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Review

Water Resources Potential, Utilization, Challenges, and Management Strategies in Amhara Region, Ethiopia: A Systematic Review

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ABSTRACT

This review paper provides a systematic assessment of the water resource potential, utilization patterns, and management practices in Ethiopia's Amhara Region. It addresses four key research questions: (1) What is the extent of Amhara's water resource potential and current utilization? (2) What are the major obstacles to sustainable water management? (3) What opportunities exist to enhance water resource management? (4) Where are the critical research gaps, especially in agricultural water use? Following PRISMA 2020 guidelines, a comprehensive literature review was conducted using Scopus, Web of Science, and PubMed data bases covering publications from 2010 to 2024. The keywords used for relevant literature included Amhara, water resources, irrigation, and hydropower. Out of 1,000 screened publications, 201 met inclusion criteria for thematic analysis. The region holds an estimated 54.4 billion m³ of surface water and 2.6 billion m³ of groundwater annually, yet less than 5% is utilized. The major challenges which limited the utilization include declining rainfall (−3.2 mm/year), rising temperatures (+0.28°C/decade), underdeveloped irrigation (<10% of 900,000 ha potential), weak institutional capacity, and ecological threats such as water hyacinth. The review highlights the need for technological innovation, institutional reform, and community engagement are very crucial interventions to address the challenges and ensure sustainable water security and agricultural productivity in the Amhara Region.

Keywords: climate change, hydropower, irrigation, sustainability

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Highlights

- The Amhara region holds substantial water potential, both surface and groundwater.
- The Systematic review was conducted based on 201 relevant studies (2010-2024) using PRISMA 2020 methodology and thematic analysis.
- Critical research gaps were identified in agricultural water management and groundwater mapping.
- Technological innovation, institutional reform, and community engagement are recommended for the sustainable water management.

Graphical Abstract

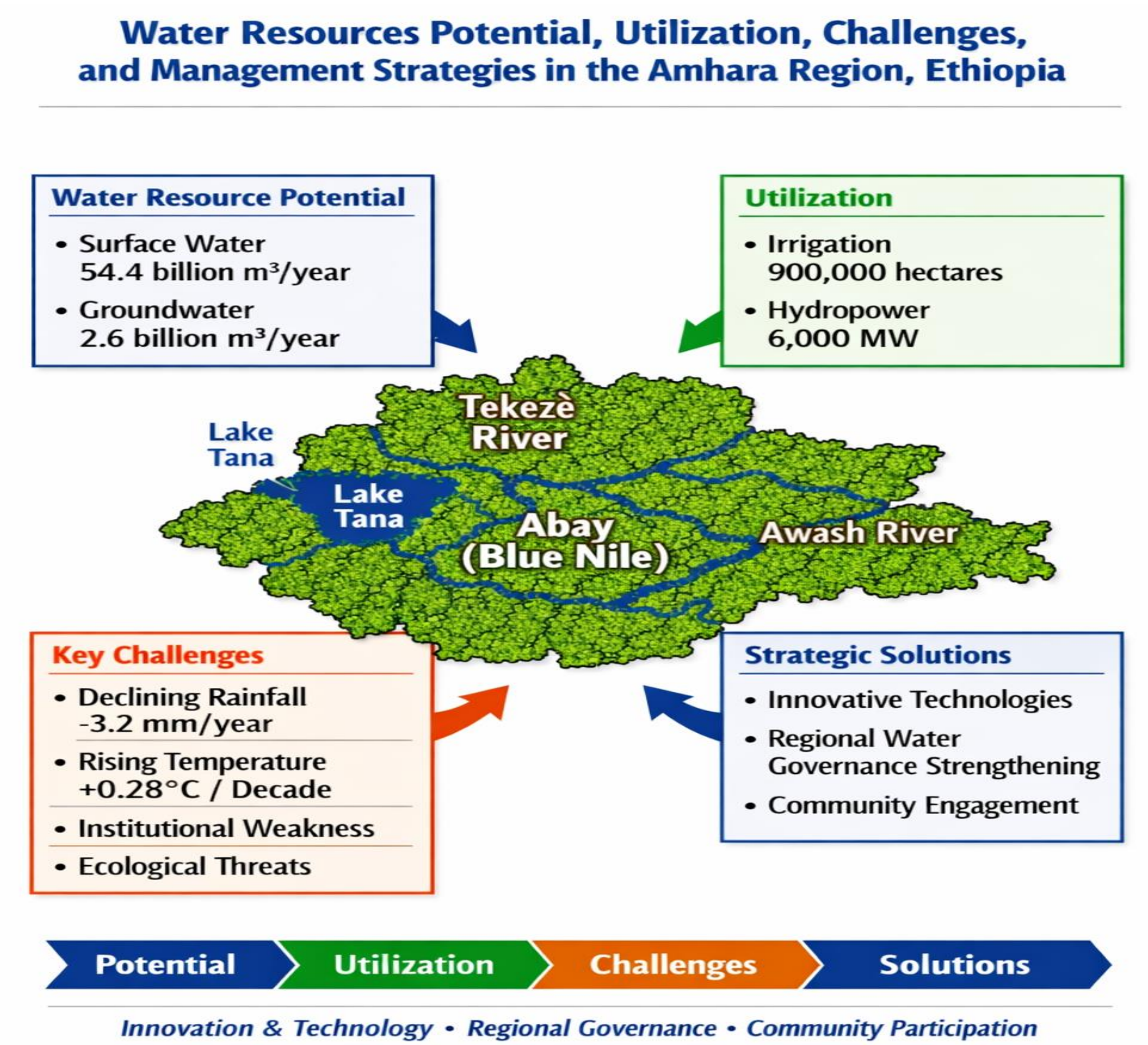

Figure 1. Graphical abstract summarizing water resource potential, utilization, challenges, and strategies in the Amhara Region, Ethiopia.

1. Introduction

Water resources are foundational to global socio-economic development, public health, and environmental sustainability. However, the effective management of these resources remains a major global challenge, particularly in the face of increasing climate variability, population pressure, and unsustainable practices (Alemayehu et al. 2020a; Birhanu 2023a; Teferi et al. 2021). Moreover, many developing countries, especially in sub-Saharan Africa, struggle to utilize their water resources efficiently due to infrastructural, institutional, and technological limitations(Teferi et al. 2025).

Ethiopia, often referred to as the "water tower of East Africa" due to its substantial highland rainfall and extensive river systems, has an estimated annual renewable freshwater volume of 123 billion m³ (Geremew and Damtew 2020; Jewaro and Diler 2021).Despite this potential, less than 5% of surface water resources are harnessed (World Bank 2020), contributing to recurring water scarcity, low agricultural productivity, and energy insecurity. The underutilization is compounded by fragmented water governance, limited infrastructure, and poor adoption of water-saving technologies (Awulachew 2010) .

Within Ethiopia, the Amhara Region is both water-rich and water-stressed—hosting Lake Tana, the largest freshwater body in Ethiopia and the source of the Blue Nile, which contributes about 40% of the Nile Basin flow (Awulachew 2010). The region possesses vast agricultural potential with an estimated 650,000–700,000 hectares suitable for medium- and large-scale irrigation and 200,000–250,000 hectares for small-scale schemes (Amhara Bureau of Agriculture, 2022). However, less than 10% of this potential is currently utilized, primarily due to infrastructural gaps, financial constraints, and technical inefficiencies (Gebrekidan et al. 2024).

The Amhara Region possesses considerable hydropower potential, yet its development is constrained by seasonal river flow variability and limited water storage infrastructure (Ethiopian Electric Power, 2023). Climate change further intensifies water insecurity through shifting rainfall patterns and rising temperatures, contributing to recurrent droughts and increased evapotranspiration (Degefu and Asefa 2024; Mekonnen and Amsalu 2018).These pressures, combined with land degradation and population growth, underscore the urgent need for sustainable water management strategies in the region.

Human pressures, such as land degradation, deforestation, population growth, and unsustainable agricultural practices, have further intensified the degradation of water ecosystems in the region. This has shifted water usage from natural to artificial systems and disrupted the spatial and temporal distribution of water (Assegide et al. 2022a; Mersha et al. 2016). Additionally, water bodies like Lake Tana face threats from invasive species, pollution, sedimentation, and unregulated abstraction, all of which pose ecological risks(Alemayehu et al. 2020a).

