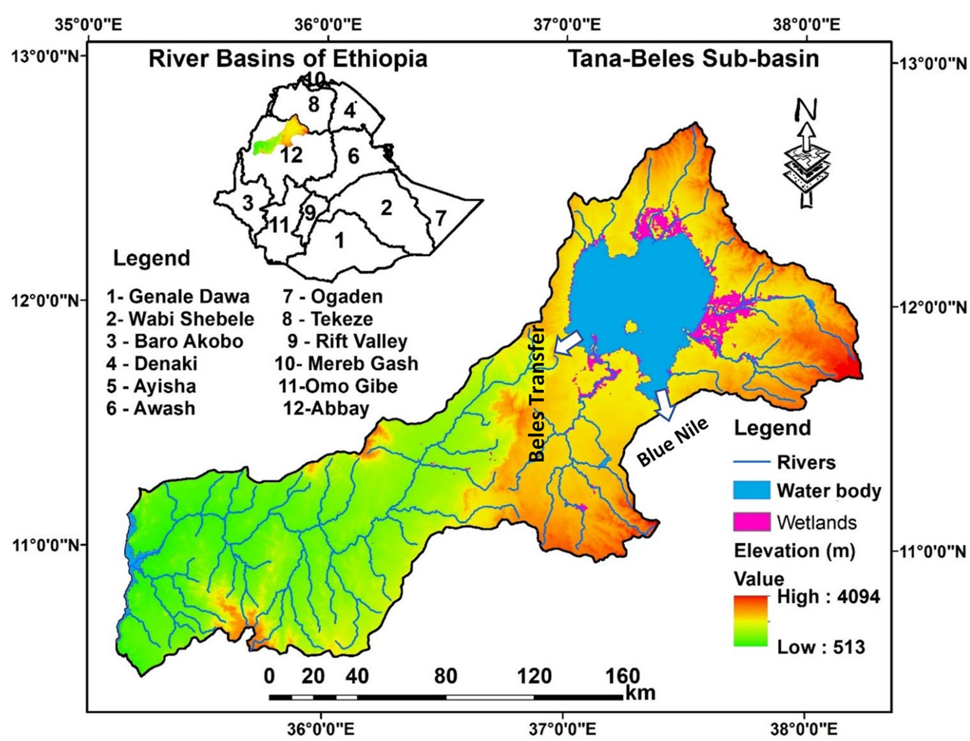


Fig. 1 Location of Tana-Beles sub-basin, elevation variation, and water bodies

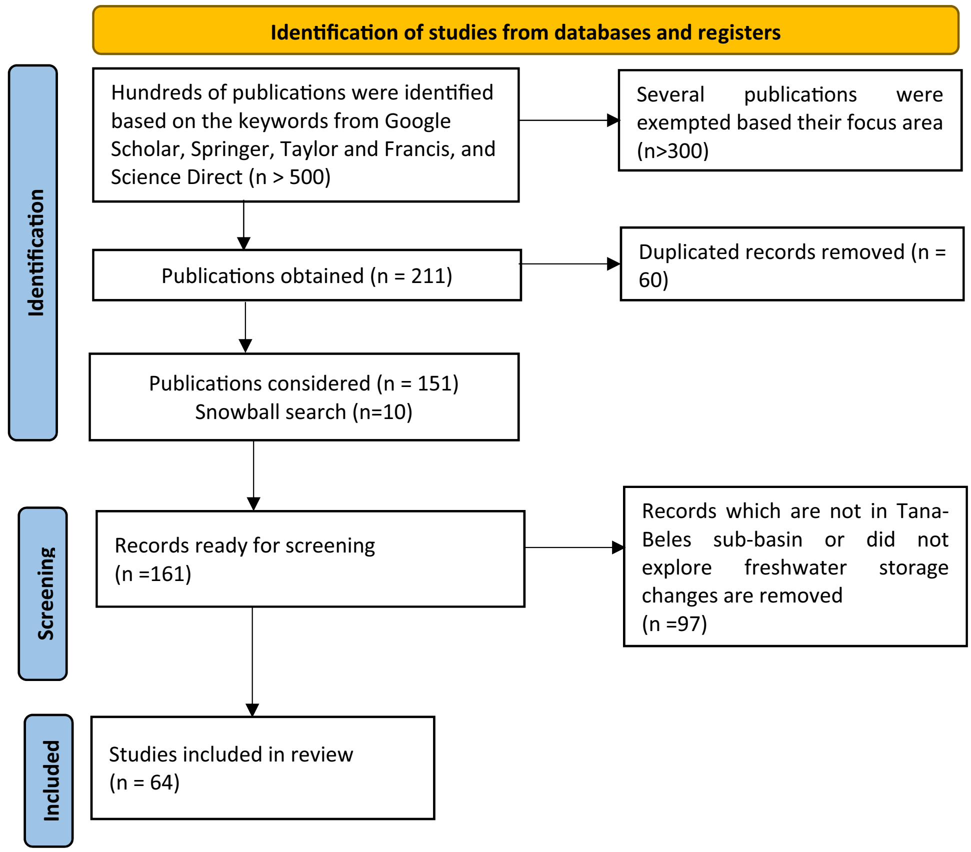


Fig. 2 PRISMA flow diagram on article search and selection methods used in the systematic analysis. 'n' in the flow diagram refers to the number of publications

collected were peer-reviewed articles, book chapters, reports, and Ph.D. and M.Sc. thesis works.

Hundreds of publications were identified from the databases per search and then filtered based on their focus area. A total of 211 publications were collected on water storage from the four databases. There were duplicated records, 60 in total, which were removed from the original list. Snowball's collection of literature resulted in additional 10 publications. In the third stage, we applied screening criteria for the publications. Two screening criteria were applied; firstly, publications needed to explore surface or sub-surface water storage seasonal or long-term changes. The second criterion was making sure geographically the study focus areas were in Tana or Beles sub-basin. A total of 64 publications (see "Appendix" for a comprehensive list) passed the screening criteria from a total of 161 publications. These were considered for the s systematic review in this study. The publication's temporal scale ranges from 1940 to 2022 in terms of the data used in their analysis and from 2003 to 2022 in terms of their publication year.

