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þÿUrban Water Supply Demand Divergence in Gondar City: Drivers, Dynamics, and Future Scenarios

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DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL STUDIES

URBAN WATER SUPPLY–DEMAND DIVERGENCE IN GONDAR CITY: DRIVERS, DYNAMICS, AND FUTURE SCENARIOS

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April, 2026

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URBAN WATER SUPPLY–DEMAND DIVERGENCE IN GONDAR CITY: DRIVERS, DYNAMICS, AND FUTURE SCENARIOS

By Getachew Sinku Gessie

A DISSERTATION SUBMITTED TO THE DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL STUDIES, IN FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN GEOGRAPHY AND ENVIRONMENTAL STUDIES (SPECIALIZATION IN GEOGRAPHY OF NATURAL RESOURCE MANAGEMENT)

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April, 2026

Bahir Dar, Ethiopia

DECLARATION

This is to certify that the thesis titled "URBAN WATER SUPPLY–DEMAND DIVERGENCE IN GONDAR CITY: DRIVERS, DYNAMICS, AND FUTURE SCENARIOS", submitted in fulfillment of the requirements for the degree of Doctor of Philosophy in Geography and Environmental Studies (Specialization in Geography of Natural Resource Management) in the Department of Geography and Environmental Studies, Bahir Dar University, is a record of original work carried out by me and has never been submitted to this or any other institution to obtain any other degree or certificate. The assistance I received during the course of this investigation has been duly acknowledged.

Getachew Sinku Gessie	29-04-2026	______________________________
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Approval of Dissertation for Defense

I hereby certify that I have supervised, read, and evaluated this dissertation titled "URBAN WATER SUPPLY–DEMAND DIVERGENCE IN GONDAR CITY: DRIVERS, DYNAMICS, AND FUTURE SCENARIOS", by **Getachew Sinku Gessie** prepared under my guidance. I recommend the dissertation be submitted for oral defense (mock-viva and viva voce).

Daniel Ayalew Mengistu	29-04-2026	______________________________
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Approval of Dissertation

We hereby certify that we examined the dissertation entitled "URBAN WATER SUPPLY–DEMAND DIVERGENCE IN GONDAR CITY: DRIVERS, DYNAMICS, AND FUTURE SCENARIOS" by **Getachew Sinku Gessie,** and submitted in fulfillment of the requirements for the degree of Doctor of Philosophy in Geography and Environmental Studies (Specialization in Geography of Natural Resource Management with the regulation of University and meets the accepted standards with respect to originality and quality.

Board of Examiners

External Examiner	Signature	Date
Internal Examiner	Signature	Date
Chairperson	Signature	Date
Advisor	Signature	Date

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Full Form
AfDB	African Development Bank
AfWA	African Water Association
AGW	Anthropogenic Global Warming
AL	Apparent Loss
ALOS PALSAR	Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar
ALC	Active Leakage Control
ANRS	Amhara National Regional State
AR	AR
AWF	AWF
AWWA	American Water Works Association
BABE	Background, Active, Bursts, and Events (approach)
BAC	Billed Authorized Consumption
CAGR	Compound Annual Growth Rate
CARL	Current Annual Real Losses
CC-HV	Climate Change and Hydrological Variability
CDSWC	Construction Design and Supervision Works Corporation
CF	Correction Factor
CORDEX-Africa	Coordinated Regional Climate Downscaling Experiment – Africa
CSA	Central Statistical Agency (Ethiopia)
CUSUM	Cumulative Sum Control Chart
CV	Coefficient of Variation
DEM	Digital Elevation Model
DHE	Data Handling Error
DMA	District Metered Area
DN	Diameter Nominal (meter size)

ECD SWC / ECDSWC	Ethiopian Construction Design and Supervision Works Corporation
EWURA	Energy and Water Utilities Regulatory Authority (Tanzania)
FAO	Food and Agriculture Organization
FGD	Focus Group Discussion
GCM	Global Climate Model
GCP	Ground Control Point
GCWSSS	Gondar City Water Supply and Sewerage Service
GDP	Gross Domestic Product
GPR	Ground-Penetrating Radar
GWCL	Ghana Water Company Limited
GWI	Global Water Intelligence
GWP	Global Water Partnership
ILI	Infrastructure Leakage Index
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
IUWM	Integrated Urban Water Management
IWA	International Water Association
KDWF	KDWF
KI / KII	Key Informant / Key Informant Interview
LTWPS	Lake Tana Water Pumping Scheme
MAPE	Mean Absolute Percentage Error
MAR	Managed Aquifer Recharge
MCM	Million Cubic Meters
MDICA	MGD Irrigation Command Area
MGD	MGD
MIA	Meter Inaccuracy
MNDWI	Modified Normalized Difference Water Index
MNF	Minimum Night Flow

MoWE	Ministry of Water and Energy (Ethiopia)
MoWR	Ministry of Water Resources (Ethiopia)
MRE	Meter Reading Error
MSC	MS-Consultancy Engineering Firm
NDWI	Normalized Difference Water Index
NIR	Near-Infrared
NIRAS	NIRAS International Consulting (firm)
NMA	National Meteorological Agency (Ethiopia)
NRW	NRW
NSE	Nash-Sutcliffe Efficiency
OECD	Organization for Economic Co-operation and Development
PBC	Performance-Based Contract
PBIAS	Percent Bias
PELT	Pruned Exact Linear Time (change-point algorithm)
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RL	Real Loss
RMSE	Root Mean Square Error
RSS	Root Sum Square
RUSLE	Revised Universal Soil Loss Equation
Rwater	Raw water from AR (variable)
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
SIV	System Input Volume
SPI	Standardized Precipitation Index
SRES	Special Report on Emission Scenarios
SSP	Shared Socioeconomic Pathway
SWAT	Soil and Water Assessment Tool
Swater	Spring water contribution (variable)
SWIR	Shortwave Infrared

Tana	Lake Tana (used as shorthand)
Twater	Treated water production (variable)
TWS	Total Water Supply (variable)
UARL	Unavoidable Annual Real Losses
UC	Unauthorized Consumption
UN/DESA	United Nations Department of Economic and Social Affairs
UN Water	United Nations Water
UNECA	United Nations Economic Commission for Africa
UNESCO	United Nations Educational, Scientific and Cultural Organization
UN Habitat	United Nations Human Settlements Programme
USAID	United States Agency for International Development
UWD	Unmet Water Demand
WEAP	WEAP System
WEF	World Economic Forum
WHO	World Health Organization
WHO/UNICEF	WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene
WWAP	World Water Assessment Programme

ABSTRACT

Urban water security in Sub-Saharan Africa is increasingly challenged by rapid urbanization, climate variability, aging infrastructure, and institutional constraints. This study explains the water supply–demand divergence in Gondar City, Ethiopia, using a sequential explanatory mixed-methods design that integrates time-series analysis, remote sensing, NRW (NRW) accounting, WEAP modeling, and stakeholder interviews. The analysis shows that the central problem is a structural source-capacity deficit created by delayed infrastructure expansion and progressive reservoir sedimentation. NRW reaches 36.12% of system input, with real losses accounting for 28.41%, further reducing the share of available water that reaches consumers. Long-term supply trends (2011–2024) were analyzed using Mann–Kendall tests, change-point detection, and lagged climate correlations. Reservoir storage change was quantified from Sentinel-2 imagery and validated against bathymetric evidence, while NRW was estimated using the AWWA water balance framework. Future supply–demand trajectories (2025–2045) were simulated under population growth, climate scenarios (RCP 4.5 and 8.5), sedimentation, groundwater decline, and planned infrastructure interventions. Results show that reservoir-based supply remained largely stagnant, while groundwater and spring contributions increased significantly, confirming a reactive shift from surface water to alternative sources. Even where total registered supply rose, household access did not improve because rising demand and distribution losses continued to outpace supply expansion. The study contributes empirically through the first integrated longitudinal analysis of multi-source water change in a secondary Ethiopian highland city, methodologically by combining remote sensing, AWWA water balance analysis, and WEAP modeling under data-scarce conditions, and theoretically by advancing socio-hydrological understanding of path-dependent source substitution and maladaptation. The study recommends prioritized source augmentation, integrated NRW reduction, sediment management, and phased demand management within a coordinated urban water governance framework.

Keywords: Urban water security; supply–demand divergence; reservoir sedimentation; NRW; socio-hydrology; WEAP modeling; remote sensing; climate change

CHAPTER ONE
INTRODUCTION

1.1 Background of the Study

Rapid urban population growth and economic growth have placed unprecedented pressure on freshwater resources worldwide. Although nearly three-quarters of the Earth's surface is covered by water, less than 2.5% is accessible for consumption (Adams et al., 2019; Oki & Kanae, 2006). Consequently, water scarcity has become one of the most pressing global challenges, particularly in rapidly expanding urban areas (IPCC, 2022; UN-Habitat, 2022). Global water use increased from approximately 1,000 km^3 per year in 1950 to approximately 3,700 km^3 per year by 2000, driven largely by population growth, urbanization, and industrial development (Shiklomanov, 2000). By 2030, global freshwater demand is expected to exceed available supply by 40% (WEF, 2023).

Currently, approximately 2.2 billion people lack safely managed drinking water, obtained from an improved source that is available on premises, accessible when needed, and free from fecal and priority chemical contamination (WHO/UNICEF, 2023). This definition serves as the basis for monitoring progress toward *Sustainable Development Goal (SDG) 6.1*, which seeks to ensure safe and affordable drinking water for all. The burden is especially severe in sub-Saharan Africa, where approximately 387 million people lack even basic drinking water services, and many others depend on unreliable or unsafe sources (WHO/UNICEF, 2023).

Climate variability further intensifies these challenges of urban water supply. Changes in rainfall patterns, rising temperatures, and increased evapotranspiration alter the hydrological cycle, reducing both surface water availability and groundwater recharge, while demand for domestic, agricultural, and energy use continues to rise (IPCC, 2023; Roth et al., 2018). Reservoirs play a vital role in storing water and buffering seasonal supply fluctuations. Worldwide, more than 60,000 large reservoirs provide a combined storage capacity estimated to be between 6,000 and 8,000 km^3 (Perera et al., 2023). However, sedimentation steadily reduces their effectiveness. Current estimates suggest that reservoirs lose approximately 70–80 km^3 of storage capacity each year, and total global storage may already have declined by 25–50% over recent decades

(Annandale et al., 2016; Perera et al., 2023). If these trends continue, future losses will pose a significant threat to global water security. Much of this problem is linked to soil erosion and land degradation, which increase sediment loads entering reservoirs (FAO, 2017; McDonald et al., 2014).

Water loss within distribution systems poses an additional challenge. NRW is defined as the difference between the volume of water entering a distribution system and the volume billed to authorize customers. NRW consists of three components: real losses resulting from leaks, pipe bursts, and overflows; apparent losses caused by metering inaccuracies, unauthorized consumption, and data handling errors; and unbilled authorized consumption, such as water used for firefighting or system flushing (Mutikanga et al., 2013). For detail and operational definition of NRW and its components (See Chapter Two: Literature Review). In many developing countries, NRW accounts for 20–70% of total water production (Araújo Junior et al., 2022; Oviedo-Ocaña et al., 2020).

Efficient water utilities demonstrate that substantial reductions in NRW (NRW) are achievable. Singapore and the Netherlands maintain NRW levels of about 5%–6% through leakage control, meter replacement, and automated billing systems (World Bank, 2016). In contrast, NRW exceeds 40% in many Sub-Saharan African cities, including Yaoundé (52.5%), Accra (54%), Dar es Salaam (48%), Mwanza (37%), and Addis Ababa (40%–42%) (AfWA & USAID, 2015; Beker & Kansal, 2023; Nono et al., 2024; Unto, 2024). Reducing NRW improves service reliability, increases utility revenue, and delays costly infrastructure investments (Putri et al., 2021). However, NRW is not only a technical issue; it also reflects policy and administrative shortcomings. Effective reduction therefore requires technical measures, institutional reforms, and sound financial management (Dangui & Jia, 2022).

Urban water systems in Ethiopia reflect many of these broader challenges. In numerous cities, residents depend on informal water vendors who often charge high prices while supplying water of uncertain quality, creating economic and public health concerns (Dery & Bisung, 2022; OECD, 2021). Although Ethiopia possesses substantial overall water resources, their uneven spatial distribution, climate variability, and aging infrastructure have limited the development of reliable urban water supply systems. With the urban population growing at approximately 4%

per year (UN-Habitat, 2022), ensuring access to safely managed drinking water has become increasingly urgent, especially in secondary cities where infrastructure investment has not kept pace with population growth (WHO/UNICEF, 2023).

Gondar City, one of the largest and oldest continuously inhabited urban centers in northwestern Ethiopia, clearly illustrates these pressures. The city's first gravity-fed water supply system was constructed in the 1930s and was later expanded through the development of the AR, commissioned in 2002, along with groundwater wells and protected springs (NIRAS, 2012). The reservoir was designed to serve a much smaller population over a limited time horizon. However, urban growth has outpaced infrastructure expansion, and the system has reached its design limits sooner than anticipated. Consequently, water shortages have become a structural challenge rather than a temporary operational problem.

Currently, the system serves more than 431,000 residents, far exceeding its original design population. Although NRW and distribution inefficiencies contribute to service interruptions, they are not the primary drivers of the water shortages. A more fundamental challenge is the growing mismatch between available water sources and current demand. The problem extends beyond losses within the distribution network: the existing portfolio of water sources is insufficient to meet present and future needs, and its reliability is increasingly constrained by seasonal variability, source limitations, and infrastructure expansion delays. Addressing water supply challenges in Gondar City therefore requires not only reducing system losses but also strengthening source development, improving storage reliability, and expanding supply infrastructure to keep pace with continued urban growth.

1.2 Statement of the Problem

Urban water supply systems in many developing countries are increasingly challenged by rapid population growth, climate variability, declining source reliability, infrastructure limitations, and high levels of NRW (Koop et al., 2017). Although significant efforts have been made to expand water supply infrastructure, many cities continue to experience persistent water shortages because demand growth often exceeds the pace of system development. These challenges are particularly evident in rapidly growing secondary cities, where infrastructure investment frequently lags behind urban expansion.

Gondar City exemplifies these challenges. Over the past several decades, the city's population has grown rapidly, resulting in a substantial increase in water demand. While the urban water supply system has been expanded through the development of surface water, groundwater, and spring sources, the available supply has not kept pace with growing demand. Consequently, many households experience intermittent water supply, prolonged service interruptions, and increasing dependence on alternative water sources.

The AR, which forms a major component of the water supply system of the city, was developed as part of a long-term water supply expansion program. The project design was completed in 1997, while reservoir impoundment and operational commissioning were finalized in 2002. The reservoir was designed with a live storage capacity of approximately 5.3 million cubic meters (MCM), a projected design life of 25 years, and a planning population of approximately 20,000 residents based on population projections available at the time (Haregeweyn et al., 2012; NIRAS, 2012). However, population growth substantially exceeded the planning assumptions used during project design, placing increasing pressure on the water supply system shortly after commissioning.

In addition to increasing demand, the reliability of existing water sources has declined over time. Reservoir sedimentation has progressively reduced the effective storage capacity of the AR, thereby limiting its ability to regulate seasonal water availability. Groundwater resources have also shown signs of declining performance. For example, groundwater production from the KDWF declined by 28.1% between 2019 and 2022 due to falling yields and operational constraints.

Although NRW remains a significant challenge within the distribution network, water shortages in Gondar are not solely attributable to distribution losses. Recent assessments indicate that existing water production satisfies only about one-third of the total water demand, resulting in a substantial supply deficit. While estimates vary depending on whether gross production, effective supply, or registered demand are considered, all assessments indicate that current supply falls considerably below existing requirements. Consequently, the city faces a widening gap between available water resources and growing demand.

Despite numerous studies on Gondar's water system, the literature remains fragmented. Research has focused on watershed hydrology, sediment dynamics, reservoir sedimentation, water quality, and distribution deficits, and governance challenges (Admas et al., 2022; Haregeweyn et al., 2012; Desye et al., 2021; Abebe, 2018). However, an integrated assessment linking hydrological change, water supply, and climate variability is still lacking. Four major research gaps persist: the lack of integrated analysis of source variability, reservoir sedimentation, and distribution losses; the use of cross-sectional rather than longitudinal designs; the absence of remote sensing in seasonal reservoir monitoring; and the limited application of AWWA water balance and socio-hydrological frameworks in Gondar.

This study therefore seeks to assess the current and future water supply situation of Gondar City by examining historical supply dynamics, quantifying reservoir storage loss, evaluating distribution inefficiencies, and projecting future supply-demand conditions under alternative development scenarios. The findings are expected to support strategic planning and contribute to the long-term sustainability of the city's water supply system.

1.3 Research Objectives

1.3.1 General Objective

The general objective of this study is to explain the divergence between urban water supply and demand in Gondar City, Ethiopia, by quantifying the relative contributions of source depletion, distribution inefficiencies, and demand growth over time, and by projecting future trajectories under alternative infrastructure and climate scenarios.

1.3.2 Specific objectives

The specific objectives of the study are to:

- To analyze the trends and change-point dynamics of water supply in Gondar City using a sequential explanatory mixed-methods approach.
- To evaluate how reservoir depletion and distribution inefficiencies jointly affect Gondar's water security by quantifying their combined effect on effective water supply and identifying management implications.
- To project the 2025–2045 supply-demand divergence using WEAP model under climate, population, and infrastructure scenarios, and assess interventions to enhance water security.

1.4 Research Questions

The following research questions address the study's three objectives.

Objective 1: Trends and Patterns

- What are the long-term annual and seasonal trends in supply volume from the AR, groundwater wells, and springs (2011–2024)?
- When do statistically significant changes occur in the supply time series?
- How does rainfall variability correlate with source-specific supply, and what is the magnitude of the delayed climate response?

Objective 2: Constraints and Drivers

- What proportion of the AR's original live storage capacity has been lost since commissioning, and at what rate did loss occur between 2016 and 2024?
- What is the total volume of NRW, and how is it distributed between apparent and real losses?
- How do reservoir storage depletion and distribution inefficiencies drive current supply shortages?

Objective 3: Scenarios and Interventions

- How will water demand evolve under alternative population growth and climate scenarios (RCP 4.5 and 8.5) from 2025 to 2045?
- To what extent will the MGD and Lake Tana Pumping Scheme mitigate projected supply deficits?
- Which combination of infrastructure, policy, and demand management provides the most viable path to water security by 2045?

1.5 Scope of the Study

This study examined water availability in Gondar City by analyzing the AR, groundwater wells, and springs, and evaluated the impacts of seasonal variations, sedimentation, and water loss. The projections account for climate change, population growth, and infrastructure projects, such as the MGD and the proposed LTWPS. By integrating historical analysis with scenario modeling, this study underscores the issue of water insecurity in Gondar City.

This study evaluated water insecurity in Gondar City by analyzing water availability in relation to demand. Quantitatively, it employed time-series trend analysis, seasonal analysis, change-point analysis, and scenario analysis using the WEAP model. Qualitatively, it incorporated KIIs and FGDs. The findings indicate historical trends in water availability and distribution losses, as well as the impacts of sedimentation, while projecting future supply and demand under various scenarios.

The geographic scope was limited to the municipal water supply system of Gondar City, including its source catchments. The temporal scope encompassed a historical analysis (2011–2024), remote sensing analysis (2016–2024), NRW assessment for 2024, and future projections from 2025 to 2045. This study excluded water quality analysis, except where directly relevant to treatment constraints, detailed hydraulic pressure modeling of the distribution network, and comprehensive socioeconomic assessments of water insecurity. The focus was on water quantity and system performance, thereby providing a foundation for future research on water quality and socioeconomic impacts.

1.6 Significance of the Study

This study is organized into eight chapters. Chapter One introduces the study and covers the background, problem statement, research objectives, research questions, scope, significance, and structure of the dissertation.

Chapter Two reviews the literature and theoretical foundations related to climate change, urban water supply, NRW, the supply-demand nexus, and socio-hydrology. Chapter Three presents the study area and its physical, hydrological, and socioeconomic characteristics.

Chapter Four describes the research methodology, including the sequential explanatory mixed-methods design, data sources, sampling procedures, analytical methods, and ethical considerations. Chapters Five, Six, and Seven present the empirical findings and address the study's main research objectives.

Chapter Five analyzes long-term and seasonal water supply trends, change-point dynamics, and climate responsiveness using trend analysis, change-point detection, and qualitative evidence.

Chapter Six examines the factors that reduce the effective water supply by assessing AR storage changes and NRW using Sentinel-2 imagery, DEM-based volume estimation, and the AWWA water balance framework. Chapter Seven evaluates future water security between 2025 and 2045 using the WEAP model, considering population growth, climate change, sedimentation, groundwater depletion, and planned infrastructure developments, including the MGD and the proposed LTWPS.

Chapter Eight summarizes the major findings, draws conclusions, and provides recommendations for policy, planning, and future research. The dissertation concludes with references and appendices containing supporting data, accuracy assessments, and modeling outputs

1.7 Organization of the Study

This dissertation is organized into eight chapters. Chapter One introduces the study, outlining the background, problem statement, research objectives, research questions, scope, significance, and the structure of the dissertation. Chapter Two reviews the literature and theoretical foundations related to climate change, urban water supply, reservoir sedimentation, NRW, the supply demand nexus, and socio-hydrology. Chapter Three presents the study area and its physical, hydrological, and socioeconomic characteristics.

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CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

This chapter establishes a theoretical and empirical foundation for examining urban water supply systems under multiple interacting stresses. The discussion progresses from external environmental drivers, particularly climate change, to infrastructure-related challenges, such as reservoir sedimentation and distribution losses, and finally to management frameworks and governance arrangements. This structure highlights the interconnection between climate variability, sediment accumulation, and NRW, which collectively influence urban water security. This chapter also provides the conceptual basis for the scenario-based modeling presented in Chapter Seven and identifies the key theoretical and empirical gaps addressed by this dissertation.

2.2 Key Concepts and Definitions

Climate Change and Hydrological Variability refer to long-term changes in temperature and precipitation that affect water availability through altered rainfall patterns, increased evapotranspiration, and more frequent droughts and floods. Hydrological variability includes both short-term fluctuations in streamflow and long-term changes in the availability of water (Arias et al., 2023). In this study, climate change was represented by RCP 4.5 and RCP 8.5 scenarios (IPCC, 2013).

NRW refers to water entering the distribution system that does not generate revenue. It includes physical losses from leaks, apparent losses from metering inaccuracies and unauthorized consumption, and authorized but unbilled usage (Kingdom et al., 2006; Lambert et al., 1999; Mutikanga et al., 2011).

Urban Water Demand is the total volume of water required to meet domestic, commercial, industrial, and public needs in an urban area over a specified period. It is influenced by population growth, economic development, climate change, and technological development (Dias & Ghisi, 2024).

Urban Water Supply refers to the infrastructure and processes used to abstract, treat, store, and distribute water to urban consumers. It includes water sources, treatment facilities, reservoirs, transmission systems and distribution networks (Trifunović, 2020).

Water Security is the capacity of a population to maintain sustainable access to adequate quantities of safe water for human well-being, livelihoods, and socioeconomic development while managing water-related risks and protecting ecosystems (UN Water, 2013). This study encompasses water availability, service reliability, infrastructure performance, and institutional effectiveness.

2.3 Theoretical Frameworks

This section develops the theoretical framework for the study, moving from climate-hydrology linkages through infrastructure processes to integrated management frameworks. Together, these provide the theoretical foundation for the integrated analytical approach applied across the dissertation.

2.3.1 Global Warming and Hydrological Impacts

Climate change fundamentally alters the global water cycle. Increased precipitation can enhance water availability, while rising temperatures intensify evapotranspiration and diminish surface water resources (O'Hara & Georgakakos, 2008). In Ethiopia, temperature records show a consistent upward trend, with an average increase of 0.28°C per decade between 1960 and 2006 (Simane et al., 2016) and 0.37°C per decade over the past 50 years, with climate models projecting increases of up to 3.3°C in key Ethiopian regions by the 2050s (Gizaw & Gan, 2017). Precipitation patterns, however, are more variable, with a decline of approximately 20% recorded in eastern and southeastern Ethiopia over the past five decades (Degefu et al., 2021), compounded by multi-year droughts (2020 – 2023).

For Gondar, situated in the northwestern Ethiopian highlands, these regional temperature trends translate into increased evapotranspiration losses from the AR, a mechanism quantified through satellite-based volume estimates (see Chapter Five). Beyond periodic drought cycles, cumulative climatic shifts are reshaping hydrological regimes, increasing spatiotemporal variability in both surface water and groundwater, and undermining the reliability of urban water systems already operating under stress (Tilahun et al., 2023).

2.3.2 Climate Change Scenario Frameworks

Climate change fundamentally alters the global water cycle. Increased precipitation can enhance water availability, while rising temperatures intensify evapotranspiration and diminish surface water resources (O'Hara & Georgakakos, 2008). In Ethiopia, temperature records show a consistent upward trend, with an average increase of 0.28°C per decade (1960 – 2006) (Simane et al., 2016) and 0.37°C per decade over the past 50 years, with climate models projecting increases of up to 3.3°C in Ethiopia by the 2050s (Gizaw & Gan, 2017). Precipitation patterns, however, are more variable, with a decline of approximately 20% recorded in eastern and southeastern Ethiopia over the past five decades (Degefu et al., 2021), compounded by multi-year droughts from 2020 to 2023.

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2.3.3 IWA/AWWA Water Balance Framework for NRW Estimation

IWA water balance framework, developed between 1999 and 2000, classifies all water entering a distribution system into authorized consumption and NRW (Figure 2.1). NRW is further divided into real and apparent losses (AL). Real losses are physical losses caused by leaks, pipe bursts, and overflow within the transmission and distribution network, and are influenced by infrastructure conditions, operating pressure, maintenance practices, and supply intermittency (Farley & Trow, 2003). Apparent losses occur when water is delivered but not billed because of meter inaccuracies, unauthorized consumption, or data handling errors. Although water reaches consumers, utilities fail to measure or recover revenue from it, reducing financial performance and distorting demand estimates (IWA, 2021).

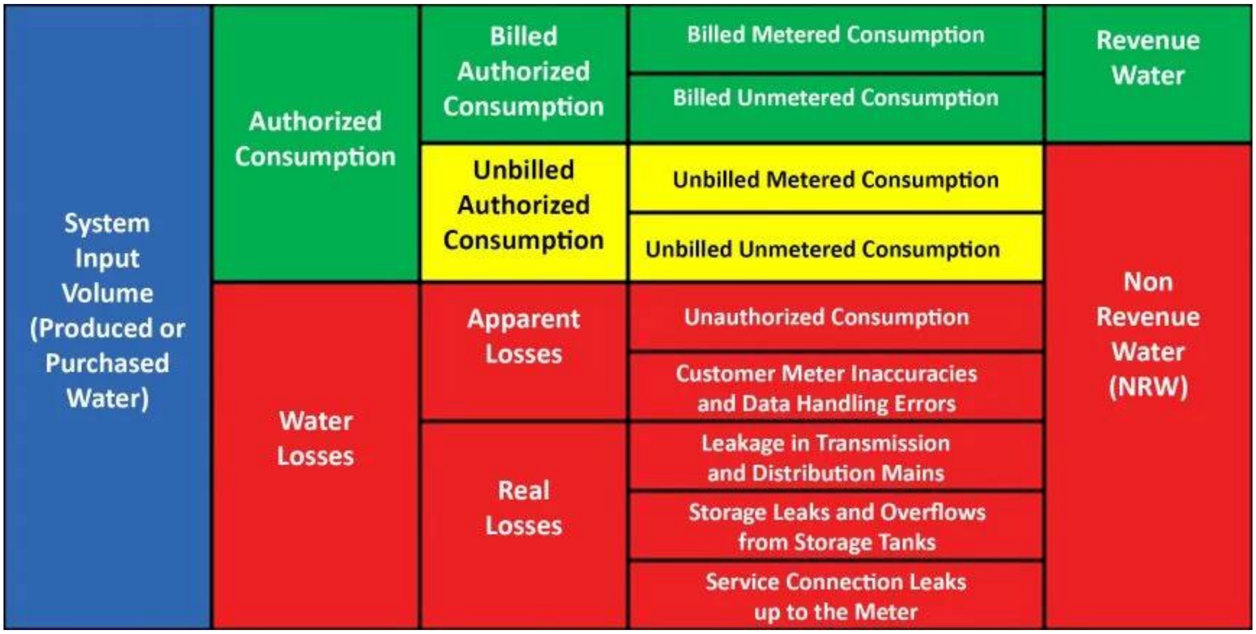

Figure 2.1 Water balance components of NRW (Adapted from IWA, 2009; AWWA, 2017)

When local data are unavailable, benchmark default values from peer-reviewed literature are applied to estimate NRW components. Meter inaccuracy typically introduces errors of 5% to 10%, with higher rates where meters are aging or poorly maintained. Unbilled authorized consumption generally ranges from 5% to 15%, data handling errors from 1% to 2% under normal record-keeping conditions and up to 5% where systems are poor, and manual meter reading errors between 1% and 3%, reducible to below 1% with automated systems (AWWA, 2009; IWA, 2009; Mutikanga et al., 2013; Dos Santos et al., 2017).

2.3.4 Supply-Demand Nexus Theory and Socio-Hydrology

The Supply-Demand Nexus framework examines urban water security as the product of interactions among natural resources, infrastructure systems, and governance mechanisms. It reframes water scarcity not simply as a physical shortage but as the outcome of systemic inefficiencies operating across the supply chain. Deteriorating infrastructure increases water losses, reduces utility revenues, constrains maintenance capacity, and thereby reinforces a self-perpetuating cycle of inefficiency and persistent scarcity (Flores & Ghisi, 2024; Liu et al., 2024). Population growth, urban expansion, and the proliferation of informal settlements compound demand-side pressures, with unauthorized connections bypassing metering and imposing additional strain on fragile infrastructure (Arregui et al., 2011; Jokar et al., 2016; Zhao et al., 2017).

The socio-hydrological paradigm enriches this perspective by emphasizing the co-evolution of water systems and human societies through feedback loops, path dependence, and institutional responses to environmental stress (Pahl-Wostl, 2019). In the Ethiopian context, socio-political dynamics including weak regulatory enforcement, fragmented institutional coordination, and reactive crisis management are significant contributors to water insecurity that are frequently underemphasized relative to physical drivers (Grasham & Neville, 2020).

In Gondar City, progressive sedimentation of the AR triggered an institutional response of expanding groundwater abstraction. However, this expansion was pursued reactively and without adequate assessment of aquifer sustainability, creating new socio-ecological risks in the form of accelerating groundwater depletion. These co-evolutionary processes, where one problem generates responses that create new problems, help explain why infrastructure investment alone rarely achieves sustainable water security in the absence of corresponding governance reform.

It should be noted, however, that the water crisis in Gondar City is not driven solely by systemic or institutional inefficiencies. The city faces a genuine and acute physical shortage: source capacity is structurally insufficient for the current population, not merely mismanaged. The socio-hydrological framework is applied here not to minimize the physical dimension but to show how institutional failures compound and accelerate physical limitations, making the overall crisis more severe than either dimension alone would produce.

2.3.4 Reservoir Management Strategies

Sustainable reservoir management requires interventions at both the watershed and reservoir levels. Watershed measures including afforestation, terracing, and soil conservation practices reduce sediment yield at source. In Ethiopia's, such interventions reduced sediment accumulation by approximately 38% (Addisu et al., 2015). Regional studies confirm that sedimentation rates in East Africa exceed global averages due to steep terrain, intense seasonal rainfall, and widespread land degradation (Kuma et al., 2024; Zeleke et al., 2013).

At the reservoir level, options include sediment flushing, sluicing, bypassing, and dredging. While dredging is technically feasible, its cost-effectiveness is highly context-specific and often uncertain (Morris, 2020). A recurring limitation in existing sedimentation studies is their reliance on infrequent bathymetric surveys conducted at decadal intervals, which miss inter-annual and seasonal variability in storage dynamics. This gap underscores the value of integrating remote sensing into continuous monitoring programs, an approach applied in Chapter Five of this study.

2.3.5 Supply-Demand Nexus Theory and Socio-Hydrology

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2.4 Empirical Literature

2.4.1 Global Urban Water Supply Trends

Water consumption has grown substantially worldwide alongside rapid urbanization and economic development (OECD, 2021; UN-Habitat, 2020). Developing countries face the greatest challenges, including aging pipelines, intermittent supply, and high water loss rates (IWA, 2021; World Bank, 2022). In many developed countries, industrial growth and changing lifestyles are simultaneously driving demand upward (OECD, 2021; WWAP, 2019). Without sustained infrastructure investment, global water supply reliability is projected to decline (Buurman & Padawangi, 2020).

Climate change deepens uncertainty over future water availability, with higher temperatures, shifting rainfall, and more frequent droughts affecting cities worldwide, particularly those dependent on reservoir systems (Gosling & Arnell, 2016). In Ethiopia, high-emission scenarios are projected to worsen supply-demand imbalances unless water management practices are substantially improved (Alemu & Dioha, 2020). Globally, agriculture accounts for over 70% of freshwater use, industry for 16%, and municipal uses for 14% (FAO, 2021). Addressing these pressures requires integrated strategies that combine demand management, infrastructure modernization, and adaptive governance (Feizizadeh et al., 2021).

2.4.2 Urban Water Supply in Sub-Saharan Africa

Urban water systems across sub-Saharan Africa face compounding challenges. Around 420 million people lack reliable access to safe water, while 780 million lack adequate sanitation (UN-Habitat, 2020). Aging distribution systems, weak institutions, inadequate infrastructure investment, and poorly coordinated project implementation collectively undermine service delivery (AfDB, 2019; WaterAid, 2018; WHO/UNICEF, 2019). Utilities lose substantial water volumes to leaks, illegal connections, and metering errors, reducing the revenue available for essential maintenance (IWA, 2021). Governance challenges including limited accountability, regulatory weakness, and corruption further constrain institutional capacity to respond to growing demand.

A frequently overlooked dimension of the regional literature is its concentration on capital cities and large metropolitan areas. Rapidly growing intermediate urban centers with populations of 200,000 to 700,000 sometimes referred to as secondary cities; remain comparatively understudied despite facing distinct and acute water security challenges (Tibebu et al., 2022). These cities often lack the financial, technical, and institutional resources of national capitals, not because reservoir physics differ between city classes, but because institutional capacity, planning resources, and investment access are structurally unequal. Gondar exemplifies this category of city, and this study explicitly situates its analytical frameworks within this intermediate urban context. The intent is not to claim that reservoirs behave differently in secondary cities, but to acknowledge that the institutional and financial environment for managing them does, with consequences for how problems develop and what responses are feasible.

2.4.3 Urban Water Supply in Ethiopia

Ethiopian cities face serious and persistent water supply challenges. Roughly 35% of water deliveries in four major cities go unbilled (Beker & Kansal, 2023). Dire Dawa meets only about one-third of its water needs, while 50 to 65% of residents in Mekelle and Addis Ababa have reliable access (Ayele et al., 2023). These deficiencies reflect the combined effects of rapid urban growth, aging infrastructure, and inadequate institutional capacity (Timotewos et al., 2023). Nationally, over 42% of Ethiopians experience water stress, with renewable freshwater availability below 500 m^3 per person annually (Abraha et al., 2022). Population growth, infrastructure deterioration, institutional fragmentation, and climate variability interact to reduce the reliability, efficiency, and accessibility of urban water services across the country (Beker & Kansal, 2023; Nyika & Dinka, 2023), framing Gondar's specific challenges within a broader national pattern.

2.4.4 Global Patterns of Reservoir Sedimentation

Sediment accumulation progressively reduces reservoir storage capacity and threatens water supply reliability worldwide. Globally, reservoirs lose an estimated 0.5% to 1% of storage capacity annually through sedimentation, with developing countries experiencing losses of 0.5% to 3% per year, potentially rendering some reservoirs non-functional within decades (Gonzalez Rodriguez et al., 2023; Kuma et al., 2024). Wang et al. (2023) found that 64% of large reservoirs worldwide are experiencing storage loss, with sedimentation as the primary cause, providing a sobering global context for the challenges observed in the AR.

2.4.5 Regional Sedimentation Challenges in East Africa

In East Africa, sedimentation is particularly acute due to high-intensity seasonal rainfall, steep terrain, and widespread land degradation from agriculture and deforestation. These conditions accelerate sediment transport into reservoirs, causing rapid storage loss and, in some cases, structural failure (Kuma et al., 2024). Even modest annual sediment losses accumulate into severe long-term storage deficits, worsening water shortages and reducing the operational lifespan of reservoirs serving growing urban populations (Chen et al., 2021). These regional dynamics reinforce the importance of proactive watershed protection and reservoir sediment monitoring.

2.4.6 Remote Sensing Techniques for Sedimentation Assessment

Remote sensing and geospatial analysis have become reliable tools for monitoring reservoir storage dynamics (Rashid, 2023). Traditional bathymetric approaches using multibeam echo-sounders and GPS interpolation remain the standard for high-accuracy volume measurement (Yan et al., 2018), with ground-penetrating radar offering an alternative for generating three-dimensional bathymetric maps (Lachhab et al., 2015). In the Ethiopian context, Haregeweyn et al. (2012) applied bathymetric methods to assess sedimentation in the AR, providing a foundational dataset for subsequent studies.