Despite several research efforts, substantial gaps remain in the areas of integrated water resource management, technological adoption, and data availability. Weak coordination between research institutions and water governance authorities has resulted in poor translation of scientific knowledge into actionable plan (Gebrehiwot and van der Veen 2021) For instance, data-driven approaches such as Artificial Intelligence (AI), Geographic Information Systems (GIS), Remote Sensing (RS), and decision-support tools remain underutilized in areas like flood forecasting, irrigation scheduling, and groundwater assessment(Gebrehiwot & van der Veen 2021).

In order to show the main research gaps on the water resource of Amhara region, Ethiopia, this review aims to provide a systematic assessment of water resource potential, utilization, and management in the Amhara region, Ethiopia. The specific objectives are to identify and critically analyze the current state of water resource potential and utilization practices; examine the major challenges impeding sustainable water resource management and development; highlight opportunities and strategic interventions for improved water governance; identify research gaps in water resource assessment and agricultural water management; and provide actionable recommendations to enhance sustainable water use for improved livelihoods and regional development.

2. Materials and Methods

The materials utilized for this review comprised Google Scholar, Web of Science, PubMed literature journals, an official government reports, with specific inclusion and exclusion criteria regarding publication year, language, and article quality. The aim was to identify the quantitative potential of water resources and the elements necessary to address the escalating water demand and formulate plans for development and management within the sector.

A systematic literature review was conducted following PRISMA 2020 guidelines. combinations of the keywords “Amhara”, “water resources”, “surface water”, “groundwater”, “irrigation”, “hydropower”, and “water management”. Gray literature from the Ethiopian Ministry of Water and Energy and regional bureaus was also included. After screening titles, abstracts, and full texts, 200 publications (2010–2024) met the inclusion criteria. Data were extracted into a structured database and analyzed using content analysis to identify thematic clusters.

In the initial stage, articles concentrating on water resource utilization, development, and management were gathered utilizing content analysis techniques. In the subsequent stage, a comprehensive assessment of published literature was conducted to comprehend the existing and previous state of knowledge on water resource development, management, and utilization in the Amhara regional state, Ethiopia.

The Scopus database, Web of Science, and PubMed were employed to identify the relevant literature. A total of 1000 publications, encompassing book chapters, research articles, review articles, and Conference proceedings, were utilized. Subsequently, a file in comma-separated values (CSV) format containing information on the articles (such as authors, title, source, publication year, author’s affiliation, abstract, keywords, document type, etc.) was exported from the Scopus, Web of Science, or PubMed database.

A careful review of the publication titles, abstracts, full-text, and studies focusing on water resource utilization, development, and management, was undertaken using screening for inclusion and exclusion criteria. One of the exclusion criteria was the year of publication for the articles. Additionally, only English-language publications were included in this study.

A total of 201 relevant articles meeting the inclusion criteria were selected for further analysis, covering the publication dates from 2010 to 2024 (Fig. 2). In conjunction with the database search methods, literature was also searched utilizing the well-known "snowball" strategy, which involves searching the reference lists of research data to uncover new papers for inclusion and identifying those that cite the paper under study.

After screening titles, abstracts, and full texts, 201 publications (2010–2024) met the inclusion criteria. Data were extracted into a structured database and analyzed using content analysis to identify thematic clusters. The overall process of study identification, screening, and inclusion is summarized in Figure.2, following the PRISMA 2020 flow diagram.

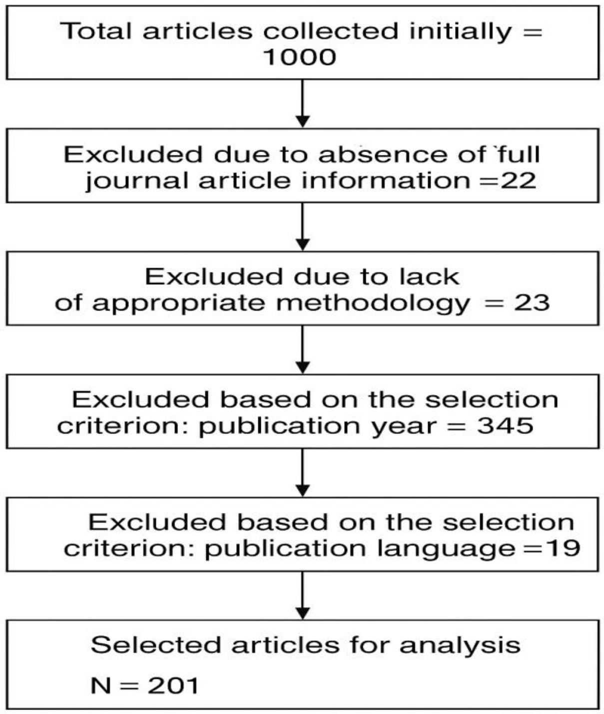

Figure 2. PRISMA 2020 Flow Diagram of Study Selection, N stands for the number of articles.

The publication trend of articles on water resources potential, utilization, challenges and management strategies in the region clearly showed that there is vertical increment of articles published in all cases which indicates that the problem of water is aggravating in the region (Figure3:)

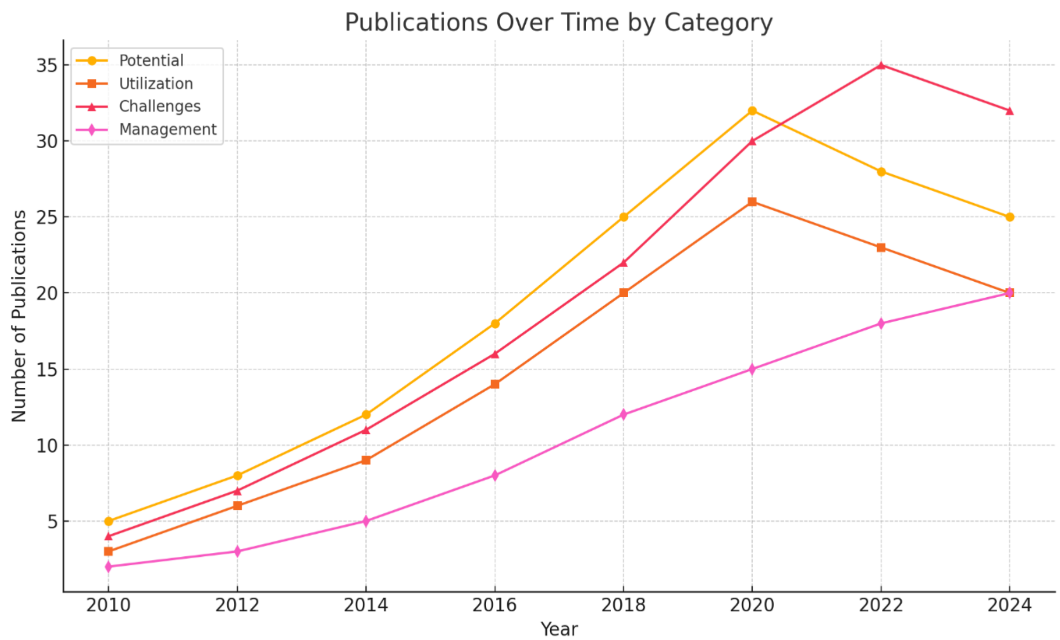

Figure 3. Number of publications trends reviewed between 2010 to 2025 in the Amhara region

The publication trends show a steady rise in research output related to water resources in the Amhara Region since 2010. This reflects growing academic interest in water resource potential, utilization, challenges, and management strategies.

3. Results and Discussion

3.1 Water resources potential of Amhara Region

The Amhara National Regional State in Ethiopia is endowed with significant water resources, encompassing extensive surface water bodies, considerable groundwater reserves, and substantial hydropower potential. The potential for water resource utilization exists in both surface and subsurface forms. The effective assessment and utilization of these resources are crucial for regional development, addressing escalating water demands, and mitigating the impacts of climate variability. Advanced technologies such as GIS, RS, AI tools, and Machine Learning Algorism (MLA) are increasingly vital tools for optimizing the management and planning of these critical resources(Dereje Ayalew 2012).

3.1.1 Surface water potential

The Amhara Region's surface water potential is primarily defined by its major river basins, including the Blue Nile (Abay), Tekeze, Awash, and Denakil. These rivers and their tributaries form a dense drainage network that contributes significantly to the region's hydrological wealth. The Blue Nile Basin, in particular, is a cornerstone of Ethiopia's water resources, originating from Lake Tana within the Amhara Region(Birhanu 2017; Getahun et al. 2023).(Yohannes et al. 2017; Zemo & Termansen 2018)Lake Tana, as the source of the Blue Nile, represents a critical hydrological and ecological asset (Abate et al. 2019; Alemu and Desta 2018).