2.3 Articles' organization and analysis

An Excel tabular template was developed to organize the collected articles based on selected parameters that the articles focused on or studied. First, article registration was done by providing a unique identifier in the template for those publications that passed the screening criteria and were imported to the Endnote 7 library [47]. Relevant information was extracted from the articles which include the year of publication, authors, the title of publication, and spatial and temporal scale of the studies (the list of articles with some of the extracted information can be found in the "Appendix"). This was followed by extracting variables of interest for this systematic review. These include the investigated storage type, the geographic location of the studies, applied storage performance indicators, addressed storage critical issues and suggested storage management options. The percentage of the article count was used to examine the frequency of the studied variable of interest. The lower percentage of articles that cover the variable of interest shows a higher probability of the research gap in the topic.

3 Results

3.1 Major storage research focus themes

Surface and sub-surface storages in Tana-Beles sub-basin can be broadly categorized into natural and built storages (Fig. 3). The natural storage consisted of Lake Tana,

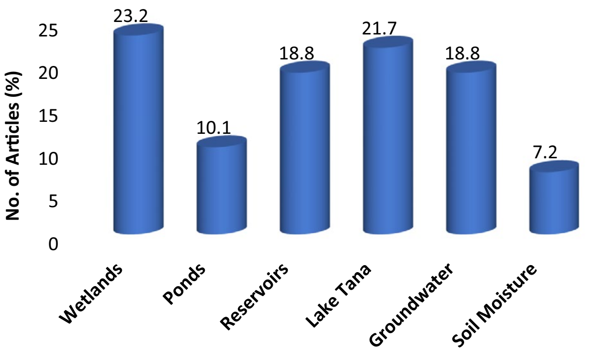


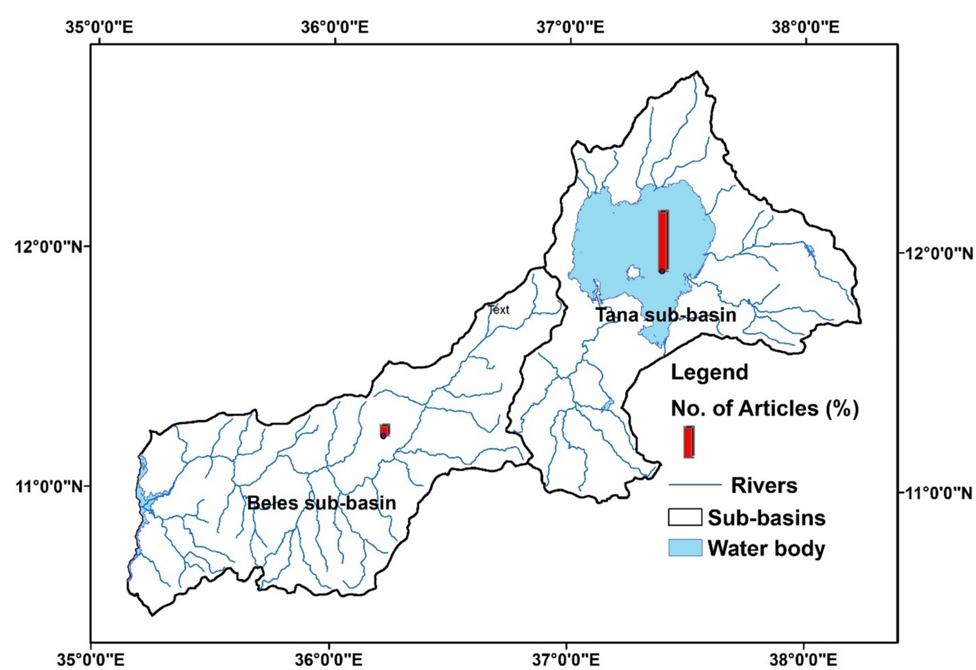
Fig. 3 Articles research focus areas on the different storage types in the Tana-Beles sub-basin expressed as the percentage of total articles reviewed

wetlands, groundwater, and soil moisture. Whereas the built storage consisted of dam reservoirs and ponds. Most of the studies in the sub-basin were focused on natural storage (71% of the articles) than built storage (29% of the articles). Built storage in the sub-basin includes dam reservoirs and water harvesting ponds. There are six dams in the sub-basin that currently store water. Koga Dam was the earliest in the sub-basin which was completed in 2002 and was operational in 2010 [48] and Selameko was completed in 2007 [49]. The construction of water harvesting ponds was promoted in the early 2000s [26].

Article distribution among storage types showed that studies about wetlands were leading by accounting for 23% of articles followed by studies focusing on Lake Tana, which accounts for 22% of the articles. Given the importance of the wetlands and the lake for different livelihoods in the sub-basin, more studies on these natural resources are expected. In line with this, the studies on the wetlands explored mainly wetland degradation in size and quality affecting its services for the community and environment [13, 50–52]. Studies about groundwater and built reservoir storage account for equal shares in the total articles (19% each). The studies that focused on Lake Tana, built reservoirs, groundwater, and soil moisture mostly explored freshwater storage loss, volume, and quality deterioration that were affecting the intended services for humans and ecosystems [9, 21, 53–55]. Water harvesting ponds and soil moisture accounts for 10% and 7% of the articles, respectively. The articles on water harvesting ponds were mainly focused on infrastructure issues affecting performance and services [56–58].

In terms of the relative concentration of research on the two parts of the sub-basin, most of the studies were focused on the Lake Tana sub-basin (86%) than the Beles sub-basin (14%) as shown in Fig. 4. This could be due to the relatively high hydrological data availability (length, spatial coverage, and quality) in the Lake Tana sub-basin [8]. The second reason could be the accessibility of the different surface storage in the Lake Tana sub-basin part as compared to the Beles sub-basin part [59]. The third reason could be the desert-like weather of the Beles sub-basin [44]. Additionally, [60] argues that the lower part of the Beles basin has been considered the periphery of the country, which indicates less economic activity in the region and thus less research outputs about the basin.