Satellite-based monitoring offers a complementary and more temporally continuous approach. Vanthof and Kelly (2019) demonstrated that combining Sentinel-1 radar imagery with high-resolution CubeSat data improved surface area detection for small reservoirs. Tiwari et al. (2016) used Landsat imagery integrated with digital elevation models and dam height surveys to assess long-term sediment accumulation. Narasayya et al. (2013) combined multispectral imagery, water level records, and land use data to analyze reservoir storage dynamics over extended periods. A consistent limitation across these studies is the use of infrequent surveys, making seasonal remote sensing approaches (See Chapter Six), and a meaningful methodological advance for capturing inter-annual variability in storage dynamics.

2.4.7 System Inefficiencies in Water Distribution

As distribution networks age, technical inefficiencies grow. Meter accuracy degrades with cumulative flow volume, pipe condition, and supply intermittency rather than age alone (Fourie et al., 2020). Velocity-type meters can lose approximately 1% accuracy per 1,000 km of cumulative flow (Criminisi et al., 2009), and errors can reach 15% at very low flow rates below 30 L/h, dropping below 2% at higher flows (Mendoza & Benavides-Muñoz, 2021). Volumetric meters are particularly susceptible to intermittent supply, as air entrainment causes over-registration and introduces systematic measurement bias (Ferrante et al., 2022, 2023). Human and administrative errors, including meter-reading mistakes, data-entry errors, and estimated billing, further compound inaccuracies in consumption records (Mutikanga et al., 2011).

Non-technical losses through water theft, illegal connections, meter tampering, and billing errors add another layer of NRW. These losses can account for 10% to 20% of system input volume in poorly performing networks, directly undermining utility financial health and the capacity to maintain and upgrade infrastructure (Alegre et al., 2016; Mutikanga et al., 2013).

2.4.8 Measurement Approaches for NRW

The top-down approach estimates water loss by comparing total system input with billed consumption. Based on operational records, billing data, and field measurements, it applies the IWA/AWWA water balance framework to classify NRW into real losses and apparent losses (AWWA, 2009). This approach provides an overview of system-wide water losses, supports utility benchmarking, and offers a practical basis for NRW assessment and management in data-limited environments (Farley & Trow, 2003; Farley et al., 2008; Wyatt, 2010).

2.4.9 Climate Change Impacts on Future Water Availability

Climate change intensifies water scarcity globally by disrupting the hydrological cycle through higher temperatures, shifting precipitation patterns, and more frequent and severe droughts (IPCC, 2022). Increased evapotranspiration driven by warming temperatures reduces effective water availability even where total precipitation does not decline significantly (Guan et al., 2024).

In Ethiopia, projections for the Omo-Gibe Basin under RCP 4.5 and 8.5 indicate precipitation reductions of up to 13.8% and streamflow declines of around 11% by mid-century (Chelkeba et al., 2023). For the Megech watershed, which supplies the AR and will feed the planned MGD, June to August river flows could decrease by up to 29.4%, posing serious risks to Gondar's water supply (Asitatikie & Gebeyehu, 2021). Temperature increases of 2.1 to 4.8°C projected for the region are expected to intensify evapotranspiration further, compounding supply reductions even under scenarios where rainfall does not decline substantially (Roth et al., 2018). These projections represent a plausible range based on ensemble model outputs and are applied in the WEAP scenario modeling in Chapter Seven to bound the range of likely climate impacts.

2.4.10 Simulation of the Supply-Demand Nexus

The WEAP model system is a widely used decision-support tool that integrates hydrological, economic, and environmental dimensions of urban water management (Yates et al., 2005). WEAP enables users to project future water needs under scenarios combining population growth, climate change, land use change, and policy interventions, while simulating the operation of supply infrastructure including reservoirs, pipelines, wells, and sector-specific demands.

Applications of WEAP span diverse contexts. In Xiamen, China, the model projected future water shortages and found that conservation measures could reduce demand by 6.97% to 16.44% (Kou et al., 2018). In Jeddah, Saudi Arabia, it forecast a 504 MCM supply gap by 2030 (Al-Shutayri & Al-Juaidi, 2019). Ethiopian studies have demonstrated that supply-demand imbalances will worsen without substantial improvements in water management, particularly under high-emission scenarios (Alemu & Dioha, 2020; Assegide et al., 2023). A key strength of WEAP is its capacity to evaluate the combined effects of urban growth, climate change, and infrastructure investment decisions on water security, even under data-scarce conditions, provided the model is properly calibrated, validated, and subjected to uncertainty analysis (Birhanu et al., 2018; Yates et al., 2005).

2.4.11 Identified Research Gaps

Research on urban water supply in Ethiopia has grown considerably over the past two decades and now spans sedimentation, water quality, demand analysis, hydraulic network modeling, NRW estimation, and governance assessment. However, studies have predominantly examined these dimensions independently, without integrating them into a coherent analytical framework capable of explaining the cumulative supply-demand divergence. Previous work on Gondar has addressed water quality, AR sedimentation, urban demand trends, and hydraulic network modeling. While these contributions are valuable, none has established an integrated framework connecting sedimentation, rising demand, aging infrastructure, distribution losses, and institutional responses within a single longitudinal analysis.

Regarding NRW, while several Ethiopian studies have estimated water losses and some have proposed modifications to leakage performance indicators including the ILI, the AWWA/IWA water balance framework for systematically disaggregating NRW into its real and apparent loss components has been rarely applied in secondary Ethiopian cities. This limits the ability to design targeted, component-specific interventions. Similarly, while WEAP modeling has been applied at the national and basin level in Ethiopia, comprehensive scenario modeling that simultaneously incorporates population growth, climate variability, reservoir sedimentation, groundwater depletion, and competing irrigation demands remains limited for secondary cities like Gondar (Alemu & Dioha, 2020; Assegide et al., 2023).

A further gap exists in the predominance of cross-sectional and short-term analyses across the Ethiopian literature, which is insufficient for detecting long-term trends, identifying regime shifts, or capturing seasonal dynamics in multi-source water systems. For the AR specifically, storage assessments have typically been conducted at decadal intervals and rarely integrate seasonal remote sensing indices such as NDWI and MNDWI with digital elevation data for volumetric estimation. Finally, socio-hydrological approaches that integrate physical water dynamics with institutional behavior, adaptive responses, and governance feedbacks remain underutilized in the Ethiopian highland context, limiting the theoretical depth of existing water security assessments.

2.4.12 Conceptual Framework

The conceptual framework shown in Figure 2.2 organizes the dissertation around four interrelated components: external drivers, watershed and reservoir processes, distribution system performance, and system outcomes. Together, these components and their feedback relationships define the scope of analysis.

External drivers include climate change, population growth, and land use change. These operate beyond the direct control of water utilities but fundamentally shape system conditions. Climate change reduces reservoir inflows and increases evapotranspiration from the AR. Population growth expands urban water demand across domestic, commercial, industrial, and public institutional categories, including hospitals, educational institutions, military facilities, and government offices. Land use change in the Angereb and Megech watersheds intensifies soil erosion and increases downstream sediment loads entering the reservoir system.

These external drivers shape watershed and reservoir processes. Erosion and sediment deposition progressively reduce the AR's storage capacity, while climate variability alters inflow timing and volume, affecting the quantity of raw water available for treatment. Groundwater sources in the Koladiba and AWFs are similarly affected by reduced recharge and progressive over-abstraction.

From the treatment plant, water enters the distribution system, where operational conditions and infrastructure state determine delivery efficiency. The distribution system boundary begins at the outlet of the treatment facility and extends through transmission mains, service reservoirs, distribution pipes, and service connections to the consumer meter. NRW originates within this system through physical losses from leaking pipes and bursts, and through apparent losses from metering inaccuracies and unauthorized consumption. These losses reduce the volume of water reaching consumers and erode utility revenues, constraining the maintenance budget and perpetuating a cycle of degradation.

Importantly, the framework also captures water demands and competing uses along the supply corridor from source to city. The MGD, once operational, will serve both Gondar City and the MGD Irrigation Command Area, introducing a significant inter-sectoral allocation dimension. Water extraction points along the Megech and Angereb river corridors, including settlements drawing from surface and groundwater sources between the dam and the city, and the longer-term potential of the Lake Tana pumping scheme, are all reflected in the demand nodes of the WEAP model in Chapter Seven. This ensures that competing demands are explicitly accounted for in supply-demand projections rather than treating Gondar City as the sole user of available resources.

System outcomes, including the supply-demand divergence, service coverage, per capita supply, and financial performance of the utility, emerge from the interaction of all upstream components. The framework is therefore used as the basis for integrating historical analysis with scenario-based projections

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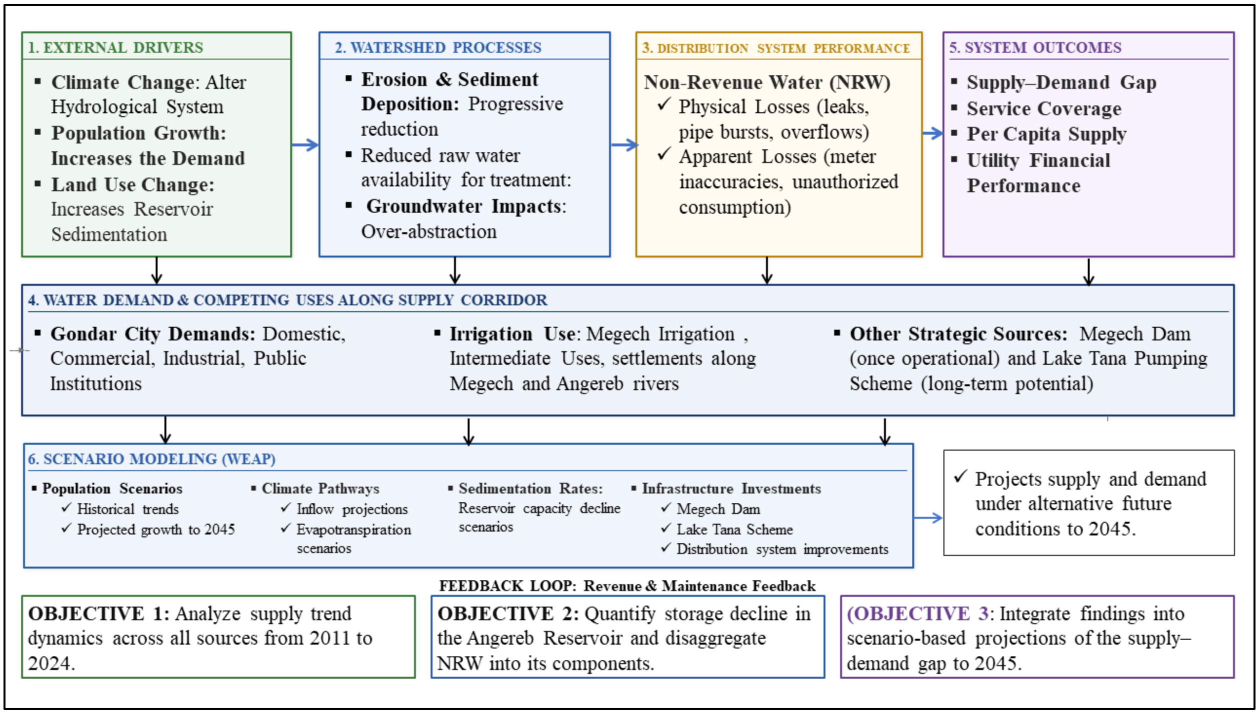

Figure 2.2 Conceptual framework of the study

CHAPTER THREE
DESCRIPTION OF THE STUDY AREA

This chapter describes the biophysical and socioeconomic context of Gondar City, the study area for this dissertation. It covers the city's location, climate, topography, hydrology, water supply infrastructure, historical background, economic activities, and population dynamics. Together, these attributes explain why Gondar is a critical and representative case for studying urban water supply–demand divergence and why the analytical frameworks applied in Chapters Four through six are appropriate for its specific conditions.

Taken together, Gondar's rapid population growth, its dependence on a single aging reservoir, the progressive decline of groundwater sources, and the city mountainous topography which limits alternative source development create the precise conditions of vulnerability that this dissertation investigates. The physical and demographic attributes described here form the contextual basis for the trend analysis (Chapter Five), reservoir volume and NRW assessment (Chapter Six), and scenario modeling (Chapter Seven).

3.1 Physical Attributes

3.1.1 Location

Gondar is located in the Amhara Regional State of northwestern Ethiopia, approximately 727 kilometers north of the capital Addis Ababa and 120 kilometers northeast of Bahir Dar (Figure 3.1). The city sits at the foothills of the Semien mountain range at an average elevation of 2,200 meters above sea level, within an administrative region covering 192.3 km^2. It is well connected by road to Adwa, Aksum, and Metema, with the latter route extending to Sudan, reinforcing Gondar's role as a significant regional trade and transit hub. The city also serves as the primary gateway to the Semien Mountains National Park, a UNESCO World Heritage Site that anchors its tourism economy.

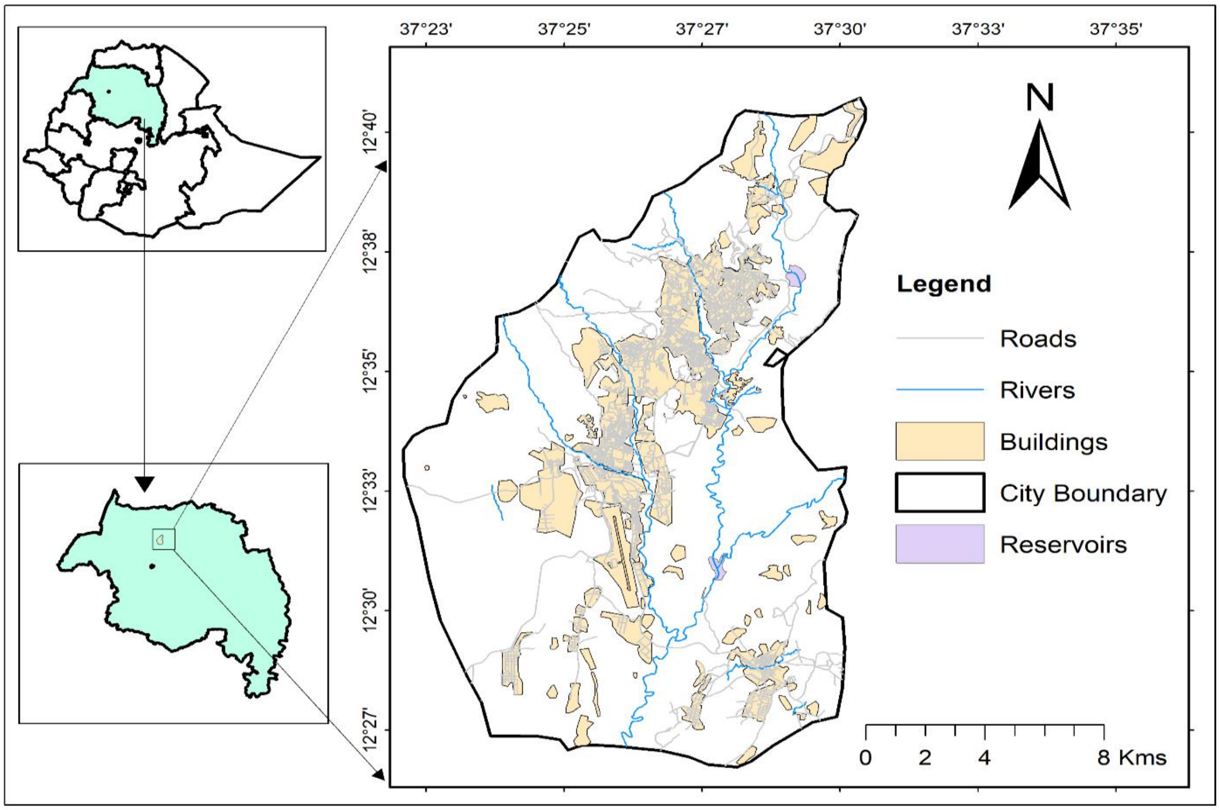

Figure 3.1 Location of Gondar City

3.1.2 Climate

As shown in Figure 3.2 Gondar experiences a tropical highland climate shaped by its elevation and the seasonal movement of the Intertropical Convergence Zone (ITCZ). Monthly precipitation and temperature data from 1990 to 2024 reveal a strongly seasonal pattern, with a main rainy season from June to August accounting for approximately 90% of annual rainfall, and a pronounced dry season from January to March (NMA, 2024). Long-term records for Gondar station show a clear warming trend, with average annual temperature rising from about 18.7°C to 20.0°C over the past four decades, a rate of 0.33°C per decade. This differs slightly from the 0.28°C per decade figure reported in Chapter Two, which refers to the broader Ethiopia-wide trend rather than the Gondar station record. Rainfall has fluctuated considerably over the same period, ranging from 701.4 mm in 2011 to 1,861.5 mm in 2014, a 2.6-fold difference within just a few years (NMA, 2024). This hydroclimatic variability has direct consequences for urban water management because the AR receives nearly all of its inflow during the brief June to

August window, making stored water after the wet season essential for meeting the city's needs during the dry months that follow.

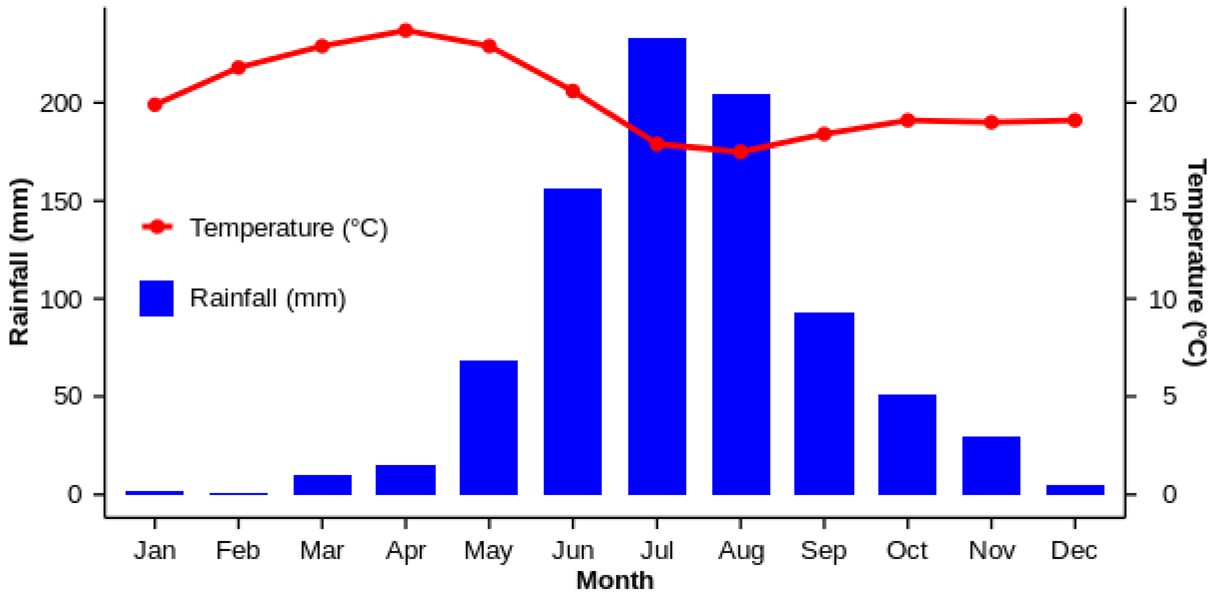

Figure 3.2 Monthly average precipitation and temperature of Gondar City (1990-2024)

3.1.3 Topography and Hydrology

The landscape of Gondar consists of rolling hills descending southward toward Lake Tana, with elevations ranging between 1,863 and 2,966 m (Figure 3.3), a range that defines drainage patterns across the Megech and Lesser Angereb river systems. The Lesser Angereb joins the Megech southeast of the city, while the Megech originates north of Gondar, flows south toward the lake, and splits into two branches before reaching it. East of the city at 2,123 meters, the AR was built beginning in 1986 and became fully operational in 2002, collecting water from the Lesser Angereb within a catchment area of approximately 90 square kilometers (NIRAS, 2012). The MGD, currently under construction approximately 40 km southeast of Gondar, is planned to store 185 MCM of water for urban use (ANRS & ECDSWC, 2021). The rivers in this area exhibit pronounced seasonal fluctuations, with high flows during the rainy season and very low or no flow in the dry season, which severely limits surface water availability.

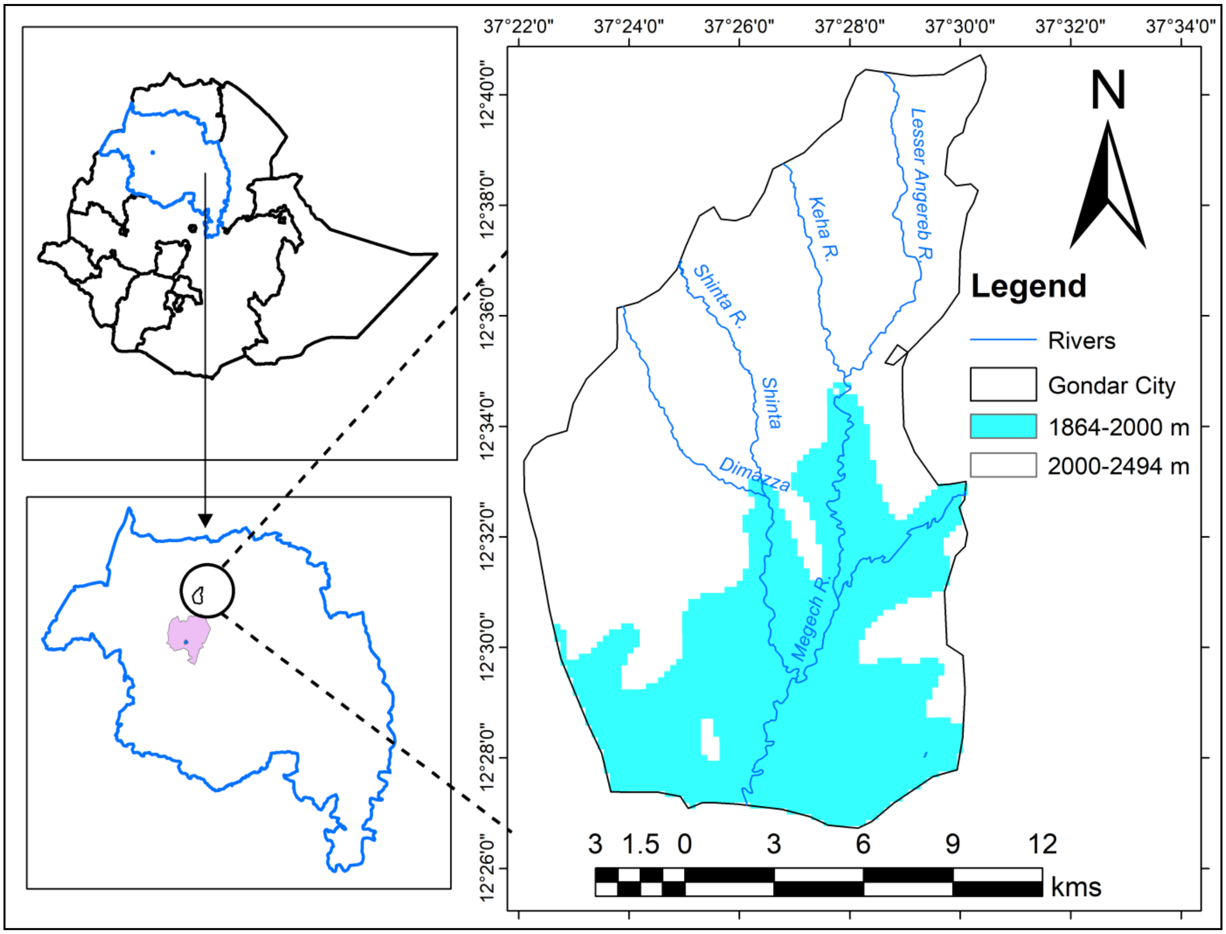

Figure 3.3 Topography and hydrology of Gondar City

3.2 Water Supply Infrastructures

The water supply of Gondar is derived from three main sources: the AR, groundwater from the Koladiba and AWFs, and protected springs (Figure 3.4). The AR has served as the primary source of water since 2002, with a design yield of approximately 90 L/s (7,776 m³/day). To supplement this, the KDWF, located approximately 25 km north of the city, was developed in phases from the early 2000s. Although its 16 boreholes have a combined design yield of approximately 50 L/s, more than half are now non-operational owing to declining groundwater levels, aging pumps, and unreliable electricity (GCWSSS, 2018; MSC, 2023). The AWF provides additional but variable groundwater, whereas protected springs contribute seasonally and often dry up between October and May. Together, the operational sources produce an estimated 40,000–45,000 m³ of water per day, which is less than half of the city's estimated demand of over 90,000 m³/day. This deficit reflects both declining source capacity and distribution inefficiency. NRW is estimated at approximately 36 percent, meaning that more than one-third of the produced water does not generate revenue. As of 2024, only approximately 45 percent of the population has access to piped water, and service is typically available for only 8 to 12 hours per day, well below the 24-hour service standard. Households without piped connections rely on communal kiosks, water vendors, or unprotected sources, often at higher cost and lower quality.

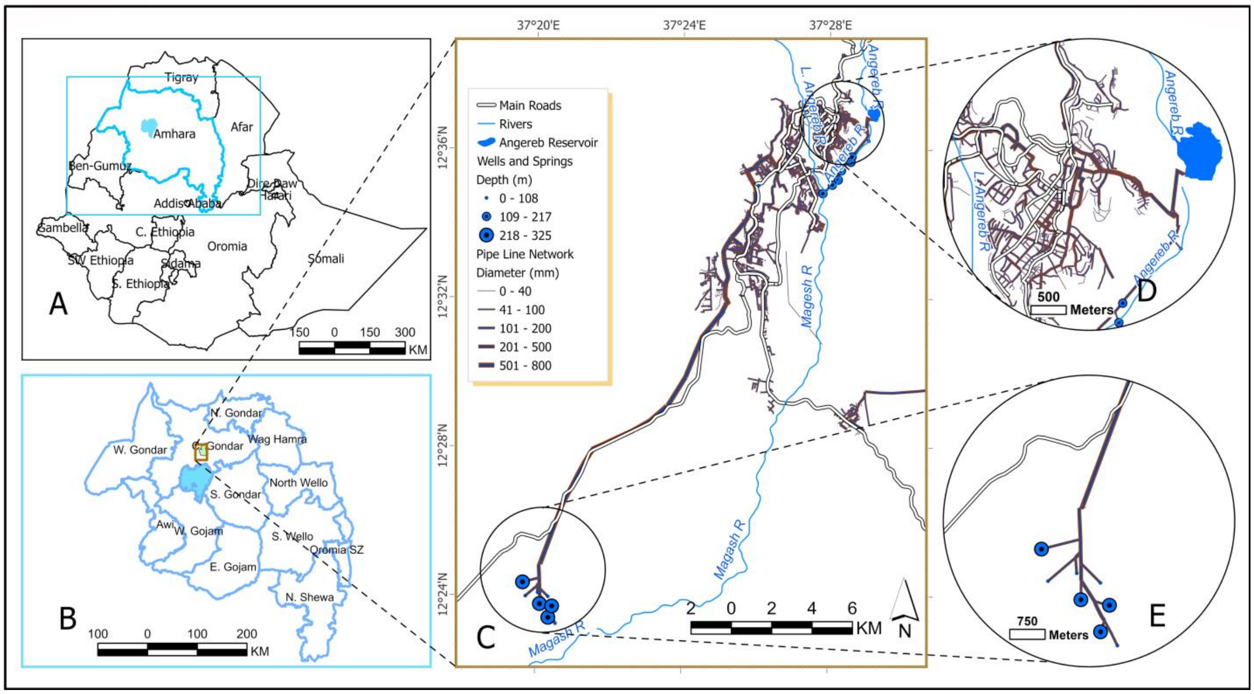

Figure 3.4 Location and water supply infrastructure of Gondar City: (a) Ethiopia and the Amhara Region; (b) Amhara Region with Gondar City highlighted; (c) major water sources and pipelines; (d) AR area; (e) Kola Diba wellfield area.

3.3 Socio-economic Context

3.3.1 Historical Background

In 1636, Emperor Fasilides established Gondar as Ethiopia's permanent capital, ending the tradition of mobile royal camps and creating one of the countries's first planned urban centers (Horvath, 1969; Wubneh, 2023). The Fasil Ghebbi (Royal Enclosure), built at that time, is now a

UNESCO World Heritage Site and the most visible symbol of the city's historical significance. During the Gondarine era (17th–mid-18th century), Gondar flourished as Ethiopia's political, religious, and cultural heart, with churches such as Debre Berhan Selassie becoming defining landmarks of Ethiopian Orthodox Christianity that still attract pilgrims and visitors (Woredekal, 1985). The city's political prominence declined in the late 18th and early 19th centuries during the Zemene Mesafint (Era of the Princes), which led to the relocation of the national capital (Horváth, 1969). Despite this, Gondar retained its importance as a major regional center, and its historical and cultural assets continue to anchor its economic and civic identity (Tesfa Regassa & Xin, 2022).

3.3.2 Economic Activities

The Economy of Gondar City relies on trade, services, government institutions, and tourism, with trade enterprises accounting for 54% of registered businesses and services accounting for 27% (Gondar City Administration, 2021). The surrounding lowlands produce cotton and sesame that feed regional commercial networks and generate employment and foreign exchange revenues. Tourism is a strategically growing sector: the Fasil Ghebbi complex and Semien Mountains National Park draw substantial domestic and international visitors, sustaining hotels, restaurants, tour operators, and informal service enterprises (Tesfa Regassa & Xin, 2022). The concentration of trade and tourism in the older city center, however, places disproportionate stress on the most deteriorated sections of the water distribution network, where pipes are the oldest and pressure management is the least reliable.

Government institutions represent a major, often underappreciated category of water demand in the urban sector. The University of Gondar, with over 40,000 students and staff, generates consistently high-volume consumption across its academic, residential, and medical facilities, while the University of Gondar Comprehensive Specialized Hospital and other public hospitals, health centers, military and police installations, schools, and administrative offices create a non-negotiable base load that cannot be deferred during supply shortfalls. These institutions require reliable water for clinical care, sanitation, food preparation, and laboratory use, making interruptions particularly consequential. Concurrently, industrial demand is rising, driven by expanding food processing, textile, beverage, and small-scale agro-industries, and is projected to outpace domestic demand over the next decade (Wubneh, 2023; GCWSSS, 2024). This combined and growing pressure from residential, institutional, commercial, and industrial users falls on a water system that was never designed to operate at anything close to its current scale.

3.3.3 Population

Population of Gondar City has grown rapidly and continuously over the past four decades. From an estimated 80,000 residents in the mid-1980s, the city expanded to 112,249 by 1994 and to 207,044 by the 2007 census, an average annual growth rate of 4.7% over that period, driven primarily by rural-urban migration and the administrative incorporation of surrounding rural communities (CSA, 2008). The CSA projected the population at 323,875 by 2015 and 360,600 by 2017, and estimated it at 465,973 by 2022 (CSA, 2013). The 2024 administrative boundary population is estimated at 431,113, with broader metropolitan projections including peri-urban areas reaching approximately 465,973 (Figure 3.5).

The AR was designed in the 1980s to serve approximately 20,000 people, reflecting planning assumptions rather than the population at commissioning. By the time the reservoir became operational in 2002, population had already exceeded 100,000 (CSA, 2008). As a result, the system entered service under substantial demand pressure, indicating how rapid population growth outpaced infrastructure planning and contributed to persistent water deficit. If the current growth rate is sustained, population of the city could reach approximately 710,000 by 2034 (Wubneh, 2023). This trajectory will intensify pressure on housing, employment, and urban services across the board, but water supply faces perhaps the most acute challenge given the long lead times required for infrastructure development and the already substantial deficit in current service delivery.

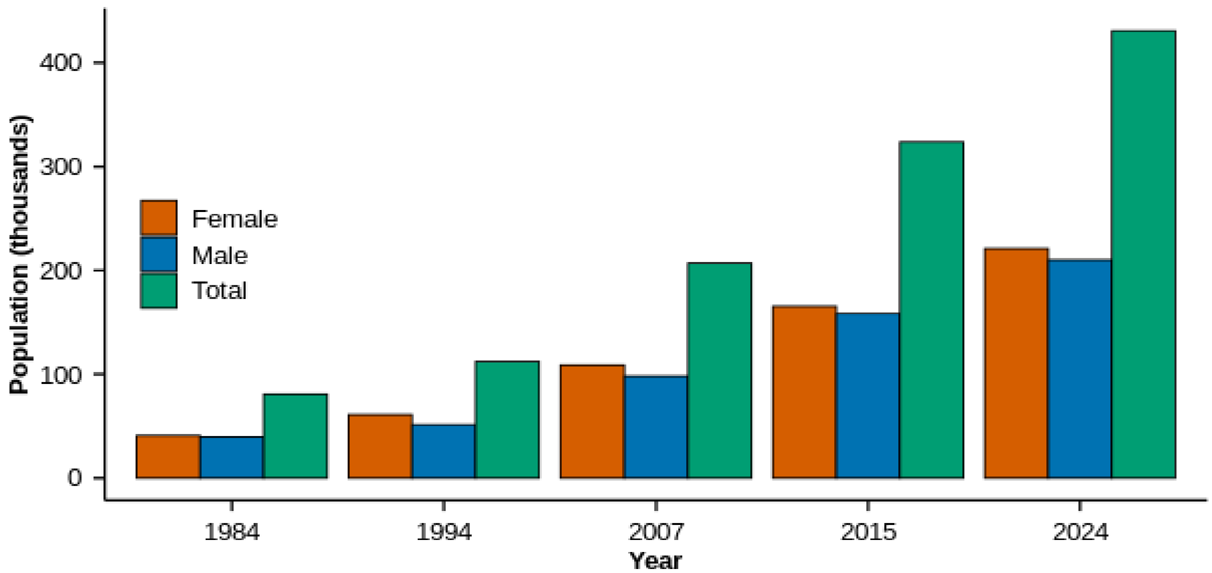

Figure 3.5 Population of Gondar City 1984-2024

CHAPTER FOUR
RESEARCH METHODOLOGY

This chapter explains how the study was designed and conducted, how data were collected and processed, and why the chosen methods and techniques were appropriate for investigating urban water supply-demand divergence in Gondar City. It covers the research philosophy, design, sampling strategy, data sources, analytical methods, and ethical considerations.

4.1 Research Design, Philosophy, and Justification

The philosophical orientation underpinning this design is pragmatism, which holds that the value of any research approach lies in its capacity to address the research problem and its practical consequences, treating methodology as a tool rather than a fixed philosophical commitment (Creswell & Plano Clark, 2018).

Neither quantitative nor qualitative methods alone are sufficient. Quantitative approaches measure trends, detect change points, and project future scenarios but struggle to capture inter-institutional dynamics, local knowledge, and governance constraints. Qualitative approaches provide this depth; however, their findings are harder to generalize and more susceptible to subjectivity. Together, the two approaches compensate for each other's limitations and produce a more complete account of the research problem (Creswell & Plano Clark, 2018).

The philosophical orientation underpinning this design is pragmatism, which selects methods based on what works best for the question at hand rather than committing to any single view of knowledge or reality (Creswell & Plano Clark, 2018). This makes it well-suited for applied research on complex urban systems. Within this framework, the study employs a sequential explanatory design: quantitative data on supply trends, change points, storage loss, and NRW are first collected and analyzed, after which qualitative data from key informants and focus groups are used to explain and contextualize the quantitative findings.

4.2 Sampling Strategy

Gondar City was selected purposively based on several factors. It is one of Ethiopia's secondary cities, experiencing persistent and severe water shortages with long-term supply deficits.

Although previous studies have examined different aspects of the city’s water system, no integrated assessment has linked source variability, reservoir sedimentation, distribution losses, and future demand scenarios. The researcher’s familiarity with the city’s water system and institutional context also provided practical support for the field investigation.

The study population comprised water utility managers, treatment plant operators, and households. Nine key informants were purposively selected from the GCWSSS (GCWSSS), the Angereb treatment plant, and the Gondar City administration. Four focus group discussions were conducted at four GCWSSS branch offices, with six residents from different neighborhoods in each group, resulting in 24 participants.

For the quantitative component, sampling was not required because the study used all available datasets, including monthly water supply records (2011- 2024). Sentinel-2 imagery that met the selected cloud cover criteria and all available billing records for 2024. Therefore, sampling error did not apply to the quantitative analysis.

For the qualitative component, the sample size was determined based on data saturation, defined as the point at which additional data collection produces no new themes or insights (Guest et al., 2006; Saunders et al., 2018). Saturation was achieved after six key informant interviews, with later interviews confirming previously identified themes related to reservoir decline, groundwater dependence, NRW, and institutional challenges. Similarly, focus group saturation was reached after the third discussion, as the fourth group mainly reinforced existing themes, including seasonal water shortages, household coping strategies, service limitations, and reliance on informal water vendors (IV).

4.3 Data Sources and Collection

4.3.1 Meteorological Data

Monthly rainfall and mean temperature data for Gondar meteorological station were obtained for the full period 2011–2024. For analyses aligned with the satellite imagery period, a subset covering 2016–2024 was used. These data were used to characterize the city's climatic conditions and to compute the Standardized Precipitation Index (SPI) for lagged correlation analysis with water supply variables (McKee et al., 1993).