Hydrological studies estimate the region's irrigable land potential at approximately 900,000 hectares, including about 650,000–700,000 hectares suitable for large to medium-scale irrigation schemes(Gemeda et al 023). These surface water resources present promising avenues for enhancing agricultural productivity and food security.

The region's hydropower potential, estimated at around 6,000 MW, positions it as a vital energy hub within Ethiopia's renewable energy portfolio (Berhanu et al. 2014; Worqlul et al. 2015).Technological advancements such as (GIS), (RS), (AI), and (MLA) have increasingly facilitated detailed spatial and temporal analyses of water resources, improving resource mapping, flow prediction, and decision-making support (Bekele and Drake 2003; Mideksa, Muluken, and Eric 2023)

Studies focusing on specific watersheds within the region illustrate the irrigable potential. For instance, in the Muga watershed in East Gojjam Zone, assessments revealed a mean monthly flow of 11.4 m^3/s, identifying approximately 3,443 hectares (5.1% of the total watershed area) as potentially suitable for surface irrigation development.

Similarly, in Jabitehnan Woreda, West Gojjam Zone, the simulated mean monthly and annual water yields for Geray and Debolah Watersheds were found to be substantial (0.98 m^3/s and 11.73 m^3/s, respectively, for annual water yields), indicating an actual surface irrigation potential of 4,499.7 hectares. Such localized assessments underscore the broader, untapped capacity for surface water utilization across the region for agricultural expansion and other uses (Mideksa et al. 2023).

The water potential in the region encompasses a diverse array of sources, including rainfall, rivers, lakes, and both annual and perennial springs. Effectively harnessing and managing these resources is crucial for addressing the challenges faced and realizing the full potential of water for sustainable development in Ethiopia.

While the region serves as a significant source of water for the country, its own accessible water resources for domestic and agricultural use are limited. Approximately 90% of Ethiopia's water sources are concentrated within four main river basins: Abay, Tekeze, situated in the region, where 80% of the basin populations reside (Samson 2010). The contribution of each of the Nile's main tributaries, including the Blue Nile with 50 BM^3 (Salleh 2016; Wolka et al. 2018).

Despite the region's erratic rainfall patterns, the average annual rainfall ranges from 600mm to 1600mm. The catchment area contributing to renewable surface water in the region exceeds 134,056 km^2. This is being changed into surface water and enriching the groundwater, depending on the nature of geological formation of the catchments, is expected to supply water for domestic purpose, the designated possible irrigable land and other economic needs by constructing diversions, dams, pumping the water after storage and/or boreholes (shallow or deep)(Awulachew et al. 2024).

Presently, surface water and meteorological data are systematically collected and processed through existing hydro-meteorological networks. Understanding a river basin extends beyond mere engineering concepts, encompassing the scale and dynamics of a resource essential for collective benefit(Getahun and Selassie 2013; Halefom et al. 2018; Kumar et al. 2022). It is widely advocated that the most logical unit for water resources planning and optimizing the utilization of available water resources is the river basin (Mitchell 2005; Loucks et al. 1981). In the region, natural lakes and reservoirs include Lake Tana, Koga, as well as several crater lakes such as Zengeni, Gudena Yetilba, Ardibo (75km2), and Logia (35 km2), among others. The spatial distribution of surface water potential in the Amhara Region is illustrated in Figure 4**.**

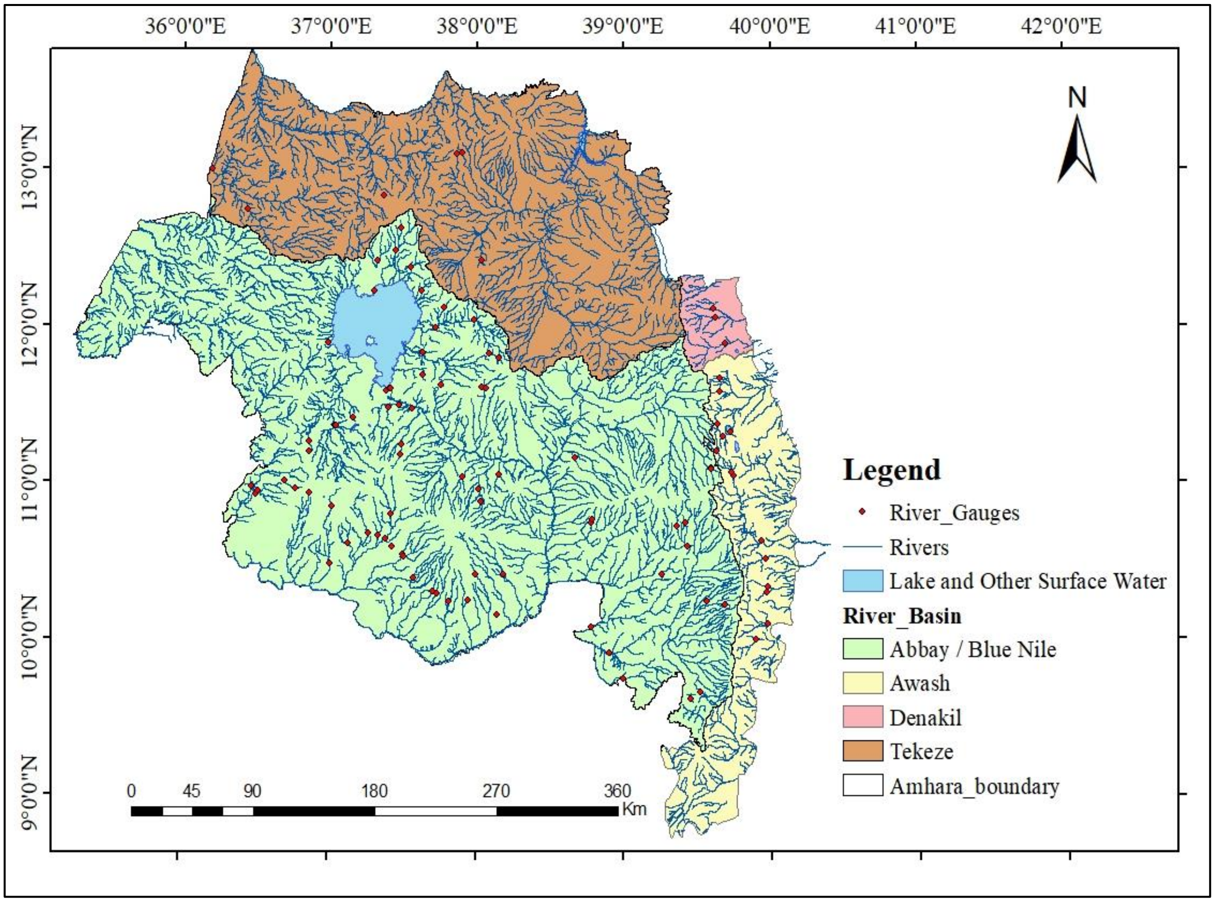

Figure 4. Map of surface water potential in the Amhara Region, Ethiopia.

Data source: processed by the authors using GIS from the Ministry of Water and Energy (MoWE) surface water Databases.

3.1.2 Groundwater Potential

Groundwater represents a crucial and often underexploited component of the Amhara Region's hydrological system, providing essential water supply for domestic, agricultural, and industrial uses, especially in dry seasons or areas where surface water is limited (Molla et al. 2017; Teshome et al. 2020). The region's complex hydrogeology is largely shaped by extensive basaltic volcanic formations, which govern the aquifer characteristics and groundwater distribution.(Tian et al. 2022; Zhang et al. 2021) . Groundwater resources, though less comprehensively mapped, contribute substantially to local water supply, particularly within alluvial floodplains and shallow aquifers (Gelagay & Minale 2016; M. Kassie et al. 2013).

Recent hydrogeological investigations within industrial and rural development sites such as the Amhara Industrial Agro-Parks (IAIP) and Rural Transformation Centers (RTC) — notably in the Bure and Moto areas — have identified two principal aquifer systems: (1) a shallow, unconfined aquifer hosted in weathered basalt and clay layers, and (2) a deeper, confined aquifer within fractured basalt bedrock (Gebrekidan, et al. 2024a, 2024b). These aquifers show variable groundwater levels, with the shallow aquifer water table typically ranging from approximately 5.5 to 8.3 meters below ground level (mbgl), while the confined deeper aquifers display static water levels between 2.8 and 13.3 MBGl (Milham 1994; Moseley 2001; Zemo and Termansen 2018). Such depth variation suggests distinct recharge and storage dynamics, necessitating tailored management approaches(Gebrekidan, Weldemariam, et al. 2024b).