Fig. 4 Articles research focuses on the sub-basin, geographical location divided into the Tana and Beles parts



3.2 Historical trend of scientific publications

In terms of historical trends of storage studies, the earliest publication was in 2003 about water harvesting pond challenges [56] followed by groundwater contribution to Lake Tana [61]. There was at least one publication on the different storage types by 2014. In general, the number of publications about storage showed an increasing trend from 2003 to 2022, with the highest publication record in 2017 (i.e., 12 articles) (Fig. 5). In terms of storage types, wetlands were the most frequently studied, with a total of 16 articles, followed by Lake Tana (15 articles). In contrast, soil moisture was the least studied storage type, with a total of 7 articles.

3.3 Storage services

Most articles consider storage as a means of enhancing food security, drinking water supply, energy, ecosystem services (i.e., biodiversity and environmental services), and tourism. Several storage services were identified in the articles including farming, hydropower, ecosystem, fishery, drinking water supply, livestock water supply, grazing, tourism, nutrient trap, sediment retention, and carbon sequestration. While almost all studies discuss one storage service per storage type a total of five broad categories were used to represent the different storage services discussed in the articles. These were agriculture, the ecosystem, water supply, tourism, and energy (Fig. 6). Most of the studies considered agriculture as the main storage service (44.5%) which is in line with the dominant livelihood of the sub-basin, farming. Ecosystem services were the second dominant storage service (38.2%) in the sub-basin given the importance of the lake and wetlands. Water supply, tourism, and energy services were present in 10.9%, 3.6%, and 2.7% of the articles, respectively. When looking at storage services by individual storage types, Lake Tana provides all the identified five services while wetlands provide the same services except hydropower. Built-in reservoirs and groundwater storages were mostly for agriculture, domestic water supply, and ecosystem services while water harvesting ponds provide agriculture and water supply services. Soil moisture storage was mainly used for agricultural purposes. Most of the sub-surface storage services were focused on domestic water supply which could be due to the difficulties or the demand for technologies in accessing those storages.

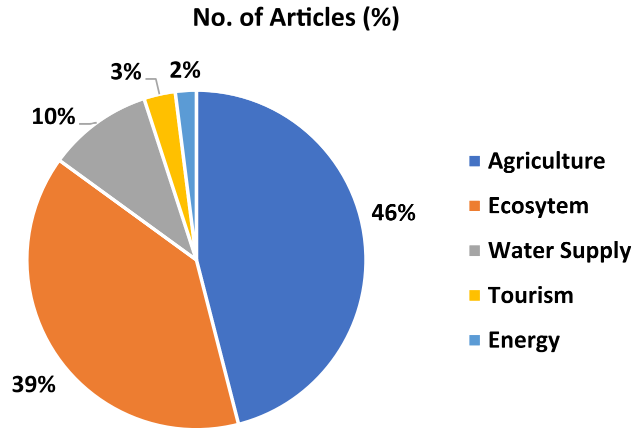


Fig. 6 Major storage services in the Tana-Beles sub-basin discussed in the reviewed articles

3.4 Storage performance indicators

Several indicators were used in the articles to measure critical storage parameters. These indicators were categorized

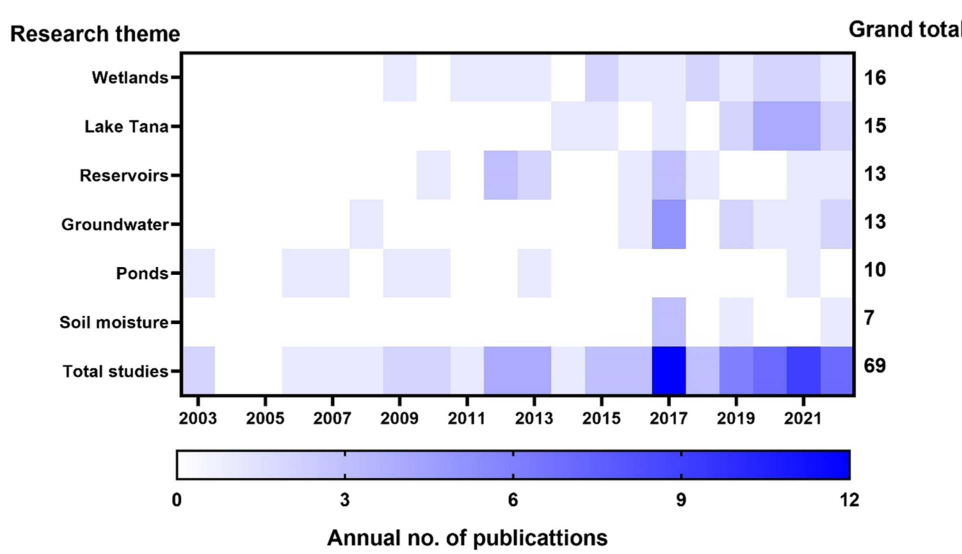


Fig. 5 Historical trends of literature on the different storage types during 2003–2021