4.3.2 Satellite-Based Data

Sentinel-2 imagery: Sentinel-2 satellite imagery was used to delineate the water surface area of the AR. These images are available at a 10-meter spatial resolution with a five-day revisit frequency (Sekertekin et al., 2018). Twenty Sentinel-2 images, four per year covering 2016, 2018, 2020, 2022, and 2024, were freely downloaded from the Copernicus Open Access Hub. Images were selected to correspond to the middle months of the four climatic seasons: January for winter, April for spring, July for summer, and October for autumn. For each season, images with less than 5% cloud cover captured closest to the middle of the month (between the 12th and 18th day) were preferred. Where exact mid-month imagery was unavailable due to acquisition gaps or cloud cover, the nearest cloud-free image within a plus or minus ten-day window was used (Sekertekin et al., 2018).

ALOS PALSAR DEM: A 12.5-meter resolution Digital Elevation Model (DEM) derived from ALOS PALSAR data was obtained from the Alaska Satellite Facility. The DEM provided detailed topographic information used to extract elevation values within delineated water surface polygons and to compute reservoir volumes (Ngula Niipele & Chen, 2019).

4.3.3 Water Utility Data

Monthly water supply records from January 2011 to March 2024 were obtained from the GCWSSS (GCWSSS). These records cover five variables: raw water abstracted from the AR, treated water leaving the treatment plant, groundwater abstraction from the Angereb and KDWFs, spring water contributions, and total water supply delivered to the distribution network (GCWSSS, 2024). Billing data disaggregated by meter size (DN15 to DN80) for the 2024 calendar year were also obtained from GCWSSS.

Bathymetric survey data of the AR collected in 2015 were provided by GCWSSS and used to validate satellite-derived volume estimates. These data were also analyzed and reported in Tessema et al. (2024).

4.3.4 Qualitative Data

Primary qualitative data were gathered through three complementary methods: field observation, key informant interviews, and focus group discussions.

Field observation*:* Field validation at the AR involved collecting 200 GPS ground control points to assess the accuracy of satellite-derived water surface delineations against field conditions, following established accuracy assessment procedures (Congalton & Green, 2019). Reservoir volume estimates derived from satellite imagery were validated using the 2015 bathymetric survey obtained from GCWSSS, which provides elevation-area-volume relationships at one-meter intervals and serves as the primary independent reference for storage capacity assessment (Tessema et al., 2024). For the NRW analysis, billing data corrections were validated using GCWSSS meter reading error records from September 2024, which reported 1,366 errors among 38,505 readings, representing a verified error rate of 3.6% that was consistently applied in the water balance calculations (GCWSSS, 2024).

Key informant interviews*:* Semi-structured interviews were conducted with senior professionals from GCWSSS, the Angereb treatment plant, and the Amhara Regional Water Bureau. A structured checklist guided the discussions to ensure all relevant themes were covered. Interviews were recorded using a mobile device to preserve the completeness and accuracy of responses.

Focus group discussions*:* Focus group discussions served as a supplementary data collection method, bringing together residents from different neighborhoods to discuss water supply conditions and experiences. Discussions were held at four GCWSSS branch offices, with six participants per group. To avoid biasing participants before they had articulated their own experiences, focus group discussions were conducted prior to the household survey. Open-ended questions guided each session. The summarized insights from discussions were used to enrich and triangulate data obtained from the key informant interviews.

4.4 Data Analysis

4.4.1 Trends and Change-Point Dynamics of Water Supply

The trend and change-point analysis drew exclusively on monthly water supply records from 2011 to 2024. Before analysis, the time series data were checked for missing values and autocorrelation. Minor gaps, accounting for less than 3% of observations and attributable to recording lapses, were filled using linear interpolation to ensure continuity (Box et al., 2008). Anomalies linked to documented operational disruptions, such as maintenance shutdowns and power outages, were retained rather than removed, since they reflect actual system behavior rather than data errors (Yue et al., 2002).

Long-term trends were analyzed using the Mann-Kendall test with pre-whitening to address autocorrelation, while the magnitude of change was estimated using Sen's slope estimator with 95% confidence intervals (Sen, 1968; Yue et al., 2002). Seasonal variations were assessed using the Seasonal Mann-Kendall test across four seasons: winter (December–February), spring (March–May), summer (June–August), and autumn (September–November) (Hirsch et al., 1982). Change points were identified using the Pettitt test for single shifts (Pettitt, 1979) and the PELT algorithm for multiple shifts (Killick et al., 2012), with results validated using CUSUM control charts (Page, 1954). Climate impacts were evaluated using the Standardized Precipitation Index (SPI) at 3-, 6-, 12-, and 24-month timescales (McKee et al., 1993), followed by lagged cross-correlation analysis between SPI values and water supply variables (Box et al., 2008).

4.4.2 Reservoir Storage Assessment Using Remote Sensing

Sentinel-2 imagery from 2016 to 2024 was used to generate the Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI) for each selected season (Xu, 2006). These indices were applied to delineate water surface areas, and image processing, including filling of no-data pixels, was completed in ArcGIS. Twenty NDWI and MNDWI images were processed to produce seasonal water surface area maps.

Elevation values within each delineated water surface polygon were extracted from the ALOS PALSAR DEM, with the median elevation taken as the representative water surface elevation for each date (Avisse et al., 2017). Reservoir volumes were calculated by combining the water surface polygons with DEM elevation data using the ArcGIS 3D Analyst Surface Volume tool. Derived volumes were validated against the 2015 bathymetric survey data, and accuracy was assessed using confusion matrices based on ground control points distributed around the reservoir (Congalton & Green, 2019). A correction factor was applied to address any systematic bias identified during validation.

4.4.3 NRW Estimation

NRW estimation followed the AWWA water balance framework (AWWA, 2009). System Input Volume (SIV) was calculated as the total volume of treated reservoir water, groundwater, and spring contributions supplied during 2024. Billed Authorized Consumption (BAC) was obtained from GCWSSS billing records for the same period.

Apparent losses were estimated from meter inaccuracies, data handling errors, meter reading errors, and unauthorized consumption. Where local measurements were unavailable, values from peer-reviewed studies were applied (Mutikanga et al., 2013; Ncube & Taigbenu, 2019). A weighted meter accuracy of 92.5% was applied to DN15 and DN20 meters, which represent 77.1 % of billed water volume (2,129,701 m^3). Meter reading errors were estimated at 3.6% based on 1,366 errors among 38,505 readings recorded in September 2024 (GCWSSS, 2024). Data handling errors and unauthorized consumption were each assumed at 2% of BAC following established benchmarks (Mutikanga et al., 2013). Real losses were calculated as the difference between SIV, BAC, and apparent losses. Uncertainty was assessed using the root-sum-square method to generate 95% confidence intervals (Al-Washali et al., 2020; Silva et al., 2018).

4.4.4 WEAP Scenario Modeling

The WEAP model was used to simulate water allocation and flows within Gondar's supply system (Yates et al., 2005). The model included supply nodes for the AR, Angereb and KDWFs, the MGD, and the Lake Tana pumping scheme, along with demand nodes for Gondar City and the MGD Irrigation Command Area. Reservoir behavior was simulated using water balance equations incorporating inflows, evaporation, releases, spill, and seepage losses. Groundwater sources were represented as finite aquifer systems with declining yields due to progressive drawdown.

The model was calibrated using monthly supply data from 2015 to 2018 and validated with independent data from 2020 to 2023. The year 2019 was excluded because it was treated as a transition year affected by system changes and operational instability, including the effects of the Koladiba commissioning. Eight scenarios were developed to represent alternative futures, incorporating three population growth rates (3.5%, 4.0%, and 4.5% annually), two climate pathways (RCP 4.5 and RCP 8.5 from CORDEX-Africa), and sedimentation rates ranging from 3.0% to 3.9% annually, and alternative MGD allocation arrangements: 70% irrigation and 30% urban use versus 80% urban and 20% irrigation (Wubneh et al., 2022).

4.4.5 Qualitative Data Analysis

Qualitative data from key informant interviews, focus group discussions, and field observation were analyzed using inductive thematic coding (Creswell & Plano Clark, 2018). Transcripts were analyzed in three stages. Open coding identified initial concepts emerging directly from the data. Axial coding organized related concepts into broader analytical categories. Selective coding refined and integrated these categories into core themes. Emergent themes were triangulated across informants and against quantitative findings to strengthen analytical rigor and reduce the influence of individual bias.

4.4.6 Integration of Methods

Quantitative and qualitative results were integrated at two levels. At the interpretive level, statistical findings on trends, change points, storage loss, and NRW components were presented alongside direct quotations and thematic summaries from key informants, allowing the numbers to be explained in terms of lived operational and institutional realities. At the modeling level, WEAP scenario assumptions, particularly future demand growth rates and water allocation rules, were validated and refined through stakeholder input gathered during key informant interviews.

CHAPTER FIVE

TREND AND CHANGE-POINT DYNAMICS OF WATER SUPPLY IN GONDAR CITY

Abstract

Urban water systems in sub-Saharan Africa are under increasing pressure due to climate variability, aging infrastructure, and institutional constraints. This study examined the long-term trends and climate responsiveness of water sources supplying Gondar, Ethiopia, using monthly data from the AR, groundwater wells, and springs (2011–2024). The study applied Mann–Kendall tests, change-point detection, and the SPI with lagged correlations, complemented by interviews and focus groups. The results showed that the reservoir output remained stable ($\tau = 0.048$, $p = 0.369$), whereas groundwater ($\tau = 0.391$, $p < 0.001$) and spring supply ($\tau = 0.256$, $p < 0.001$) increased significantly. Change-point analysis revealed key shifts: surface water decline in July 2013, groundwater expansion in July 2017, and spring integration in June 2019. The SPI lag analysis indicated distinct response times: reservoir supply responded inversely after 11–12 months, groundwater after 3–12 months, and springs after 3 months. Despite increased production, household access did not improve because of population growth and distribution losses. Groundwater offsets the static reservoir output, but unmanaged use poses long-term risks. Incorporating climate-response lags and detected change points into seasonal allocation strategies is vital for strengthening urban water resilience during demographic surge.

Keywords: *Change-point analysis; Climate resilience; Ethiopia; Groundwater; Socio-hydrology; urban water supply*

5.1 Introduction

Urban water systems in developing countries face increasing pressure from population growth, aging infrastructure, climate change, and institutional weaknesses (Koop et al., 2017; McDonald et al., 2014). These challenges reduce service reliability and disproportionately affect low-income communities through irregular supply, increased water-related health risks, and lost productive time (Barbier et al., 2024; Barbier & Burgess, 2024; Wu et al., 2017). However, urban water insecurity is often driven less by absolute water scarcity than by inadequate infrastructure and weak institutional capacity (Beker & Kansal, 2023; Sharma et al., 2021).

This study examines how these pressures have influenced urban water supply dynamics over time by analyzing changes in source contributions and registered production volumes in Gondar City, Ethiopia. Using a time-series approach combined with institutional analysis, the study investigates patterns of source substitution and the factors driving transitions among surface water, groundwater, and spring sources.

Ethiopian highland cities face significant socio-hydrological challenges because water availability is strongly controlled by seasonal rainfall patterns. The Kiremt season (June–August) contributes more than 80% of annual precipitation, while Belg rains (March–May) provide limited rainfall and Bega (December–January) represents a prolonged dry period with minimal recharge (Mariye et al., 2022; Meresa & Taye, 2019; Wagesho et al., 2013). These seasonal extremes contribute to reservoir depletion, delayed groundwater recovery, and fluctuations in spring yields (Mekonnen, 2023). Consequently, sustainable urban water management requires strategies that account for temporal variability and align infrastructure capacity with changing hydrological conditions (Dias & Ghisi, 2024; Hurlimann & Wilson, 2018; Sisay et al., 2017).

Gondar City, with a population exceeding 431,000 (CSA, 2013), provides an important case for understanding urban water transitions in highland environments. The AR, commissioned in 2002, has been the primary source of supply but is increasingly constrained by sedimentation, declining storage capacity, and treatment limitations. Severe dry-season shortages from December to May coincide with reduced availability from reservoirs, wells, and springs (Wubneh, 2023). Although expanded groundwater development and spring rehabilitation have partially compensated for declining surface water availability, the interaction of aging infrastructure, climate variability, and fragmented institutional responses requires a more systematic assessment.

Previous studies on Ethiopian urban water systems have focused mainly on service coverage (Abebe, 2018), water quality (Desye et al., 2021), and NRW (NRW) (Beker & Kansal, 2023). However, these cross-sectional studies provide limited understanding of temporal changes, including shifts from surface water dependence to increasing reliance on groundwater (Alemu & Dioha, 2020). Important gaps remain in integrating: (1) long-term trend analysis of multi-source water contributions; (2) change-point detection to identify hydrological and management transitions; (3) seasonal analysis of adaptation patterns; and (4) institutional explanations of source substitution processes.

This study addresses these gaps through three objectives: (1) to quantify long-term and seasonal trends in water production from the AR, groundwater wells, protected springs, and total system output using statistical trend analysis; (2) to identify structural changes associated with climate variability, infrastructure interventions, and management shifts through change-point analysis, SPI assessment, and lagged correlation analysis; and (3) to examine the socio-institutional factors influencing observed water supply transitions and their implications for sustainable urban water governance.

By integrating hydrological analysis with institutional perspectives, this study makes three contributions. Empirically, it provides a systematic assessment of Gondar's multi-source water supply evolution from 2011 to 2024. Methodologically, it demonstrates a sequential mixed-methods approach that combines time-series analysis with institutional interpretation. Theoretically, it advances understanding of path-dependent adaptation, showing how responses to declining surface water availability can reshape urban water systems and create new vulnerabilities under highland conditions.

5.2 Materials and Methods

5.2.1 Study Area

Gondar City is located approximately 750 km north of Addis Ababa in northwestern Ethiopia, at an elevation of about 2,200 meters above sea level (Figure 3.4). The city experiences strong seasonal rainfall variability, with more than 80% of annual precipitation occurring between June and August, followed by an extended dry season from October to May (Assfaw, 2020). Mean annual rainfall is approximately 1,200 mm, while average monthly temperatures range from 16°C to 24°C.

Gondar's water supply system consists of three main source types: surface water from the AR, groundwater from boreholes, and local springs. The AR, commissioned in 2002, is the city's primary surface water source. It was designed with an active storage capacity of 5.28 Mm^3 (Tessema et al., 2022). Recent bathymetric assessment indicates that sedimentation reduced live storage by 62.28% between 1997 and 2022, representing an annual loss rate of 2.9–3.9% and leaving approximately 1.32 Mm^3 of available storage in 2022 (Tessema et al., 2022). This study adopts Tessema et al.'s estimates as the primary reference because they are based on the most recent bathymetric survey. Earlier studies reported lower storage losses due to differences in baseline periods and assessment methods (Haregeweyn et al., 2012; ANRS & ECDSWC, 2021).

Groundwater supply comes from thirteen operational boreholes, including eight in the AWF and five high-yield wells in the KDWF commissioned in 2017. Two low-yield springs provide supplementary local supply but are not connected to the main distribution system. Together, these sources provide approximately 1.8 Mm^3 of registered production annually, which remains insufficient to meet increasing demand, particularly during the dry season from December to May.

5.2.2 Research Design

This study employed a sequential explanatory mixed-methods design, beginning with quantitative analysis followed by qualitative interpretation. The quantitative phase identified long-term trends, seasonal patterns, and structural changes, while the qualitative phase provided contextual explanations based on stakeholder perspectives (Figure 5.1).

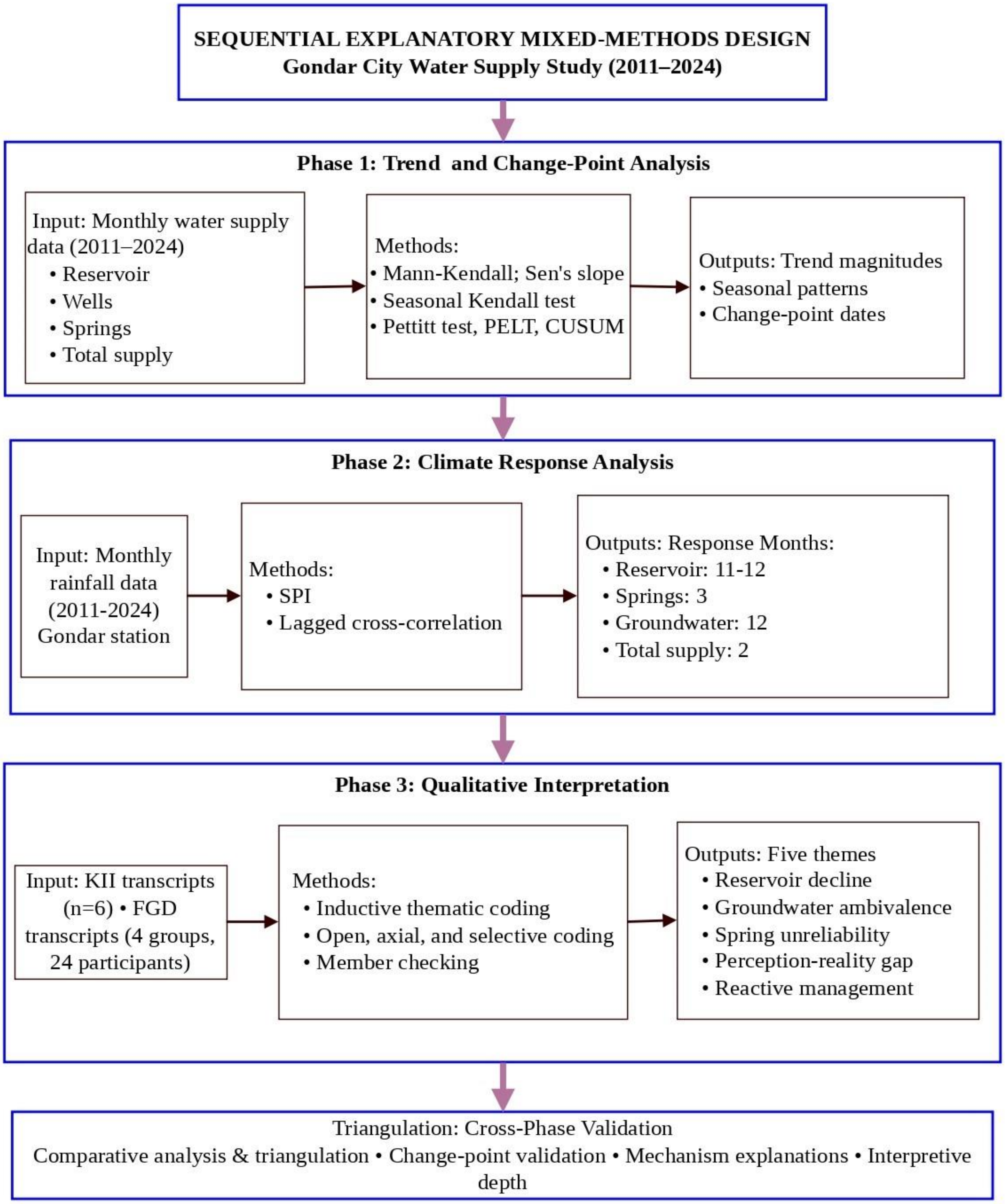

Figure 5.1 Sequential explanatory mixed-method analytical framework

5.2.3 Data Collection

Monthly water supply records (January 2011–March 2024, 14 years) were obtained from the GCWSSS. The period begins with the earliest consistently digitized, quality-assured abstraction data; earlier records are fragmented with >15% missing values. The resulting 168 monthly observations give sufficient length for robust trend detection, given the pronounced seasonal signals. All quantitative datasets are available as Supplementary Table S1 online.

The records covered five primary variables (units: m^3 $month^{-1}$): raw water from the AR (Rwater), treated water from treatment plant (Twater), groundwater abstraction (Wwater), spring contributions (Swater), and total water supply for distribution (TWS). The total water supply (TWS) is the sum of treated water, groundwater, and spring contributions (TWS = Twater + Wwater + Swater). The corresponding climatic variables, monthly rainfall (mm) and mean temperature (°C), were obtained from the National Meteorological Agency, 2024 for the Gondar station.

Qualitative data were collected from April 15 to 20, 2024, through six KIIs and four FGDs involving 24 participants. KIs were purposively selected based on: (1) direct involvement in Gondar's water supply management; (2) current or recent operational or policy responsibility; (3) institutional representation (GCWSSS, treatment plant, regional water bureau); and (4) willingness to participate in the study.

5.2.3.1 Data Processing

All quantitative datasets were assessed for missing values, outliers and inconsistencies. Minor gaps (less than 3% of observations) resulting from recording lapses were addressed using linear interpolation to ensure the continuity of the data. Anomalies attributable to documented operational disruptions, including maintenance shutdowns and power outages, were retained to reflect the actual system behavior. For analyses requiring cross-source comparability, the data were harmonized to monthly intervals, converted to volumetric units (m^3), standardized to continuous time indices, and normalized via z-score transformation.

5.2.3.2 Data Analysis

Quantitative analysis was conducted in R (Posit Cloud) using the tidyverse, zoo, trend, and change-point packages. Long-term trends were analyzed using the Mann–Kendall test and Sen's slope estimator. Seasonal variation was assessed using the Seasonal Mann–Kendall test. Significant shifts were detected using the Pettitt, PELT, and CUSUM methods. Climate responses were evaluated using the SPI and lagged correlation analysis. The causes of the observed patterns were explored via thematic analysis of KIIs and FGDs.

These methods were selected for their suitability in analyzing time-series water data. The non-parametric Mann–Kendall test is robust to non-normality (Mohamed et al., 2024; Yue et al., 2002) and can be modified to correct for serial correlations using pre-whitening and autocorrelation methods (Box et al., 2008; Ljung & Box, 1978). Sen's slope provides robust estimates of trend magnitude with confidence intervals (Hamed & Rao, 1998; Sen, 1968). The SPI captures multi-timescale drought conditions (McKee et al., 1993), lagged correlations reveal response timing (McKee et al.), and change-point methods identify regime shifts (Killick et al., 2012; Page, 1954; Pettitt, 1979).

5.2.3.3 Qualitative Data Analysis:

Qualitative data were analyzed using inductive thematic coding, following established procedures for mixed-methods research (Creswell & Plano Clark, 2018). Interview transcripts were read iteratively to identify recurring patterns related to water source reliability, institutional performance, and local coping strategies. The coding process proceeded in three stages: (1) open coding, which involved identifying initial concepts emerging from the data; (2) axial coding, in which related concepts were organized into broader analytical categories; and (3) selective coding, through which core themes were identified and refined.

Emergent themes were subsequently triangulated with quantitative findings to contextualize statistical results within broader socio-institutional and water management dynamics. A triangulation strategy was employed to enhance analytical rigor and minimize potential bias by systematically comparing accounts across multiple informants, as well as between interview narratives and relevant documentary sources.

5.3 Results

5.3.1 Descriptive Overview of Water Supply Sources

Table 5.1 shows the temporal dependence in the water supply series, focusing on whether monthly values show persistence across time lags. The autocorrelation results indicate the degree to which supply in one month is related to supply in previous months, helping to distinguish stable source behavior from more irregular fluctuations.

Table 5.1 Summary statistics for water supply sources (2011–2024) (m^3 $month^{-1}$)

Source	N	Mean	Median	SD	Variance	Min	Max	Range	CV
Rwater	168	269604	277336	37284	1.39×10^9	150776	367384	216608	0.138
Twater	168	253580	260696	34913	1.22×10^9	141729	345341	203612	0.138
Wwater	168	83141	52152	53741	2.89×10^9	20022	189806	169784	0.646
Swater	168	3580	2642	2687	7.22×10^6	377	13345	12968	0.751
TWS	168	338005	318234	65012	4.23×10^9	203141	513600	310459	0.192

Note: CV = Coefficient of variation (SD/Mean). All values are monthly volumes in cubic meters.

Reservoir-fed sources exhibit remarkably stable averages and low variation (CV ≈ 0.14), reflecting consistent, infrastructure-driven supply. In contrast, supplemental well and spring sources have high coefficients of variation (CV > 0.6), indicating substantial operational fluctuation and their responsive, adaptive use during shortages. These descriptive patterns suggest a structural imbalance: steady but stagnant surface supply supplemented by highly variable subsurface sources.

5.3.2 Autocorrelation Structure and Pre-whitening

Reservoir-fed sources exhibit stable averages and low variation (CV ≈ 0.14), reflecting consistent, infrastructure-driven supply. In contrast, supplemental well and spring sources have high coefficients of variation (CV > 0.6), indicating substantial operational fluctuation and their responsive, adaptive use during shortages. These descriptive patterns suggest a structural imbalance: steady but stagnant surface supply supplemented by highly variable subsurface sources.

5.3.3 Long-Term Trends (2011–2024)

Surface water from the AR remained consistent throughout the study period, whereas contributions from groundwater and springs increased substantially (Table 5.1).

Table 5.1 Mann–Kendall trend test results by source

Variable	T	P	Z	Sen's Slope (m^3 $month^{-1}$)	Lower 95% CI	Upper 95% CI
Rwater	0.048	0.369	0.898	563.5	-704.7	1,917.40
Twater	0.045	0.398	0.846	492.3	-672.6	1,764.00
Wwater	0.391	<0.001	7.387	9,078.40	7,678.00	10,340.70
Swater	0.256	<0.001	4.825	202.9	115.7	299.6
TWS	0.471	<0.001	8.902	11,414.10	9,645.60	13,173.80

Note: Kendall's Tau (τ) measures the strength and direction of the monotonic trend in monthly abstraction over time. Z is the standardized Mann–Kendall test statistic. Sen's slope (m^3 $month^{-1}$) estimates the magnitude of the monthly change, with 95% confidence intervals. $P < 0.05$ indicates a statistically significant trend.

Water supply from the AR exhibited no significant long-term trend during the study period (Rwater: $\tau = 0.048$, $p = 0.369$; Twater: $\tau = 0.045$, $p = 0.398$). Although Sen's slope estimated an increase of 563.5 m^3 $month^{-1}$, the 95% confidence interval (-704.7 to 1,917.4 m^3 $month^{-1}$) included zero, confirming the absence of a statistically significant change. This stagnation is consistent with the reservoir's progressive sedimentation. According to Tessema et al. (2024), the AR was commissioned in 1997 with a live storage capacity of 5.28 Mm^3, which had declined to approximately 1.32 Mm^3 by 2022 due to sediment accumulation, representing a loss of 62.28% at an annual reduction rate of 2.9–3.9%. Key informants supported this interpretation, describing the reservoir as increasingly unable to meet growing water demands. As one engineer noted, "The reservoir is like a dying battery. It holds less water every year. The reservoir that served us for 15 years is now only half as useful" (KI-2). Another informant explained that concerns over declining reservoir performance prompted a strategic shift toward groundwater development as early as 2013 (KI-1).

In contrast, groundwater abstraction increased significantly over the study period (Wwater: $\tau = 0.391$, $p < 0.001$), with a Sen's slope of 9,078 m^3 $month^{-1}$ (95% CI: 7,678–10,341). This increase reflects the commissioning of the Koladiba wellfield around 2017 and the growing dependence on groundwater to compensate for declining surface-water storage. However, key informants also expressed concerns regarding sustainability, noting evidence of declining well yields shortly after commissioning. As one participant stated, "*The wells saved us, but now we worry about them drying too. Some are already showing declining yields*" (KI-5). Operational records similarly indicate reductions in production from several wells, suggesting that groundwater abstraction may be approaching or exceeding local recharge capacity.

Spring-water contributions also increased significantly (Swater: $\tau = 0.256$, $p < 0.001$), with a Sen's slope of 203 m^3 $month^{-1}$ (95% CI: 116–300). This improvement is largely attributed to spring rehabilitation and maintenance activities initiated in 2019. Nevertheless, qualitative evidence highlighted the seasonal unreliability of spring sources. One focus group participant observed, "*The springs come and go. After good rain, they flow, but during dry periods, they disappear. You cannot rely on them*" (FGD-3).

Overall, total registered water supply increased significantly during the study period (TWS: $\tau = 0.471$, $p < 0.001$), with a Sen's slope of 11,414 m^3 $month^{-1}$ (95% CI: 9,646–13,174). Despite these gains, per capita water availability did not improve significantly because population growth absorbed most of the additional production (Figure 5.2). Based on CSA projections, the population increased from approximately 307,000 in 2011 to 431,000 in 2024, representing growth of about 40%. Although total registered production rose from approximately 203,141 to 513,600 m^3 $month^{-1}$, average supply remained only about 22 L $person^{-1}$ day^{-1}, substantially below the WHO minimum service standard of 50 L $person^{-1}$ day^{-1}.

Qualitative findings further revealed a disconnect between increasing aggregate production and household water access. Residents consistently reported persistent shortages despite rising system-wide supply. One participant remarked, "The numbers may show more water, but my tap still runs dry for days. *Where is this water going*?" (FGD-3). Another noted, "*There are more people, but the same amount of water reaches my area. Of course, it is worse*" (FGD-2). Key informants attributed much of this discrepancy to high NRW (NRW) losses, estimated at 35–40% (KI-1; KI-4), indicating that a substantial proportion of produced water is lost through leakage, unauthorized consumption, and operational inefficiencies before reaching consumers.

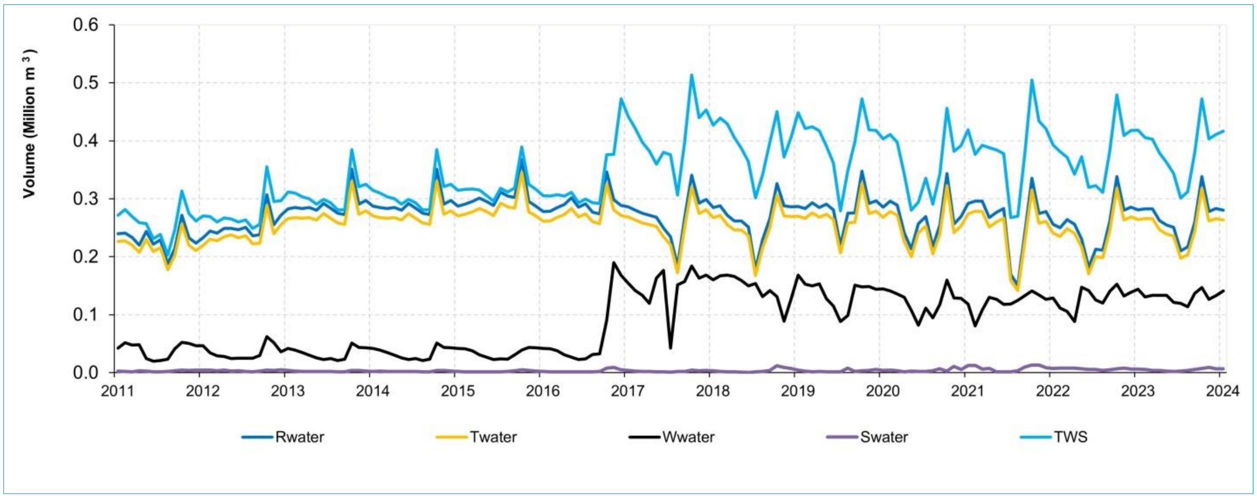

Figure 5.2 Long-term monthly water supply trends in Gondar City (2011–2024)

5.3.4 Seasonal Trends of Water Supply (2011-2024)

As shown in Table 5.2, seasonal patterns reveals water supply is most vulnerable during the dry season, from December to May, when groundwater abstraction increases sharply to compensate for the declining reservoir storage and reduced spring discharge. Seasonal dynamics were analyzed using four equal three-month periods: winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). Sen's slope estimates were used to quantify the average seasonal change in the water supply (m^3 per season).

During winter, the total water supply increased significantly, driven primarily by a substantial rise in groundwater abstraction (8,687 m^3 per season) and a smaller increase in spring-water contribution (347 m^3 per season). However, this increase does not indicate improved water security in the region. Rather, it reflects a crisis-response strategy adopted to offset declining reservoir levels and shortages of treated surface water. As reservoir storage decreases and spring discharge weakens, water utilities become increasingly dependent on groundwater and remaining spring sources. Residents consistently identified winter as the most difficult period for accessing water. As one participant explained, "*December to February, we know the taps will be dry. We prepare by storing water in containers, but it is never enough*." Thus, the apparent increase in supply conceals a pattern of emergency source substitution, rather than enhanced service reliability.

Table 5.2 Statistically significant seasonal variations in water supply from multiple sources in Gondar City

Season	Variable	T	P	Z	Sen's slope (m^3 $season^{-1}$)	Lower 95% CI	Upper 95% CI
Winter	Wwater	0.462	0.025	2.248	8686.6	520.2	12993.3
	Swater	0.44	0.033	2.138	346.5	68	623.4
	TWS	0.495	0.016	2.409	11178.3	5479.3	16430.3
Spring	Wwater	0.487	0.024	2.266	9554.4	191.1	15162.9
	TWS	0.603	0.005	2.812	9218.1	4513.5	16859.7
Summer	Wwater	0.484	0.018	2.358	8800.4	1529.8	13248.7
	Swater	0.681	<0.001	3.344	262.4	127.3	372.5
	TWS-	0.571	0.005	2.796	8474.8	3313.2	15005
Autumn	Swater	0.549	0.007	2.687	435	151.6	735.3
	TWS	0.725	<0.001	3.518	13163.9	9265	17459.8

Note: τ is Kendall's tau indicating the strength and direction of the seasonal trend. $P < 0.05$ indicates significance, Z is the standardized statistic, and Sen's slope (m^3 $season^{-1}$) shows the average seasonal change. 95% confidence intervals excluding zero indicate significant trends. Only significant results are shown.

During spring (March–May), the total supply increased by 9,218 m^3 per season, almost entirely due to additional groundwater abstraction (9,554 m^3 per season), whereas spring discharge showed no meaningful improvement. By late spring, many springs slow considerably or cease flowing altogether, and continued evaporation further reduces reservoir storage. Consequently, households often depend on private water vendors for their water supply. As one respondent noted, "In spring, we buy water from vendors. It is expensive, sometimes half our daily income, and we never know if it is clean." Therefore, the increase in groundwater abstraction reflects a coping mechanism for water scarcity rather than an improvement in water availability.

During summer (June–August): The spring-water contributions increased by 262 m^3 per season, whereas the total supply rose by 8,475 m^3 per season. Rainfall enhances groundwater recharge, revitalizes spring flows, and enables households to supplement supplies through rooftop rainwater harvesting, thereby reducing pressure on the municipal system. Nevertheless, heavy rainfall creates operational challenges at the AR. Increased sediment inflow causes high turbidity in raw water, forcing treatment plants to reduce production or temporarily suspend operations. As one key informant explained, "*When the heavy rains come, the reservoir water turns to mud. We have to reduce treatment or shut down entirely*." Consequently, although water availability improves, treatment and distribution become increasingly difficult.

Autumn (September–November): The total supply increased by 13,164 m^3 per season, supported largely by improved spring recharge, which contributed an additional 435 m^3 per season. Key informants described this period as a temporary rebound, during which groundwater levels partially recovered and water became more accessible before the onset of the next dry season. However, these gains are short-lived and insufficient to fully compensate for the deficits that accumulate during winter and spring.

Overall, water supply system follows a recurring cycle of seasonal stress and recovery (Table 5.2). Winter scarcity triggers intensive groundwater abstraction, spring represents the most critical period of vulnerability, summer rainfall provides relief but introduces treatment disruptions associated with sediment-laden reservoir water, and autumn offers temporary recovery before the cycle repeats.

Figure 5.3 Seasonal water supply contributions in Gondar City by sources (2011–2024)

5.3.5 Rainfall Variability and Water Supply Responses

During the study period, Gondar experienced a marked hydroclimatic transition. Between 2011 and 2015, the city endured persistent drought conditions, with both the 12-month and 24-month SPI frequently reaching severe to extreme drought levels (Figure 5.4). During the peak of the 2015 El Niño event, both indices (<−2), indicating the intensity of the rainfall shortages. Following 2016, conditions gradually improved, transitioning to predominantly near-normal and wet conditions. This recovery culminated between 2021 and 2024, when the 12-month SPI remained above 1.5 for several consecutive months, indicating a prolonged period of above average rainfall. This pronounced shift toward wetter conditions provides an important context for understanding the subsequent changes in water-source performance and urban water supply dynamics (Table 5.3).

Table 5.3 Lagged correlations between climate variables and water supply

Variable	Predictor	Best Lag (months)	Pearson r	p-value	Response Type
Rwater	Rainfall	11	-0.454	4.84×10^{-9}	Inverse (managed)
	SPI-24	11	-0.304	4.89×10^{-4}	
	SPI-12	12	-0.207	1.44×10^{-2}	
Twater	Rainfall	11	-0.456	3.98×10^{-9}	Inverse (managed)
	SPI-24	11	-0.304	4.89×10^{-4}	
	SPI-12	12	-0.208	1.41×10^{-2}	
Wwater	SPI-24	12	0.432	4.06×10^{-7}	Slow positive (recharge)
	SPI-12	12	0.409	5.85×10^{-7}	
	Rainfall	3	0.231	3.35×10^{-3}	
Swater	Rainfall	3	0.568	5.49×10^{-15}	Fast positive
	SPI-24	3	0.499	6.55×10^{-10}	
	SPI-12	12	0.449	3.06×10^{-8}	
TWS	Rainfall	2	0.419	3.56×10^{-8}	Mixed (2-month aggregate)
	SPI-24	12	0.278	1.57×10^{-3}	

Note: Labels indicate the hydrological and operational mechanisms inferred from the correlation patterns; see the discussion section for full interpretation

Several key relationships emerge between the water sources and rainfall patterns. Lagged correlation analysis revealed four distinct rainfall–response relationships within Gondar's water supply system, indicating the differing hydrological and operational controls governing reservoirs, springs, groundwater, and overall water availability.