Spatial heterogeneity in groundwater potential across the region is influenced by multiple interrelated factors including lithology, topography, land use, drainage density, lineament density, soil properties, and rainfall distribution (Haile, et al. 2017). For instance, hydrogeological mapping in the Nili River catchment of the Tekeze Basin revealed groundwater potential classes ranging from very poor (16.1%) to moderate (31.7%), with the remainder categorized as poor (24.6%) and good (27.6%) potential zones (Alemayehu & Getahun, 2021). Similarly, in East Belesa district, approximately 40.8% of the area was identified as high groundwater potential and 58.6% as moderate potential (Tang et al. 2021).

These spatial assessments underscore the importance of integrated groundwater potential mapping to optimize groundwater development sustainably, especially for water-scarce communities and emerging agricultural or industrial zones. However, the limited extent of comprehensive hydrogeological data and the variability of aquifer recharge mechanisms, particularly under changing climate conditions, remain significant challenges (Masha et al., 2023)

Moreover, the region's predominantly volcanic geology presents specific hydrogeological complexities such as fractured and heterogeneous basalt aquifers, which complicate prediction of aquifer yield and recharge potential (Kebede 2013)). This calls for enhanced site-specific investigations utilizing modern geophysical, remote sensing, and machine learning approaches to improve aquifer characterization and sustainable yield estimation (Pointet 2022a)). The spatial distribution of groundwater potential in the Amhara Region is illustrated in Figure 5**.**

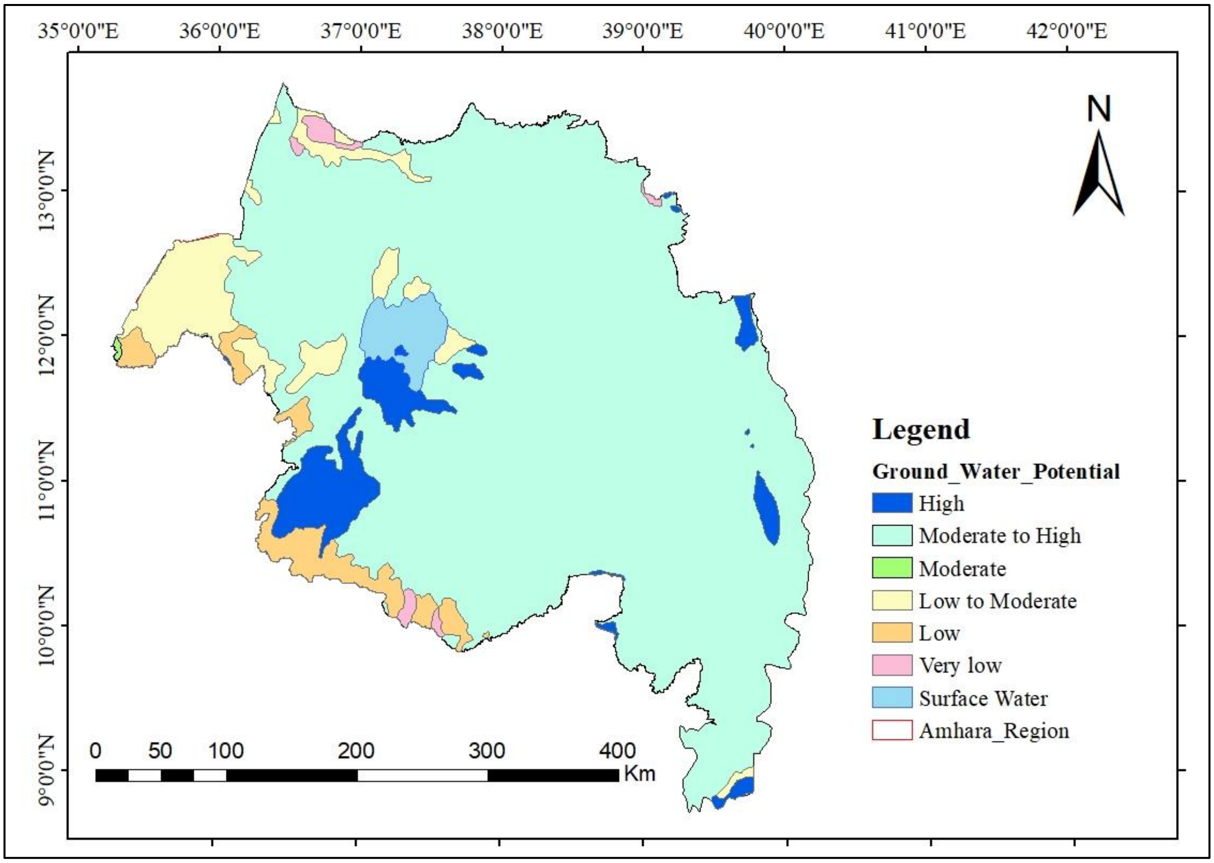

Figure 5. Map of groundwater potential in the Amhara Region, Ethiopia.

Data source: The Ministry of Water and Energy (MoWE) groundwater Databases (2023), processed by the authors using GIS. Groundwater potential is classified into high, moderate, and low zones based on aquifer productivity.

Surface water dominates renewable water supplies, with limited but locally significant groundwater recharge primarily occurring in floodplain alluvial deposits. Existing hydro-meteorological monitoring networks provide essential data but are hindered by spatial gaps and inconsistent quality, particularly in remote highland areas(Amsalu and Mulu 2025; Dar 2016).

Despite recognized potentials, recent literature consistently identifies several critical limitations and knowledge gaps. There is a pronounced lack of integrated groundwater studies addressing recharge dynamics, aquifer characterization, and sustainable extraction limits. Existing data on groundwater quantity and quality remain fragmented, impeding its systematic integration into water resource planning(Mekoya et al. 2024a).

Current hydrological models insufficiently capture the pronounced inter- and intra-annual variability of precipitation and river flow, leading to uncertainties in water availability projections and infrastructure design(Tace et al. 2022).

The lack of adequate reservoirs and dams limits the regulation of highly seasonal flows, restricting year-round irrigation and hydropower production and increasing vulnerability to floods (Bezabih 2021a, 2021b; Worku and Sahile 2017)

Hydro-meteorological data are unevenly distributed and often of limited accessibility. Additionally, regional technical capacity for advanced data analysis and the deployment of AI and MLA tools is inadequate, constraining evidence-based water management (Belete et al. 2023; Shumet and Mengistu 2016)
Research addressing ecological impacts of water development projects (e.g., on Lake Tana ecosystems) and the inclusion of community-based water management remain limited. Socioeconomic factors and gender mainstreaming in water governance require further investigation (Altherr et al. 2019; Makanda et al. 2022; Teweldebrihan & Dinla 2024)
Although climate variability poses a major risk, detailed downscaled climate impact assessments linking future scenarios to water availability and demand are lacking, hindering adaptive planning(Asaye et al. 2025)

3.3 Water Resources Utilization in the Amhara Region

The utilization of water resources in the Amhara Region faces numerous challenges, both historical and ongoing. As human development progresses and the demand for water for basic and specialized needs increases, water remains a pivotal resource underpinning economic, social, and political development (Bilal 2024) .However, temporal and spatial variability in water availability often limits access and usage across different sectors. Moreover, insufficient funding, political issues, and limited research on integrated water resources planning and management have resulted in suboptimal water resource utilization in the region (Altherr et al. 2019; Nigate et al. 2017a, 2017b)

Although the region's water development program has received substantial donor funding over the years, it continues to encounter deep-rooted and complex challenges. Many small dams, diversion structures, and reservoirs built under these initiatives have underperformed, failing to meet their intended objectives (Belete et al. 2023) .These infrastructures have also caused environmental and social issues, including land inundation, increased prevalence of waterborne diseases such as malaria, river blindness, and schistosomiasis, as well as problems like waterlogging and soil salinization (Bekele et al. 2019). Land tenure conflicts further complicate water resource development, often leading to disputes over access and rights to water and irrigated land(Mekoya et al. 2024a, 2024b).