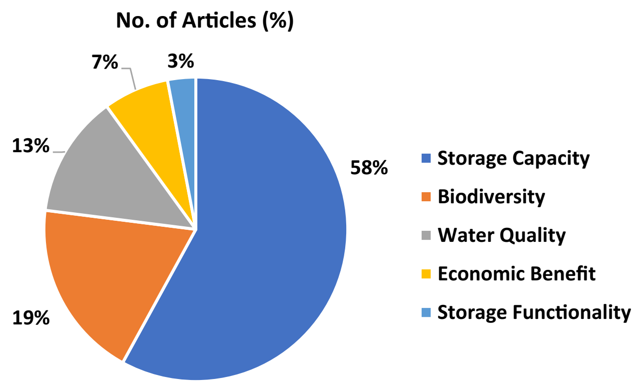


Fig. 7 Major storage performance indicators in Tana-Beles sub-basin

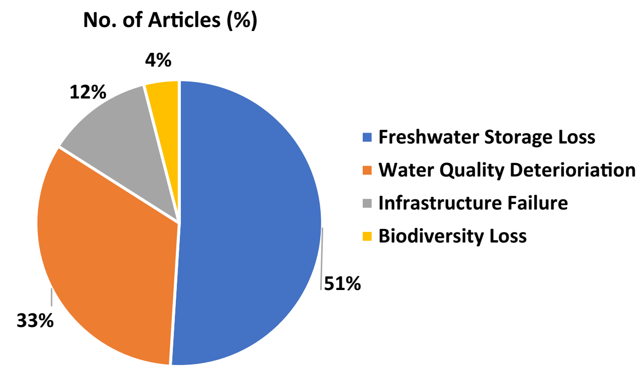


Fig. 8 Four critical freshwater storage issues identified in Tana-Beles sub-basin

into five broad terms: storage capacity, biodiversity, water quality, economic benefit, and storage functionalities (Fig. 7). The storage capacity indicators were water quantity, sedimentation, wetland size, reservoir volume or area, lake level fluctuation, lake evaporation, irrigation withdrawal, and water availability. Similarly, the biodiversity indicators were fish or micro-invertebrate or aquatic animal abundance, phytoplankton density, biodiversity loss, water hyacinth coverage, nutrient trap efficiency, and carbon sequestration. The water quality indicators include different water quality parameters such as nitrogen and phosphorous. Whereas, the economic indicators include income, expenditure, food self-sufficiency, and asset holding. The storage functionality indicator includes infrastructure reliability and resilience. Among the five broad storage indicators, storage capacity was the most repeatedly used indicator in the articles (56.6%). This was followed by biodiversity (18.9%) and water quality (13.2%) indicators, which were also major concerns in the sub-basin. For instance, [62–64] indicated that water hyacinth expansion over Lake Tana resulted in the loss of fish populations. Economic benefit and storage functionality was associated with water harvesting ponds and accounted for 7.5% and 3.8% of storage issues in the literature. This was due to mainly the frequent infrastructure failure or functionality issues and the concern about the economic return of water harvesting ponds. The first three major indicators (storage capacity, biodiversity, and water quality) have been used for wetlands, Lake Tana, and built-in reservoir storage. The evidence from the studies showed that the critical issue associated with surface and sub-surface storage was mainly on storage capacity.

3.5 Critical storage issues

There are several storage issues discussed in the articles which can be categorized into four broad terms: freshwater storage loss, water quality deterioration, infrastructure failure, and biodiversity loss (Fig. 8). Sedimentation, draining wetlands or water loss, irrigation, urbanization, eucalyptus tree plantation, pond size, and climate change were grouped into freshwater water storage loss issues. On the other hand, farming, nutrient loading, solid waste disposal, and overgrazing were used to indicate water quality deterioration issues. The infrastructure failure issue includes poor site selection, design and construction, shortage of construction material, large labor need, limited economic return, and waterborne diseases. Whereas the issues associated with biodiversity loss include water hyacinth, leather tanning, and vegetation clearance. Among the four broad storage issue categories, freshwater storage loss was the dominant storage issue discussed in the articles (50.4%), which goes in line with the observed water scarcity challenges in the face of climate change and population growth. This was followed by water quality deterioration (32.7%) and infrastructure failure (12.4%). The additional storage issue discussed in the articles was biodiversity loss (4.4%). Some storage issues were associated with particular storage types. For instance, infrastructure failure issues in the articles were associated with water harvesting ponds [26, 65, 66]. Biodiversity loss was associated with wetlands and Lake Tana, whereas freshwater storage loss encompasses all identified storage types.

3.6 Suggested storage management options

The systematic review indicated that several management options could be applied for sustainable storage management. These could be categorized into four broad terms: context-based water harvesting systems, integrated watershed management, improving institutional policies and practices, and optimal sub-surface water use (Fig. 9). Integrated watershed management

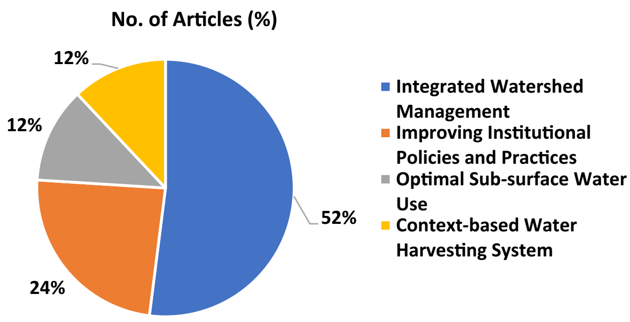


Fig. 9 Frequently suggested storage management options in the Tana-Beles sub-basin

in the articles refers to the management of both storage and catchment draining to the storage [17, 67, 68]. The management includes wetland conservation, catchment management, waste management, biodiversity conservation, irrigation and water management, and water hyacinth management strategies. Improving institutional practices refers to the institutional settings to plan, design and implement appropriate management strategies and collaboration with stakeholders for a similar objective [52, 69]. It includes land use planning and management, wetland regulation, storage database development, stakeholder collaboration, policy change on storage, and enacted buffer zone protection, particularly around wetlands and Lake Tana. Optimal subsurface water use includes soil moisture conservation and groundwater use that depicts the collection and conservation of water in the sub-surface [56, 70]. Integrated watershed management was the most repeatedly suggested storage management option in the articles (51.8%) followed by improving institutional policies and practices which accounted for 23.2% of the articles. The rest of the two groups account for 12.5% each mainly targeting sub-surface storages and water harvesting ponds.

3.7 Synthesis of findings on storage in Tana-Beles sub-basin

We provided a synthesis of findings (Table 1) on the different storage types in the Tana-Beles sub-basin and selected parameters (i.e., prevailing conditions, causal factors, and management options. Here are six overarching threads that stood out from the analysis.