Reservoir withdrawals exhibited a significant negative correlation with rainfall at an 11-month delay. Rather than reflecting a direct hydrological response, this relationship appears to result from operational management. During wetter periods, water managers reduce reservoir abstraction to conserve the water stored for subsequent dry seasons. As one key informant explained, "*When the rains are good and springs flow, we rest the reservoir. It is our only buffer* *for the next dry period*” (KI-1). Therefore, the observed lag reflects adaptive reservoir management rather than delayed hydrological processes.

Spring discharge showed a strong positive correlation with rainfall after a three-month lag. This rapid response suggests that spring flow is sustained by relatively shallow groundwater systems, characterized by short recharge-to-discharge pathways. Consequently, seasonal rainfall fluctuations are rapidly transmitted to spring sources, making them highly sensitive to short-term climatic variability.

Groundwater abstraction displayed a positive correlation with long-term precipitation conditions, represented by SPI-24, at a 12-month lag. This delayed response is consistent with the behavior of deep confined or semi-confined aquifers commonly found in the Ethiopian highlands, where recharge processes require considerable time as water percolates through thick, unsaturated zones. The results suggest that groundwater availability improves following sustained wet periods, thereby enabling greater abstraction. Importantly, this relationship indicates that increased groundwater pumping is associated with favorable long-term recharge conditions rather than necessarily reflecting overexploitation. However, because groundwater-level monitoring data are unavailable for Gondar, it remains impossible to determine whether the abstraction rates at individual well fields exceed the local recharge rates.

Total water supply responded positively to wetter conditions with a relatively short, two-month lag. This rapid response reflects the combined influence of climate-sensitive spring discharge and adaptive groundwater management, both of which contribute to increased water availability shortly after rainfall conditions improve.

A major limitation of this study is the absence of systematic groundwater-level monitoring. Groundwater dynamics were inferred from abstraction records rather than direct observations of aquifer behavior because no long-term borehole monitoring network currently exists in Gondar, Ethiopia. Although the positive relationship between SPI-24 and groundwater abstraction is consistent with recharge-driven responses, direct groundwater-level measurements are required to verify the recharge mechanisms, estimate sustainable yields, and identify potential areas of localized over-abstraction. Current water supply planning largely operates on monthly and seasonal timescales that implicitly follow long-term recharge patterns; however, formal conjunctive management strategies integrating reservoirs, springs, and groundwater resources remain absent. Therefore, establishing a comprehensive groundwater monitoring program should be considered the highest priority for strengthening evidence-based water resource management and improving the long-term resilience of Gondar's urban water supply system.

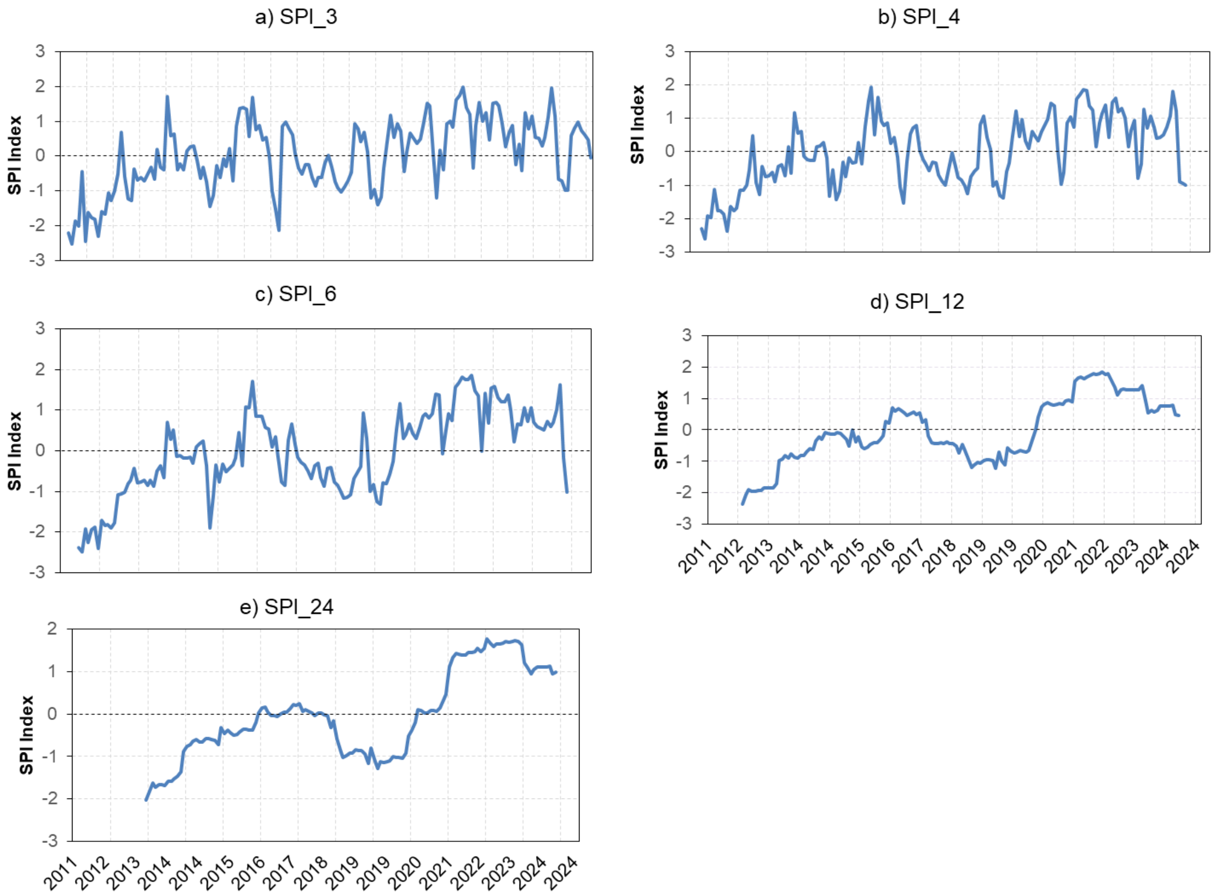

Figure 5.4 SPI for Gondar City (2011–2024)

5.3.6 Change-Point and Regime Shift Analysis

Key change points indicated fundamental shifts in water supply of Gondar City. Pettitt and PELT tests, supported by CUSUM plots, identified major turning points in reservoir variables in July 2013, groundwater and total supply in July 2017, and spring water in June 2019 (Table 5.4).

Table 5.4 Change-point analysis of Gondar's water supply sources (2011–2024)

Variable	Pettitt Test	p-value	PELT Change-Points
Rwater	41456	1.92×10^{-5}	July 2013, March 2018
Twater	41456	2.56×10^{-5}	July 2013, March 2018
Wwater	42917	$< 2.2\times10^{-16}$	July 2017, August 2018, April 2019
Swater	43617	7.16×10^{-5}	Nov 2016, July 2017, Oct 2021, Dec 2021
TWS	42917	$< 2.2\times10^{-16}$	Aug 2012, July 2013, July 2017

Note: Pettitt test statistics indicate change magnitude, with larger values showing stronger shifts. P-values (e.g., $1.92 \times 10^{-5} = 0.000019$) show statistical significance, with values < 0.05 considered significant. The PELT algorithm identifies dates of significant regime shifts.

These change points align with specific documented events: reservoir decline in July 2013, which led to drought-induced intake exposure and pumped abstraction; groundwater expansion in July 2017, coinciding with the commissioning of the Koladiba wellfield; and spring increase in June 2019, which followed rehabilitation programs. Since 2017, the system has operated under a new regime that is increasingly dependent on groundwater.

5.3.7 Contextual Interpretation of Change Points

The detected change points correspond closely with documented operational events, confirming that the statistical breaks identified by the PELT algorithm reflect genuine transformations in Gondar’s water-supply system (Figure 5.5).

The July 2013 reservoir change point followed the severe drought conditions of 2011–2012, which exposed the AR intake structure and necessitated a transition from gravity-fed abstraction to a pumped withdrawal. This event marked a fundamental shift in reservoir operations and highlighted the system’s vulnerability to prolonged droughts.

The July 2017 groundwater change point coincided with the commissioning of the Koladiba wellfield, which consists of five high-yield production wells. This development represents a deliberate strategic shift toward groundwater-based supply as a means of compensating for declining surface-water reliability. However, operational records indicate that the yields from the

Koladiba wells declined relatively rapidly after commissioning, suggesting that groundwater abstraction may have exceeded the initial expectations of sustainable production. This pattern is consistent with groundwater development occurring before comprehensive aquifer characterization and long-term yield assessments were completed.

The June 2019 spring-water change point followed the completion of a spring rehabilitation program and coincided with improved recharge conditions associated with the wetter period that emerged after 2016. Together, these factors contributed to enhanced spring discharge and increased integration of spring sources into the municipal-supply system.

Additional PELT change points correspond to documented operational disruptions and infrastructure improvements. The March 2018 breakpoint aligns with a major treatment-plant maintenance shutdown and prolonged power interruptions recorded in the GCWSSS maintenance logs, whereas the August 2018 change point coincides with the installation of new pumps at the Angereb wellfield, as documented in procurement records.

The key informants strongly supported these interpretations. As one informant recalled, *"By mid-2013, we realized the reservoir would never fully recover and that the intake pipes were exposed. We had to install pumps just to draw water, which changed everything"* (KI-2). Reflecting on the 2017 groundwater expansion, another respondent noted, *"When Koladiba came online in 2017, we suddenly had more water than ever before. It was a game-changer, but also a worry, as we did not really know how much we could safely extract"* (KI-5).

Following 2017, a new operational regime emerged in which surface water production stabilized at lower levels, while groundwater and spring sources expanded to maintain the overall system output. This transition improved short-term supply resilience but also increased dependence on groundwater resources, the long-term sustainability of which remains uncertain. As one key informant cautioned, *"We are surviving, not managing. Every year, we scramble, drilling another well or repairing a spring, but there is no comprehensive plan"* (KI-1). This observation underscores a broader shift from proactive resource management to reactive adaptation, highlighting the need for integrated and evidence-based water resource planning.

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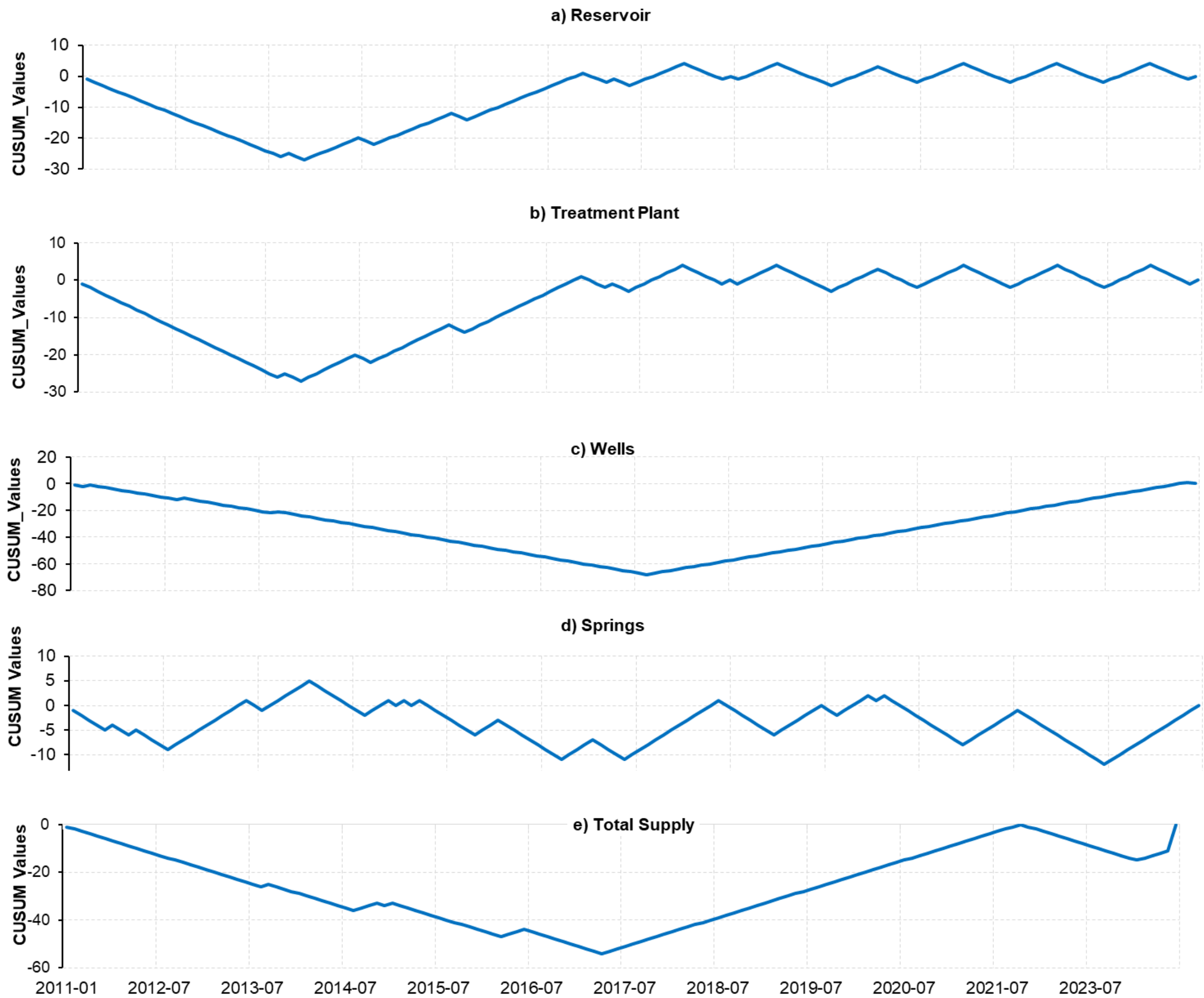

Figure 5.5 CUSUM control charts of water supply sources (2011–2024)

5.3.8 Integrated Qualitative Findings: Thematic Analysis

To provide context for the quantitative findings and better understand the challenges facing Gondar's water supply system, interview and focus group transcripts were analyzed using thematic analysis. Five dominant themes emerged, explaining the observed supply trends while capturing the perceptions and lived experiences of water managers and residents.

Theme 1: Reservoir Decline

Participants consistently perceived the reservoir as a declining, increasingly unreliable source of water. Key informants attributed this deterioration to sedimentation, aging infrastructure, and repeated drought impacts, all of which have reduced the storage capacity and operational reliability over time. One key informant described the reservoir as *"like a dying battery; it holds less every year,"* while another noted, *"We lose more each year to silt."* These perceptions reinforce the quantitative evidence showing reduced dependence on surface-water sources following the major operational changes identified after 2013.

Theme 2: Wells as Essential but Precarious

Groundwater emerged as the most important source of supply resilience, particularly following the expansion of wellfield development. However, the participants expressed considerable uncertainty regarding its long-term sustainability. As one respondent explained, *"The wells saved us, but now we worry about them drying up,"* while another observed that *"some are already showing declining yields."* These concerns mirror the quantitative findings that groundwater abstraction has become increasingly important, whereas groundwater monitoring remains largely absent.

Theme 3: Springs as Seasonal and Unreliable Sources

Participants described springs as highly dependent on rainfall and therefore unreliable as a primary source of supply. One focus-group participant explained, *"After good rain, they flow; during dry times, they disappear,"* while another remarked that *"springs are bonus water, not a base supply."* These perceptions are consistent with the lag-correlation analysis, which demonstrated a rapid spring response to rainfall and highlighted the strong climatic sensitivity of spring-fed water supplies.

Theme 4: Increased Supply but Unmet Household Needs

Despite official records indicating increased total water production, most residents reported little or no improvement in their household water access. Participants frequently emphasized the disconnect between reported supply increases and their everyday experiences. As one respondent stated, *"The numbers may show more water, but my tap still runs dry,"* while another observed, *"There are more people, but the same amount of water reaches us."* This theme reveals a critical perception–reality gap, suggesting that gains in production have not translated into equitable or reliable service delivery at the household level.

Theme 5: Reactive Rather than Strategic Management

Participants consistently characterized the water supply system as reactive rather than proactive. Key informants described management practices as being focused on responding to immediate shortages rather than implementing long-term solutions. As one participant explained, *"We're just getting by, not truly managing,"* while another noted, *"There isn't a strategic plan; we're merely reacting to emergencies."* These observations align closely with quantitative evidence showing repeated shifts among reservoirs, groundwater, and springs as managers adapt to recurring supply crises.

The frequency with which these themes emerged further emphasizes their significance. Theme 1 was mentioned by all six key informants and the 12 focus group participants. Theme 2 was identified by five key informants and eight focus group participants. Theme 3 was raised by four key informants and 16 focus group participants. Theme 4 emerged exclusively among residents, being mentioned by twenty-two focus-group participants but by none of the key informants. Theme 5 was discussed by four key informants and 18 focus group participants. The prominence of Theme 4 among residents highlights the disconnect between institutional assessments of system performance and household water access experiences.

Thematic Network

The five themes form an interconnected causal network that explains the evolution of Gondar's water-supply system. Perceived reservoir decline (Theme 1) encouraged greater dependence on groundwater resources (Theme 2), which provided short-term relief but generated new concerns regarding sustainability. Reliance on groundwater, combined with limited planning and monitoring capacity, reinforces the pattern of reactive management (Theme 5). Springs offered periodic seasonal relief (Theme 3) but remained too variable to function as a dependable water supply. Most importantly, the benefits of increased production failed to reach many households (Theme 4), creating a persistent gap between system-level performance indicators and user experience. Together, these interconnected themes portray a water supply system operating in a continuous state of adaptation and crisis management.

Integrated Insight

The qualitative findings reveal that water supply system functions within a recurring cycle of vulnerability and adaptation. The decline in reservoir reliability forced diversification toward groundwater resources; however, this transition occurred without sufficient monitoring, long-term planning, or comprehensive resource management. Springs provide temporary seasonal support but are highly climate-sensitive. Most critically, increases in total water production have not translated into equivalent improvements in household access, partly because of distribution inefficiencies and rapid population growth, factors that are not captured by aggregate production statistics. Consequently, the central challenge facing Gondar is not merely increasing water production but improving the sustainability, management, and distribution of available water resources.

5.4 Discussion

The integrated statistical and qualitative analyses confirmed the fundamental reconfiguration of Gondar's water supply architecture between 2011 and 2024. The AR exhibited no significant long-term trend, whereas groundwater abstraction and spring contributions increased significantly. Change-point detection revealed a clear transition sequence: reservoir decline from July 2013, groundwater expansion from July 2017 (coinciding with Koladiba wellfield commissioning), and spring integration from June 2019 (following the implementation of rehabilitation programs).

These findings indicate that the observed growth in the total registered supply reflects source substitution rather than system expansion: wells and springs compensated for the stagnating reservoir output. However, this substitution has not translated into improved household access, which is a critical distinction for measuring urban water security. A key reason is that supply increases have been outpaced by population growth: with the population rising approximately 40% (from 307,000 in 2011 to 431,000 in 2024) and NRW losses of 35–40%, per-capita net supply reaching households has not improved. Therefore, this study demonstrates that production-centered metrics conceal the distributional failures that determine whether water security is actually experienced at the household level.

The rapid decline in the KDWF yields after commissioning deserves particular attention. Operational records and key informant accounts indicate that production from these high-yield wells decreased relatively quickly after 2017. This is consistent with a scenario in which wells were commissioned and intensively pumped before adequate hydrogeological characterization was completed, leading to localized drawdown and yield reduction. This fact underscores the urgency of systematic groundwater monitoring (Recommendation 1 below) and the development of conjunctive use plans (Recommendation 6) before commissioning additional extraction infrastructure. The root causes of the severe water shortage in Gondar are as follows: (1) a reservoir that has lost 62.28% of its live storage since 1997, from 5.28 Mm^3 to approximately 1.32 Mm^3 by 2022 (Tessema et al.), with no systematic desiltation; (2) a rapidly growing population whose demand has exceeded the design capacity of infrastructure designed for an earlier demographic baseline; (3) groundwater development without adequate aquifer characterization or monitoring; (4) NRW losses of 35–40% due to aging and poorly maintained distribution networks; and (5) reactive, crisis-driven institutional management lacking long-term strategic planning.

Therefore, management responses must address all five dimensions: information systems (groundwater monitoring), operational adjustments (seasonal protocols), infrastructure rehabilitation (reservoir desiltation), loss reduction (NRW reduction), and institutional governance (coordination and strategic planning). Simply increasing production through additional sources, without addressing losses, demand management, and distribution equity, will not resolve the service deficit experienced by the households. Accordingly, this study proposes seven prioritized, actionable measures.

Recommended Actions:

1. **Establish a groundwater monitoring regime**: This addresses the absence of water-level data and concerns about declining yields identified in this study. The critical 12-month SPI response ($r = 0.432$) demonstrates the aquifer's sensitivity to long-term moisture conditions; however, without water level records, it is impossible to determine safe yield, detect overexploitation, or validate recharge rates. Success indicators include the installation of monitoring wells, monthly water-level reporting, and establishment of abstraction thresholds.
2. **Adopt a seasonal operations protocol**: these accounts for the 11-month reservoir management lag, 2-month total supply response, and recurring winter scarcity. A formalized protocol would allow preemptive allocation adjustments before the dry season, rather than reactive crisis pumping. Success indicator: formal adoption of a seasonal operations plan with measurable reductions in dry season shortfalls.
3. **Plan and fund AR rehabilitation**: Although large-scale desiltation is capital-intensive and technically complex, and therefore a long-term rather than short-term action, the 2013 change point and the documented loss of 62.28% of live storage (from 5.28 Mm^3 in 1997 to approximately 1.32 Mm^3 by 2022, per Tessema et al. 2022) make this a strategic imperative. Studies of comparable highland reservoirs (e.g., Koga Reservoir) have provided methodological precedents. A feasibility study and financing plan should be initiated immediately, even if implementation is phased over years. The success indicators were the recovered storage volume and improved dry-season reliability.
4. **Formalize the spring sources**: The 3-month spring response ($r = 0.568$) and the 2019 change point indicates that springs are valuable rapid-response sources. Formal protection, consistent yield monitoring, and integration with operational planning can improve their reliability. The success indicators were legally protected spring sites, consistent yield records, and integration with operational dispatch systems.
5. **A conjunctive use framework was developed**: Integrating the distinct climate response times of each source type (reservoir: 11-month inverse; springs: 3-month; groundwater: 12-month; total supply: 2-month) into a formalized allocation strategy would optimize

system performance across seasonal phases. Success indicator: adoption of a conjunctive use plan with evidence of optimized seasonal-source allocation.

Prioritization Rationale

The recommended actions were ranked according to urgency and practicality. Groundwater monitoring (Action 1) is the highest priority because management decisions currently lack reliable aquifer data, yet the city is increasingly groundwater-dependent. Seasonal operations (Action 2) offer a rapid and low-cost means of addressing climate-response mismatches. Reservoir rehabilitation (Action 3) is strategically critical but capital-intensive; therefore, it is medium- to long-term. Formalizing springs (Action 4) and reducing NRW (Action 5) target specific and tractable operational problems. Conjunctive use planning (Action 6) and institutional coordination (Action 7) establish the governance architecture needed to transform crisis-reactive management into proactive, integrated water governance.

Gondar's evolution reflects the dynamic interactions between climatic forcing and institutional responses. Seasonal rainfall extremes interact with operational constraints to create complex and adaptive pathways. Delayed responses to reservoir sedimentation, traceable to the 2013 change point, encouraged reactive source diversification, which introduced resilience through redundancy but without integration. The result is a strong path dependency: each crisis response creates new dependencies that constrain future options (Galaitsi et al., 2016; Ren et al., 2021).

The gap between aggregate production statistics and household experiences has significant implications for water security measurements. Per capita registered production did not improve significantly over the study period, and when NRW losses of 35–40% were subtracted, the per capita net supply reaching households declined relative to demand. This finding directly challenges the use of total production as an indicator of water security. This supports emerging critiques of production-centered water governance and strengthens calls for service-oriented indicators that capture the reliability, accessibility, and equity of provision (Fentie et al., 2024; Jepson et al., 2021; Mantey, 2024).

Gondar’s trajectory resembles patterns observed in other rapidly urbanizing regions. In Bengaluru, India, deep drilling into hard-rock aquifers temporarily sustained supply but increased long-term groundwater pressure (Kulkarni et al., 2021). In Mexico City, extensive groundwater pumping contributed to severe aquifer depletion and land subsidence (Castellazzi et al., 2016). Gondar’s highland hydrogeological conditions and rainfall-driven recharge provide comparatively stronger potential for sustainable groundwater management, but only if systematic monitoring and adaptive management practices are implemented before critical thresholds are reached.

5.5 Conclusions

This study used a sequential explanatory mixed-methods approach to examine the long-term and seasonal dynamics of Gondar City’s water supply from 2011 to 2024. Quantitative analysis showed that registered output from the AR remained largely stagnant, while groundwater abstraction and spring development expanded considerably, becoming the main drivers of overall production growth. Despite this aggregate increase, seasonal scarcity persisted during winter and spring, per capita supply showed no statistically significant improvement, and household access did not improve.

The AR, designed with a live storage of 5.3 MCM, has experienced severe long-term storage decline since commissioning. Because the satellite series (2016–2024) and the bathymetric survey (1997–2022) use different baselines, their percentages are not directly comparable. For this reason, the bathymetric estimate of 62.28% live-storage loss, from 5.28 Mm^3 to approximately 1.32 Mm^3, is treated as the authoritative long-term measure, while the satellite analysis is used to characterize seasonal and inter-annual decline.

Change-point detection identified several regime shifts: declining reservoir reliability from 2013, groundwater expansion from 2017, and spring integration from 2019. The rapid decline of Koladiba yields after commissioning underscores the risk of intensive groundwater extraction without prior aquifer characterization. Lagged correlation analysis revealed source-specific climate response times: inverse 11–12 months for the reservoir, 3 months for springs, 12 months for groundwater, and 2 months for total supply.

Achieving sustainable urban water security in Gondar requires a transition from reactive coping to proactive integrated management. Key priorities are: (1) establishing groundwater monitoring; (2) introducing seasonal operational protocols; (3) rehabilitating the AR; (4) formalizing spring sources; (5) reducing NRW; (6) developing conjunctive use strategies; and (7) strengthening interagency coordination.

Future research should address: well-specific monitoring to assess drawdown and sustainable yield; household-level surveys to quantify access inequalities; optimization modeling for seasonal allocation; comparative studies across Ethiopian highland cities; and downscaled climate projections to assess system vulnerability under 2030–2050 scenarios.

Overall, this study demonstrates the value of mixed-methods socio-hydrological analysis for understanding physical and institutional drivers of urban water resilience in resource-constrained, rapidly urbanizing environments. By combining statistical evidence with stakeholder perspectives, it provides a replicable framework for diagnosing urban water supply transitions and informing context-appropriate policy responses in the Global South.

CHAPTER SIX
RESERVOIR STORAGE FLUCTUATIONS AND WATER LOSS IN GONDAR CITY

Abstract

Urban water security in Gondar, Ethiopia, is increasingly at risk due to reservoir depletion and distribution inefficiencies. The AR, the city's main water source, has experienced significant storage loss, while growing demand has widened the supply gap. Despite this, the combined influence of reservoir fluctuations and distribution losses remains poorly studied. Findings indicate that this chapter addresses that gap using a mixed-methods approach integrating remote sensing and qualitative assessment. Reservoir volume was derived from Sentinel-2 imagery (2016–2024) using the NDWI and MNDWI, achieving 80–100% accuracy with a kappa coefficient of 0.6–1.0. These were integrated with the ALOS PALSAR digital elevation model to estimate surface–volume relationships. Validation against a bathymetric survey indicated high consistency (MAPE = 0.8%, RMSE = 18,000 m³). NRW was also quantified based on the AWWA water balance framework. Results show a total reservoir storage loss of 19.05% (2.32% annually), with the steepest decline (−9.72%) between 2022 and 2024. Seasonally, spring exhibited the most severe decline (−39.3%, annualized −5.6%), with sharp reductions from winter to spring (18.9% to 44.9%). Although partial summer recovery occurred, it did not offset cumulative losses. NRW reached 36.12% (±1.42%), consisting of 28.41% real losses and 7.71% apparent losses. The combined effects of reservoir degradation and water loss endanger Gondar's water security, requiring coordinated interventions in leak detection, meter upgrading, watershed rehabilitation, and institutional reform.

Keywords: AR, Gondar City, Integrated water management, NRW, Urban water scarcity

6.1 Introduction

Reservoir storage loss and water loss in distribution systems are two distinct but simultaneous challenges that together undermine urban water supply reliability. To avoid confusion, this chapter distinguishes between two related but different indicators: (i) satellite-derived active-storage variation for the 2016–2024 period and (ii) bathymetry-derived cumulative live-storage loss since commissioning. The first captures short-term seasonal and interannual fluctuation, whereas the second provides the longer-term sedimentation baseline. Water loss in the distribution network is then assessed separately using the AWWA water balance framework. Together, these measures show that source-side depletion and network losses reduce the quantity of water available to users through different mechanisms and therefore require different interventions.

Storage loss due to sedimentation is irreversible without costly interventions such as dredging, whereas seasonal drawdown is an expected operational cycle: reservoirs are designed to store water during rainy seasons and supply it during dry seasons. The critical issue arises when accumulated sediment so reduces live storage capacity that the reservoir can no longer meet dry-season demand even when full at the end of the wet season. Water loss in the distribution network, resulting from leaks, aging infrastructure, pipe bursts, and metering inaccuracies, further reduces the effective supply reaching consumers, compounding source-side deficits (Al-Washali et al., 2018; Ociepa, 2021). Importantly, meter inaccuracies cause revenue loss rather than physical water loss, since the water is consumed but not billed. Both sedimentation-induced storage loss and distribution water loss occur simultaneously in Gondar, necessitating integrated assessment, even though they operate through different mechanisms and require different interventions.

Urban water supply systems in Ethiopia face severe structural stress. Most cities experience erratic rainfall, advanced watershed degradation, significant distribution inefficiencies, and limited storage capacity (Abraha et al., 2022). NRW commonly exceeds 35–41.8%, contributing to low service coverage (42–70%) and substantial unmet demand (Beker & Kansal, 2023). Institutional and financial constraints, including inadequate cost recovery, low per capita water allocation, and persistent water quality concerns, intensify shortages. These conditions require integrated solutions combining technical improvements with financial reform and governance strengthening (Mekonnen, 2023; V. Roth et al., 2018).

Gondar City, a historic imperial capital in northwestern Ethiopia, exemplifies these challenges. The AR, which has served as the city's principal water source since 2002, now supplies approximately 65% of total demand, but its live storage capacity has been severely depleted by sedimentation, estimated at a loss exceeding 62% of original design capacity (Tessema et al., 2024). It is important to distinguish between live (active) storage and total reservoir capacity: live storage is the usable volume above the dead storage elevation, while total capacity includes both live and dead storage. Sediment accumulation progressively reduces live storage capacity, ultimately threatening the viability of the reservoir well within its intended design period. Groundwater resources have also declined, with only seven of the original 16 wells remaining operational, now meeting only 24.8% of demand (MSC, 2023). Per capita water consumption is projected to rise from 35.3 litres per person per day in 2015 to 67.5 litres by 2045 (ANRS & ECDSWC, 2021). The convergence of depleting sources and rising demand creates an acute and worsening supply deficit that cannot be resolved through operational efficiency improvements alone.

Previous studies in Gondar have addressed water quality (Desye et al., 2021; Zewdu et al., 2024), decadal volumetric change in the AR (Haregeweyn et al., 2012; Zeleke et al., 2013; Tessema et al., 2024), water demand estimation (Abebe, 2018; Negash et al., 2023), and distribution system performance (Azene, 2019). However, none examined intra-annual (seasonal) storage dynamics derived from multi-temporal remote sensing, nor quantified NRW components using a structured water balance methodology. While seasonal fluctuations in reservoir storage are an inherent design feature of any surface water supply system (reservoirs fill during wet seasons and deplete during dry seasons), what matters for water security assessment is the magnitude and trajectory of storage across cycles, and whether sufficient live storage remains to bridge dry-season demand. Understanding these dynamics is essential for identifying when and why supply fails.

This study addresses these gaps by combining multi-temporal Sentinel-2 remote sensing analysis of reservoir storage dynamics with the AWWA top-down water balance approach to quantify NRW. By characterizing both source-side depletion and distribution-side losses, this study provides an integrated diagnostic framework for Gondar's water supply system. The analysis also introduces a replicable remote-sensing methodology for seasonal reservoir monitoring in data-scarce, reservoir-dependent urban contexts. Critically, this study situates findings within Gondar's broader water crisis: sedimentation has so severely reduced Angereb's live storage that sustainable water security will require major investment in new source development, a conclusion that distribution-side efficiency improvements alone cannot change.

6.2 Materials and Methods

6.2.1 Study Area

Gondar City is located in northwestern Ethiopia (12°34′25″ N – 12°37′42″ N latitude, 37°28′16″ E – 37°31′34″ E longitude) and is approximately 737 km from Addis Ababa and 180 km from Bahir Dar (Figure 3.4).

Gondar, which served as the capital of Ethiopia from the 17th to 19th centuries, remains a significant cultural and political center. According to the Central Statistical Agency (CSA, 2013), the city has a population of 431,113. Currently, Gondar's water infrastructure is under increased stress due to accelerated sediment accumulation in its reservoirs. The operational efficiency of the AR, which has served as the principal water supply for Gondar City since 2002, has been compromised by a gradual loss of storage capacity caused by sedimentation (Haregeweyn et al., 2012). Groundwater wells and springs supplement the supply. An anticipated Megech River reservoir project remains incomplete; as a result, water diversion from Lake Tana is under consideration.

6.2.2 Research Design

This study employed a sequential explanatory mixed-methods design to examine the impact of reservoir fluctuations and system losses on water supply in Gondar City. The quantitative phase was followed by qualitative inquiry to explain the findings (Bowen et al., 2017; Toyon, 2021). The methodological flow of the study is shown in Figure 6.1.

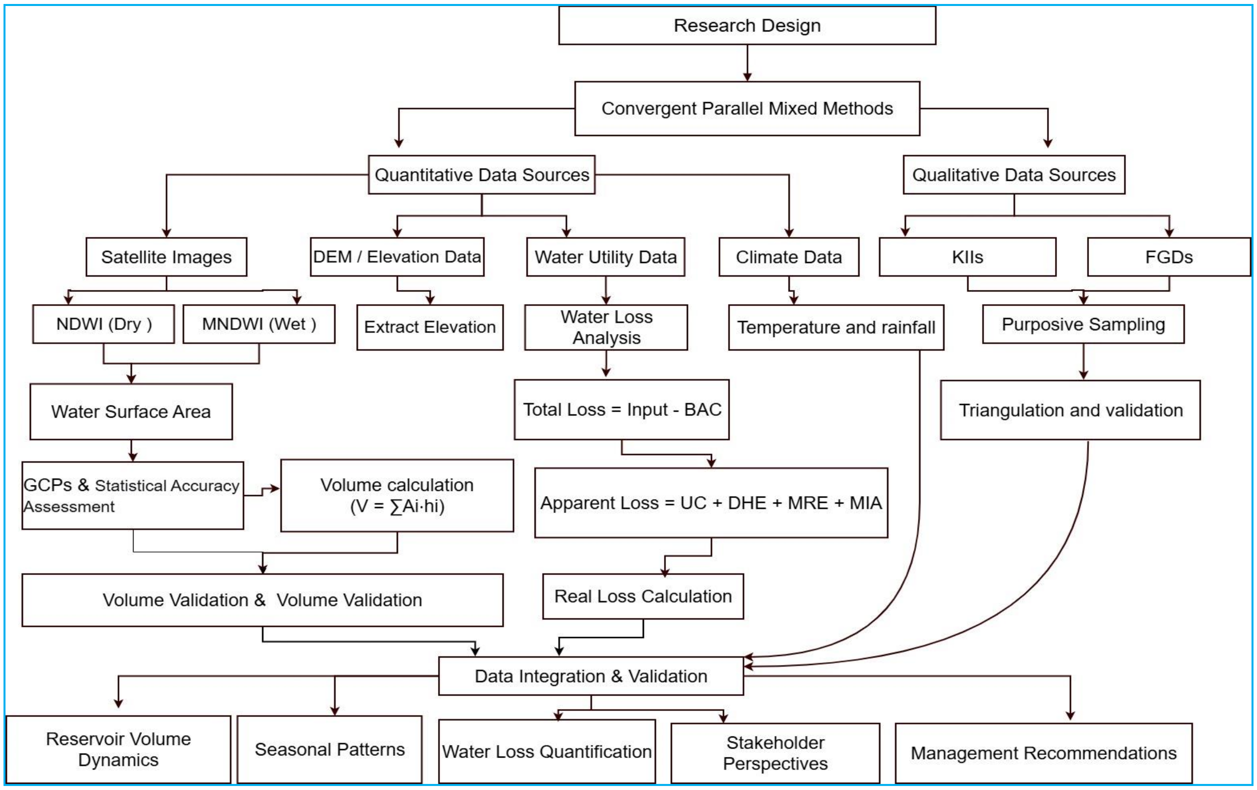

Figure 6.1 Methodological flow chart of the study

Initially, quantitative data on reservoir volume changes and water losses were collected and analyzed to identify key trends and statistical patterns. To provide deeper context for these quantitative findings, qualitative data were subsequently gathered through KIIs and FGDs. Thematic analysis of these qualitative data was then conducted. The insights from this qualitative phase were triangulated with the initial quantitative results to explain, validate, and provide a more nuanced understanding of the observed impacts on water supply dependability. Qualitative data were integrated to contextualize the quantitative results with on-the-ground insights into water supply issues.