Water bodies in the region serve dual crucial roles. Firstly, they regulate river flows, protect springs and wetlands, and maintain environmental balance. Secondly, they provide essential water supplies to meet increasing human demands for domestic consumption, agricultural irrigation, and industrial use (Mekonnen & Hoekstra 2016). However, intensive land use combined with population pressure and economic activities near rivers exacerbates the over-extraction and degradation of water resources, threatening their sustainable management (Alemie et al. 2023; Ayalew et al. 2022a 2022b)

While over-abstraction can have adverse environmental consequences, it is important to balance the benefits derived from water utilization with the need to preserve ecological integrity. Sustainable water management in Amhara thus requires careful planning to mitigate negative impacts while maximizing water's contributions to human development and environmental health (Danbauchi Sanchi n.d.; Larrea et al. 2023). Table 1 summarizes selected studies on water resources in the Amhara Region, covering rainfall variability, groundwater quality, irrigation feasibility, and hydropower potential.

Table 1. Selected studies on water resources in the Amhara Region

Title	Main findings	References
Rainfall variability and trends in western Amhara: implication for sustainable water management and agricultural productivity	Detected rainfall trends affecting agricultural planning and water management.	Asaye et al. (2025)
Modeling on comprehensive evaluation of groundwater quality … Bahir Dar City, Amhara, Ethiopia	Mapped groundwater quality and suitability for drinking and agriculture.	Alemu et al. (2024)
Impacts of Irrigated Water Use on Household's Income … South Wollo Zone, Amhara	Showed that irrigation significantly increases household income.	Kebede (2024)
Evaluation of small hydropower plant at Ribb irrigation dam	Analyzed feasibility and design performance of small hydro plant.	Bezabih (2020)
Evaluation of groundwater and surface water quality suitability … Kombolcha town area	Assessed suitability for drinking and irrigation using WQI.	Berhe (2020)
Feasibility Study of Irrigation Development … Jabi Tehnan Woreda	Evaluated potential for irrigation in response to climate variability.	Ashebir (2021)
Irrigation suitability evaluation of Zamra scheme … and Assessment of surface water resource and irrigation practices in Gudo Beret Kebele	Identified irrigable lands and constraints in small-scale irrigation.	Environmental Systems Research (2020)
Assessment of water resource management practice: Golina irrigation project	Highlighted challenges: sedimentation, limited water and infrastructure.	Yaregal et al. (2015)
System evaluation and challenges of sustainable water supply in Arerti town	Found inadequate supply, equity issues; recommended zoning & technology upgrades.	Mesfin et al. (2016)
Evaluation of hydraulic performance on Lower Areb small-scale irrigation scheme	Examined water delivery efficiency and infrastructure effectiveness.	Awulachew et al. (2022)

Water resource utilization in the Amhara Region has undergone substantial transformation driven by increasing human demand and changing consumption patterns. This transition has led to significant alterations in the spatial and temporal distribution of water resources, accompanied by ecological impact(Pointet 2022).

3.4 Water Resources Management in Amhara Region, Ethiopia

Both surface water and groundwater are extensively harnessed depending on the catchment geology, with infrastructure such as diversions, dams, and boreholes (shallow and deep) playing a pivotal role in water supply for irrigation, domestic use, and industrial purposes (Gebremedhin, et al. 2024a 2024b). This growing reliance underscores the urgent need for comprehensive integrated water resources management (IWRM) and basin-level master plans across the region's major river basins to optimize economic development opportunities while maintaining ecosystem integrity (Bilal 2024).

Despite the abundance of lakes and rivers, the region faces persistent water quality challenges. Water bodies in both urban and rural areas are frequently subjected to pollution from untreated waste disposal and agricultural runoff, exacerbated by low awareness and cultural attitudes towards water conservation. Such pollution threatens aquatic ecosystems, biodiversity, and public health, demanding enhanced community engagement and regulatory enforcement to reduce contamination sources (Alayu and Yirgu 2018; Amare 2019; Assegide, et al. 2022b) Moreover, the long-term implications of water pollution are often overlooked in environmental plan and public discourse, necessitating increased advocacy and education on water quality issues(Tull 2018).

Groundwater resource development in Amhara remains constrained by limited hydrogeological knowledge. Existing studies provide insufficient delineation of aquifer systems, water balance analyses, and aquifer parameterization, hindering effective management and sustainable exploitation (Gebremariam et al. 2022; Kassahun et al. 2019). Strengthening technical capacity, expanding hydrogeological investigations, and adopting advanced monitoring technologies are critical for maximizing groundwater's contribution to regional water security (Abera et al. 2021; Mekonen and Berlie 2020; Tadesse, Bosona, and Gebresenbet 2013)

Moreover, soil erosion presents a severe threat to sustainable water and land resource management, with annual loss of about 119 million tons of productive topsoil leading to 2-3% reductions in agricultural productivity each year (Molla et al. 2017; MoWIE 2021). This erosion not only diminishes the land's capacity to retain water but also exacerbates sedimentation in reservoirs and water infrastructure, further complicating resource management(Alemayehu et al. 2020b).Together, these challenges highlight the necessity for integrated strategies combining watershed management, pollution control, groundwater development, and capacity building. Enhancing stakeholder participation, strengthening institutional frameworks, and applying modern technologies are essential to sustainably harness Amhara's water resources for socio-economic development and environmental resilience(Alemayehu et al. 2023a).

3.5 Water Resources Utilization in Amhara Region

The Amhara region benefits from relatively abundant rainfall and substantial water resources; however, the local population has yet to fully capitalize on these assets through effective water resource development, irrigation technologies, water supply expansion, and hydropower exploitation. Sustainable water resource development remains a critical pathway for enhancing the region's socio-economic progress and ensuring optimal utilization of its hydrological endowments (Alemayehu et al. 2023a 2023b)

To maximize benefits, development strategies must adopt a pluralistic approach that promotes both large- and small-scale water resource projects. Small-scale initiatives, such as localized irrigation schemes and community-managed water supply systems, are particularly vital in Amhara. These projects minimize the socio-economic trade-offs often associated with large dams and reservoirs, which can displace agricultural lands, grazing areas, and forests essential for rural livelihoods (Gebrekidan, Gebremedhin, et al. 2024a, 2024b; Gebrekidan, Weldemariam, et al. 2024a)

Inclusive stakeholder participation is a cornerstone of successful water resource development. Establishing robust partnerships between government bodies and rural communities ensures shared responsibility in project implementation, operation, and sustainability (Alemayehu and Getu 2016a, 2016b; M. Bagyaraj et al. 2019). Furthermore, empowerment of women is crucial, as they bear a disproportionate burden related to water collection and management in rural settings. Evidence indicates that water projects managed by local communities, with active involvement of women, demonstrate higher sustainability and effectiveness compared to those managed solely by bureaucratic institutions(Alemayehu et al. 2020b; M. Bagyaraj et al. 2019; Tadesse et al. 2017)

In conclusion, the water resource development plan in Amhara must emphasize integrated, participatory approaches that balance large infrastructure development with community-scale projects, prioritizing social equity and environmental sustainability to ensure long-term benefits for all stakeholders.(M Bagyaraj et al. 2019; Tadesse et al. 2017)

3.5.1 Irrigation potential and utilization

Currently, there are around 207 small- and large-scale irrigation projects implemented across the region, collectively irrigating about 56,144.5 hectares of land (BoARD Amhara 2021). Irrigation is crucial in the region for enhancing sustainable agriculture, increasing household income, and mitigating the impacts of rainfall variability(Alemayehu et al. 2023b; Bantider et al. 2023).Temporal data shows fluctuating irrigation development trends over the last decade. In 2010, the irrigated area was approximately 30,800 hectares, which increased to about 46,100 hectares in 2011. A peak was observed in the 2018/19 cropping season with 932,700 hectares under irrigation, followed by a sharp decline to 220,600 hectares in 2019/20 and a moderate recovery to 325,800 hectares in 2020/21. These fluctuations may be attributed to variability in rainfall, sedimentation in irrigation canals, management challenges, and infrastructural constraints(Kebede 2013; Pointet 2022a).

While many small-scale irrigation schemes mostly traditional exist and serve about 1.9 million people with an average of 0.2 hectares per household, the advancement of modern irrigation infrastructure remains limited (ORDA, 2019). Regional efforts by organizations such as ORDA have resulted in the construction of about 200 small-scale irrigation schemes covering around 12,017 hectares and benefiting nearly 68,000 households (ORDA 2019). However, these figures represent only a fraction of the region's irrigation potential.(Pointet 2022a).The considerable underutilization of irrigation resources underscores the need for enhanced investment in water infrastructure, adoption of modern irrigation technologies such as solar-powered pumps, capacity building for farmers, and integrated watershed management strategies. Furthermore, climate-smart water management approaches and incorporation of irrigation planning into regional development policies are necessary to maximize the benefits from the region's water resources(Temesgen and Yonas 2016).