Table 1 Synthesis of findings on prevailing storage conditions, causal factors, and management options in the reviewed literature

Storages	Variables	Prevailing conditions	Causal factors	Management options
Wetlands	Storage volume	Declining [51, 52]	Agricultural expansion [51, 52], draining water [51]	Wetland conservation [13, 50, 51]
	Water quality	Declining [50]	Sedimentation and nutrient loading [50, 79],	Waste management [80]
	Biodiversity	Declining [76]	Agricultural expansion [76]	Biodiversity conservation [81]
Lake Tana	Storage volume	Declining [16, 54, 71]	Sedimentation [54], water hyacinth [71], agriculture, and energy withdrawal [16]	Catchment and Lake management [17, 54, 78]
	Water quality	Declining [55, 73]	Sedimentation and nutrient loading [55, 73], water hyacinth [82]	Catchment and wetland management [83, 84]
	Biodiversity	Declining [55, 77, 78]	Water quality deterioration [55, 77], and water hyacinth expansion [63, 78]	Catchment and Lake management [55, 84]
Built-in reservoirs	Storage volume	Declining [24, 53]	Sedimentation [24, 53],	Catchment and reservoir management [22, 85–87]
	Water quality	Declining [49]	Sedimentation and nutrient loading [49]	Catchment and reservoir management [49, 88]
	Biodiversity	Declining [53]	Nutrient loading [53]	Catchment management [53]
Groundwater	Storage volume	Declining [9, 19, 72]	Land degradation [19], agricultural & built-up area expansion [9, 72]	Upland restoration [19, 72]
	Water quality	Declining [74, 75]	Nutrient loading into wells [74, 75]	Waste management [74, 89]
Ponds	Storage volume	Declining [56, 65]	Sedimentation [56], leakage [65]	Re-thinking of pond design [27]
	Infrastructure failure	Increasing [26]	Site selection, design, and construction [26]	Re-thinking of pond planning, design, and construction [66, 90]
Soil moisture	Storage Volume	Declining [21]	Agricultural expansion [21]	Catchment management [91]

3.7.1 First, storage volume is decreasing

Previous studies depicted that storage volume in the sub-basin is declining regardless of the storage type; wetlands [51, 52], Lake Tana [16, 54, 71], built-in reservoirs [24, 53], water harvesting ponds, groundwater [9, 19, 72], and soil moisture [21].

Factors driving storage decreases vary. In wetlands, agricultural expansion (i.e., conversion of wetlands into farmland) and draining water for domestic use and irrigation [51, 52] are the main causal factors for the storage volume decline. For instance, Wubie, Assen [52] indicated that wetlands in the Gumara watershed declined by more than 72% from the year 1957 to 2005. In Lake Tana, sedimentation [54], water withdrawal for agriculture and energy [16], and water hyacinth [71] are the factors for the decline of lake storage. For instance, Lemma, Frankl [54] showed that about 30 million tons of sediment are deposited into the Lake and only 3% of these leave the Lake through the two outlets (i.e., Blue Nile River and Beles transfer). Sedimentation is the main causal factor for the decline of storage volume in reservoirs and water-harvesting ponds [24, 53]. Land degradation [19] because of farmland expansion [21] and expansion of built-up areas [9, 72] are the main causal factors for the decline of groundwater and soil moisture storage volume. In terms of the rate of decline water-harvesting ponds failed faster than other storage types, followed by wetlands' rate of decline which were changed to agricultural land and impacted by sedimentation.

3.7.2 Second, water quality of storage is declining

In addition to storage volume, previous studies indicated that storage water quality in the sub-basin is declining regardless of storage types; wetlands [50], Lake Tana [55, 73], built-up reservoirs [49], ponds [26], and groundwater [9, 19, 72]. There were no studies that indicate the water quality status of water harvesting ponds and soil moisture in the sub-basin. The main causal factors for storage quality deterioration are sedimentation and nutrient loading on wetlands [50], Lake Tana [55, 73], and built-up reservoirs [49]. This is due to the expansion of farmland and urban areas. Water hyacinth is the other causal factor for Lake Tana's water quality deterioration [63]. Similarly, contaminant loading into groundwater wells from agricultural and urban areas was the main causal factor for groundwater quality issues [74, 75].

3.7.3 Third, biodiversity is under threat

Studies mainly associated the reduction of biodiversity with the decline of storage in quantity and quality. Biodiversity loss is observed in wetlands [76], Lake Tana [55, 73], and built-up reservoirs [53, 77]. Studies were not found associating biodiversity loss with ponds and sub-surface storage (i.e., soil moisture and groundwater). Farmland expansion is the causal factor for the decline of biodiversity in wetlands, affecting both the quantity and quality of the storage. While in Lake Tana, water quality deterioration [55, 77] and expansion of water hyacinth [63, 78] are the main causal factors for its biodiversity loss. For built-up reservoirs, nutrient loading from catchments is the main causal factor for their biodiversity loss [53].

3.7.4 Fourth, the storage gap will increase

Studies have shown that climate change and variability are among the concerns regarding storage in the Tana-Beles sub-basin affecting water availability [92, 93]. In the future, climate change projected as increases in temperature, evapotranspiration and uncertainty in rainfall amount, will exacerbate challenges since the inadequate water storage infrastructure will not meet the increasing demand [94]. A reduction in water availability due to climate change and inadequate infrastructure is already affecting the livelihoods of local communities that depend on water resources [12]. The World Food Program, WFP, estimated that more than 20 million people in Ethiopia require food assistance in 2022 due to various reasons (https://www.wfp.org/countries/ethiopia). Records show that Ethiopia has been under a food deficit since the 1980s [95] while the population of Ethiopia is expected to reach nearly 145 million in 2030 [96].