6.2.3 Data Sources and Collection Tools

This study integrated quantitative and qualitative data to assess the impact of volume fluctuations in the AR and distribution losses on the water supply of Gondar City. The quantitative component involved satellite-based reservoir mapping, topographic and bathymetric data, and utility records used to estimate NRW in the system. The qualitative component consisted of KIIs and FGDs, which provided operational insights and user perceptions.

6.2.3.1 Satellite Imagery

To assess seasonal variations in the water surface area of the AR, 20 satellite images were acquired from the Sentinel Hub platform (2016–2024). This dataset comprises four images from Sentinel-2 Level-1C and 16 images from Sentinel-2A, corresponding to four acquisitions per year over five years (Table 6.1).

Table 6.1 Sentinel-2 Imagery for AR surface water detection (2016–2024)

Year	Winter (Jan)	Spring (Apr)	Summer (Jul)	Autumn (Oct)
2016	L1C_37PC_20160118	L1C_37PC_20160417	L1C_37PC_20160716	L1C_37PC_20161014
2018	L2A_37PC_20180117	L2A_37PC_20180417	L2A_37PC_20180716	L2A_37PC_20181014
2020	L2A_37PC_20200116	L2A_37PC_20200416	L2A_37PC_20200715	L2A_37PC_20201013
2022	L2A_37PC_20220116	L2A_37PC_20220416	L2A_37PC_20220705	L2A_37PC_20221013
2024	L2A_37PC_20240116	L2A_37PC_20240415	L2A_37PC_20240715	L2A_37PC_20241012

6.2.3.2 Topographic and Climate Data

A 12.5-meter resolution DEM derived from ALOS PALSAR data was obtained from the Alaska Satellite Facility to supply detailed topographic information, owing to its moderate spatial resolution (Ngula Niipele & Chen, 2019). This level of detail is particularly critical for bathymetric analyses of small water bodies, like the AR study area. Bathymetric survey data from GCWSSS were used to confirm the reservoir's dead storage elevation.

GCPs were identified primarily using high-resolution Google Earth imagery when available throughout the study period (Forget et al., 2021). During times without suitable historical imagery, reference points were established from permanent water bodies, bridge locations, and direct field observations. The accuracy assessment incorporated 200 GCPs distributed around the reservoir, including permanent water sites, and were supported by field verification to confirm the consistency between satellite-derived estimates and actual conditions. All images were subjected to atmospheric correction to standardize reflectance values.

Climate data, including rainfall and temperature records for Gondar from 2016 to 2024, were obtained from the National Meteorological Agency of Ethiopia (NMA, 2024) to evaluate the impact of climate on the surface area of the AR.

6.2.3.3 Water Utility data

To estimate NRW, water utility data were acquired from different sources. BAC data by meter size (DN15–DN80) were sourced from GCWSSS. Benchmark values from the literature addressed gaps in local NRW components: UC and DHE were set at 2% of BAC (Mutikanga et al., 2013). A weighted meter accuracy of 92.5% for DN15/DN20 meters was used to account for MIA (Ncube & Taigbenu, 2019), representing 77.1% of billed water (2,129,701 m^3). In September 2024, 1,366 errors were recorded out of 38,505 readings, yielding a 3.6%-MRE due to manual or recording errors.

Qualitative data were collected through KIIs and FGDs using structured guides. Nine KIs were purposively selected from GCWSSS, Angereb treatment facility, and the city administration. FGDs were conducted at four GCWSSS branch offices in Gondar, each with six participants visiting to pay bills. These data complemented the remote sensing results by providing expert insights and residents' experiences. Data types, purposes, and sources are summarized in Table 6.2.

Table 6.1 Data types, purpose, and sources used in the study

Data Type	Purpose	Source(s)
Sentinel-2A Satellite Imagery (10 m)	Estimation of reservoir surface area	Copernicus Data Space
ALOS PALSAR DEM (12.5 m)	Extraction of elevation data	Alaska Satellite Facility
Bathymetric Data of AR	Determination of dead storage elevation	GCWSSS, 2024
MIA (DN15/D20)	Assess water loss due to MIA	Ncube & Taigbenu, 2019
UC and DHE benchmarks	Quantify UC in Gondar City	Mutikanga et al., 2013
MRE benchmarks	Benchmark water loss from MRE	GCWSSS, 2024
BAC	Calculate total water loss	GCWSSS, 2024
Expert's opinion	Understand reservoir dynamics	KIIs (2024)
Residents' perceptions	Identify water supply challenges	FGDs (2024)

6.2.4 Data Analysis

6.2.4.1 Reservoir Volume Estimation

Water surface boundaries derived from Sentinel-2 imagery were combined with a DEM to estimate the water storage capacity. The extent of water in the AR was delineated using NDWI and MNDWI. Water-surface elevations were determined using the basin topography represented by the DEM and used to quantify the reservoir volume and its seasonal fluctuations, as described below.

NDWI and MNDWI were selected because they effectively distinguish water from land in turbid conditions common in AR, and have been validated in similar contexts (Deoli et al., 2021; Xu, 2006). MNDWI addresses NDWI's limitations in built-up areas by using SWIR instead of NIR.

Step 1: Delineation of water surface areas

The water surface area reflects the reservoir's spatial extent at a specific time. By measuring the reservoir water level (WL) for each season, the surface area and the DEM enable calculation of total water storage (Endalew & Mulu, 2022; Ouma, 2016). NDWI and MNDWI were applied to

Sentinel-2 imagery to delineate the water surface area of the AR, aiding in the identification of water bodies, including turbid, calculated accordingly Eq. 1Eq. 2

$$\mathrm{DWI} = (\mathrm{Green} - \mathrm{NIR})/(\mathrm{Green} + \mathrm{NIR}) \qquad \text{Eq. 1}$$

$$\mathrm{MNDWI} = (\mathrm{Green} - \mathrm{NIR})/(\mathrm{Green} + \mathrm{SWIR}) \qquad \text{Eq. 2}$$

Where Green, NIR, and SWIR represent the reflectance values in the green, NIR, and SWIR bands, respectively.

Step 2: Combining water surface area with DEM

The water storage of the AR between 2016 and 2024 was quantified by combining reservoir surface boundaries (extracted from NDWI and MNDWI) with a DEM that defines water surface elevation. The DEM provided basin topography and served as the elevation reference for assigning height values to each delineated water extent. For each observation date, elevation values within the water surface polygon were sampled from the DEM, and the median of these values was taken as the representative water-surface elevation (Avisse et al., 2017; Singh et al., 2018).

Step 3: Compute the reservoir volume

The ArcGIS 3D Analyst *Surface volume* tool was then used to compute the volume of water stored above the reservoir bed, representing the active storage capacity for each observation period (Eq. 3

$$\mathrm{V} = \sum \mathrm{A_i}.\ \mathrm{h_i} \qquad \text{Eq. 3}$$

Where V is the reservoir volume, A_i is the surface area at elevation level i, and h_i is the water height corresponding to that area. The integration of remote sensing data with the ArcMap "*3D volume tool"* enabled the precise quantification of water storage fluctuations (Foteh et al., 2018).

Step 4: Calculate volume change

The volume change between successive periods was subsequently calculated as (Eq. 4

$$\text{Volume change} = \frac{\text{Current Volume} - \text{Previous Volume}}{\text{Previous Volume}} \qquad \text{Eq. 4}$$

The CAGR technique was used to determine the yearly volume change in the AR Eq. 5

$$\text{Anualized Volume Change} = \left(\frac{\text{Current Volume} - \text{Previous Volume})^{\frac{1}{n}}}{\text{Previous Volume}} - 1 \right) * 100 \qquad \text{Eq. 5}$$

Where 'n' is the number of years in the period.

6.2.4.2 Distribution Loss Estimation

The AWWA top-down water balance approach was employed to estimate NRW in Gondar City. This method was selected for its structured framework and applicability in contexts with limited data availability. NRW refers to the volume of water that enters the distribution network but is not accounted for as authorized consumption. It also represents the difference between the total water entering the system and the authorized consumption (AC), which includes all legally used water, both authorized and unauthorized consumption (Al-Washali et al., 2016). The quantity of NRW is calculated based on Eq. 5

$$\text{NRW} = \text{Apparent Loss} + \text{Real Loss} = \text{SIV} - \text{BAC} \qquad \text{Eq. 6}$$

Where SIV is SIV (total water supplied to the network), BAC is billed authorized consumption

Water loss in the distribution system is divided into real losses and apparent losses. Real losses refer to the tangible water that leaks from pipes, storage tanks, and reservoirs. In water supply systems, apparent losses are primarily caused by DHEs, unauthorized consumption, and metering (Al-Washali et al., 2018; Choi et al., 2022). Unauthorized consumption is considered to be consumed without authorization when it is used without approval, usually through illegal connections or theft. Errors in data handling involve mistakes in recording or billing information, whereas unmeasured usage pertains to water that is not metered, such as public taps or firefighting activities (Mutikanga et al., 2013). Meter inaccuracies occur when meters do not accurately measure consumption, often due to aging or malfunctioning equipment. Apparent losses in the distribution system are calculated as shown in Eq. 7

$$\text{Apparent Loss} = \text{UC} + \text{DHE} + \text{MRE} + \text{MIA} \qquad \text{Eq. 7}$$

Where UC represents unauthorized consumption, DHE represents DHEs, MRE represents meter reading errors, and MIA represents meter inaccuracies.

6.2.4.3 Qualitative data analysis

The qualitative data analysis employed a triangulation approach to integrate insights with quantitative data on changes in AR volume and water losses. Perspectives from KIIs and FGDs confirmed the reservoir dynamics and water availability observed through remote sensing. This validation ensured that temporal changes in reservoir volume were consistent with real-world conditions and expert knowledge. By combining quantitative measurements of reservoir fluctuations with qualitative insights from KIIs and FGDs, the study provided a comprehensive understanding of how reservoir volume changes and water losses influence water supply reliability in Gondar City.

6.2.5 Uncertainties and Methodological Limitations

The study addresses uncertainties to ensure robust findings, primarily stemming from satellite imagery limitations. The 10-meter spatial resolution can result in mixed-pixel effects at land-water boundaries, affecting accuracy, particularly in narrow areas (Fisher et al., 2016). Additionally, rain season cloud cover can create data gaps, biasing seasonal analyses. To counteract these, a strict image selection protocol was employed, favoring images with less than 5% cloud cover within a ±10-day window. The use of NDWI and MNDWI indices, along with consistent reservoir boundary clipping, further reduced classification errors.

The ALOS-PALSAR DEM has a vertical error of ±2–5 m, which affects the accuracy of reservoir volume estimates (Xu et al., 2024). This inaccuracy propagates into the derived water surface elevation, potentially leading to a systematic bias in storage volume estimates. To address this, a bathymetry-based calibration was carried out with the authoritative 2015 bathymetric survey as a reference. Initial satellite-derived volumes were compared to reference volumes interpolated from the bathymetric elevation–area–volume curve to determine a uniform CF. This calibration, as described in the validation section (see section 2.6), accurately aligned the remote sensing data with the reservoir's known storage profile, significantly reducing volumetric uncertainty.

The uncertainties associated with NRW and its components were quantified using benchmark values and error propagation methods. For the apparent losses, component uncertainties were obtained from Mutikanga et al. (2013), encompassing metering inaccuracies (±2%), meter reading errors (±1%), DHEs (±0.5%), and unauthorized consumption (±2%). These independent uncertainties were combined using the root-sum-square (RSS) method, as expressed in Eq. 8

$$\sigma Y = \sqrt{\sum_{i} \sigma^{2}\ x_{i}} \qquad \text{Eq. 8}$$

Where σy is the uncertainty of the derived quantity (AL, RL, and NRW) and σXi are the uncertainties of the independent input variables (such as SIV, BAC, MRE, and DHE resulting in y). For real losses, calculated as the difference between the System SIV and Background Apparent BAC, and for total NRW, uncertainty propagation was conducted analogously, using Eq. 8

Three uncertainties were performed for apparent loss, real loss, and total NRW. RSS was used to estimate realistic confidence intervals, effectively accounting for measurement errors and data limitations encountered in urban water distribution systems (Al-Washali et al., 2020; Silva et al., 2018).

6.2.6 Validation of results

6.2.6.1 Water surface area

The accuracy of the NDWI- and MNDWI-based water-pixel classifications was assessed using a confusion matrix derived from 200 ground control points (GCPs). Reference data were selected to represent both water and non-water classes across the study area and observation periods. Where available, high-resolution historical imagery from Google Earth was used to identify stable reference locations (Forget et al., 2021). For periods lacking suitable historical imagery, GCPs were established using permanent water bodies, stable land-cover features, and field observations. Overall accuracy and the Kappa coefficient (κ) were calculated to evaluate the level of agreement between the classified satellite images and the reference data, following approaches commonly applied in remote-sensing accuracy assessment studies (Su et al., 2024; Yang & Hong, 2024).

6.2.6.2 Reservoir Volume Estimates

Satellite-derived reservoir volumes were validated against a 2015 bathymetric survey that provides elevation–area–volume relationships at 1-m vertical intervals between 2113 and 2138 m. For each observation date, reservoir water extent was delineated from the satellite imagery, and the corresponding water-surface elevation was extracted from the DEM. This elevation was then matched to the bathymetric elevation–volume curve to obtain a reference reservoir volume. When the extracted elevation coincided with a surveyed level, the reference volume was obtained directly from the bathymetric dataset. When the elevation fell between surveyed levels, the reference volume was estimated using linear interpolation between the two nearest elevation–volume points. This procedure generated paired satellite-derived and bathymetry-based volume estimates for each observation date, which were subsequently used to assess the uncertainty of the satellite-derived reservoir volume estimates.

These paired datasets were subsequently used to assess the uncertainty of the volume estimations. The agreement between the remote sensing–derived volumes and the bathymetry-based reference volumes was evaluated for each season using two error metrics. The RMSE (Eq. 9Eq. 10

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(V_{sat,i} - V_{ref,i}\right)^2} \qquad \text{Eq. 9}$$

$$\mathrm{MAPE} = \frac{100}{n}\sum_{i=1}^{n}\frac{\left[V_{sat,i} - V_{ref,i}\right]}{V_{ref,i}} \qquad \text{Eq. 10}$$

Where $V_{sat,i}$the satellite-derived volume for observation isi, $V_{ref,i}$ is the corresponding reference volume from bathymetry, and n is the total number of observations.

Analysis revealed a consistent systematic bias (overestimation) in the raw satellite volumes. To correct this, a CF was derived as the mean of the proportional differences between the reference and satellite volumes (Eq. 11

$$\mathrm{CF} = \frac{1}{n}\sum_{i=1}^{n}\frac{V_{ref,i}}{V_{sat,i}} \qquad \text{Eq. 11}$$

Analysis revealed a consistent systematic bias in the raw satellite-derived volumes, characterized by a tendency to overestimate reservoir storage. To correct this bias, a CF was calculated by taking the mean of the proportional differences between the bathymetry-based reference volumes and the satellite-derived volumes.

6.2.6.3 Validation of NRW Estimates

Validation of the NRW result involved comparison with benchmark values and operational data from the GCWSSS, supported by insights from KIIs and FGDs. Expert knowledge and field verification further verified the findings, ensuring the reliability, consistency, and practical validity of the reported results.

6.3 Results

6.3.1 Accuracy Assessment of Surface Area and Volume Estimation

NDWI and MNDWI-based classifications performed consistently across all seasons, with overall accuracies of 80–100% and kappa coefficients of 0.6–1.0. Both producers' and users' accuracies for water (W) and non-water (NW) classes frequently exceeded 80%. After bias correction, satellite-derived volume estimates achieved a MAPE of 0.8% and an RMSE of 18,000 m^3, confirming adequate precision for detecting the storage trends observed over the study period.

6.3.2 Reservoir water surface area dynamics (2016–2024)

Multi-temporal NDWI and MNDWI analysis revealed substantial spatiotemporal variation in the AR's water surface area (Figure 6.2). Maximum coverage reached 405,943 m^2 in July 2018 (wet-season peak), while the dry-season minimum fell to 167,295 m^2 in April 2024, a 58.8% seasonal reduction. These fluctuations are consistent with the design intent of seasonal storage reservoirs: water is stored during the wet season for use during the dry season. What is significant is the magnitude of seasonal drawdown and the progressive decline in even wet-season peak storage, indicating that available live storage is insufficient to sustain supply through the dry season.

Seasonal transitions show clear patterns (Table 5.3): surface area decreased by 18.5–44.3% from winter to spring, recovered by 30.7–111.4% from spring to summer, and declined moderately through autumn. The widening of the winter-to-spring decline from −24.6% in 2016 to −44.3% in 2024 reflects both reduced stored volume at the start of the dry season and accelerated dry-season drawdown due to growing demand and reduced live storage capacity from sedimentation.

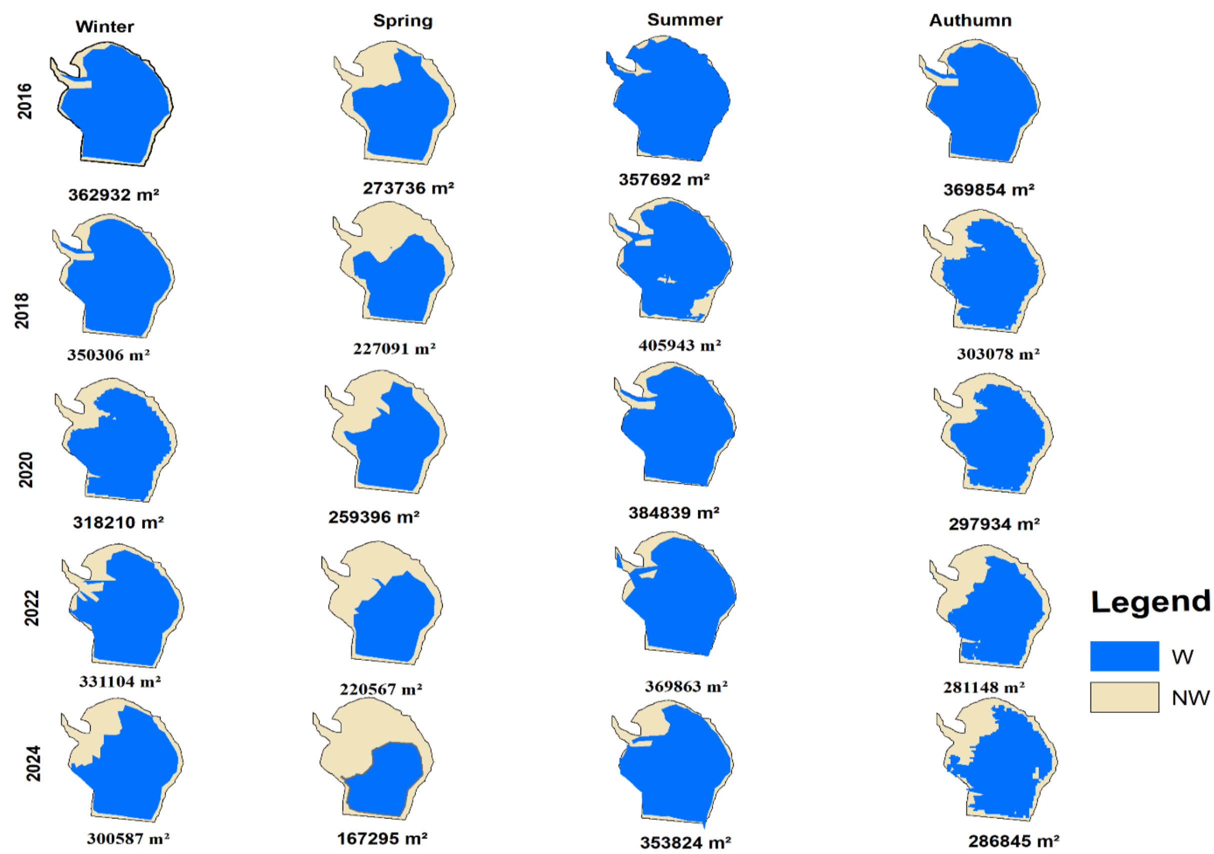

Figure 6.2 Water surface area of the AR across seasons (2016-2024)

Seasonal transitions show clear patterns (Table 6.2): surface area decreased by 18.5–44.3% from winter to spring, recovered by 30.7–111.4% from spring to summer, and declined moderately through autumn. The widening of the winter-to-spring decline from −24.6% in 2016 to −44.3% in 2024 reflects both reduced stored volume at the start of the dry season and accelerated dry-season drawdown due to growing demand and reduced live storage capacity from sedimentation.

Table 6.2 AR water surface area changes (2016-2024)

Year	Winter to Spring (%)	Spring to Summer (%)	Summer to Autumn (%)
2016	-24.57	30.67	3.4
2018	-35.29	78.78	-25.32
2020	-18.49	48.36	-22.58
2022	-33.37	67.6	-23.99
2024	-44.33	111.4	-18.93

This pattern underscores the critical need for adaptive water resource management to ensure a reliable supply. Between 2016 and 2024, the water surface area experienced a prolonged decrease, accompanied by slightly greater rainfall and stable temperatures, despite the ongoing reduction indicated by the trend line in Figure 6.3.

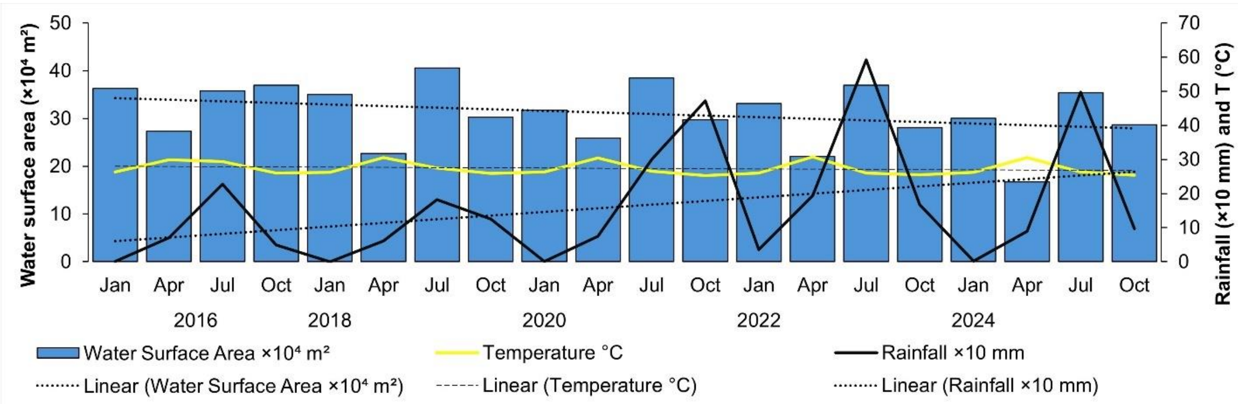

Figure 6.3 Trends of water surface area of AR, rainfall, and temperature (2016-2024)

6.3.3 AR Volume fluctuation (2016–2024)

6.3.3.1 Cumulative Reservoir Volume Changes

Average annual reservoir volume declined steadily between 2016 and 2024 (Table 6.4). Key informant interviews identified sedimentation-driven loss of live storage capacity as the main cause of this decline. The slower biannual loss observed between 2018 and 2020 (−2.14%, or 1.07% per year) coincided with reported silt removal activities and slightly improved rainfall conditions. In contrast, the sharper decline between 2022 and 2024 (−9.72%, or 4.98% per year) suggests that the reservoir is moving toward a critical threshold beyond which it may no longer reliably meet dry-season demand. Over the full study period, the average annual storage reduction rate was 2.32%. By 2024, the average seasonal volume had fallen to approximately 1.12 MCM, equivalent to about 21.1% of the original 5.3 MCM design capacity. This indicates that about 79% of the reservoir's live storage has been lost since shortly after impoundment.

Table 6.3 Changes in the average volume of the AR (2016–2024)

Year	Average volume (m³)	Period	Biannual Δ Volume (%)	Annualized Δ Volume (%)
2016	1,188,748	2016	—	—
2018	1,120,388.3	2016-2018	-5.75	-2.92
2020	1,096,449.5	2018-2020	-2.14	-1.07
2022	1,065,816.5	2020-2022	-2.79	-1.41
2024	962,272.8	2022-2024	-9.72	-4.98
Total	226,475	2016-2024	-19.05	-2.32

6.3.3.2 Inter-seasonal volume dynamics (across seasons)

Seasonal volume transitions follow expected patterns for a single-purpose surface water supply reservoir (Figure 6.4): volumes decline from winter through spring (low rainfall, high evaporation, continued abstraction), partially recover during summer (wet season recharge), and then decline through autumn and into winter. The magnitude of within-year fluctuations has increased over the study period, with volume losses from winter to spring ranging from −25.1% in 2016 to −44.9% in 2024. This indicates that less water is being stored at the start of each dry season due to reduced live storage capacity from cumulative sedimentation.

FGDS participants reported increasingly severe dry-season supply failures: "There is a severe water shortage as we move from winter to spring; taps can remain dry for days" and "In the spring season—the hottest and driest period—water can be unavailable for weeks." Some households reported dependence on water transported by vehicles or donkey carts. Key informants corroborated that spring scarcity is driven by reduced reservoir inflows, elevated evaporation, and high demand, while summer operations are complicated by turbidity from flood-driven sediment pulses. These qualitative observations are consistent with the quantitative trajectory of storage decline and confirm that the problem extends beyond seasonal management to structural source inadequacy.

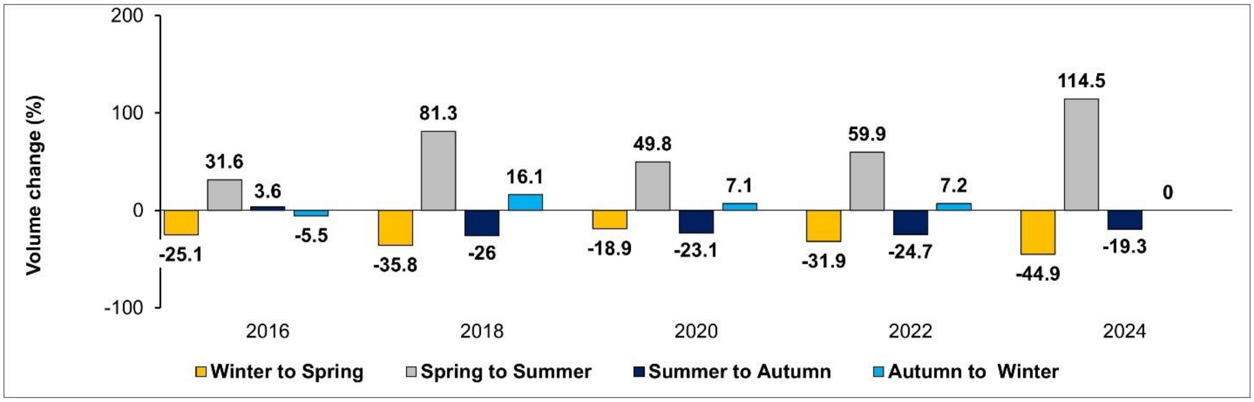

Figure 6.4 Seasonal fluctuations in the AR volume

6.3.3.3 Annual volume fluctuation (across seasons)

Figure 6.5 presents cumulative volume changes for each season from 2016 to 2024. Winter volumes declined by 17.6% cumulatively (2.4% per year), meaning the reservoir enters each dry season with progressively less storage. Spring exhibited the most severe cumulative loss (−39.3%; −5.6% per year), driven by the compounding effects of low rainfall, high evaporation, abstraction for supply, and reduced live storage from sedimentation. The spring season represents Gondar's most critical supply risk period.

Summer volumes showed a modest net decline of 1.1% over the study period (annualized −0.1%), indicating that wet-season recharge still partially replenishes the reservoir, but not enough to compensate for cumulative storage losses. Key informants noted that operational constraints, including limited treatment capacity and turbidity during floods, restrict the system's ability to capture and utilize available inflows fully. Autumn volumes declined by 23% cumulatively. Focus group participants reported that water supply remained relatively more stable during autumn, supported by residual wet-season storage; some key informants attributed this to reduced household demand following the harvest period and fewer infrastructure failures.

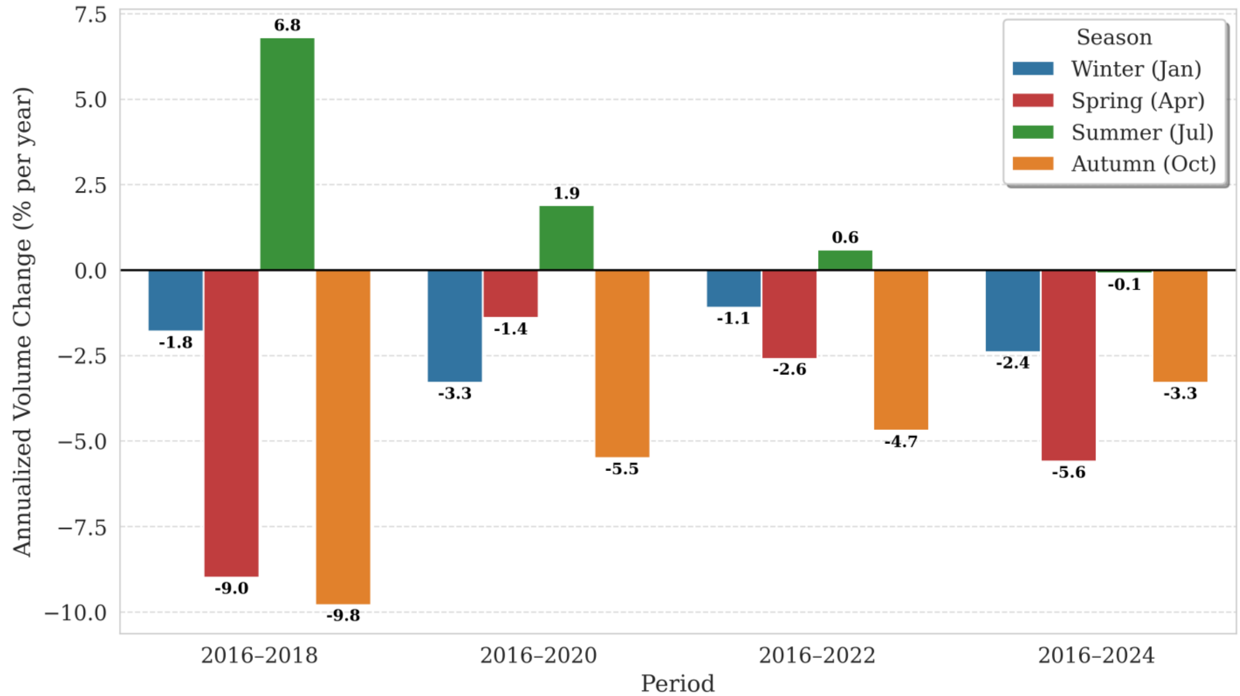

Figure 6.5 Seasonal trends in AR volume changes (2016–2024)

6.3.4 Water Loss Estimation in the Distribution Network

The total System Input Volume was 4,529,270 m^3, against a Billed Authorized Consumption of 2,893,848 m^3. DN15 and DN20 meters collectively accounted for 77.1% of billed consumption (Table 6.4). This is not in itself a problem; small-diameter residential meters are standard and appropriate for cities where domestic use dominates (typically 70% or more of total consumption). The issue in Gondar is not meter diameter but meter age and the absence of systematic asset management. Without scheduled calibration testing and timely replacement of aged meters, small meters accumulate under-registration errors over time (Kiliç, 2021).

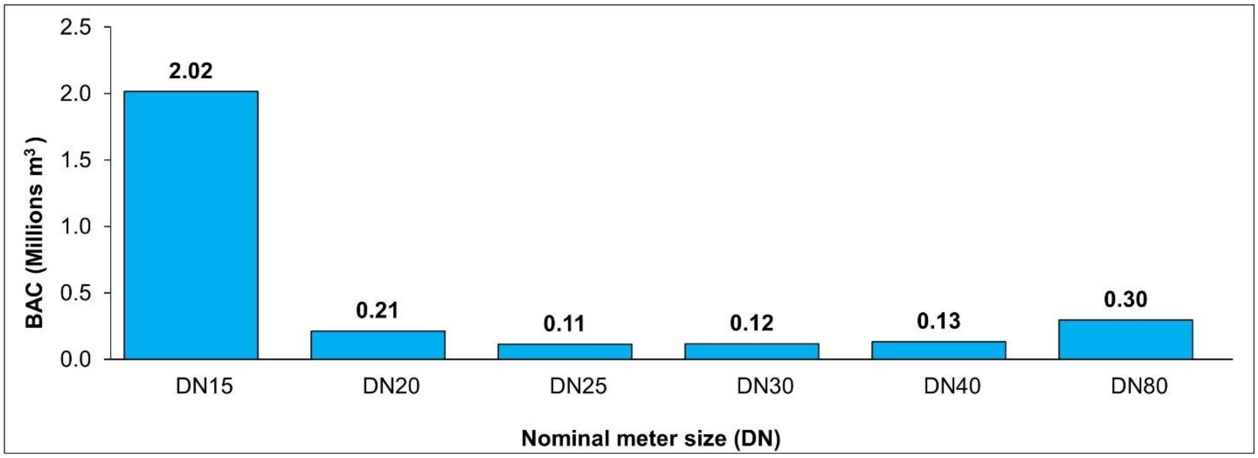

Figure .6 Water consumption of Gondar City by meter size (2024)

As shown, the estimated total NRW was 36.12% (±1.42%) of System Input Volume, with real losses (1,287,026 m^3; 78.6% of NRW) arising from leaks, pipe bursts, and system failures. Focus group participants confirmed frequent visible leaks along main distribution lines, often caused by road construction activity and heavy vehicle traffic over unprotected pipelines. Key informants attributed many failures to aging cast-iron pipes that are prone to fracture under maintenance pressure or at times of peak demand. Reducing real losses requires infrastructure rehabilitation, active leak control, and pressure management, not metering interventions. Apparent losses, by contrast, are addressed through meter asset management, tamper detection, and billing system improvements.

The magnitude and pattern of real losses align with GCWSSS operational records, confirming that infrastructure deterioration and operational practices are primary drivers of NRW. Combining apparent and real losses, the NRW was calculated using Eq. 6 and summarized in Table 6.5.

Table 6.4 Quantity of NRW and its components in Gondar City, 2024

Component	Volume (m^3)	% of SIV	Uncertainty (m^3)
System Input Volume (SIV)	4,529,270	100	–
Billed Authorized Consumption (BAC)	2,892,848	63.87	–
NRW (NRW)	1,636,422	36.13	±64,455
Real Loss	1,287,026	28.41	±64,351
Apparent Loss (total)	349,396	7.71	±3,800
MIA (meter inaccuracies)	179,939	3.97	±3,599
DHE (data handling errors)	44,594	0.98	±223
MRE (meter reading errors)	80,269	1.77	±803
UC (unauthorized consumption)	44,594	0.98	±892

Governance and maintenance dimensions are critical to understanding why NRW persists at this level. Several structural factors prevent effective loss control. The utility operates under chronic financial constraints: low tariffs and under-collection limit revenue available for pipe rehabilitation, meter replacement, and leak repair programmes. Intermittent supply, itself a consequence of inadequate source capacity, causes repeated pressure transients during filling cycles, accelerating pipe fatigue and meter wear. Maintenance is largely reactive rather than planned, meaning leaks are repaired only after visible failure rather than through systematic active leak control. Meter reading is predominantly manual, introducing recording errors that accumulate into billing inaccuracies. Inadequate cadastral records of the pipe network hamper targeted intervention. NRW will persist, and real losses in particular will grow, until investment in infrastructure rehabilitation, pressure management, and institutional capacity is commensurate with the scale of the problem.

6.4 Discussion

6.4.1 Seasonal fluctuations and Long-term decline of volume

The AR exhibits clear within-year storage cycles consistent with its operational design as a seasonal storage reservoir: wet-season filling followed by dry-season drawdown. This is not a management failure but an inherent characteristic of surface water supply systems in seasonally variable climates. What is of concern is not seasonal variability per se, but rather the progressive reduction in the volume available at the start of each dry season, and the growing gap between that storage and the city's dry-season demand.

The long-term loss of reservoir storage is driven by sedimentation, not climate variability. Rainfall totals from 2016 to 2024 were slightly above average, yet storage volumes fell steadily. Key informants were unanimous: sedimentation is the main cause. Bathymetric evidence corroborates this conclusion. By 2024 the average seasonal volume was about 1.12 MCM, just 21.1 percent of the original 5.3 MCM design capacity. About 79 percent of live storage has disappeared in only 17 years, well short of the reservoir's design life. Climate does shape the yearly cycle of filling and depletion, but sediment accumulation controls the long-term decline. This distinction matters for management. Interventions that target climate variability, like rainwater harvesting, only address a secondary factor. The real priority is tackling sedimentation through watershed rehabilitation and sediment management.

These findings are consistent with reservoir deterioration patterns documented in comparable East African contexts, including Ndakaini, Kenya (Kagombe et al., 2020), Kabale, Uganda (Obialor et al., 2019), and several Ethiopian reservoirs (Ayele et al., 2021; Mariye et al., 2022). The Angereb case, however, represents a particularly acute trajectory due to severe upstream watershed degradation (Daba et al., 2023).