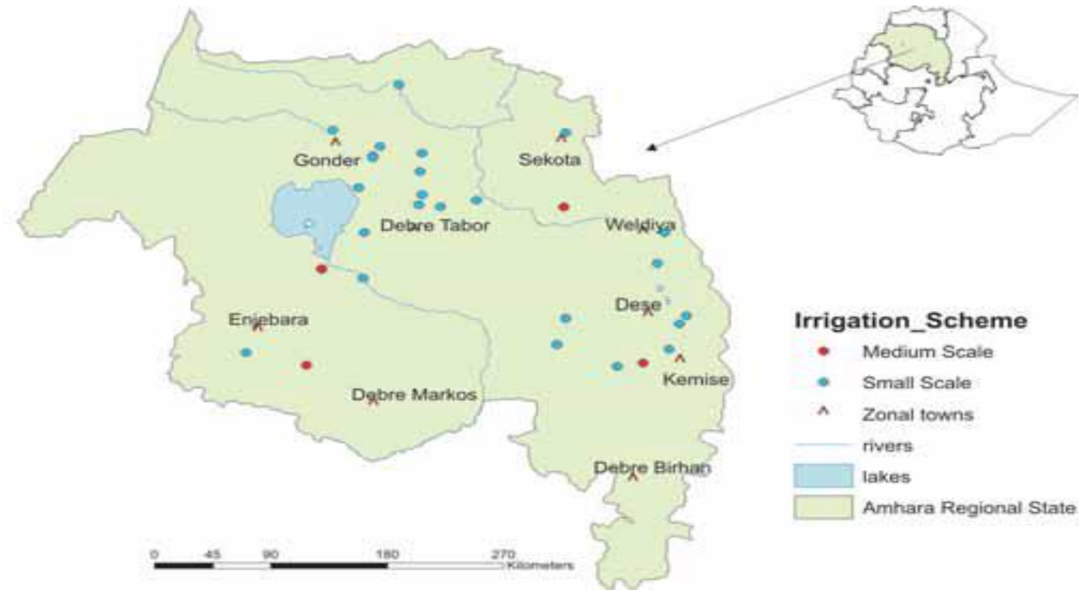

Figure 6. map of irrigation schemes in Amhara Region, Ethiopia

Data source: processed by the authors using GIS.

The table presents a comprehensive overview of irrigation development in Ethiopia's Amhara Region, revealing both progress and challenges in agricultural water management. The data highlights the region's ambitious irrigation expansion, with massive projects like Ribb (199,925 ha under construction) and Melech (31,821 ha) demonstrating the government's commitment to transforming agricultural productivity(Irrigation & Drainage Systems Engineering 2019; Sebnie, Adgo, and Kendie 2020; Yohannes et al. 2017). However, significant gaps emerge between current achievements and full potential, as seen in the Koga scheme which currently irrigates only 6,200 of its 10,000-hectare potential. The inclusion of both large-scale infrastructure projects and smallholder schemes (like Farta's 2,000 ha system) reflects a strategic approach to addressing different agricultural needs across the region(Assegide, , et al. 2022; Mekonnen and Amsalu 2018).

The table serves as a valuable snapshot of current efforts, but also highlights areas requiring further attention, particularly in accelerating project completion and improving data collection for more comprehensive planning(Yohannes et al. 2017). The contrast between the scale of ambition (with projects like Beles Integrated targeting 100,000 ha) and current realities suggests that while the foundation for agricultural transformation is being laid, significant work remains to bridge these gaps. Future updates to this data could provide crucial insights into whether implementation rates are improving and how these projects are actually impacting regional food security and farmer livelihoods(Genet Tassew 2013a, 2013b).

Table2. Existing irrigation schemes in Amhara Regional State, Ethiopia

Name of Scheme	Scale	Irrigation Type	Water Source	Planned Area (ha)	Actual Area (ha)	Planned Beneficiaries	Actual Beneficiaries	Reference
Alawuha	Medium	Diversion	River	360	41.57	610	706	*Amhara Region Irrigation Bureau* (2020)
Aba Golege	Medium	Diversion	River	-	311.01	-	115	*Amhara Region Irrigation Bureau (2020)*
Koga	Large	Reservoir	River (Blue Nile)	7000	5400	15000	10200	*World Bank (2015)*
Ribb	Large	Diversion	River	20000	8000	25000	12000	*FAO (2017)*
Geray	Medium	Diversion	River	618	114.68	480	583	*Amhara Region Irrigation Bureau (2020)*
Gimbora	Medium	Diversion	River	310	206.27	1024	872	*Amhara Region Irrigation Bureau (2020)*
Fendika	Small	Diversion	River/Spring	50	35	120	95	*Awulachew et al. (2007)*
Tana-Beles	Small	Pump	Lake Tana	30	25	80	65	*MoWR (2010)*
Debre Yakob	Small	Shallow Well	Groundwater	15	10	40	30	*Amhara Region Irrigation Bureau (2018)*
Woreta	Small	Diversion	River	20	18	60	50	*IFAD (2016)*
Yetnora	Small	Rainwater Harvest	Seasonal Pond	10	8	25	20	*CSA (2019)*

Table3: Planned and under construction Irrigation schemes in Amhara Region, Ethiopia

Irrigation scheme	Irrigated Area (ha)	Status / Description	Potential (ha)	Reference
Koga	6,200	Completed	10,000	*MoA (2023)*
Megech	31,821	Under construction	40,000	*MWIE (2023)*
Ribb	199,925	Under construction	250,000	*MWIE (2023)*
Angereb	23,000	Under construction	30,000	*BoWIE Amhara (2023)*
Gumara	23,000	Under study	35,000	*BoWIE Amhara (2023)*
Lake Tana shore irrigation	37,000	Under study	50,000	*ENTRO (2022)*
Tekeze Basin Irrigation	N/A	Identified potential area	70,000	*MWIE (2023)*
Beles Integrated Irrigation	N/A	Planned large-scale project	100,000	*MWIE (2023)*
Gilgel Abay Irrigation	N/A	Feasibility study ongoing	60,000	*BoWIE Amhara (2024)*
Farta Small-Scale Irrigation	2,000	Functional smallholder scheme	2,500	*BoWIE Amhara (2023)*
Dangila Irrigation	1,500	Rehabilitation planned	2,000	*BoWIE Amhara (2024)*

The table shows that, some schemes (Alawuha, Geray) exceeded beneficiary targets, suggesting adaptive local engagement despite infrastructural shortfalls. Small-scale systems (Fendika, Yetnora), while modest in scale (10–50 ha), play a critical role in rural livelihoods, leveraging diverse water sources like springs, groundwater, and rainwater harvesting(Birhanu 2023a, 2023b).

Discrepancies between planned and actual outcomes underscore systemic challenges, including funding constraints, technical limitations, and environmental variability. For instance, *Koga*'s reservoir system achieved 77% of its target area, while diversion-based schemes like *Ribb* and *Geray* struggled, highlighting the efficiency of reservoir storage versus river-dependent methods. The inclusion of small-scale schemes reflects their grassroots importance, though limited documentation (e.g., missing data for *Aba Golege*'s planned metrics) points to gaps in monitoring. Overall, the data reveals a tiered irrigation landscape where large projects drive regional food security but face scalability issues, while small-scale initiatives fill localized gaps with flexible, low-tech solutions(Birhanu 2023b).

Factors contributing to the limited utilization and development of water resources encompass several aspects. These include the significant temporal and spatial variability of water, with many major rivers flowing into neighboring countries, accounting for approximately 97% of the total flow. Additionally, governmental prioritization of other sectors over water, coupled with a lack of technical expertise to support water development efforts and inadequate leadership within water management divisions, further hampers progress. Moreover, the uneven spatial and temporal distribution of water resources compounds these challenges. Ethiopia, however, holds diverse prospects for advancing water resource utilization, presenting opportunities and facing associated challenges, as outlined in Awulachew's work on water-centered growth, innovations, and interventions in the country(Mosavi, Ozturk, and Chau 2018).

3.5.2 Water Supply

Water is a vital shared resource essential for sustaining livelihoods, economic development, and human well-being. Despite Ethiopia's abundant water resources, only a limited portion has been developed to support drinking water supply, hydropower, agriculture, and other sectors. Access to sufficient and clean water for domestic purposes—including drinking, food preparation, washing, and sanitation—is directly linked to improved health outcomes and productivity (Guche et al. 2024a, 2024b).