Several studies in the sub-basin indicated the need to utilize both rainfed and irrigated agriculture [97–99] to overcome the food insecurity challenge. However, irrigation is about 5% of the potential in the Lake Tana sub-basin [100], and in Ethiopia in general [101, 102]. Likewise, only 46% of the population in Ethiopia has electricity access in 2016 [103, 104] partly due to a lack of storage. Similarly, the domestic water supply has below 50% coverage in the country [105]. It is evidenced that the various water service demands in Ethiopia are not currently met. These shortages in service delivery are linked to a huge storage gap to secure food, energy, and drinking water supply. With the alarming rise in population and the high climate variability in the nation, the need for storage keeps rising and storage gaps continue to widen.

3.7.5 Fifth, suggested management options are diverse but they require integration

There are several references to catchment and lake management, upland restoration, conservation, and waste management activities to minimize storage volume losses and reverse water quality deterioration of wetlands, the lake, and built reservoirs. However, since studies were mostly focused on single storage types how these management options can be implemented in a holistic manner is not clearly indicated. Additionally, since the failure of water harvesting ponds in the past was mainly associated with poor site selection, design, and construction, proper project planning and implementation of these storage structures were suggested to be considered in the future [66, 90]. In addition, when constructing large reservoirs holistic approach is required to minimize inappropriate water use [106]. Storage management options may benefit from considering the geomorphology of the area due to its significant role in affecting water availability, distribution, and movement [5]. Astuti, Annys [107] indicated that hydrologic connectivity of the two parts in the Tana-Beles sub-basin are given less attention, which would have benefited soil and water conservation activities that can enhance water storage [108, 109].

Thus, nexus thinking [110, 111] and a holistic approach are needed to manage storage and deliver services to the ever-increasing demand. Aspects of the nexus approach on both the supply and demand side are needed. On the supply front, the use of integrated storage will provide more access to the water resources while on the demand side, there must be optimized use of water from the different storages. For instance, optimizing the allocation of water withdrawals from different storages is important.

4 Conclusions

The systematic review reflected in this paper constitutes the first holistic assessment of knowledge on surface and sub-surface storage types and associated key issues in the Tana–Beles sub-basin. Less than 5% of studies have considered different storages together as a system of integrated resources in the Tana Beles, and such efforts were limited to assessing the soil moisture and shallow groundwater storage types. No studies examined all storage options together, which could support the optimization of the use of storage resources toward the realization of nexus outcomes. Such knowledge gap means that available storages are not optimized, which limits the WEFE benefits that can be derived from water management practices in the sub-basin.

The results of this paper can be distilled into three headlines. First, storage volume and water quality in those storages are declining. While this trend is consistent with other literature (e.g., Yu, Rex [1]), the results in our paper are believed to be the first to confirm such a trend across storage types in a particular geography. Related, concurrent declines in quantity and quality had not been widely identified. Nonetheless, while evidence is tentative, it appears relative rates of decline are not uniform. Future investigation may be undertaken to further elaborate rates of decline across storage types, as well as measures tailored to storage types that may mitigate these trends.

Second, the causal factors for storage loss and water quality deterioration are agricultural expansion, land degradation, sedimentation, and increasing water withdrawals. These causal factors have been discussed in literature widely with or without relation to storage. However, there is evidence these factors are major causes of storage loss both in quantity and quality. Thus, promoting soil and water conservation measures to ensure water resources are utilized efficiently must continue using context-based approaches. This will help in availing water for the competing demands of agriculture, domestic use, and industry.

Third, the storage gap will increase because of climate change, population, and economic growth while current management options are fragmented due to various management approaches as well as institutional mandates. For instance, different water storages are managed by different stakeholders in the sub-basin, e.g., groundwater sources for drinking water are managed by the Water Supply and Sewerage Offices, and the Bureau of Agriculture and/or Irrigation and Lowland Development Bureau manages most of the small-scale irrigation water sources. The management options implemented for different storage types therefore vary and tackling such fragmentation requires optimization of water for different uses and coordination among sectors. However, most reviewed studies focus on only one service per storage type while in reality multiple services can be obtained from a given storage type that would require coordination among sectors and optimization of the resource. The need for a holistic approach to water management, considering the interconnectedness of water resources, ecosystem health, and community livelihoods is paramount. These will help to ensure the long-term availability and quality of water resources in the sub-basin.

5 Recommendations

Even though there are a decent number of studies on the Tana-beles basin's water resources, the number of literatures that focuses on storage were limited. Furthermore, compared to surface storage there is limited focus on sub-surface storages in the literature of Tana-Beles sub-basin. Most studies that focused on analyzing different storage mostly prefer studying the surface water storage options. Future studies need to further explore the amount, availability, and use of sub-surface storage to promote the conjunctive use of different water resources of the sub-basin.

The study found different storage types are under different jurisdictions, as a result, treating water storage as an integrated resource with optimized management will become a challenge. Therefore, bringing different stakeholders into one platform may assist in planning for likely scenarios of further storage decline and better storage management. Although some of the challenges are unavoidable and require further research bringing together the different actors in the basin will assist in understanding current trends and designing solutions to better adapt to changes that arise from climate, population and economic changes on water resources use and demand.

This study suggests that a nexus approach is needed to achieve sustainability storage management and service provisions to various sectors in optimized ways. The findings of the systematic review provide a basis for future studies on water resource management in the Tana-Beles sub-basin and other river basins in Ethiopia and beyond. The knowledge obtained from the systematic review can inform decision-making processes and enable the implementation of sustainable water resource management strategies by considering all types of storages. Further research is needed to address the identified key issues, characterize the different types of storage vis-a-vis water demand by various sectors, determine the most effective approach to integrate surface and sub-surface storage and as a result fully utilize the concept of integrated storage management.

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Author contributions MTT and TTA wrote the main manuscript text. TTA prepared all figures and tables. All authors (TTA, MTT, GYE, JL, and AS) reviewed the manuscript.

Data availability All data generated or analyzed during this study are included in this published article as an "Appendix".