6.4.2 Drivers of storage decline

Sedimentation and land-use changes in the watershed, driven by climatic variability, steep slopes, intense rainfall, deforestation, and unsustainable farming practices, accelerate sediment delivery to the reservoir (Daba et al., 2023). Concurrently, rising urban demand from Gondar depresses reservoir levels during the dry season. Soil erosion leads to increased sediment inflow, reduced live storage, increased vulnerability to dry seasons, and increased abstraction pressure. This, combined with reduced revenue, limits maintenance and catchment rehabilitation, exacerbating sedimentation. The pattern of seasonal recovery followed by rapid depletion is consistent with trends observed in Ndakaini, Kenya (Kagombe et al., 2020), Kabale in Uganda (Obialor et al., 2019), and several reservoirs in Ethiopia (Ayele et al., 2021; Mehari Mariye et al., 2022; Mequanent et al., 2022). However, the AR distinctly illustrates how sedimentation and climatic variability jointly undermine urban water security.

6.4.3 Water quality implications

Sedimentation has direct consequences for water quality, compounding storage problems. Low water volumes during dry seasons (Table 5.5Figure 5.5

6.4.4 Distribution losses and NRW

NRW of 36.12 percent represents a significant efficiency challenge that compounds source-side scarcity. However, it is important to maintain perspective on what NRW reduction can and cannot achieve. In a city where the principal reservoir has lost about 79 percent of its original live storage capacity, reducing NRW from 36 percent to 20 percent, a substantial engineering and management achievement would increase available supply by approximately 15 percent of current system input volume. This improvement is meaningful but cannot substitute for the development of a major new water source. NRW reduction is therefore necessary but insufficient as a standalone response to Gondar's water crisis.

Real losses, which account for 28.41 percent of system input volume, constitute the dominant component of NRW and arise from physical infrastructure deterioration, including aging cast iron pipelines prone to fracture, inadequate surge protection, and reactive maintenance practices that allow losses to accumulate between failure events. These conditions are common in rapidly growing secondary cities in sub-Saharan Africa, where infrastructure investment has not kept pace with population growth (Aycheh et al., 2024; Araújo Junior et al., 2022). Apparent losses, which account for 7.71 percent, largely reflect revenue losses due to meter under-registration, particularly in aged DN15 and DN20 meters. These are standard residential meter sizes and are not inherently problematic; the core issue is the absence of a structured meter testing, calibration, and replacement program. Meter inaccuracies primarily result in revenue loss rather than physical water loss, but they reduce the utility's financial capacity to invest in infrastructure rehabilitation, creating a feedback loop that further exacerbates real losses.

Comparisons with other Ethiopian cities provide useful context. In Addis Ababa, real losses account for approximately 64 percent of NRW (Unto, 2024), while high losses in Bahir Dar have similarly been linked to aging infrastructure (Aycheh et al., 2024). The structural drivers of NRW in Gondar, including low tariffs, reactive maintenance systems, aging infrastructure, intermittent supply, and institutional capacity constraints, are broadly consistent across Ethiopian urban water utilities. This pattern highlights the need for both sector-wide institutional reform and site-specific technical interventions (Bantider et al., 2023).

6.4.5 Socioeconomic and environmental impacts

The combination of reservoir volume degradation and water loss results in substantial social, economic, and ecological consequences. Intermittent supply and prolonged dry-season shortages exacerbate inequality, as wealthier households' access private wells or purchase water from vendors, whereas poorer households disproportionately bear the burden of scarcity. At times of low pressure, it causes contamination through backflow and intrusion, posing significant public health concerns. Economically, revenue losses constrain maintenance and capital spending, perpetuating infrastructure deterioration (Choi et al., 2022). Ecologically, sediment accumulation degrades riverine ecosystems, alters downstream habitats, and reduces resilience to climatic extremes. These changes directly impact on the agriculture and fisheries that underpin local livelihoods (Morris, 2020). Without coordinated watershed and infrastructure management, Gondar City's water supply is at risk of collapse as the AR rapidly loses capacity, forcing greater dependence on emergency transfers or more expensive alternatives.

6.4.6 Implications for management

The scale of Angereb's storage loss—about 79% of original live capacity within 17 years—raises a fundamental question of economic viability: whether restoring the reservoir through dredging is technically feasible and financially justifiable given the extent of sedimentation and the proximity of the city downstream. The answer to this question is likely negative, or at best marginal. The AR cannot be relied upon as the long-term primary source for Gondar's growing population. The primary management imperative is therefore investment in a new water source, specifically the completion of the Megech River reservoir project or substantive water diversion from Lake Tana. Without this, other interventions will not resolve the city's water crisis. This is the most important conclusion of this study, and it extends beyond the analytical scope of remote sensing and NRW assessment.

Within the constraints of available resources and what this study's evidence base supports, the following prioritized interventions are recommended, in order of impact:

New source development: Urgent completion of the Megech River reservoir or Lake Tana diversion to provide adequate long-term supply capacity. This is the only measure that can fundamentally resolve Gondar's water crisis.

Active Leak Control and pipe rehabilitation: Systematic district metering, night-flow analysis, and targeted pipe replacement, focused on the highest-loss zones identified through pressure monitoring. This study's findings on real loss magnitude provide the justification; pressure zone analysis and leakage modelling are recommended as next steps.

Meter asset management: Implementation of a scheduled meter testing, calibration, and replacement programme for aged DN15 and DN20 meters, with gradual introduction of automated meter reading to eliminate manual reading errors.

Watershed rehabilitation: Reforestation, riparian buffer establishment, and agroforestry promotion in the Angereb catchment to slow future sediment inflow. This measure can reduce sedimentation rates but cannot restore lost storage. It is relevant to any future upstream reservoir development.

Institutional reform: Progressive tariff restructuring to improve cost recovery, financial planning capacity for capital investment, and establishment of clear accountability mechanisms for NRW reduction targets. Governance reform is a prerequisite for sustained technical improvement.

It is important to note that the evidence base for these recommendations derives from the remote sensing analysis and the AWWA water balance assessment conducted in this study. Recommendations regarding pressure management, active leak control methodology, and zone-specific interventions require further dedicated analysis including pressure monitoring and pipe condition surveys beyond the scope of this chapter. Recommendations are therefore grounded in the study's findings on the magnitude and structure of NRW and reservoir decline, while acknowledging the need for complementary investigations to design specific intervention programmes.

6.4.7 Limitations and Future Research Directions

Reservoir volumes were estimated from satellite surface areas and a DEM rather than contemporaneous bathymetry, introducing uncertainty in absolute storage even though seasonal and inter-annual patterns hold. The non-revenue water assessment relied on utility records and AWWA benchmarks, requiring estimates for some components. WEAP scenarios depend on assumptions about population growth, allocation rules, and infrastructure implementation, so projections represent plausible trajectories, not exact forecasts. Future work should include more frequent bathymetric surveys, improved source-level metering, and updated climate and demand data.

Non-revenue water stands at 36.12 % (±1.42 %), split into 28.41 % real losses and 7.71 % apparent losses. Real losses, driven by leaks, pipe bursts, and infrastructure failures, make up 78.6 % of NRW and are the main target for physical intervention. Apparent losses mainly result from aged meter under-registration and call for better meter asset management rather than leakage control.

The scale of storage loss at AR means that NRW reduction and watershed rehabilitation, while essential, cannot solve Gondar’s water crisis on their own. A new water source is the foundational intervention. Efficiency improvements should proceed in parallel to maximise the utility of existing supply and strengthen financial viability, but they complement rather than substitute for new source development.

CHAPTER SEVEN

Assessing Future Water Security in Gondar City

Abstract

This study applies a scenario-based WEAP model to evaluate the combined impacts of population growth, reservoir sedimentation, groundwater depletion, irrigation expansion, and climate change on water security in Gondar City, Ethiopia. The current water supply system, which primarily depends on the AR and groundwater sources, meets only approximately one-third of the estimated daily demand of 35,100 m³. Planned infrastructure developments include the MGD and the LTWPS (LTWPS). Eight scenarios were evaluated to assess the impacts on the water supply–demand divergence from 2025 to 2045, consistent with a 20-year water supply planning horizon. The model was calibrated using data from 2015 to 2018 and validated with data from 2020 to 2023, demonstrating high accuracy (NSE = 0.878; PBIAS = −0.095%; RMSE = 0.0237 MCM yr^{-1}). Under the reference scenario, total projected unmet water demand over the planning period reaches 374.8 MCM. Although the MGD provides temporary relief, its long-term effectiveness is constrained by reservoir sedimentation and competing irrigation demands. The LTWPS substantially reduces shortages but does not fully eliminate them. Integrated urban water management is essential to achieving sustainable water security.

Keywords: Gondar City; Lake Tana; Scenario Analysis; Urban Water Management; water shortage, WEAP model

7.1 Introduction

Water supply, increasingly intensified by population growth and climate change, is highly sensitive to seasonal and hydrological variation (He et al., 2021; McDonald et al., 2021). Although surface water remains the main source for many cities, it is especially vulnerable to climatic effects and long-term shifts. As a result, groundwater often serves as a critical buffer during urban water shortages and droughts (Jasechko et al., 2024).

Urban water demand is driven by population growth, economic development, and changing consumption patterns across residential, commercial, institutional, and agricultural sectors. Global projections suggest that urban water demand may increase by nearly 80% by 2050 (Flörke et al., 2018; Nyika et al., 2023; van Vliet et al., 2021). According to UN Water (2021), approximately 40% of the global population experiences urban water scarcity for at least one month each year. This challenge is particularly acute in rapidly growing cities of developing countries, where climate change, declining water quality, and high rates of population growth place increasing pressure on already limited water resources (Beker & Kansal, 2023).

In Ethiopia, water scarcity hits secondary cities hardest, where limited infrastructure, weak management, and scarce data hamper planning and service delivery (Abraha et al., 2022). Despite notable freshwater potential, the country is water-stressed, with roughly 1,109 m^3 per capita per year according to the Falkenmark index (Falkenmark et al., 1989). Climate projections indicate that rising temperatures and shifting rainfall will further reduce water availability and lengthen dry spells across many regions (Asitatikie & Gebeyehu, 2021).

7.1.1 Water Stress in Ethiopian Basins

Increasing water stress across Ethiopian basins is fueled by climate change, infrastructure expansion, and competing demands. In the Lake Tana sub-basin, planned irrigation and hydropower projects are expected to lower lake levels and shrink surface area, threatening downstream flows and ecosystem stability (Alemayehu et al., 2009; Wubneh et al., 2022). Without stronger water management and adaptation, scarcity is likely to worsen (McCartney et al., 2010; Tigabu et al., 2021).

River flow variability is also rising in several Lake Tana sub-basins. Catchments like Ribb and Kiltie may see higher annual flows but with more extreme seasonal swings, complicating storage and management (Ayalew, 2020). Projections further point to declining summer flows that could reshape hydrological regimes and downstream supply (Worqlul et al., 2018).

WEAP-based modelling underscores the mounting pressure. Full implementation of planned irrigation and hydropower in the Lake Tana basin could lower mean annual lake levels by roughly 0.44 m and reduce surface area by about 30 km² (Alemayehu et al., 2009). Under a high-emission scenario (RCP8.5), levels may drop by up to 5.16 m, disrupting navigation, ecosystems, and livelihoods (Yasuda et al., 2022).

Studies of Tana watersheds also reveal declining spring rainfall and reduced wet-season flows, limiting water for reservoir storage and hydropower (Wubneh et al., 2022). In the Awash Basin, irrigation growth, rapid population increase, and higher evapotranspiration are projected to cut downstream dry-season flows by 10–25%, sharpening competition between farms, cities, and the environment (Gedefaw et al., 2019; Mersha et al., 2018)

7.1.2 The Megech Watershed and Gondar City

The Megech watershed, which drains Gondar City into Lake Tana, faces rising temperatures, greater evaporation, and shifting rainfall (Asitatikie & Gebeyehu, 2021; Wubneh et al., 2022). These pressures mirror wider trends across the Lake Tana basin, where climate change, irrigation growth, and population increase are tightening competition for water. Effective watershed management, including sediment control, demand management, and adaptive planning, is now critical for long-term water security (Admas et al., 2024).

The watershed also hosts the proposed MGD and irrigation scheme. Although total annual flow may rise by 5.9 to 8.3 percent under future climate scenarios, seasonal shifts and higher evaporation could intensify pressure on both urban and irrigation demands and raise the risk of extreme summer floods (Eshete et al., 2022). Rising temperatures and evapotranspiration might cut effective reservoir storage by as much as 45 percent by 2054 (Asitatikie & Gebeyehu, 2021). Projections beyond the 30-year design horizon carry much greater uncertainty and are cited for context only; this study limits its design projections to 2045.

Sediment transport from steep slopes and intense rain also threatens reservoir sustainability. Higher sediment yield can shorten a reservoir’s operational life. Land-use changes have altered watershed response. SWAT modelling shows cultivated land dropped from 67.28 percent in 2003 to 51.95 percent in 2018, while grassland and plantation area expanded, leading to an estimated 5.23 percent reduction in mean annual streamflow (Kassahun et al., 2024).

Gondar City, a major tourist destination and UNESCO World Heritage Site, faces a severe supply deficit. Its population of roughly 431,113 (CSA, 2013) needs an estimated 35,100 m^3 per day. Current production is about 11,467 m^3 per day, meeting only one-third of demand (GCWSSS, 2024). Since commissioning in 2002, AR has lost roughly 62.3 percent of its storage capacity, falling from 5.28 MCM to 1.32 MCM by 2022 because of sedimentation (Tessema et al., 2024). This accumulation rate exceeded original design expectations, indicating that watershed conservation and sediment management were not adequately integrated. At the current pace, the reservoir could become ineffective within the next decade.

Groundwater abstraction from the Angereb and Kola Diba Well Fields supplements municipal supply, but yields have fallen sharply due to long-term over-pumping. At KDWF, pumping capacity has dropped by about 70 percent, a significant planning shortfall. Corrective steps, including aquifer recharge and well rehabilitation, are recommended. Many residents now depend on vendors and tanker deliveries and live with irregular supply.

Two major infrastructure projects have been proposed to address these deficits. The MGD, a multipurpose reservoir with 70 percent of capacity for irrigation and 30 percent for municipal supply, is expected to serve both agricultural and urban needs. The Lake Tana Water Transfer Project aims to supply Gondar directly through a large-scale water transfer system. Although construction schedules and future climate remain uncertain, both projects are considered in this study based on their planned capacities and operational objectives.

7.1.3 Research Gap and Study Objectives

Many WEAP studies cover Ethiopian river basins, but integrated assessments of water supply and demand in secondary cities are rare. Research has concentrated on basin-scale hydrology or single infrastructure projects, seldom addressing urban systems that face sedimentation, groundwater depletion, population growth, and climate change all at once. Previous work examines regional hydrology (Saketa et al., 2022), climate impacts on water availability (Asitatikie & Gebeyehu, 2021; Arsiso et al., 2017), and urban demand modelling (Alemu & Dioha, 2020). Yet a comprehensive analysis that pulls these threads together for Gondar City is still missing.

To fill the gap, this study uses a scenario-based WEAP modelling framework to evaluate Gondar's water supply and demand over a 20-year planning horizon from 2025 to 2045. The analysis includes both existing and planned infrastructure: the AR, groundwater well fields, the MGD, and the Lake Tana Water Transfer Project, along with projected urban and agricultural demands. Key drivers such as population growth, sedimentation, and rainfall variability are explicitly considered to assess system performance, estimate future shortages under alternative development scenarios, and identify strategies for long-term urban water security.

7.2 Materials and Methods

7.2.1 Study Area

Gondar served as the capital of Ethiopia from the 17th to the 19th century and functioned as a major trade Centre linking the highlands to the Red Sea (Pankhurst, 1982). The city is situated between 12°30′–12°42′N and 37°20′–37°35′E, within the Megech watershed, which is part of the Upper Blue Nile Basin, approximately 75 km north of Lake Tana (Figure 7.1). The Kola Diba Well Field (KDWF) is located approximately 18–20 km south-southwest of the city. Gondar experiences a subtropical highland climate characterized by distinct wet (June–September) and dry (November–May) seasons, with the majority of precipitation occurring in July and August (Assfaw, 2020). Urban expansion has placed considerable strain on water infrastructure originally designed for a much smaller population, contributing to the current water crisis (NIRAS, 2012).

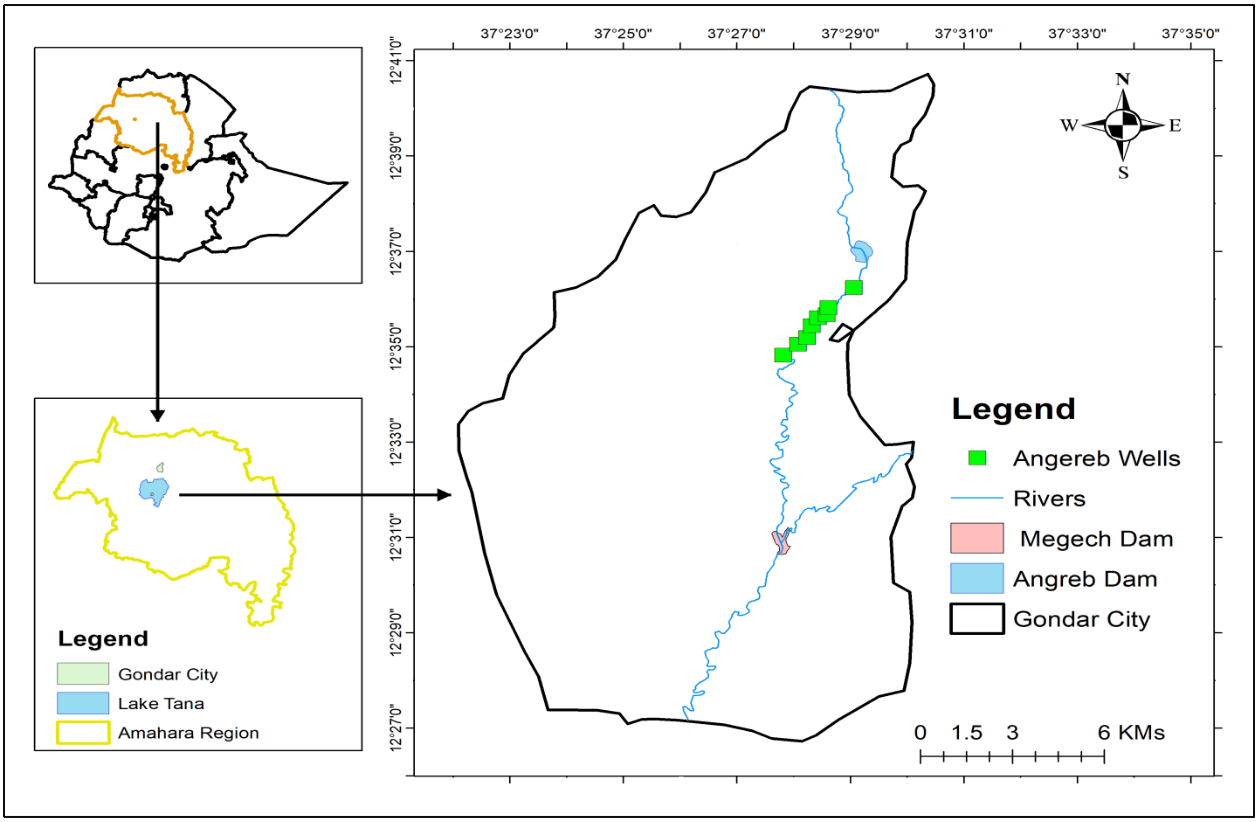

Figure 7.1 Location of Gondar City and water supply sources

Gondar City's water supply primarily relies on the AR (AR) and groundwater wells. Groundwater is extracted from boreholes located in the AWF (AWF) and KDWF; however, declining aquifer levels and aging infrastructure have rendered several wells non-functional. Springs contribute only a negligible and unreliable portion of the supply. The AR, established in 2002, remains the main surface water source, providing approximately 90 L s^{-1} (MSC, 2023). The MGD (MGD) is intended to alleviate water shortages in Gondar City but is primarily designed for irrigation. The LTWPS is considered the critical long-term solution for water security in the city (MSC, 2023).

7.2.2 Water Supply System

Figure 7.2 presents the WEAP schematic of the water supply system in Gondar. In this diagram, reservoirs are represented by green triangles, groundwater sources by red squares, demand sites by red circles, and return flows by blue circles. Return flows represent the portion of water delivered to a demand site that is not consumed and re-enters the system—for example, treated wastewater discharged to a downstream river reach or to a treatment node. Green arrows illustrate the direction of water movement between supply, transmission, and demand components. The Megech Basin watershed boundary is outlined in green.

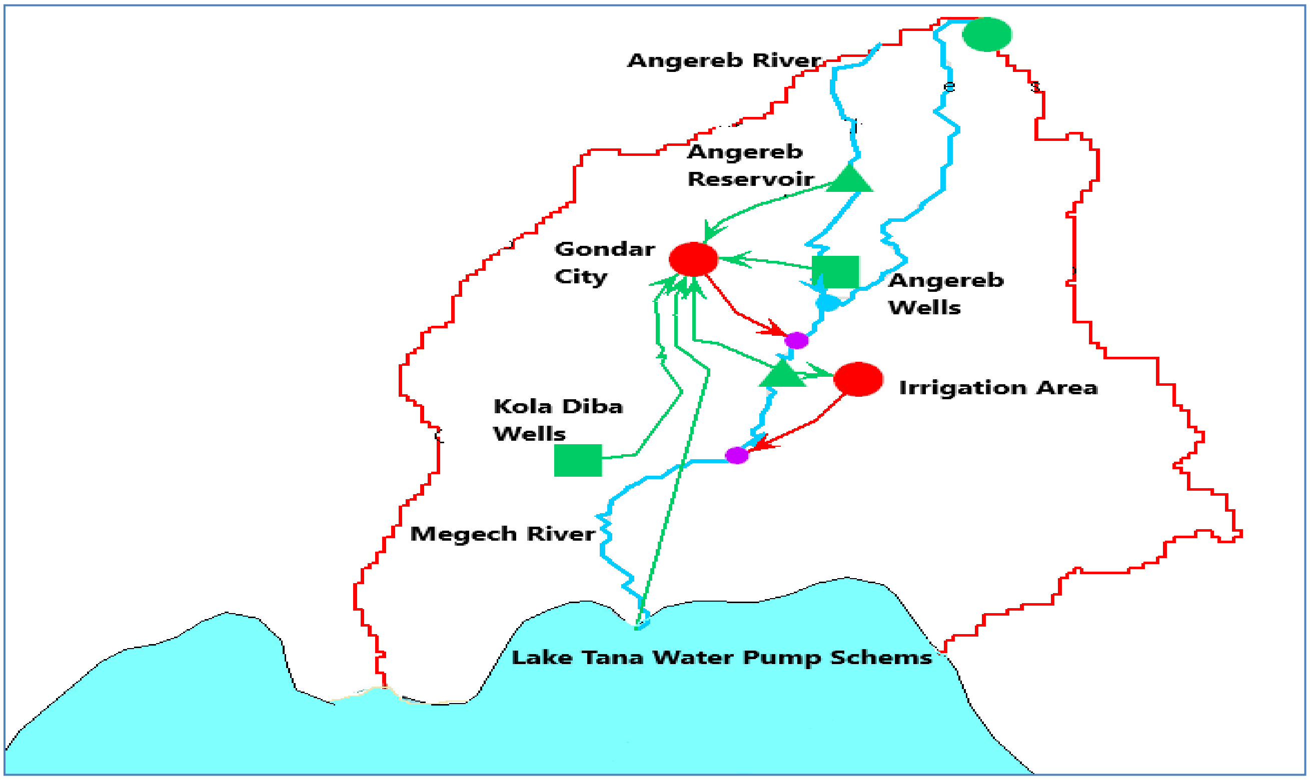

Figure 7.2 Schematic representation of Gondar water supply system in WEAP

The system consists of existing supply sources (AR, KDWF, and AWF) and future sources (MGD and LTWPS) (MSC, 2023). Planned future additions include the MGD, with a total storage capacity of 182 MCM and expected operation by 2028, and the LTWPS, designed to supply 60,480 m^3 day^{-1} from 2035 onwards. The LTWPS abstraction volume (approximately 0.03% of mean annual lake inflow) is consistent with volumes assessed by McCartney et al. (2010) as within safe ecological limits for Lake Tana; however, long-term monitoring of lake levels and ecology is recommended. Groundwater well fields are modelled with a 7–9% annual decline in pumping capacity, reflecting the impacts of long-term over-abstraction (GCWSSS, 2024).

There are two demand sites: Gondar City (431,113 people in 2024), with per capita water demand projected to increase from 10 m^3 yr^{-1} in 2024 to 36 m^3 yr^{-1} in 2045, and the MGD Irrigation Command Area (MDICA). Per capita annual demand is calculated as the product of per capita daily design demand and 365 days, adjusted for system losses. The MDICA is projected to expand from 7,311 ha to 17,000 ha by 2045, with a unit water demand of 7,910 m^3 ha^{-1} yr^{-1}. The MGD is now expected to operate from 2028, with 30% of its yield allocated to Gondar City and 70% to irrigation; the LTWPS is projected to begin operation in 2035.

7.2.3 Data Sources

The model inputs were compiled from reports, hydrological records, and climate projections (Table 7.1). Urban population projections were obtained from MSC (2023), while water use and supply data were sourced from GCWSSS (2012–2024). Historical river flow data for the Angereb and Megech rivers (1952–2007) were acquired from GCWSSS (2018) and the Ministry of Water and Energy (MoWE, 2009). Climate projections under RCP4.5 and RCP8.5 (2020–2049) were derived from downscaled CORDEX-Africa outputs (Wubneh et al., 2022). Reservoir evaporation and sedimentation parameters were based on feasibility and bathymetric studies (GCWSSS, 2018). Strategic planning data for the LTWPS and MGD were obtained from MSC (2023).

Table 7.1 Datasets used for WEAP Modelling

Datasets	Data Description	Temporal Range	Source(s)
Population	Population data and growth rate	2015–2045	CSA (2013); MSC(2023)
Water utility	Consumption m^3 per person yr^{-1}. (Urban) and m^3 ha^{-1} yr^{-1} (Irrigation)	2015–2045	GCWSSS (2024)
	Surface and groundwater supply	2015–2024	GCWSSS (2024)
	Angereb River monthly flows	1952–2007	GCWSSS (2018)
	Megech River monthly flows	1952–2007	MoWE (2023)
Climate	Rainfall and climate data	2024	NMA (2024)
	Climate change scenarios	2020–2049	Wubneh et al. (2022)
Irrigation	MDICA area and water demand	Up to 2045	MoWE (2009)
	Water allocation rules	—	
Infrastructure	LTWPS design capacity	2023	GCWSSS (2024)
	Strategic water planning	2012–2045	NIRAS (2012)
	Groundwater abstraction capacity	2015–2024	GCWSSS (2024)
	MGD storage and design capacity	—	GCWSSS (2018)
Reservoir volume loss	AR volume by sedimentation	2022–2024	Tessema et al. (2024)

7.2.4 WEAP Model Configuration

The WEAP system was used to model water sharing and movement through the environment. The model structure included supply nodes (AR, AWF, KDWF, and LTWPS), demand sites (Gondar City, MDICA), transmission links, return flows, and aquifer storage components.

Demand Representation: Sectoral water demand (D) was calculated using Eq. 12

$$D = A \times U \qquad \text{Eq. 12}$$

Where A is the activity level (population or irrigated area) and U is the unit water demand coefficient (m^3 per person per year for urban demand; $m^3\ ha^{-1}\ yr^{-1}$ for irrigation). Annual demand was disaggregated into monthly values using seasonal demand factors. The model incorporated system losses, return flows, and demand management measures. A system loss rate of 36% is applied for 2024, reducing to 18% by 2045 through planned network improvements (NIRAS, 2012).

Reservoir Mass Balance: Reservoir dynamics were simulated using the continuity equation as Eq. 13

$$St + 1 = St + It - Et - Rt - Spt - Lt \qquad \text{Eq. 13}$$

Where S is storage (MCM), I is inflow, E is evaporation, R is release, Sp is spill, and L is seepage loss at time t. The MGD volume-elevation relationship was defined using design curves.

Groundwater Representation: Groundwater was modeled as finite aquifer nodes with annual yields of 1.04 MCM for KWF and 0.41 MCM for AWF (MSC, 2023). Abstraction was constrained by the WEAP mass balance condition based on Eq. 14

$$\text{Outflow} \leq \text{Recharge} + \Delta\text{Storage} \qquad \text{Eq. 14}$$

Annual pumping capacity declined by 9%, reflecting progressive drawdown. Exceedances were recorded as unmet water demand (UWD).

7.2.5 Sedimentation and Climate Impacts

Sedimentation and Climate Impacts: Reservoir sedimentation was implemented as a linear annual storage reduction. AR storage decreases by 3.0–3.9% yr^{-1}, leading to functional failure around 2029 (Tessema et al., 2024). A similar volume loss rate was assumed for the MGD due to high erosion rates in the Megech watershed. Sedimentation at this rate reflects a design and watershed management gap: effective reservoir management should have included catchment conservation measures, and these are recommended for implementation alongside any new infrastructure. Climate change impacts were modelled using CORDEX-Africa RCM outputs under RCP4.5 and RCP8.5, with projected changes including seasonal evapotranspiration increases (up to 45% in summer) and altered river flows (Wubneh et al., 2022.

Environmental Flow Requirements: Environmental flow (EF) requirements have been estimated using the Tennant (Montana) method. A minimum EF of 10% of mean annual streamflow of the Megech River is applied as a downstream constraint in all scenarios. This value represents a basic ecological threshold; future studies should apply locally calibrated EF assessments. The EF constraint is incorporated in the WEAP allocation rules and is listed in the scenario assumptions in Table 6.2.

Validation and Calibration: Model calibration was conducted for the period 2015–2018 by adjusting parameters such as supply yield, reservoir water deliveries, and transmission losses to minimize discrepancies between simulated and observed treated water outputs. Model validation was then performed using an independent dataset from 2020 to 2023. Model performance was evaluated using the NSE, PBIAS and RMSE.

7.2.6 Scenario Development and Key Assumptions

The Reference Scenario served as the foundation for eight scenarios evaluated over the 2025–2045 planning period (Table 7.1). The Reference Scenario assumes: baseline sedimentation for the proposed MGD (3.0–3.9% yr^{-1}), groundwater decline at 7–9% yr^{-1}, medium population growth (4% yr^{-1}), commissioning of MGD in 2028 (30% urban / 70% irrigation) and LTWPS in 2035, and an environmental flow constraint of 10% of mean annual Megech River flow.

Table 7.1 Scenario definitions for water supply and demand projections in Gondar

Scenario	Key Assumptions
Reference (Baseline)	Current sources only (AR, AWF, KDWF); population growth 4% yr^{-1}; groundwater decline 7–9% yr^{-1}; sedimentation 3.0–3.9% yr^{-1}; MGD commissioned in 2028 (70/30 irrigation/urban split); LTWPS commissioned in 2035; annual per capita demand rising from 10 m^3 (2024) to 36.5 m^3 (2045); AR projected to cease operation by 2029; environmental flow requirement estimated at 10% of mean annual flow of the Megech River
Low Population Growth	Population growth rate reduced to 3.5% yr^{-1}; all other parameters as Reference
High Population Growth	Population growth rate increased to 4.5% yr^{-1}; all other parameters as Reference
AR Collapse	Complete functional loss of AR by 2029; all other parameters as Reference
High Sedimentation (MGD)	MGD experiences annual storage reduction of 3.9% yr^{-1}; all other parameters as Reference
Irrigation Demand Growth	MDICA expands from 7,311 ha to 17,000 ha by 2045; demand 7,910 m^3 ha^{-1} yr^{-1}; all other parameters as Reference
Revised Allocation (80/20)	MGD allocation revised to 80% urban and 20% irrigation; all other parameters as Reference
S7: Climate Change (RCP4.5 / RCP8.5)	CORDEX-Africa climate projections applied (2020–2049); ET and streamflow adjustments included

The WEAP model incorporates a system loss rate of 36% representing existing network performance in 2024 (GCWSSS, 2024). Planned infrastructure improvements are expected to reduce losses to 18% by 2045. Demand management strategies including more efficient water-use technologies, pricing adjustments, and conservation initiatives are projected to reduce effective demand by 0.5% in 2027, rising to 4.3% by 2045 (NIRAS, 2012). These assumptions are applied consistently across all scenarios.

7.2.7 Infrastructure Allocation Rules

The WEAP allocation algorithm prioritizes domestic water supply over irrigation. Under the Reference Scenario, 70% of MGD available water is designated for irrigation and 30% for urban supply. An environmental flow allocation of 10% of mean annual streamflow is applied as a binding downstream constraint, ensuring a minimum flow is maintained to Lake Tana and the Megech River ecosystem. This constraint affects available water for both urban and irrigation uses.

7.2.8 Sensitivity and Uncertainty Considerations

Sensitivity analysis examined how variations in key parameters affect total unmet demand over the planning period. Parameters were varied ±10% and ±20% from baseline using the sensitivity coefficient S (Eq. 15

$$S = \frac{\Delta O/O}{\Delta P/P} \qquad \text{Eq. 15}$$

Values of $S > 1$ indicate high sensitivity; $S < 0.5$ indicate low sensitivity.

7.3 Results

7.3.1 Validation and Sensitivity Analysis

Due to the unavailability of disaggregated data for individual water sources, calibration was conducted using aggregated total supply from all sources (Figure 7.2). Despite this constraint, the model demonstrated strong performance (NSE = 0.878; PBIAS = −0.095%; RMSE = 0.0237), providing confidence that the model reliably represents the overall behavior of the water supply system.

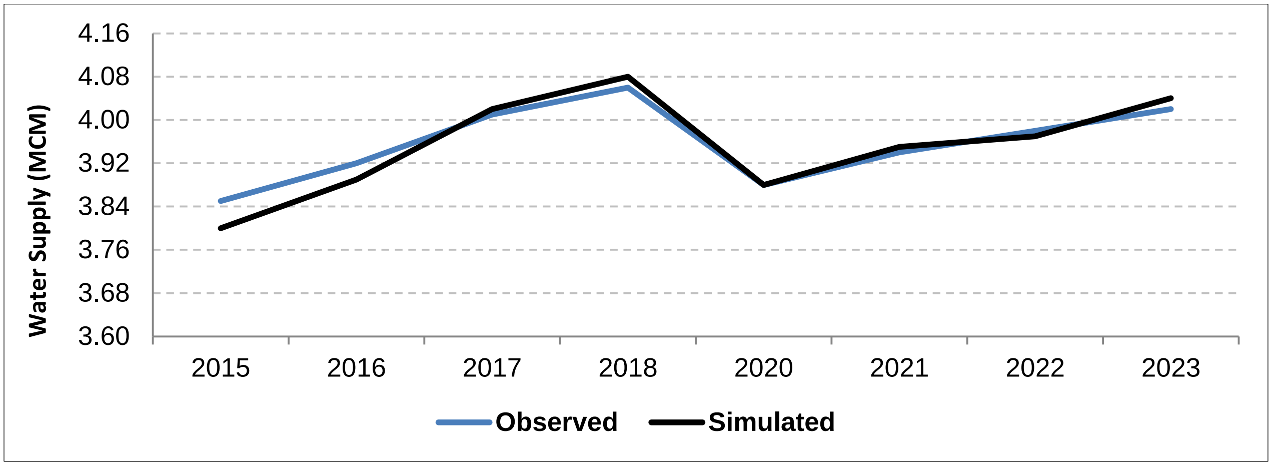

Figure 7.2 Observed vs. simulated total water supply for Gondar (2015–2023)

The sensitivity analysis reveals a significant vulnerability in the current plan. A population growth sensitivity coefficient of 12.6 indicates that a 1% increase in the population growth rate results in a 12.6% rise in the number of people lacking adequate water supply — confirming population growth as the primary demand-side driver.

Following LTWPS implementation in 2035, the MGD (531.8 MCM; 69.7% of total supply) and LTWPS (201.2 MCM; 26.4%) become the dominant supply sources, generating a projected physical surplus of 421.0 MCM over the planning period. Under RCP8.5, cumulative supply decreases by 9.0% relative to the no-climate-change reference, while RCP4.5 results in an 8.9% increase. Sedimentation reduces supply by 23.2–55.6% depending on rate. An 80/20 urban allocation policy reduces supply to irrigation by 45.3% relative to the Reference Scenario. The 30.6% supply difference between RCP4.5 and RCP8.5 by 2045 underlines the need for proactive climate adaptation.

7.3.2 Projected water demand for Gondar City (2025–2045)

Annual water demand in Gondar is projected to increase steadily under all population growth scenarios (Table 7.2). Under the Reference Scenario, annual demand rises from 4.85 MCM in 2025 to 51.12 MCM by 2045. Low population growth reduces total demand over the planning period to 402.19 MCM, while high growth increases it to 457.10 MCM — a difference of approximately 55 MCM, highlighting the importance of incorporating demographic uncertainty into water supply design.

Table 7.2 Projected water demand of Gondar City (MCM) (2025–2045)

Scenarios	2025	2030	2035	2040	2045	2025–2045
Reference	4.85	8.74	15.75	28.37	51.12	425.67
Low population growth	4.83	8.54	15.09	26.67	47.14	402.19
High population growth	4.87	8.99	16.6	30.63	56.54	457.1

Population growth is the dominant driver of rising water demand. The 55 MCM difference in total projected demand between low- and high-growth scenarios demonstrates the critical need to incorporate demographic uncertainty into long-term water resource planning. Reliance on static supply strategies will prove insufficient. Water security depends on adaptable infrastructure, stronger demand management, and integrated urban–agricultural planning.