According to the Amhara Regional Water Resources Bureau, clean water supply coverage in the region is estimated at around 89%, with rural coverage close to 89% and urban coverage slightly above 91% (Amhara Bureau of Water Resources Development, 2015). Groundwater remains the primary source for most rural communities, with safe supplies derived from shallow wells, spring developments, and deep wells. Populations without access to improved sources often rely on rivers, unprotected springs, hand-dug wells, or rainwater harvesting (Abera et al. 2021; Mekonen and Berlie 2020; Tadesse et al. 2013).

Despite its critical importance, groundwater development has historically been underemphasized, although recent efforts aim to improve groundwater management and expand access (Mengistie et al. 2021). Additionally, water-based livelihoods are significant for various population groups in the region, including fishermen and artisans such as tanners and potters, who rely extensively on water availability and quality for their economic activities .(Gebrehiwot et al. 2014).

3.5.3 Hydropower

Water resources in the Amhara Region are extensively harnessed for hydropower generation, which primarily supports industrial activities, service sectors, and urban households. Hydropower development in Ethiopia is predominantly under state control, with the country's total installed capacity estimated at approximately 6,000 MW, a substantial portion of which is contributed by the Amhara Region (Mekonnen & Amsalu 2018a).

Despite the region's considerable hydropower potential, the generation of reliable and firm power is constrained by several hydrological and topographical factors. These include limited steep elevation drops, high but highly seasonal river flows, and significant inter-annual variability in water availability (Tesfaye et al., 2019). Consequently, large-scale infrastructure such as high dams and extensive reservoirs are often necessary to regulate flows and ensure consistent power production (Kibret and Tulu 2014a, 2014b)

Ethiopia is widely recognized as having one of Africa's greatest hydropower potentials, ranking second only to the Democratic Republic of Congo, largely due to its favorable topography and abundant water resources(Mohammed 2024).Continued investment in hydropower infrastructure within the Amhara Region is therefore crucial to meet growing energy demands and support sustainable economic development(Pointet, 2022b, 2022a).

4. Water Resource Challenges and Strategic Interventions

Water-related hazards such as floods, landslides, and droughts account for approximately nine out of ten natural disasters globally, a trend that also heavily affects the Amhara Region. Climate change is projected to intensify these hazards, placing additional stress on already scarce water supplies (Jjemba 2021). The hydrological dynamics within the region's river basins pose complex geopolitical and socioeconomic challenges, as water access remains fundamental to human well-being. Priority water uses include agricultural production, domestic consumption, electricity generation, and industrial activities. Competition over water resources among communities and across borders often generates conflicts that threaten human health and disrupt ecological systems (Gebrekidan, Gebremedhin, et al. 2024a, 2024b; Gebrekidan, Weldemariam, et al. 2024a).To mitigate these challenges, include expanding irrigation infrastructure, strengthening watershed management, investing in multipurpose reservoirs, and promoting community-based water governance. Institutional reforms and regional cooperation are also essential to ensure equitable and sustainable water allocation.

4.1 Water Weeds and Invasive Species

The dissemination of invasive aquatic plants, particularly water hyacinth (Eichhornia crassipes), poses significant threats to socio-economic livelihoods and aquatic ecosystems in Ethiopia. Water hyacinth has aggressively invaded major water bodies in the Ethiopian Rift Valley Basin, including parts of the Amhara Region, leading to reduced aquatic biodiversity, impaired water flow, and challenges to water resource management (Berhanu et al. 2025) . The weed also accelerates evapotranspiration losses and degrades water quality by trapping sediments and organic matter. Strategic interventions in the region have included mechanical removal campaigns, community-based monitoring, and pilot biological control trials, though challenges remain due to rapid regrowth and limited institutional capacity.

4.2 Sedimentation Overloading in Water Bodies

Sedimentation, often linked to irrigated agriculture and land degradation, remains a critical challenge in Amhara's water bodies. Sediment transported from upstream areas accumulates in lower river basins and irrigation canals, leading to siltation, canal damage, and increased flood risks for downstream communities (Kassie and Mengistu 2022; Mengistu and Assefa 2020) Sediment overload causes soil erosion on croplands and deteriorates aquatic habitats, necessitating sustainable watershed and agricultural management to mitigate sediment pressures (Belete et al. 2023; Kassegne and Leta 2020; Shumet and Mengistu 2016).

4.3 Institutional Drawbacks in the Water Sector

Effective water resource management in Amhara is hindered by institutional weaknesses and limited stakeholder engagement. Although Ethiopia is recognized as a water tower of Africa, water scarcity and sanitation challenges persist due to poor governance, lack of coordinated stakeholder frameworks, and under-resourced institutions(Berhanu et al. 2025).The absence of inclusive water management bodies undermines the implementation of government plans and community participation. Strengthening institutional capacity and enhancing multi-stakeholder collaboration are essential to improve water governance, share knowledge, and increase community awareness about sustainable water management goals (Tadesse et al. 2013)

4.4 Limited Application of Advanced Techniques in Water Resources Management in Amhara Region, Ethiopia

Despite the growing global interest in artificial intelligence (AI) and machine learning (ML) applications for water resources management, the Amhara Regional State of Ethiopia remains significantly underrepresented in this field. Most existing studies have been concentrated in other regions, such as the Awash Basin, Addis Ababa, or areas surrounding Lake Tana, with minimal implementation and testing of IoT- and ML-based systems in the semi-urban and rural contexts of Amhara (Gobeze et al. 2023a, 2023b). One of the critical challenges is the lack of long-term, high-resolution datasets. The majority of the models employed are based on short-duration or low-resolution satellite and in situ data, which severely affects the robustness and predictive accuracy of applications in flood forecasting, groundwater modeling, and water quality assessment (Fontes 2020; Pointet 2022a; Shiferaw & Holden 1998a; Zemo & Termansen 2018). Expanding the application of these advanced techniques could strengthen flood forecasting, groundwater modeling, and water quality assessment, provided that long-term, high-resolution datasets are developed.

Furthermore, there is a clear deficiency in integrating GIS, machine learning, and field-based observations into unified decision-support tools specifically tailored for the ecological and hydrological diversity of the Amhara landscape. This lack of spatially explicit, data-driven frameworks limits the practical applicability of AI in resource planning and early warning systems. In addition, while smart irrigation systems and water demand forecasting tools have been piloted in other parts of Ethiopia, such as Addis (Damtew and Geremew 2020; Kitessa et al. 2021)Ababa, their implementation in the fragmented smallholder farming systems typical of Amhara has yet to be explored(Leggesse et al. 2024). Another major gap lies in the absence of governance and institutional integration of AI technologies(Tace et al. 2022). Although promising models exist, there is limited research addressing how AI outputs can be translated into actionable policies or be adopted by local water management institutions for drought and flood risk mitigation (Berhanu et al., 2025; Uddin et al., 2021).

Table4: Application of AI, in water resources management in Amhara Region, Ethiopia:

Title	Study Area	Methods	Key Findings	References
Urban flash flood hazard mapping using machine learning, Bahir Dar	Flash flood risk in urban Bahir Dar	RF, SVM, XGBoost comparinghydrologic+topographic features	Identified vulnerable areas; ML significantly improved prediction accuracy	*Leggesse et al. (2024)*
Flood prediction in Amibara (Awash Basin)	Flood hazard in Amibara district	RF, SVM, LSTM, Linear Regression on 9 geofactors	RF performed best; blending satellite & field data enhanced mapping	*"Integrating Satellite Images…" (2024)*
IoT & ML-based smart irrigation system	Irrigation automation (Addis Ababa Area)	IoT sensors, ML model (soil/environmental data)	Reduced crop water use by ~6–7%; early prototype	*Beyene & Zeyede (2022)*
Groundwater quality modeling, Bahir Dar	Groundwater quality spatial evaluation	GIS + WQI (not ML)	Identified WQI hotspots; indicates potential for ML–GIS integration	*Mulat Alemu et al. (2024)*
ML & remote sensing for Lake Tana water quality	Remote water quality (TN, TP) monitoring	Ensemble ML + RS data	Ensemble ML best; limited data resolution & temporal biases	*Frontiers (2024)*
Predicting optical water quality in Ethiopian highlands	Lake Tana region	RF, XGB on RS data for chlorophyll, TDS, TUR	RF & XGB effective, but limited in situ data	*Academia.edu (2024)*

5. Suggested Management Actions

Efficient and sustainable management of water resources remains a pressing concern in the Amhara Region, where imbalanced water usage between upstream and downstream areas has resulted in both ecological degradation and socioeconomic challenges. Recent literature emphasizes the need to transition from irrational and inefficient water use particularly in the upper basin irrigation schemes—towards more rationalized, conservation-oriented practices. Strategies such as canal lining and the adoption of water-saving irrigation technologies are critical to enhancing water use efficiency and increasing the effective utilization ratio.