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Appendix

Lists of literature used in this study for the systematic review

S. no.	Literatures	Paper/report title	Storage type
1	Mucheye, T., et al. (2018)	Significance of wetlands for sediment and nutrient reduction in Lake Tana Sub-Basin, Upper Blue Nile Basin, Ethiopia	Wetlands
2	Negash, A., et al. (2011)	Assessment of the Ecological Status and Threats of Welala and Shesher Wetlands, Lake TanaSub-Basin (Ethiopia)	Wetlands
3	Wubie, M. A., et al. (2016)	Patterns, causes and consequences of land use/cover dynamics in the Gumara watershed of lake Tana basin, Northwestern Ethiopia	Wetlands
4	Wondmagegne, T., et al. (2012)	Seasonality in Abundance, Biomass and Production of the Phytoplankton of Welala and Shesher Wetlands, Lake Tana Sub-Basin (Ethiopia)	Wetlands

S. no.	Literatures	Paper/report title	Storage type
5	Mequanent, D. and A. Sisay (2015)	Wetlands potential, current situation, and its threats in Tana Sub-Basin, Ethiopia	Wetlands
6	Kassa, Y. A. and T. T. Teshome (2015)	The Impact of Wetland Degradation and Conversion on Socioeconomic Values: The Case of Amhara National Regional State Tekuma Wetland, Lake Tana Sub-Basin, Ethiopia	Wetlands
7	Hunegnaw, G., et al. (2013)	Wetlands Ecosystems Coverage, Status and Threats in the Abbay River Basin	Wetlands
8	Haji, F. (2019)	A Review on The Importance, Distribution and Threat of Ethiopian Wetlands	Wetlands
9	NBI, NTEAP. (2009)	The Wetlands of the Nile Basin: Baseline Inventory and Mapping	Wetlands
10	Gezie, A., et al. (2020)	Habitat Suitability Modelling of Benthic Macroinvertebrate Community in Wetlands of Lake Tana Watershed, Northwest Ethiopia	Wetlands

S. no.	Literatures	Paper/report title	Storage type
11	Abebe, W. B., et al. (2020)	Hydrological Foundation as a Basis for a Holistic Environmental Flow Assessment of Tropical Highland Rivers in Ethiopia	Wetlands
12	Eneyew, B. G. and W. W. Assefa (2021)	Anthropogenic effect on wetland biodiversity in Lake Tana Region: A case of Infranz Wetland, Northwestern Ethiopia	Wetlands
13	Desta, M. A., et al. (2021)	Temporal and Spatial Changes in Crop Patterns, Use of inputs and Hydrological Alteration in the Case of Fogera Floodplain, Ethiopia	Wetlands
14	Desta, M. A., et al. (2022)	Impact of Rice Expansion on Traditional Wetland Management in the Tropical Highlands of Ethiopia	Wetlands
15	Gezie, A., et al. (2017)	Effects of human-induced environmental changes on benthic macroinvertebrate assemblages of wetlands in Lake Tana Watershed, Northwest Ethiopia	Wetlands
16	Wondie, A. (2018)	Ecological conditions and ecosystem services of wetlands in the Lake Tana Area, Ethiopia	Wetlands

S. no.	Literatures	Paper/report title	Storage type
17	Rämi, H. and U. OCHA-Ethiopia (2003)	Ponds filled with challenges. Water harvesting experiences in Amhara and Tigray	Ponds
18	Abebe, A., et al. (2021)	Evaluation of Rain Water Harvesting Systems for coping water shortage in the Upper Blue Nile Basin, North West Ethiopia	Ponds
19	Johnston, R. M. and M. McCartney (2010)	Inventory of water storage types in the Blue Nile and Volta river basins, IWMI	Ponds
20	Awulachew, S. B., et al. (2013)	Water management intervention analysis in the Nile Basin. The Nile River Basin	Ponds
21	Haileslassie, A., et al. (2009)	Institutional settings and livelihood strategies in the Blue Nile Basin: implications for upstream/downstream linkages,	Ponds
22	Tesfay, H. (2007)	Assessment of institutional setup and effect of household-level water harvesting in ensuring sustainable livelihood." Case study of Kobo, Almata, and Kilte Awlaelo Woredas in Amhara and Tigray Regions of Ethiopia	Ponds
23	Wondimkun, Y. and M. Tefera (2006)	Household water harvesting and small-scale irrigation schemes in Amhara Region	Ponds
24	Zelalem, W., et al. (2017)	Monitoring and Evaluation of Stocked Water Bodies for Fish Production and their Ecological Status; the Case of Gomit and Selameko Reservoirs	Reservoirs
25	Zelalem, W., et al. (2017)	Monitoring and Evaluation of Stocked Water Bodies for Fish Production and their Ecological Status; the Case of Gomit and Selameko Reservoirs	Reservoirs
26	Ayele, G. T., et al. (2021)	Sediment Yield and Reservoir Sedimentation in Highly Dynamic Watersheds: The Case of Koga Reservoir, Ethiopia	Reservoirs
27	Mhiret, D. A., et al. (2016)	Estimating reservoir sedimentation using bathymetric differencing and hydrologic modeling in data-scarce Koga watershed, Upper Blue Nile	Reservoirs