7.3.3 Water supply projections from existing sources (2025–2045)

Simulated annual yield from existing sources declines from 3.35 MCM in 2024 to 1.35 MCM in 2045, a 60% reduction (Figure 7.3). AR output shrinks from 2.29 MCM to 1.20 MCM as sedimentation accelerates. Groundwater losses are sharper still: AWF declines by 84 percent (0.19 to 0.03 MCM) and KDWF by 87 percent (0.87 to 0.11 MCM). Meanwhile, annual municipal demand climbs to 45.5–54.9 MCM by 2045. Cumulatively, unmet demand from 2025 to 2045 totals 374.8 MCM, more than seven times the entire supply available from existing sources over the same period (49.56 MCM).

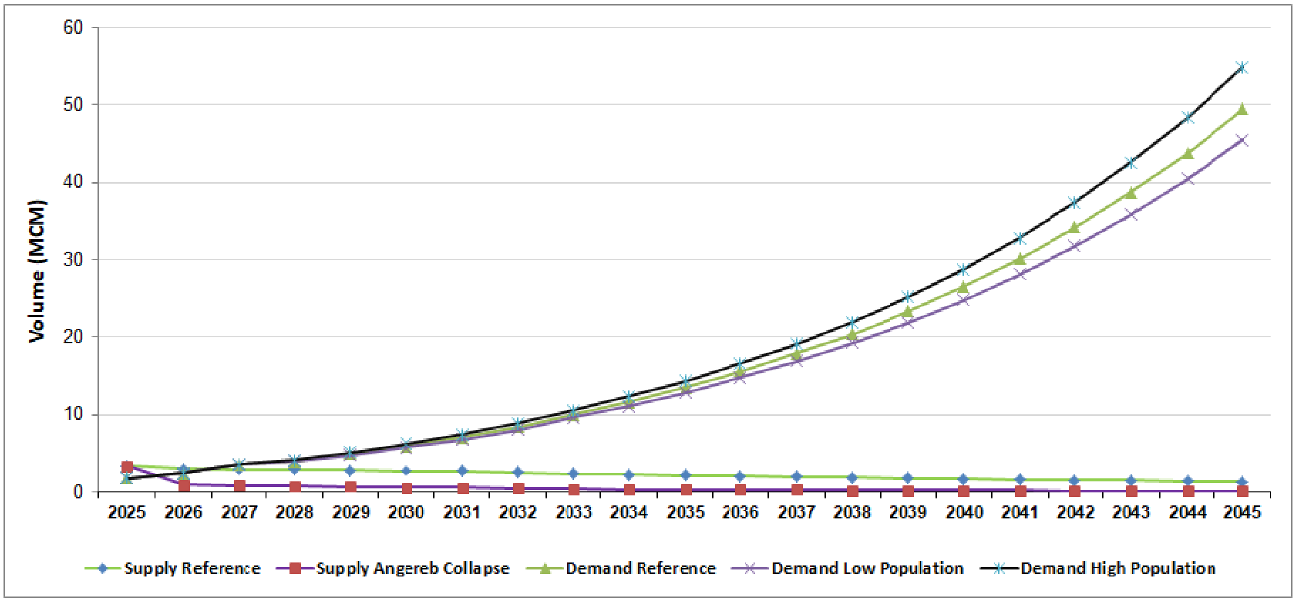

Figure 7.3 Water supply from existing sources and unmet demand in Gondar City (2025–2045)

Municipal demand rises to 45.5-54.9 MCM by 2045, a 20% spread between growth scenarios. Cumulative reference demand (374.8 MCM) exceeds existing source supply (49.56 MCM) by seven-fold.

7.3.4 MGD Operation from 2028 Onward

7.3.4.1 Performance under a 70% Irrigation and 30% Urban Water Allocation

Under the 70/30 allocation, Gondar City receives a total of 143.80 MCM from the MGD over the 2028–2045 periods, against a total projected urban demand of 203.71 MCM. This gap creates persistent annual shortages that progressively worsen after 2028 (Figure 7.4). The predominant focus on irrigation compromises the city's water security and increases vulnerability to climate variability. Without additional urban allocations or major new sources, the MGD alone cannot meet Gondar City's growing demand.

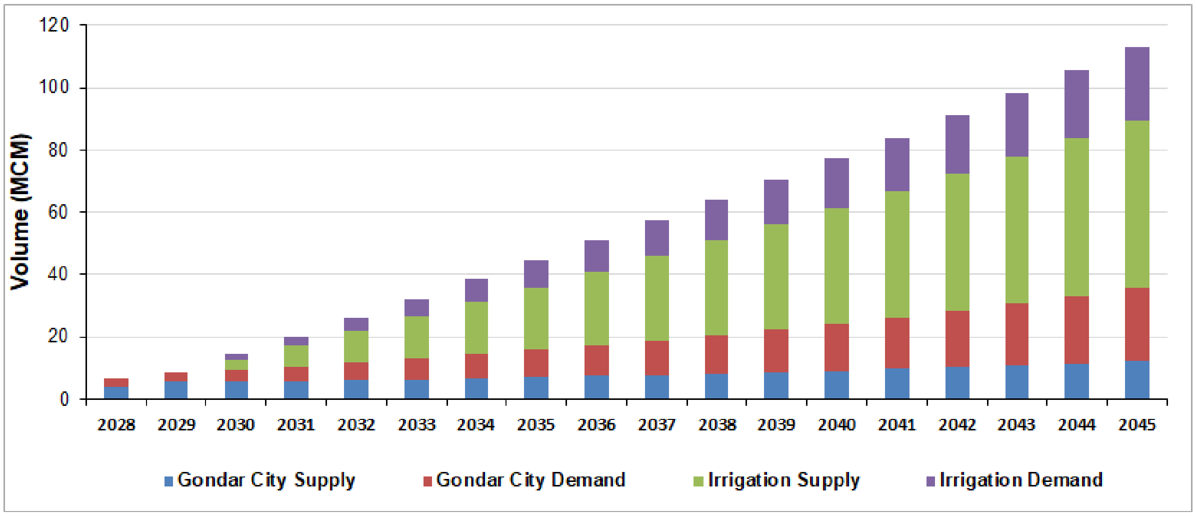

Figure 7.4 Water supply and UWD under MGD 70/30 allocation (2028–2045)

7.3.4.2 Performance under a 20% Irrigation and 80% Urban Water Allocation

Under the 80/20 allocation (Figure 7.5), Gondar City would receive approximately 3.91 MCM yr^{-1} from the MGD in the early operation years, with supply rising as the reservoir fills. Compared to the 70/30 allocation, this provides an immediate improvement in municipal supply and a noticeable reduction in UWD. However, the improvement is expected to be temporary, as urban demand continues to rise due to population growth, while reservoir yield declines from sedimentation and evaporation. Both existing sources and MGD contributions are included. The 80/20 allocation does not fully eliminate long-term shortages, indicating the need for complementary measures such as demand management, sediment-control interventions, and the LTWPS.

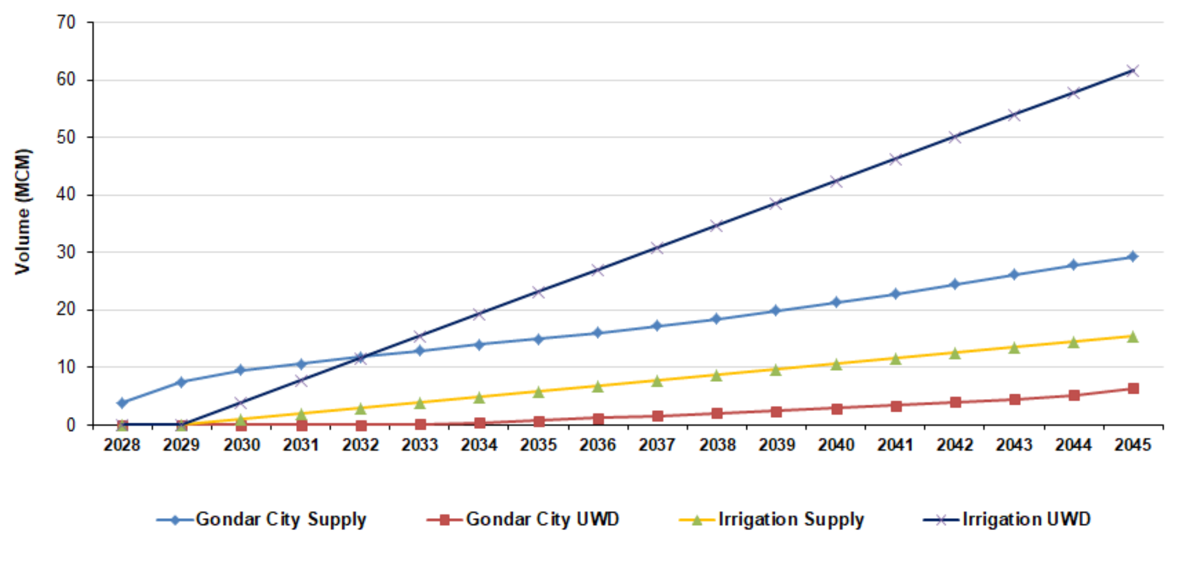

Figure 7.5 Gondar water supply and UWD under 80/20 Allocation (2028–2045)

7.3.5 Water Supply under the 80% Urban–20% Irrigation Allocation

Figure 7.6(a) shows annual urban water supply (MCM yr^{-1}) from the MGD under the 80/20 allocation across five scenarios; Figure 7.6(b) shows corresponding annual unmet water demand (MCM yr^{-1}). Together, these panels illustrate that as reservoir sedimentation progresses and irrigation expansion competes for available water, supply declines while unmet demand rises. Under the irrigation demand growth scenario, annual unmet demand reaches 21.3 MCM by 2045, compared with 17.8 MCM under the climate-only scenario. The figure demonstrates that allocation policy strongly shapes urban outcomes, and that higher urban allocations reduce shortages but do not eliminate them when reservoir storage is constrained and demand continues to rise.

Among all scenarios, the irrigation demand growth scenario generates the highest total UWD (187.83 MCM for 2025–2045), far exceeding population growth scenarios. This confirms that unmet urban demand is driven primarily by agricultural water allocation rather than demographic growth alone. Demographic scenarios generate total UWD ranging from 29.97 MCM (low growth) to 41.76 MCM (high growth), indicating that long-term water security in Gondar City requires strict control of irrigation demand alongside equitable allocation and sediment management.

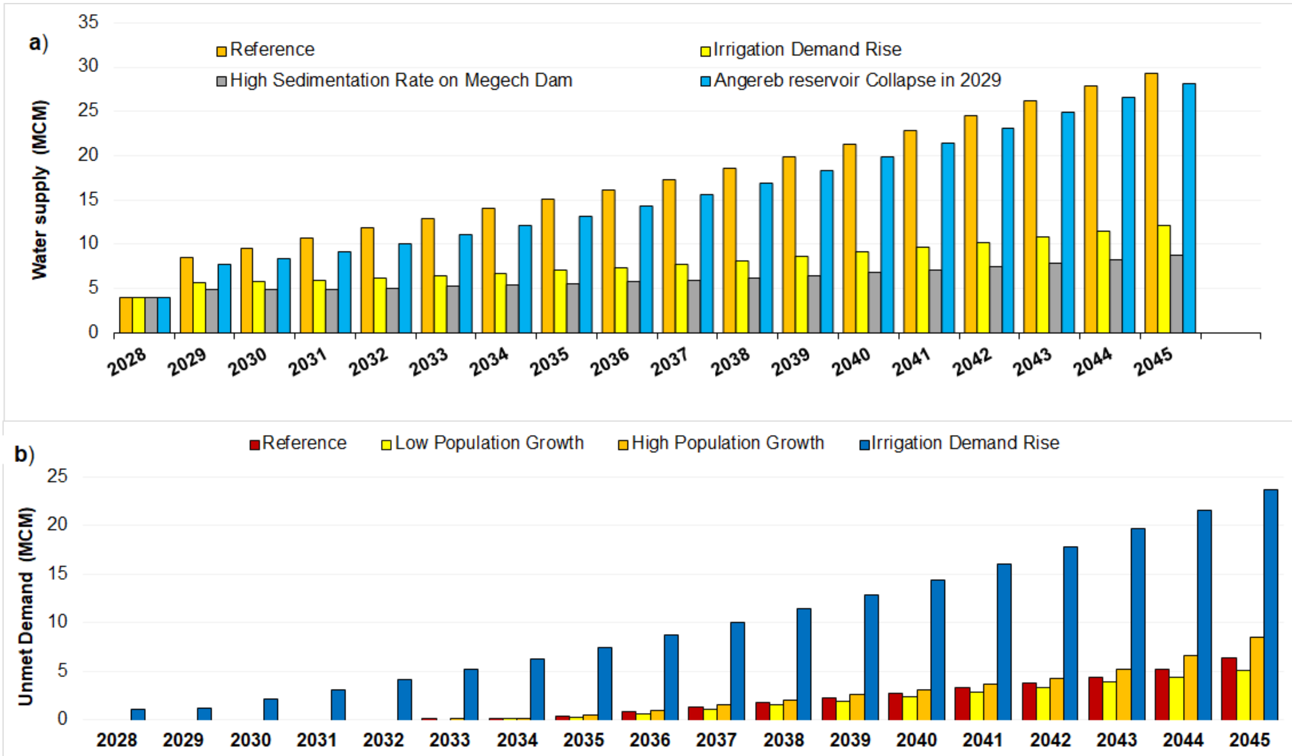

Figure 7.6 MGD urban water (a) supply and (b) unmet demand (UWD) for Gondar City under various scenarios (80/20 allocation, 2028–2045)

Achieving the 80/20 allocation requires significant institutional and policy changes. Farmers and local governments that depend on the dam for livelihoods may resist prioritizing urban supply, meaning that water permits and distribution rules must be renegotiated with appropriate compensatory measures. Complementary strategies are required, such as improving irrigation efficiency and supporting alternative livelihood opportunities. Technical reallocation alone is insufficient without active stakeholder participation and robust water governance.

7.3.6 Lake Tana Water Pump (2035–2045)

The planned commissioning of the LTWPS in 2035 is expected to mark a turning point in Gondar's water security. The LTWPS design capacity of 60,480 m^3 day^{-1} is based on MSC (2023) planning documents and represents approximately 0.03% of Lake Tana's mean annual inflow — a volume consistent with the safe ecological abstraction range assessed by McCartney et al. (2010). Nonetheless, sustained monitoring of lake levels, downstream flow conditions, and ecosystem health is essential. The long-term sustainability of the LTWPS depends on comprehensive, basin-wide management: coordinated operation of all infrastructures linked to Lake Tana, equitable water distribution among users, and continuous hydrological and ecological monitoring.

Continuous abstraction of 700 L/s (0.7 m^3/s) from Lake Tana would withdraw approximately 60,480 m^3/day, or 22.1 million m^3/year. Given the lake's surface area of approximately 3,060 km^2, this volume would theoretically lower the lake level by only 7.2 mm per year in the absence of compensating inflows or rainfall, representing less than 0.1 percent of the lake's mean depth of 9.7 meters and approximately 0.5 percent of the estimated annual Blue Nile outflow of 4 to 5 billion cubic meters. While substantial for urban supply purposes, the abstraction's direct impact on overall lake levels is therefore relatively modest.

The long-term sustainability of the LTWPS therefore depends on basin-wide management that coordinates all lake-linked infrastructures, ensures equitable water distribution among users, and maintains continuous monitoring of lake levels, downstream flow conditions, and ecosystem health.

Following commissioning, annual urban water supply for Gondar City increases from 3.91 MCM in 2028 (MGD only) to 35.66 MCM by 2045, with a total supply of 304.34 MCM over 2035–2045. Irrigation allocations increase from 3.37 MCM yr^{-1} in 2030 to 53.96 MCM yr^{-1} in 2045, totaling 458.67 MCM. Combined sectoral delivery reaches 763.01 MCM, indicating a significant improvement in overall resource distribution (Figure 7.7).

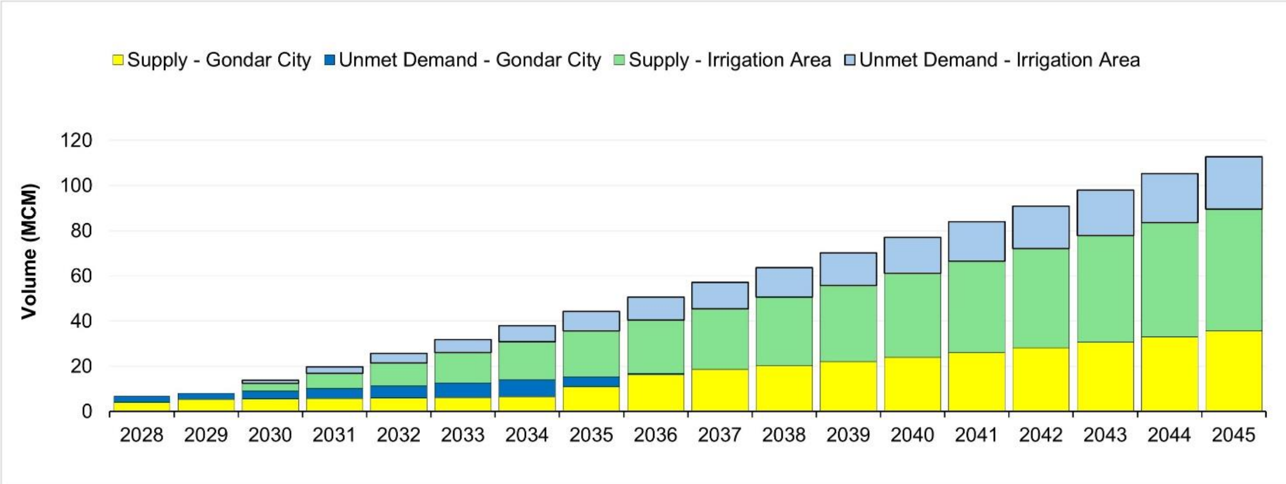

Figure 7.7 Urban and irrigation supply post-LTWPS (2035–2045)

Table 6.4 summarizes annual UWD and supply before and after LTWPS commissioning across all scenarios. Prior to commissioning (2025–2034), annual UWD ranges from 32.15 MCM (low growth) to 50.83 MCM (AR collapse). After commissioning, annual UWD falls to 8.98–16.68 MCM, representing a substantial improvement in supply reliability. If the AR fails, the LTWPS is expected to compensate for the lost capacity and stabilize overall system performance. Consistent improvements across all scenarios confirm the pivotal role of the LTWPS in reducing supply vulnerability.

Table 7.3 Water supply and unmet demand (MCM) for Gondar before and after the LTWPS

Scenarios	Pre-Pump (2025–2034) UWD	Pre-Pump (2025–2034) Supply	Post-Pump (2035–2045) UWD	Post-Pump (2035–2045) Supply	Total (2025–2045) UWD	Total (2025–2045) Supply
Reference	33.18	56.11	11.12	259.94	44.3	316.05
Low population growth	32.15	53.86	9.4	241.23	41.55	295.09
Irrigation demand rise	33.12	55.11	11.65	260.47	44.77	315.58
High sedimentation rate	39.22	52.51	8.98	259.64	48.2	312.15
High population growth	35.22	56.01	12.07	282.57	47.29	338.58
AR collapse	50.83	31.7	16.68	261.14	67.51	292.84

The LTWPS improves supply reliability, allowing for better recovery from infrastructure breakdowns and changes in water availability while managing demand pressures. If the AR fails, the project is anticipated to restore overall water supply performance and stabilize the system by making up for the lost capacity. Consistent improvements across all scenarios show that the pump significantly lowers UWD (from 33–50 MCM before the pump to 9–16 MCM (Figure 7.7).

The LTWPS will operate effectively only if the lake remains ecologically and hydrologically sustainable. Increasing the volume of water extracted could impact the water levels of the lake, downstream flow conditions. While the pump will enhance water security for Gondar City, its long-term benefits depend on a comprehensive, basin-wide management. This strategy involves the coordinated operation of all infrastructure connected to the LTWPS, equitable water distribution among users, and continuous monitoring of the basin's hydrological and ecological status.

7.3.7 Climate Change Impacts

Implementation of the LTWPS alleviates chronic water shortages, but climate change presents long-term challenges. Figure 7.7 illustrates annual water supply (MCM yr^{-1}) under three combined stressor scenarios from 2025 to 2044: (i) baseline (no climate adjustment); (ii) RCP4.5 with moderate sedimentation and medium population growth; and (iii) RCP8.5 with high sedimentation and high population growth. Compared to the baseline of 114.85 MCM total supply, the RCP4.5 pathway increases total supply to 125.0 MCM, while RCP8.5 reduces it to 108.7 MCM (a 9.0% decrease).

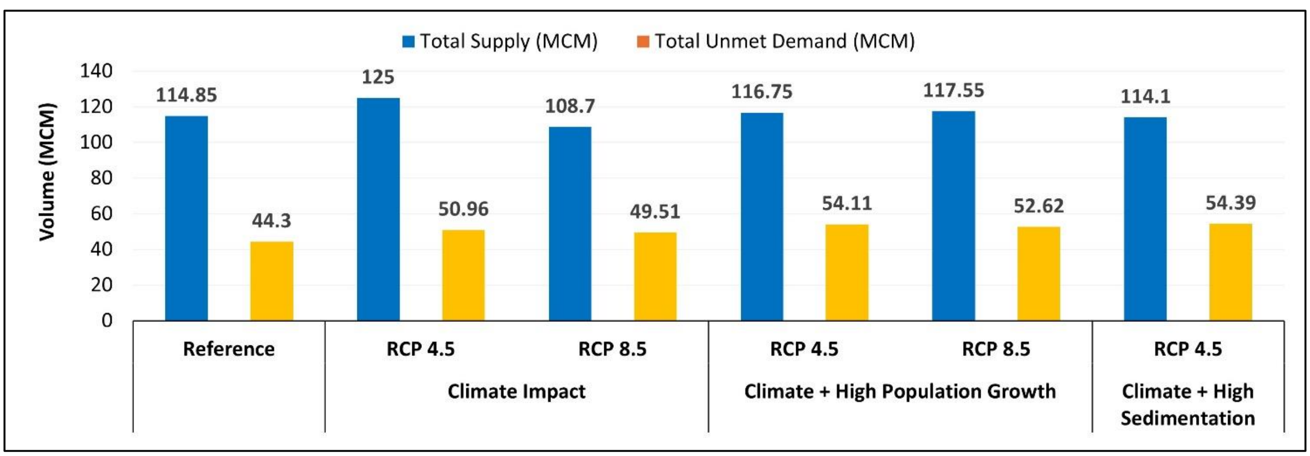

Figure 7.8 Multi-stressor impacts on Gondar water supply (2025–2044)

Under the Reference Scenario, annual UWD drops sharply after LTWPS commissioning, approaching near-zero by 2036. Under the combined high-stress scenario (RCP8.5, high sedimentation, high population growth), recovery is delayed by approximately one year (to 2037), as higher evaporation and reduced inflows simultaneously constrain reservoir and pumping yields. This demonstrates that while the LTWPS can resolve shortages under normal conditions, concurrent climate and infrastructure stressors reduce system resilience.

7.4 Discussion

The decline of existing water sources is the engine of Gondar's water crisis, a pattern familiar in rapidly urbanizing cities (Beker & Kansal, 2023; McDonald et al., 2021). Sedimentation in AR and accelerating groundwater depletion have slashed available supply, mirroring global trends of crumbling infrastructure and unsustainable use (Jasechko et al., 2024; Assfaw, 2020). The stress on KDWF echoes evidence from other fast-growing African cities, where over-pumping has cut yields and caused well failures (Oiro et al., 2020).

AR has lost more than 60% of its storage capacity to sedimentation, far worse than regional averages (Tessema et al., 2024). This loss stems from watershed conservation and sediment control measures being poorly integrated into the original design, a lesson repeated across Ethiopian and African dam projects. The reservoir's 2002 commissioning was already delayed, which further shortened its effective service life. Future reservoir planning in the region must treat sediment trap efficiency analysis, dam siting that accounts for catchment erosion risk, and catchment conservation programmes not as add-ons but as essential, built-in components.

7.4.1 Design Period Considerations

This study uses a 20-year primary design horizon (2025–2045), which is a standard practice for water supply infrastructure that typically assumes a 20–25-year planning window. Projections that stretch beyond 30 years come with considerable uncertainty regarding demographics, climate, and technology; therefore, they appear only for context alongside other published works. Planning should unfold in consecutive design periods, with infrastructure sized for the population and demand expected at the end of each period. The AR was likely sized for an earlier, lower population projection that has since been far exceeded, which helps to explain its current deficit.

The 70 percent drop in the KDWF yield from its original design capacity raises serious planning and design concerns. This loss points to over-abstraction past the sustainable aquifer yield, a problem that regular groundwater monitoring during operations would have flagged. Key recommendations include completing a comprehensive aquifer recharge assessment, rehabilitating non-functional wells, and instituting a systematic monitoring programme to avoid repeating this pattern of reactive expansion.

7.4.2 Population Growth and Rising Demand

Rapid population growth is the dominant pressure widening the supply–demand divergence (Beker & Kansal, 2023; Alemu & Dioha, 2020). Annual water demand is projected to exceed the capacity of existing infrastructure by nearly sevenfold by 2045. The sensitivity coefficient for population growth (S = 12.6) confirms that demand-side variables exert stronger system-wide influence than most supply-side parameters.

Rising demand interacts with declining effective supply caused by reservoir sedimentation and unsustainable groundwater abstraction, producing a structurally imbalanced water system vulnerable to both demographic pressures and environmental variability. Similar patterns are observed in Addis Ababa (Alemu & Dioha, 2020; Arsiso et al., 2017) and globally in cities such as Shimla and Chennai, where governance and institutional frameworks are critical determinants of urban water security beyond physical scarcity alone (Nigam et al., 2021).

7.4.3 Infrastructure Expansion and Its Limits

Developing cities frequently rely on new supply infrastructure to address growing demand, including reservoirs, inter-basin transfers, and expanded groundwater abstraction (Molle et al., 2024). However, supply-side solutions alone rarely ensure sustainable water security without complementary demand management and institutional reforms (He et al., 2021; McDonald et al., 2021). Scenario results for Gondar confirm that new infrastructure reduces deficits only under low-demand growth assumptions; high-demand conditions continue to produce significant unmet water demand.

Urban–agriculture competition adds further complexity, as water reallocation towards domestic supply can exacerbate agricultural shortages and social tensions (Zeitoun et al., 2016). High sedimentation scenarios for both Megech and ARs suggest yield could decline by over 70% by 2045 (Tesfaye et al., 2023). The sustainability of LTWPS abstraction from Lake Tana further depends on basin-level coordination, governance, and environmental protection (Nyamweya et al., 2023), and the Lake Tana Biosphere Reserve's ecological threshold must be recognised as a binding constraint on future abstraction volumes.

These findings underscore the need for integrated approaches combining technical interventions with institutional and watershed management measures — including sediment control, sustainable groundwater management, flexible allocation policies, environmental flow provisions, and demand management practices.

7.4.4 Future Challenges and Adaptive Management

Climate change, sedimentation, groundwater depletion, and increasing water demand all impact the long-term sustainability of Gondar's urban water supply. Under RCP8.5, annual water supply decreases by approximately 7–9% relative to the baseline scenario, primarily due to higher temperatures and increased evaporative losses from reservoirs. These findings are consistent with hydrological studies of the Megech watershed and the Lake Tana basin, which project that rising temperatures and altered rainfall patterns will reduce effective reservoir storage and increase seasonal variability in water availability (Asitatikie & Gebeyehu, 2021; Wubneh et al., 2022).

Sedimentation further exacerbates climate impacts by progressively reducing reservoir storage capacity. Annual storage losses of 3.0–3.9% significantly diminish long-term water yield, increasing vulnerability to climate variability. This finding aligns with prior research on reservoir sedimentation in the Upper Blue Nile Basin demonstrating that rapid sediment accumulation can severely impair reservoir performance and shorten operational lifespans (Haregeweyn et al., 2012; Tessema et al., 2024).

Sustainable water management for Gondar City therefore requires a combination of supply-side and demand-side strategies: sediment control, improved watershed management, efficient water allocation policies incorporating environmental flows, enhanced water-use efficiency, and adaptive governance responsive to demographic and climatic change. Without these measures, the benefits of new infrastructure may diminish as environmental and demographic pressures intensify.

7.5 Conclusions

This study applied a scenario-based WEAP modelling framework to assess water security in Gondar City, Ethiopia, over a 20-year planning horizon (2025–2045). Existing supply sources are projected to decline by 60% due to sedimentation and groundwater depletion, while annual urban water demand rises from 4.85 MCM in 2025 to over 51 MCM by 2045. Total unmet water demand under the Reference Scenario reaches 374.8 MCM — more than seven times the total supply available from existing sources.

Abstraction from Lake Tana, via the LTWPS, represents the most viable option identified, substantially reducing projected unmet water demand. However, maximizing its benefits requires complementary measures, including demand management, watershed protection, and addressing environmental and governance challenges within the basin. The LTWPS abstraction volume is within ecologically safe limits based on current evidence, but sustained basin-wide monitoring is essential. An integrated, adaptive management framework is necessary, combining diversified supply sources, sediment control, sustainable groundwater use, flexible allocation that includes environmental flows, and improved water-use efficiency.

Key conclusions are as follows. First, the 20-year design horizon (2025–2045) is appropriate; projections beyond 30 years carry high uncertainty and should be used for contextual reference only, not for design. Second, sedimentation in the AR, driven by insufficient watershed conservation at the design stage, has reduced storage capacity by over 60%, and similar risks apply to the MGD without proactive sediment management. Third, KDWF groundwater yield has declined by approximately 70% below design capacity, requiring urgent aquifer assessment and rehabilitation. Fourth, population growth is the dominant demand driver, with a sensitivity coefficient of 12.6 per 1% growth rate change. Fifth, the LTWPS substantially reduces annual UWD from 33–50 MCM (pre-commissioning) to 9–17 MCM (post-commissioning). Sixth, environmental flow provision (estimated at 10% of mean annual Megech River flow using the Tennant method) must be incorporated into water allocation frameworks. Seventh, Gondar's challenges reflect those of many secondary Ethiopian cities, where rapid population growth outpaces infrastructure expansion and integrated planning remains limited.

CHAPTER EIGHT

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

This dissertation examines the causes and future trajectory of urban water supply-demand divergence in Gondar City by integrating time-series analysis, remote sensing, NRW assessment, stakeholder interviews, and WEAP-based scenario modeling. The evidence demonstrates that Gondar's water crisis results not from a single failure but from interacting pressures across source availability, infrastructure performance, institutional response, and demand growth.

The first major finding is that the city's water supply system has undergone significant structural change over the study period. Long-term analysis from 2011 to 2024 shows that reservoir-based supply remained largely stagnant while groundwater and spring contributions increased in response to growing shortages. Change-point detection identified three important shifts: a transition around 2013 reflecting reservoir decline, a shift in 2017 marking groundwater expansion with the commissioning of Koladiba Wellfield, and a transition in 2019 indicating spring integration. Together, these changes demonstrate reactive rather than planned source diversification.

The second major finding is that the AR has experienced substantial storage decline and that distribution losses remain high. Remote sensing analysis from 2016 to 2024 reveals a 19.05 percent reduction in average reservoir volume, with the steepest decline occurring between 2022 and 2024. The reservoir has lost about 79 percent of its original live storage capacity since commissioning. Water balance analysis indicates that NRW accounts for 36.12 percent of system input, with real losses exceeding apparent losses. Together, these results confirm that both source depletion and distribution inefficiency are constraining effective supply. The qualitative findings reveal that Gondar's water supply system functions within a recurring cycle of vulnerability and adaptation: reservoir decline encouraged greater dependence on groundwater, which provided short-term relief but generated new sustainability concerns, while the benefits of increased production failed to reach many households, creating a persistent gap between system-level performance and user experience.

The third major finding is that future supply-demand imbalance will continue to widen unless management priorities fundamentally change. WEAP projections for 2025 to 2045 show that under the Reference Scenario, cumulative unmet demand reaches 374.8 million cubic meters, more than seven times the total supply available from existing sources. Population growth is the dominant demand driver, with a sensitivity coefficient of 12.6 per one percent growth rate change. The MGD can provide some relief under an 80 percent urban allocation, but its benefits remain limited under the current 70 percent irrigation allocation. The LTWPS offers greater potential to reduce future deficits, lowering annual unmet demand from 33 to 50 million cubic meters before commissioning to 9 to 17 million cubic meters after commissioning, provided implementation is timely and well-coordinated.

8.2 Conclusions

This study concludes that Gondar City's water insecurity is structural rather than temporary. The central problem is a widening mismatch between source capacity and urban demand, intensified by reservoir sedimentation, high NRW, delayed infrastructure expansion, and weak coordination among supply options. The AR, designed with a live storage of 5.3 million cubic meters, has lost approximately 80 percent of its usable capacity since commissioning, primarily due to sedimentation, fundamentally compromising its role as the city's primary water source. Groundwater sources developed as a compensatory measure are themselves declining, with Koladiba Wellfield yields dropping by approximately 70 percent from design capacity due to over-abstraction and inadequate aquifer characterization. The city's gradual shift from surface water to groundwater has provided short-term relief while simultaneously creating new vulnerabilities and long-term sustainability risks.

The critical gap cannot be closed through institutional reform or demand management alone. These measures are necessary but insufficient. Gondar faces a structural source-capacity deficit that requires urgent and substantial source development. Current water sources collectively meet only approximately one-third of present demand, and with the population projected to reach approximately 710,000 by 2034, the gap will widen dramatically without new sources. Source augmentation must therefore be the highest priority. Completing the MGD with a revised allocation favoring urban supply of at least 80 percent, and implementing the LTWPS in a timely manner, are essential to address the structural deficit. Without these interventions, the supply gap is projected to reach approximately 375 million cubic meters over 2025 to 2045.

While source augmentation is the primary need, it is not sufficient on its own. The study demonstrates that NRW reduction is essential: at 36.12 percent, NRW represents a significant loss of scarce water, and reducing it to 20 percent would increase available supply by approximately 15 percent of current system input. Watershed rehabilitation is equally critical, as annual sedimentation rates of 3.0 to 3.9 percent have severely undermined the AR's utility within a fraction of its intended design life. The overall challenge is not merely to add supply but to build a system that can retain and deliver it efficiently.

From a socio-hydrological perspective, Gondar's water system has evolved through path-dependent adaptation rather than planned transformation. Scarcity has triggered source substitution from surface water to groundwater to springs, but this response has not resolved the underlying deficit; it has instead redistributed pressure across the system. The rapid decline of Koladiba yields following commissioning, without adequate aquifer characterization, illustrates how short-term solutions can generate long-term vulnerabilities. Water security cannot be achieved through source expansion alone. It requires simultaneous action on source protection, loss reduction, demand management, and institutional coordination. Overall, this dissertation establishes that Gondar's water crisis is the outcome of interacting hydrological, infrastructural, and institutional processes. The problem is not simply one of insufficient rainfall or inadequate engineering capacity but also one of how the city plans, allocates, manages, and protects its water resources over time.

8.3 Recommendations

The recommendations are organized by time horizon and urgency. Gondar faces an immediate crisis requiring emergency interventions alongside medium- and long-term planning. The fundamental principle throughout is that source augmentation must be the highest priority, supported by parallel improvements in system efficiency and governance.

Immediate term (zero to twelve months)

Emergency source development must be the most critical immediate priority. The AR has lost approximately 80 percent of its live storage capacity, groundwater yields are declining by 7 to 9 percent annually, and existing sources meet only about one-third of current demand. Recommended actions include accelerating MGD completion with allocation revised to at least 80 percent urban supply; expediting LTWPS implementation to the earliest possible date; rehabilitating non-functional wells at Koladiba and Angereb Wellfields to restore lost capacity; implementing emergency water rationing protocols during critical dry-season months; and establishing emergency water trucking from Lake Tana or alternative sources during extreme shortages.

Simultaneously, immediate NRW reduction measures should be implemented through active leak detection and repair in high-loss zones; pressure management to reduce burst frequency and leakage rates; testing and replacement of aged DN15 and DN20 meters, which represent 77.1 percent of billed consumption; billing system audits to correct meter reading and data handling errors; and regularization of unauthorized connections.

Emergency response capacity should also be strengthened by developing seasonal operations protocols based on the climate response times identified in this study, establishing a water security task force with representation from all relevant agencies, and creating an emergency water supply fund for rapid response to infrastructure failures and drought events.

Medium term (one to five years)

Source augmentation projects must be completed, including the MGD with allocation revised to 80 percent urban and 20 percent irrigation; the LTWPS, which would provide 60,480 m^3 per day of additional supply; transmission infrastructure connecting new sources to the distribution network; and environmental flow provisions of at least 10 percent of mean annual Megech River flow.

AR rehabilitation should proceed through a comprehensive feasibility study for desilting; watershed rehabilitation in the Angereb catchment through reforestation, riparian buffers, and soil conservation; a sediment management plan for both Angereb and Megech reservoirs; and a reservoir monitoring program using remote sensing and regular bathymetric surveys.

A groundwater management program must be established through a monitoring network with regular water-level measurements, aquifer characterization and sustainable yield assessment, abstraction capped at sustainable yield limits for each wellfield, exploration of managed aquifer recharge, and rehabilitation of non-functional wells with appropriate design and yield assessment.