Moreover, the diversification of water sources is highlighted as essential for sustainable economic growth. While surface water continues to serve as the primary source, recent studies advocate for the complementary exploitation of groundwater to alleviate pressure on surface resources(Meresa and Gatachew 2019).This shift necessitates institutional reforms and the adoption of integrated water resource management frameworks that bridge sectoral divides and strengthen governance.

Sedimentation, predominantly resulting from upstream agricultural activities and watershed degradation, poses a significant threat to water infrastructure and ecosystem health. Sediment accumulation in downstream reservoirs and canals exacerbates flood risks and soil erosion while reducing irrigation efficiency. Notably, sediment sources extend beyond irrigation to include environmental degradation and inappropriate land use practices, indicating that sustainable watershed management must address these multifaceted drivers(Shoaib, Shamseldin, and Melville 2014; Sivapalan et al. 2005).

The application of geospatial technologies namely Geographic Information Systems (GIS) and Remote Sensing (RS)—has emerged as a transformative toolset for addressing water resource challenges in the region. GIS enables detailed spatial analyses of soil hydraulic properties, groundwater levels, irrigation scheduling, and waterlogging conditions, thereby supporting more precise and scalable water management solutions (Taye et al., 2011). Remote sensing complements this by providing timely and spatially comprehensive data on land use, crop water demand, and irrigation system performance, facilitating informed decision-making for both planners and practitioners(Behail 2018; Pointet 2022b, 2022a).

Furthermore, recent advances in integrating hydrogeomorphology and geospatial analysis have enhanced groundwater potential assessments in Amhara. By leveraging multiple thematic parameters—including land use, soil, slope, geology, and lineament density—researchers have produced groundwater suitability maps that guide exploration and sustainable extraction efforts. This approach exemplifies the growing recognition of geospatial technologies as indispensable for resource planning in water-scarce contexts(Chew et al. 2019).

Despite these technological advances, the review underscores that technological interventions must be complemented by robust institutional capacity and stakeholder engagement to ensure successful water resource development and management. The complex interplay of natural, technical, and social factors necessitates integrated approaches that balance economic development with ecological sustainability(Andualem et al. 2021a, 2021b).

Suggested management actions include strengthening watershed management to reduce sedimentation, expanding small-scale irrigation with water-saving technologies, diversifying water sources through complementary groundwater use, and investing in geospatial monitoring systems. These measures must be supported by institutional reforms, community participation, and integrated water resource management frameworks to ensure both ecological sustainability and socioeconomic resilience.

6. Conclusion

This comprehensive review highlights the paradox of the Amhara Region—a territory richly endowed with abundant water resources yet confronted by significant challenges in their sustainable management and utilization. The region's extensive surface water bodies, substantial groundwater reserves, and considerable hydropower potential provide a solid foundation for socio-economic development and improved livelihoods. However, the gap between water resource potential and actual utilization remains wide, constrained by erratic rainfall patterns, growing water demands, and infrastructural limitations.

Through critical analysis of existing literature, we identify three primary constraints: (1) insufficient assessment of water resource potential, (2) limited adoption of modern tools like GIS and remote sensing, and (3) poor integration of climate-smart practices in agricultural water management. The compounding effects of climate change, transboundary water disputes, institutional fragmentation, and watershed degradation further exacerbate these challenges.

Key findings underscore the region's vast river networks and groundwater aquifers, considerable irrigable land, and untapped hydropower capacity. Water use currently spans domestic, municipal, and agricultural sectors, along with hydropower generation, integrating both traditional and emerging technologies. Nonetheless, pervasive challenges threaten these gains, including intensified climate variability and recurrent droughts; severe sedimentation and erosion impacting infrastructure and ecosystems; the invasive spread of species such as water hyacinth; and institutional weaknesses marked by governance deficiencies, land rights conflicts, and limited technical capacity. Moreover, while advanced technologies like Geographic Information Systems (GIS), Remote Sensing (RS), Artificial Intelligence (AI), and Machine Learning (ML) offer promising avenues for improved water management, their adoption is hampered by limited data infrastructure, skill shortages, and financing constraints.

The interrelated nature of these challenges underscores the urgent need for implementing Integrated Water Resource Management (IWRM) principles. Far from being optional, IWRM is a critical framework for the Amhara Region to shift from fragmented, sectoral approaches toward holistic and coordinated water governance. Such an approach requires cross-sectoral collaboration and multi-level administrative integration to address the complex interactions among water availability, quality, and competing demands. Supported by robust data systems, modern planning tools, and strengthened institutional capacities, IWRM will enable equitable, efficient, and environmentally sustainable water resource management.

Despite the challenges, the Amhara Region holds tremendous potential for sustainable development through optimized water resource management. Strategic actions focused on enhancing data collection, fully integrating advanced geospatial and AI technologies, and fostering transdisciplinary research are essential. Additionally, meaningful community participation, gender mainstreaming, and decisive investment and reforms are crucial to creating an enabling environment for water security. By embracing these strategic pathways, the Amhara Region can unlock its vast "Blue Oil" potential, curb environmental degradation, build resilience against climate change, and ensure sustainable water availability for its growing population—thereby catalyzing long-term economic growth and improved human well-being.

The Amhara Region holds significant promise for advancing the development and sustainable utilization of its water resources. Among its many opportunities, the region benefits from abundant water sources that provide a strong foundation for future growth. Recognizing this potential, the regional government has shifted its focus toward prioritizing water resource development, supported by commitments from various funding agencies eager to bolster the water sector.

A key opportunity lies in the multipurpose use of water resources, such as integrating irrigation and hydropower generation, to maximize socio-economic benefits. Moreover, the region's higher education institutions are well-positioned to address existing knowledge gaps by producing qualified experts who can be deployed across the region. These professionals will play a crucial role in training and supporting lower-level technicians through experience sharing, technical assistance, and capacity-building initiatives.

Mainstreaming gender at all stages of water development projects—from inception to completion presents another critical opportunity to ensure inclusive and equitable resource management. Additionally, watershed management can be enhanced through the implementation of appropriate soil and water conservation practices, thereby preserving water resource potential and prolonging the operational lifespan of development projects.

Strengthening community involvement is essential for the sustainability of water initiatives. Technical research should be actively promoted alongside the establishment of participatory networks and local water committees formed with genuine community representation. The community must be empowered to select committee members, fostering trust and ownership, which are vital for the long-term success of water schemes. Community participation must extend beyond mere labor and financial contributions; it should include active decision-making on site selection, technology choices, design aspects, and overall project development.

Amhara Region has made notable progress in water resource development over recent years. Building on this foundation, future regional water resource management policies should emphasize efficient, equitable, and optimal use of available resources. Such a strategic focus will not only support sustainable development at the regional level but also contribute significantly to Ethiopia's broader socio-economic advancement.

In conclusion, the literature reviewed highlights the importance of transitioning towards more efficient water use practices, addressing sedimentation challenges through integrated watershed management, and leveraging advanced geospatial technologies for comprehensive water resource assessment and planning(Kebede 2013). Future research should focus on strengthening institutional frameworks and promoting participatory management to enhance the resilience of water systems in the Amhara Region(Muhammad et al. 2024).

Authorship contribution statement

- ***Mulatu Kassa Gedamu (M.K.***:Writing, review & editing, Writing original draft, Visualization, Methodology, Formal analysis, Conceptualization, supervision
- **Dessale Wessie (D.W)**: Formal analysis, Methodology, Visualization, Writing review & editing.
- ***Walelign Kassie (W.K):*** Writing, review & editing, Visualization, Conceptualization.
- ***Mengesha Tesfaw (M.T):Writing, review & editing, Visualization,*** Conceptualization.

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- The authors declare that there is no conflict of interest. All authors have contributed significantly to the work, and the manuscript has not been submitted elsewhere for publication.

Consent for publication

- The authors have a permission to publish their findings at any reputable journal.

Availability of data and materials

- The datasets used during the current study are available from the corresponding author on a reasonable request.

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