S. no.	Literatures	Paper/report title	Storage type
28	Yassin, F. A. and M. McCartney (2010)	Evaluating the technical performance of the Koga and Gomit reservoirs in the Blue Nile under existing conditions and possible climate change	Reservoirs
29	Mulatu, C. A., et al. (2012)	Analysis of reservoir sedimentation process using the empirical and mathematical method: case study—Koga Irrigation and Watershed Management Project; Ethiopia	Reservoirs
30	Reynolds, B. (2012)	Variability and change in Koga reservoir volume, Blue Nile, Ethiopia	Reservoirs
31	Moges, M. M., et al. (2018)	Investigating reservoir sedimentation and its implications to watershed sediment yield: The case of two small dams in data-scarce upper Blue Nile Basin, Ethiopia	Reservoirs
32	Wassie, T. A. and A. W. Melese (2017)	Impact of physicochemical parameters on phytoplankton compositions and abundances in Selameko Manmade Reservoir, Debre Tabor, South Gondar, Ethiopia	Reservoirs
33	Genet, B. (2013)	Sedimentation of Reservoirs in Amhara Region: The Case of Adrako Micro-Earth Dam	Reservoirs
34	Haregeweyn, N., et al. (2012)	Reservoir sedimentation and its mitigating strategies: a case study of Angereb reservoir (NW Ethiopia)	Reservoirs
35	Tassew, B. G. (2013)	Status of Small-Scale Irrigation Projects in Amhara Region, Ethiopia	Reservoirs
36	Mengistu, T. D., et al. (2022)	Estimation of Reservoirs Sedimentation Using Bathymetry Survey: Case Study on Tagel Night Storage Reservoir, Lake Tana Sub Basin, Ethiopia	Reservoirs
37	Lemma, H., et al. (2020)	Consolidated sediment budget of Lake Tana, Ethiopia (2012–2016)	Lake Tana

S. no.	Literatures	Paper/report title	Storage type
38	Tibebe, D., et al. (2019)	Investigation of Spatio-temporal variations of selected water quality parameters and trophic status of Lake Tana for sustainable management, Ethiopia	Lake Tana
39	Damtie, Y. A., et al. (2021)	Spatial coverage of water hyacinth (*Eichhornia crassipes* (Mart.) Solms) on Lake Tana and associated water loss	Lake Tana
40	Mequanent, D. and M. Mingist (2019)	Potential impact and mitigation measures of pump irrigation projects on Lake Tana and its environs, Ethiopia	Lake Tana
41	Womber, Z. R., et al. (2021)	Estimation of Suspended Sediment Concentration from Remote Sensing and In Situ Measurement over Lake Tana, Ethiopia	Lake Tana
42	Minale, A. S. (2020)	Water level fluctuations of Lake Tana and its implication on local communities' livelihood, northwestern Ethiopia	Lake Tana

S. no.	Literatures	Paper/report title	Storage type
43	Worqlul, A. W., et al. (2020)	Spatiotemporal dynamics and environmental controlling factors of the lake Tana water hyacinth in Ethiopia	Lake Tana
44	Asmare, T., et al. (2020)	Detecting spatiotemporal expansion of water hyacinth (*Eichhornia crassipes*) in Lake Tana, northern Ethiopia	Lake Tana
45	Misganaw, A. and B. Akenaw (2022)	Water quality sustainability assessment using the DPSIRO dynamic model: a case study of Ethiopian Lake Tana water	Lake Tana
46	Moges, M. A., et al. (2017)	Water quality assessment by measuring and using Landsat 7 etm + images for the current and previous trend perspective: Lake Tana Ethiopia	Lake Tana
47	Kaba, E., et al. (2014)	Evaluating suitability of MODIS-Terra images for reproducing historic sediment concentrations in water bodies: Lake Tana, Ethiopia	Lake Tana
48	Ligdi, E. E., et al. (2010)	Ecohydrological status of Lake Tana—A shallow highland lake in the Blue Nile (Abbay) basin in Ethiopia	Lake Tana

S. no.	Literatures	Paper/report title	Storage type
49	Dersseh, M., et al. (2022)	Water Quality Characteristics of a Water Hyacinth Infested Tropical Highland Lake: Lake Tana, Ethiopia	Lake Tana
50	Ayele, H. S. and M. Atlabachew (2021)	Review of characterization, factors, impacts, and solutions of Lake eutrophication: lesson for lake Tana, Ethiopia	Lake Tana
51	Kebedew, M. G., et al. (2021)	Sediment deposition (1940–2017) in a historically pristine lake in a rapidly developing tropical highland region in Ethiopia	Lake Tana
52	Abiy, Anteneh Z., et al. (2016)	Groundwater recharge and contribution to the Tana sub-basin, upper Blue Nile basin, Ethiopia	Groundwater
53	Woldesenbet, Tekalegn Ayele, et al. (2017)	Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin, Ethiopia	Groundwater
54	Abiy, A. Z., & Melesse, A. M. (2017)	Evaluation of watershed scale changes in groundwater and soil moisture storage with the application of GRACE satellite imagery data	Groundwater
55	Asmerom, G. H. (2008)	Groundwater contribution and recharge estimation in the Upper Blue Nile flows, Ethiopia	Groundwater
56	Akale, Adugnaw T., et al. (2019)	The effect of landscape interventions on groundwater flow and surface runoff in a watershed in the upper reaches of the Blue Nile	Groundwater
57	Leta, M. K., Demissie, T. A., & Tränckner, J. (2021)	Hydrological responses of watershed to historical and future land use land cover change dynamics of nashe watershed, Ethiopia	Groundwater
58	Van Landtschoote, A. (2017)	Hydrogeological investigation and recharge estimation of Gumera river catchment in Lake Tana basin, northern Ethiopia	Groundwater
59	Woldesenbet, Tekalegn Ayele, et al. (2017)	Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin, Ethiopia	Groundwater
60	Abiy, A. Z., & Melesse, A. M. (2017)	Evaluation of watershed scale changes in groundwater and soil moisture storage with the application of GRACE satellite imagery data	Groundwater

S. no.	Literatures	Paper/report title	Storage type
61	Nigate, Fenta, et al. (2020)	Recharge–discharge relations of groundwater in volcanic terrain of semi-humid tropical highlands of ethiopia: the case of Infranz Springs, in the Upper Blue Nile	Groundwater
62	Nigatu, Zemede M., et al. (2022)	Crop production response to soil moisture and groundwater depletion in the Nile Basin based on multi-source data	Groundwater and soil moisture
63	Birhanu, Adugnaw, et al. (2019)	Impacts of land use and land cover changes on hydrology of the Gumara catchment, Ethiopia	Groundwater and soil moisture
64	Tefera, A. H. (2003)	Water Resource Assessment and Management Options in Beles River Basin using HEC-HMS Model	Soil moisture

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