The NRW reduction program should be expanded through district metered areas for systematic leakage management, minimum night flow analysis to quantify and prioritize leaks, replacement of aging pipes in high-loss zones, installation of automated meter reading to eliminate manual errors, and strengthened revenue collection and billing systems.

Long term (five to twenty years)

An integrated urban water management framework must be developed that connects source development, demand management, land-use planning, and institutional coordination. This framework should incorporate climate projections under RCP4.5 and RCP8.5 into infrastructure planning and operations; establish inter-agency coordination mechanisms for water resource management; develop water allocation frameworks balancing urban, agricultural, and environmental needs; and build institutional capacity for planning, monitoring, and adaptive management.

Demand management should be strengthened through water conservation campaigns targeting households, institutions, and businesses; promotion of water-efficient technologies including low-flow fixtures, rainwater harvesting, and greywater recycling; progressive tariff structures to discourage waste and improve cost recovery; water use regulations for commercial and institutional users; and support for community-based water management in informal settlements.

Climate resilience must be built by incorporating climate projections into infrastructure design and operations, developing adaptive management protocols for climate variability, implementing ecosystem-based adaptation through watershed protection and natural infrastructure, building institutional capacity for climate risk assessment and management, and establishing early warning systems for drought and water scarcity.

Areas for further research

The study identifies several areas requiring further investigation: systematic groundwater monitoring and modeling for evidence-based management of water levels, quality, and sustainable yields; household-level water access studies to understand the distributional impacts of scarcity and the coping strategies of vulnerable populations; conjunctive use optimization modeling the integration of surface water, groundwater, and springs under different climatic and demand scenarios; comparative studies assessing whether Gondar's trajectory is representative of other rapidly growing Ethiopian secondary cities; downscaled climate projections to assess system vulnerability under 2030 to 2050 scenarios; cost-benefit analysis of alternative interventions; and political economy analysis to understand institutional barriers to water allocation reform.

This dissertation establishes that Gondar City's water crisis is the outcome of interacting hydrological, infrastructural, and institutional processes. The problem is not simply one of insufficient rainfall or inadequate engineering capacity but also one of how the city plans, allocates, manages, and protects its water resources over time. The critical gap cannot be closed through institutional reform or demand management alone. Gondar faces a structural source-capacity deficit requiring urgent source development, and the path to water security requires emergency measures including water rationing, well rehabilitation, and emergency transfers; accelerated source development through completing MGD with revised urban allocation of at least 80 percent and expediting Lake Tana pumping; parallel system improvements through NRW reduction, meter replacement, and watershed rehabilitation; and institutional reform through strengthened planning, coordination, and financial sustainability. Without these interventions, the supply gap is projected to reach approximately 375 million cubic meters over 2025 to 2045.

The study demonstrates the value of integrated, socio-hydrological analysis for understanding the drivers of urban water insecurity and informing context-appropriate responses, providing a replicable framework for diagnosing urban water supply transitions in rapidly growing cities of the Global South. Gondar's water crisis is ultimately a call to action. The city's historical significance, growing population, and economic importance demand a response commensurate with the scale of the challenge. Reactive crisis management is no longer adequate. What is required now is a proactive, integrated, and sustained commitment to water security.

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APPENDIX

Appendix 1: Key Informant Interview (KII) Guide

Target Respondents: Officials from the GCWSSS (GCWSSS), including treatment plant managers, engineers, and regional water bureau planners.

Objective: To explore institutional, operational, and technical perspectives on system performance, challenges, and management strategies related to Gondar's water supply.

Introduction: Thank you for participating in this study, which examines the long-term dynamics of Gondar's water supply system, associated challenges, and management responses. Your insights are highly valuable to the study.

Theme 1: Historical Trends and System Performance

1. How would you describe the performance of the AR over the past 10–15 years? Have you observed any notable changes in its reliability or performance?
2. Groundwater abstraction from the Koladiba and Angereb wellfields has increased since approximately 2017. What factors and decisions led to this expansion of groundwater use?
3. What key events or interventions (e.g., new infrastructure projects, drought events, or system failures) have significantly altered the city's water supply dynamics?

Theme 2: System Inefficiencies and Water Loss

4. There is a noticeable gap between the volume of water produced and the volume billed to consumers. What are the main causes contributing to this water loss? *(Probe: leakage from pipes, aging infrastructure, illegal connections, metering inaccuracies)*
5. What specific challenges are associated with the use of small-diameter meters (DN15/DN20), particularly under intermittent supply conditions?
6. What constraints or limitations affect maintenance, leak detection, and repair activities within the water supply system? *(Probe: budget limitations, availability of skilled labor, access to spare parts)*

Theme 3: Management, Planning, and Future Outlook

7. What is the current status of the MGD project? What factors have contributed to any delays in its completion, and how is it expected to affect the balance between urban water supply and irrigation needs?
8. What are your views on the proposed LTWPS, considering both its potential opportunities and potential challenges?
9. How would you characterize the current approach to water management in Gondar—is it primarily reactive or proactive? Please explain your reasoning.
10. What three priority actions would you recommend to most effectively improve Gondar's water supply system and ensure its long-term sustainability?

Appendix 2: Focus Group Discussion (FGD) Guide

Target Respondents: Residents from different neighborhoods (branch office areas) within Gondar City.

Objective: To capture residents' experiences regarding water access, reliability, seasonal variations in supply, and the coping strategies they employ during periods of water scarcity.

Introduction:
Thank you for participating in this focus group discussion. We are interested in hearing about your experiences with household and neighborhood water supply in Gondar. Please be assured that there are no right or wrong answers; we value your honest perspectives.

Theme 1: Household Water Access and Reliability

1. Could you describe what a typical week is like in terms of your household's access to water? *(Probe: frequency of supply, duration of supply, predictability of the supply schedule)*
2. How does water availability for your household vary across different seasons of the year? What specific measures do you take during periods of water scarcity?

3. Despite reported increases in total water production for the city, have you personally noticed any improvements in your household's water supply? If so, in what ways? If not, why do you think this is the case?

Theme 2: Source Reliability and Water Quality

4. Besides the piped water supply, what other sources of water do you and your household typically use? *(Probe: wells, water vendors, natural springs, rainwater harvesting)* How do these alternative sources compare to the piped supply in terms of cost, reliability, and perceived safety?
5. Have you observed any changes in the quality of the water supply (e.g., in terms of taste, color, or odor)? Do you have any concerns about the quality of the water you receive?

Theme 3: Coping Strategies and Impacts

6. What specific strategies do you employ when water is unavailable or insufficient to meet your household's needs? What costs, challenges, or inconveniences are associated with these coping strategies?
7. In what ways do water shortages affect your daily life and the lives of your family members? (Probe: impacts on health, time burden for water collection, ability to work or attend school, household expenses)

Theme 4: Perceptions of System Management

8. Have you noticed any infrastructure-related issues in your neighborhood that affect the water supply (e.g., leaks in pipes, open or damaged pipes)?
9. If you could convey one key message to the water managers responsible for the system, what would it be to improve the water supply for your community?

Appendix 3 Water supply and climate data for Gondar City (2011–2024)

Year	Month	Rwater	Twater (m^3)	Wwater (m^3)	Swater (m^3)	TWS (m^3)	Temp (^{o}C)	Rainfall (mm)
2011	Jul	176,189	166,216	38,364	377	204,957	18.08	190.85
2011	Aug	184,522	174,077	34,193	837	209,107	17.97	162.56
2011	Sep	275,619	260,018	55,638	1,592	317,248	18.55	130.09
2011	Oct	222,297	209,714	45,289	2,138	257,141	19.47	16.74
2011	Nov	238,343	224,852	35,808	2,116	262,776	18.86	19.54
2011	Dec	239,931	226,350	42,361	2,670	271,381	19.22	0.12
2012	Jan	241,091	227,444	51,535	2,212	281,191	19.97	0
2012	Feb	233,079	219,886	47,530	1,732	269,148	21.22	0
2012	Mar	220,058	207,602	48,175	3,029	258,806	22.68	5.49
2012	Apr	243,730	229,934	24,303	2,611	256,848	23.3	5.04
2012	May	221,703	209,154	20,022	1,681	230,857	23.19	52.87
2012	Jun	229,003	216,041	20,863	1,775	238,679	20.73	93.24
2012	Jul	188,144	177,494	23,527	2,120	203,141	17.8	333.99
2012	Aug	213,889	201,782	41,384	3,525	246,691	17.86	316.32
2012	Sep	271,684	256,306	52,584	4,183	313,073	18.6	158.88
2012	Oct	232,941	219,757	50,742	4,151	274,650	18.45	34.09
2012	Nov	223,270	210,632	46,570	4,661	261,863	18.84	53.69
2012	Dec	232,489	219,330	46,645	4,489	270,464	18.67	6.16
2013	Jan	244,173	230,352	34,115	4,677	269,144	20.27	0.42
2013	Feb	240,882	227,247	28,930	3,212	259,959	21.91	0.16
2013	Mar	248,744	234,664	27,827	4,413	266,904	23.21	7.86
2013	Apr	248,812	237,624	24,741	2,950	265,315	23.52	12.66
2013	May	246,601	232,642	24,910	3,014	260,166	22.22	151.18
2013	Jun	250,635	236,448	24,986	1,997	263,431	19.67	189.45
2013	Jul	236,441	222,254	25,145	1,647	249,046	17.04	406.68
2013	Aug	237,848	223,577	29,736	2,664	255,977	17.24	439.21
2013	Sep	306,727	288,324	62,359	4,388	355,071	18.8	150.43
2013	Oct	255,097	239,791	51,719	4,053	295,563	18.02	115.6
2013	Nov	271,726	255,422	36,140	5,100	296,662	18.52	19.72
2013	Dec	282,515	265,564	41,822	4,156	311,542	17.67	0.1
2014	Jan	284,862	267,770	39,173	2,858	309,801	19.4	2.91
2014	Feb	283,133	266,145	35,124	2,373	303,642	20.46	5.81
2014	Mar	284,644	267,565	30,254	1,961	299,780	21.52	65.77
2014	Apr	279,976	263,177	25,352	2,043	290,572	22.41	60.06

2014	May	291,775	274,268	22,598	2,099	298,965	21	170.03
2014	Jun	283,449	266,443	24,575	1,873	292,891	20.45	175.11
2014	Jul	274,849	258,358	20,707	1,571	280,636	18.26	530.45
2014	Aug	272,490	256,141	23,321	1,631	281,093	17.85	446.51
2014	Sep	351,223	330,150	50,932	3,638	384,720	18.19	304.81
2014	Oct	290,866	273,414	43,663	3,686	320,763	17.52	100.56
2014	Nov	296,951	279,134	43,060	2,995	325,189	17.65	6.87
2014	Dec	287,400	270,156	41,933	2,240	314,329	17.79	7.61
2015	Jan	284,862	267,770	39,173	2,858	309,801	18.7	0.83
2015	Feb	283,133	266,145	35,124	2,373	303,642	21.53	1.32
2015	Mar	284,644	267,565	30,254	1,961	299,780	23.37	11.36
2015	Apr	279,976	263,177	25,352	2,043	290,572	24.19	3.56
2015	May	291,775	274,268	22,598	2,099	298,965	22.59	90.67
2015	Jun	283,449	266,443	24,575	1,873	292,891	20.16	330.09
2015	Jul	274,849	258,358	20,707	1,571	280,636	19.02	327.26
2015	Aug	272,490	256,141	23,321	1,631	281,093	18.57	610.7
2015	Sep	351,223	330,150	50,932	3,638	384,720	19.25	145.27
2015	Oct	290,866	273,414	43,663	3,686	320,763	19.21	83.36
2015	Nov	296,951	279,134	43,060	2,995	325,189	18.73	49.14
2015	Dec	287,400	270,156	41,933	2,240	314,329	18.2	53.11
2016	Jan	290,928	273,472	41,159	1,837	316,468	18.62	1.18
2016	Feb	295,090	277,385	37,709	1,549	316,643	21.49	1.25
2016	Mar	301,229	283,155	30,571	1,302	315,028	23.58	58.75
2016	Apr	295,452	277,725	26,593	1,331	305,649	23.15	70.06
2016	May	288,456	271,149	22,760	1,812	295,721	20.25	350.23
2016	Jun	311,360	292,678	23,759	1,646	318,083	19.96	227.66
2016	Jul	304,569	286,295	23,147	2,317	311,759	17.46	742.9
2016	Aug	302,148	284,019	30,876	3,491	318,386	17.63	528.72
2016	Sep	367,384	345,341	39,173	4,948	389,462	18.77	197.24
2016	Oct	295,352	277,631	43,663	3,686	324,922	18.11	49.47
2016	Nov	287,491	270,242	43,060	2,995	316,297	17.77	0.6
2016	Dec	277,884	261,211	41,933	2,240	305,384	18.16	0.63
2017	Jan	278,290	261,593	41,159	1,837	304,589	18.54	0
2017	Feb	285,017	267,916	37,709	1,549	307,174	20.26	35.67
2017	Mar	290,379	272,956	30,571	1,302	304,829	22.19	13.21
2017	Apr	301,435	283,349	26,593	1,331	311,273	23.07	103.09

2017	May	285,606	268,470	22,760	1,812	293,042	21.26	177.51
2017	Jun	291,403	273,919	23,759	1,646	299,324	20.54	212.11
2017	Jul	276,949	260,332	31,163	1,670	293,165	18.42	444.29
2017	Aug	273,673	257,253	32,727	1,970	291,950	17.99	449.56
2017	Sep	346,560	325,766	90,396	7,762	375,796	18.9	211.58
2017	Oct	298,479	280,570	189,806	8,912	376,808	18.68	61.96
2017	Nov	288,324	271,025	167,837	4,886	472,456	18.41	15.4
2017	Dec	285,902	268,748	154,196	3,709	442,259	18	0.13
2018	Jan	280,372	263,550	141,396	2,885	421,179	18.44	0.1
2018	Feb	274,793	258,305	133,697	1,959	397,324	21.43	6.25
2018	Mar	271,700	255,398	119,503	2,042	382,172	22.17	15.24
2018	Apr	268,261	252,165	163,346	1,793	359,465	21.83	61.63
2018	May	249,399	234,435	176,266	1,313	380,261	22.56	99.45
2018	Jun	234,415	220,350	42,268	1,259	376,154	19.51	182.24
2018	Jul	183,428	172,422	151,273	2,024	306,112	17.67	372.58
2018	Aug	266,646	250,647	157,425	2,127	397,476	17.66	373.6
2018	Sep	340,584	320,149	184,241	4,255	513,600	18.83	121.28
2018	Oct	292,165	274,635	162,957	3,410	439,564	18.52	125.48
2018	Nov	298,965	281,027	168,188	3,979	452,991	18.08	60.57
2018	Dec	284,776	267,689	159,915	3,408	427,110	18.76	4.97
2019	Jan	288,047	270,764	166,984	2,248	438,930	19.45	0
2019	Feb	271,696	255,394	168,311	1,324	429,412	21.27	18.37
2019	Mar	261,467	245,779	166,220	1,432	405,250	22.48	22.4
2019	Apr	261,443	245,756	159,173	1,145	386,706	23.51	50.07
2019	May	251,273	236,197	149,988	625	363,743	23.72	27.76
2019	Jun	178,419	167,714	153,771	1,809	301,754	20.47	234.77
2019	Jul	229,293	215,535	131,272	2,085	340,914	18.6	263.04
2019	Aug	266,440	250,454	141,761	4,038	398,103	18.1	384.54
2019	Sep	325,905	306,351	131,159	11,709	449,977	18.87	422.3
2019	Oct	287,781	270,514	88,603	9,131	371,855	18	85.84
2019	Nov	286,222	269,049	126,862	7,475	406,299	18.5	48.1
2019	Dec	286,795	269,587	168,249	4,532	448,449	18.01	25.54
2020	Jan	283,212	266,219	152,938	2,691	421,279	18.54	1.23
2020	Feb	293,215	275,622	150,036	1,738	423,910	21.34	4.44
2020	Mar	285,123	268,016	152,981	2,093	417,271	22.86	11.88

2020	Apr	290,960	273,502	127,747	1,558	390,757	22.74	75.11
2020	May	281,046	264,183	115,172	1,437	361,715	21.59	211.76
2020	Jun	219,478	206,309	88,110	1,619	279,122	19.69	300.77
2020	Jul	274,946	258,449	98,852	7,904	348,581	17.51	587.05
2020	Aug	275,871	259,319	150,940	1,852	398,529	17.59	621.97
2020	Sep	347,424	326,579	148,091	3,077	471,997	18.81	481.81
2020	Oct	291,714	274,211	148,601	3,935	418,804	17.87	124.6
2020	Nov	296,268	278,492	144,133	5,581	417,778	17.38	4.2
2020	Dec	285,226	268,112	144,278	4,091	403,499	18.46	1.14
2021	Jan	295,864	278,112	141,181	4,176	410,505	19.17	1.63
2021	Feb	288,945	271,608	136,069	3,251	397,144	19.68	15.16
2021	Mar	241,064	226,600	129,995	1,729	342,086	23.1	1.65
2021	Apr	213,265	200,469	107,163	2,767	280,170	22.7	151.43
2021	May	257,013	241,592	81,604	2,222	294,058	20.28	203.39
2021	Jun	269,164	253,014	111,434	1,935	335,338	20.82	308.08
2021	Jul	217,890	204,817	94,725	3,199	290,650	17.11	1180.44
2021	Aug	254,965	239,667	117,814	6,584	342,714	17.77	642.21
2021	Sep	343,201	322,609	159,705	2,620	456,182	18.55	481.95
2021	Oct	256,513	241,122	128,626	11,108	381,488	18.14	66.82
2021	Nov	269,010	252,869	128,384	5,743	391,411	18.22	13.2
2021	Dec	291,594	274,098	118,357	12,297	418,911	18.45	23.4
2022	Jan	296,072	278,308	80,803	12,297	376,755	18.16	35.37
2022	Feb	295,972	278,214	107,752	6,306	392,383	20.71	3.18
2022	Mar	267,305	251,267	129,849	7,569	388,087	23.21	11.5
2022	Apr	276,712	260,109	126,532	1,714	384,012	22.91	193.47
2022	May	283,443	266,436	117,792	1,445	377,679	22.94	66.91
2022	Jun	169,486	159,317	118,513	1,839	267,269	19.73	591.57
2022	Jul	150,776	141,729	124,960	3,456	270,005	17.06	998.31
2022	Aug	241,529	227,037	133,189	9,928	378,231	17.18	383.91
2022	Sep	335,082	314,977	141,149	13,345	504,814	18.76	290.2
2022	Oct	274,191	257,740	134,300	13,132	433,681	18	176.99
2022	Nov	277,722	261,059	126,794	8,578	420,445	17.81	3.83
2022	Dec	256,095	240,729	129,140	7,428	393,030	17.86	6.63
2023	Jan	250,009	235,008	111,197	8,103	380,932	19	14
2023	Feb	264,028	248,186	105,602	7,764	371,497	21	1

2023	Mar	255,733	240,389	88,324	7,726	342,190	22	3
2023	Apr	230,437	216,611	147,150	6,822	372,736	22	206
2023	May	181,497	170,607	141,441	5,873	319,734	22	109
2023	Jun	212,915	200,140	125,610	5,376	322,541	20	430
2023	Jul	211,267	198,590	120,216	3,734	311,252	19	630
2023	Aug	261,090	245,425	140,226	4,906	383,011	19	459
2023	Sep	338,439	318,133	152,869	7,001	479,314	20	262
2023	Oct	280,473	263,644	132,617	8,143	409,078	19	205
2023	Nov	285,637	268,499	138,872	6,271	417,785	18	84
2023	Dec	280,897	264,043	143,988	6,351	418,200	18	1
2024	Jan	282,641	265,682	130,621	5,903	405,680	19	2
2024	Feb	282,771	265,805	133,554	4,077	402,869	21	3
2024	Mar	262,138	246,410	133,474	4,110	378,977	23	9
2024	Apr	254,563	239,289	133,553	2,801	362,876	24	18
2024	May	250,854	235,803	121,199	2,320	343,386	24	90
2024	Jun	209,892	197,299	119,488	2,516	301,205	21	495
2024	Jul	216,834	203,824	114,005	4,076	312,280	18	709
2024	Aug	259,979	244,380	136,786	5,462	380,118	17	533
2024	Sep	338,010	317,730	146,595	7,550	472,457	19	319
2024	Oct	278,134	261,446	126,549	9,090	402,981	19	97
2024	Nov	282,972	265,994	133,009	6,730	410,744	18	23
2024	Dec	280,121	263,314	140,802	6,940	416,418	18	0

Appendix 3 Seasonal trend analysis of water supply in Gondar City (2011–2024)

Season	Variable	Sen's Slope (m^3 Season-1)	95% CI Lower	95% CI Upper	MK tau	MK p-value
Winter	Rwater	929.76	-501.07	3692.5	0.187	0.3811
Winter	Twater	873.95	-470.97	3470.83	0.187	0.3811
Winter	Wwater	8686.56	520.22	12993.25	0.462	0.0246
Winter	Swater	346.45	68	623.4	0.44	0.0325
Winter	TWS	11178.3	5479.33	16430.33	0.495	0.016
Summer	Rwater	0	-7396.19	5545.23	0	1
Summer	Twater	0	-6952.43	5135.98	0	1
Summer	Wwater	8800.36	1529.83	13248.69	0.484	0.0184

Summer	Swater	262.38	127.33	372.54	0.681	0.0008
Summer	TWS	8474.78	3313.22	15005.04	0.571	0.0052
Spring	Rwater	-1372.57	-6907.29	3504.17	-0.141	0.541
Spring	Twater	-1403.18	-6492.81	3294.17	-0.141	0.541
Spring	Wwater	9554.39	191.11	15162.95	0.487	0.0235
Spring	Swater	53.32	-138.11	334.8	0.128	0.5815
Spring	TWS	9218.06	4513.5	16859.67	0.603	0.0049
Autumn	Rwater	227	-1811	5215.89	0.022	0.9563
Autumn	Twater	213.44	-1702	4811.3	0.022	0.9563
Autumn	Wwater	8317.03	-722.6	12122.04	0.374	0.0704
Autumn	Swater	435.03	151.6	735.33	0.549	0.0072

Appendix 4 Monthly standardized precipitation index (SPI) values for Gondar City (2011–2024)

Year	Month	SPI_3	SPI_4	SPI_6	SPI_12	SPI_24
2011	Jul					
2011	Aug					
2011	Sep	-2.2122				
2011	Oct	-2.5379	-2.31381			
2011	Nov	-1.87197	-2.60701			
2011	Dec	-2.00498	-1.92877	-2.38671		
2012	Jan	-0.44377	-1.98039	-2.48344		
2012	Feb	-2.45743	-1.12484	-1.91077		
2012	Mar	-1.6177	-1.7703	-2.26249		
2012	Apr	-1.76265	-1.75632	-1.94543		
2012	May	-1.81048	-1.87589	-1.88332		
2012	Jun	-2.31557	-2.37996	-2.39532	-2.36708	
2012	Jul	-1.58891	-1.6443	-1.70767	-2.07037	
2012	Aug	-1.66717	-1.75372	-1.82817	-1.9028	
2012	Sep	-1.05252	-1.68911	-1.81655	-1.94188	
2012	Oct	-1.27087	-1.14036	-1.8939	-1.96408	
2012	Nov	-1.00641	-1.1537	-1.7684	-1.92813	
2012	Dec	-0.51346	-1.00963	-1.08853	-1.93948	
2013	Jan	0.669752	-0.54868	-1.07085	-1.83948	
2013	Feb	-0.59409	0.483356	-1.01805	-1.8362	
2013	Mar	-1.22791	-0.92653	-0.80316	-1.85715	
2013	Apr	-1.27995	-1.27016	-0.72959	-1.84124	

2013	May	-0.3679	-0.42715	-0.43974	-1.70157	
2013	Jun	-0.68918	-0.74295	-0.77974	-0.96884	-2.03044
2013	Jul	-0.6122	-0.70846	-0.75765	-0.91248	-1.82261
2013	Aug	-0.72039	-0.60745	-0.71907	-0.81451	-1.62685
2013	Sep	-0.53046	-0.89366	-0.85662	-0.90046	-1.73663
2013	Oct	-0.3336	-0.43999	-0.72969	-0.77281	-1.66506
2013	Nov	-0.65565	-0.38284	-0.86736	-0.86989	-1.67756
2013	Dec	0.186065	-0.71667	-0.4925	-0.89679	-1.69058
2014	Jan	-0.32025	0.151719	-0.3583	-0.82068	-1.58825
2014	Feb	-0.40714	-0.65104	-0.66956	-0.80772	-1.58257
2014	Mar	1.716545	1.174395	0.691992	-0.70115	-1.52204
2014	Apr	0.579627	0.551064	0.278444	-0.60781	-1.46576
2014	May	0.62735	0.607513	0.50568	-0.62204	-1.3609
2014	Jun	-0.3856	-0.13022	-0.13666	-0.3526	-0.8922
2014	Jul	-0.22855	-0.22895	-0.11548	-0.22229	-0.75776
2014	Aug	-0.39323	-0.27068	-0.17	-0.29608	-0.72086
2014	Sep	0.150157	-0.24701	-0.16924	-0.07091	-0.63705
2014	Oct	0.257223	0.156685	-0.15614	-0.11531	-0.60185
2014	Nov	0.293508	0.169827	-0.29987	-0.14723	-0.66181
2014	Dec	-0.13614	0.278539	0.103607	-0.13783	-0.66573
2015	Jan	-0.64524	-0.18341	0.185516	-0.09086	-0.59023
2015	Feb	-0.33315	-1.322	0.233515	-0.09886	-0.59007
2015	Mar	-0.74878	-0.54	-0.36621	-0.20293	-0.59522
2015	Apr	-1.46117	-1.4264	-1.89754	-0.31112	-0.62366
2015	May	-1.12329	-1.16816	-1.1014	-0.50916	-0.72034
2015	Jun	-0.28048	-0.3154	-0.35109	-0.00222	-0.32014
2015	Jul	-0.60996	-0.73318	-0.76869	-0.39101	-0.46305
2015	Aug	-0.08967	-0.18375	-0.33227	-0.2049	-0.37248
2015	Sep	-0.31068	-0.34506	-0.52185	-0.53876	-0.43651
2015	Oct	0.209452	-0.31205	-0.44007	-0.60295	-0.50699
2015	Nov	-0.72445	0.284649	-0.34082	-0.54038	-0.48097
2015	Dec	0.861292	-0.35252	-0.17368	-0.46	-0.42671
2016	Jan	1.377746	0.767247	0.456552	-0.40007	-0.35895
2016	Feb	1.38428	1.517461	-0.37097	-0.39968	-0.36475
2016	Mar	1.352003	1.949479	1.08189	-0.31745	-0.37876
2016	Apr	0.563708	0.519035	1.047681	-0.19547	-0.38626
2016	May	1.679138	1.627444	1.705317	0.262153	-0.20482
2016	Jun	0.763279	0.916376	0.85857	0.207926	0.014733

2016	Jul	0.865794	0.78098	0.844448	0.716172	0.1392
2016	Aug	0.464115	0.854386	0.852306	0.598783	0.171305
2016	Sep	0.542628	0.259982	0.583704	0.668799	0.042155
2016	Oct	-0.04147	0.427491	0.523953	0.619421	-0.03347
2016	Nov	-1.00027	-0.16439	0.08747	0.553342	-0.04378
2016	Dec	-1.52847	-1.05512	0.354077	0.472764	-0.05204
2017	Jan	-2.14369	-1.52507	-0.16075	0.505386	0.008277
2017	Feb	0.865391	-0.29264	-0.75887	0.559032	0.042327
2017	Mar	0.967603	0.536167	-0.85432	0.490043	0.042823
2017	Apr	0.774182	0.711652	0.265298	0.541823	0.124073
2017	May	0.613452	0.788173	0.662462	0.255508	0.212153
2017	Jun	0.071241	0.044182	0.158455	0.325261	0.211022
2017	Jul	-0.34875	-0.22551	-0.16828	-0.17897	0.251079
2017	Aug	-0.51965	-0.36416	-0.27453	-0.39975	0.068232
2017	Sep	-0.25646	-0.56808	-0.34047	-0.42391	0.102506
2017	Oct	-0.25747	-0.31021	-0.50376	-0.42792	0.058598
2017	Nov	-0.62852	-0.32394	-0.68815	-0.41625	0.021151
2017	Dec	-0.85046	-0.68938	-0.37058	-0.42517	-0.03367
2018	Jan	-0.62909	-0.87573	-0.31389	-0.36665	0.025984
2018	Feb	-0.62035	-0.99397	-0.66273	-0.42212	0.030516
2018	Mar	-0.20301	-0.50897	-0.86356	-0.42683	-0.01545
2018	Apr	0.01688	-0.02203	-0.44071	-0.51055	-0.04288
2018	May	-0.32332	-0.32484	-0.4005	-0.72489	-0.32072
2018	Jun	-0.75093	-0.75885	-0.76064	-0.45839	-0.16849
2018	Jul	-0.91967	-0.84048	-0.84928	-0.65779	-0.58915
2018	Aug	-1.04292	-1.03659	-0.97497	-0.93402	-0.85093
2018	Sep	-0.88179	-1.25702	-1.17381	-1.20181	-1.02954
2018	Oct	-0.71441	-0.73398	-1.14148	-1.10959	-0.98641
2018	Nov	-0.47597	-0.57968	-1.08331	-1.04415	-0.92356
2018	Dec	0.926566	-0.49841	-0.67372	-1.04961	-0.92584
2019	Jan	0.770782	0.815739	-0.53631	-0.97483	-0.8449
2019	Feb	0.404243	1.076555	-0.39054	-0.94733	-0.86663
2019	Mar	0.678845	0.423049	0.928203	-0.94739	-0.86818
2019	Apr	0.119048	0.075872	0.300874	-0.9758	-0.94938
2019	May	-1.19799	-1.01497	-1.0026	-1.22115	-1.1746
2019	Jun	-0.94937	-0.90729	-0.83049	-0.69491	-0.80392
2019	Jul	-1.39961	-1.30239	-1.23973	-0.98012	-1.07283
2019	Aug	-1.18978	-1.3856	-1.30286	-1.1127	-1.27739

2019	Sep	-0.34364	-0.59892	-0.78483	-0.58015	-1.13009
2019	Oct	0.409374	-0.33716	-0.80628	-0.69022	-1.1517
2019	Nov	1.160969	0.480707	-0.58509	-0.73948	-1.12111
2019	Dec	0.527218	1.229668	-0.263	-0.70907	-1.09851
2020	Jan	0.937504	0.451174	0.542318	-0.6407	-1.01227
2020	Feb	0.699611	0.969713	1.166246	-0.66777	-1.01604
2020	Mar	-0.45365	0.339797	0.30455	-0.70117	-1.03447
2020	Apr	0.12661	0.098423	0.408862	-0.65304	-1.03565
2020	May	0.646836	0.617661	0.661561	-0.3282	-0.93472
2020	Jun	0.509	0.474755	0.439102	-0.00235	-0.51276
2020	Jul	0.359049	0.334149	0.310699	0.403481	-0.37227
2020	Aug	0.487895	0.603271	0.547272	0.718485	-0.20319
2020	Sep	0.967664	0.822664	0.840516	0.802777	0.110734
2020	Oct	1.515498	0.967793	0.911565	0.865732	0.087516
2020	Nov	1.450064	1.460429	0.804695	0.816591	0.027561
2020	Dec	0.102815	1.386007	0.916646	0.78714	0.023119
2021	Jan	-1.20085	0.054965	1.388479	0.813941	0.084199
2021	Feb	0.159872	-0.97984	1.370499	0.828631	0.080563
2021	Mar	-0.39524	-0.62262	-0.07418	0.820894	0.058671
2021	Apr	0.918061	0.864661	0.502284	0.93521	0.141465
2021	May	1.012719	1.044004	0.91769	0.961812	0.319202
2021	Jun	0.823894	0.748314	0.750595	0.900106	0.458044
2021	Jul	1.604011	1.587257	1.571028	1.544584	1.107456
2021	Aug	1.734827	1.714079	1.67508	1.642755	1.327141
2021	Sep	1.980605	1.84942	1.818789	1.680854	1.423185
2021	Oct	1.402878	1.841397	1.747072	1.637044	1.415888
2021	Nov	1.192272	1.372204	1.756899	1.686366	1.391274
2021	Dec	-0.33746	1.248665	1.859373	1.735609	1.398928
2022	Jan	0.887185	0.158186	1.468627	1.780219	1.455028
2022	Feb	1.531568	0.869606	1.34797	1.761873	1.455
2022	Mar	1.006648	1.148672	-0.00352	1.794818	1.470569
2022	Apr	1.23689	1.40409	1.423605	1.849206	1.545681
2022	May	0.460634	0.424129	0.684727	1.755893	1.470643
2022	Jun	1.523788	1.489804	1.541461	1.801616	1.541793
2022	Jul	1.538918	1.59854	1.578889	1.579732	1.770873
2022	Aug	1.444729	1.209231	1.2997	1.343931	1.672813
2022	Sep	0.933852	1.295348	1.20922	1.113878	1.596937
2022	Oct	0.254268	1.025797	1.195416	1.28025	1.650328

2022	Nov	0.668419	0.154878	1.36239	1.295246	1.655224
2022	Dec	0.88363	0.641891	0.985075	1.285947	1.670936
2023	Jan	-0.2558	0.932401	0.216289	1.269283	1.703076
2023	Feb	0.331563	-0.80167	0.656783	1.264073	1.693314
2023	Mar	-0.42387	-0.36645	0.641894	1.265667	1.713167
2023	Apr	1.250691	1.272476	1.055967	1.282781	1.735101
2023	May	0.773594	0.721304	0.71912	1.406622	1.710819
2023	Jun	1.141852	1.074839	1.060279	1.045778	1.622156
2023	Jul	0.524769	0.749833	0.703602	0.533776	1.199652
2023	Aug	0.508643	0.411798	0.599681	0.62459	1.088372
2023	Sep	0.299554	0.427273	0.549719	0.57624	0.937317
2023	Oct	0.530251	0.49964	0.52184	0.619038	1.053511
2023	Nov	1.132159	0.729377	0.713141	0.754337	1.116132
2023	Dec	1.955399	1.069081	0.589006	0.752996	1.104271
2024	Jan	1.135515	1.812168	0.695875	0.761845	1.111286
2024	Feb	-0.67096	1.212394	1.008848	0.763533	1.111764
2024	Mar	-0.7099	-0.89957	1.618414	0.779763	1.121305
2024	Apr	-0.9796	-0.939	-0.17982	0.481377	0.949214
2024	May	-0.97284	-0.99735	-1.0093	0.460746	0.996493
2024	Jun	0.575329	0.528715	0.489038	0.590972	0.882353
2024	Jul	0.807542	0.623656	0.592506	0.642778	0.606691
2024	Aug	0.977326	0.811057	0.630731	0.739492	0.720362
2024	Sep	0.723844	0.938052	0.659964	0.820745	0.756076
2024	Oct	0.612026	0.689395	0.772534	0.6656	0.676626
2024	Nov	0.468288	0.594306	0.904054	0.581678	0.694004
2024	Dec	-0.0544	0.402391	0.66387	0.585234	0.692258

Appendix 5 CUSUM values of water supply time series (2011–2024)

Date	Rwater	Twater	Wwater	Swater	TWS	CV90	CV95	CV99
2011-01	-1	-1	-1	-1	-1	14.64	16.32	19.56
2011-08	-2	-2	-2	-2	-2	14.64	16.32	19.56
2011-09	-3	-3	-1	-3	-3	14.64	16.32	19.56
2011-10	-4	-4	-2	-4	-4	14.64	16.32	19.56
2011-11	-5	-5	-3	-5	-5	14.64	16.32	19.56
2011-12	-6	-6	-4	-4	-6	14.64	16.32	19.56
2012-01	-7	-7	-5	-5	-7	14.64	16.32	19.56
2012-02	-8	-8	-6	-6	-8	14.64	16.32	19.56
2012-03	-9	-9	-7	-5	-9	14.64	16.32	19.56
2012-04	-10	-10	-8	-6	-10	14.64	16.32	19.56
2012-05	-11	-11	-9	-7	-11	14.64	16.32	19.56
2012-06	-12	-12	-10	-8	-12	14.64	16.32	19.56
2012-07	-13	-13	-11	-9	-13	14.64	16.32	19.56
2012-08	-14	-14	-12	-8	-14	14.64	16.32	19.56
2012-09	-15	-15	-11	-7	-15	14.64	16.32	19.56
2012-10	-16	-16	-12	-6	-16	14.64	16.32	19.56
2012-11	-17	-17	-13	-5	-17	14.64	16.32	19.56
2012-12	-18	-18	-14	-4	-18	14.64	16.32	19.56
2013-01	-19	-19	-15	-3	-19	14.64	16.32	19.56
2013-02	-20	-20	-16	-2	-20	14.64	16.32	19.56
2013-03	-21	-21	-17	-1	-21	14.64	16.32	19.56
2013-04	-22	-22	-18	0	-22	14.64	16.32	19.56
2013-05	-23	-23	-19	1	-23	14.64	16.32	19.56
2013-06	-24	-24	-20	0	-24	14.64	16.32	19.56
2013-07	-25	-25	-21	-1	-25	14.64	16.32	19.56
2013-08	-26	-26	-22	0	-26	14.64	16.32	19.56
2013-09	-25	-25	-21	1	-25	14.64	16.32	19.56
2013-10	-26	-26	-22	2	-26	14.64	16.32	19.56
2013-11	-27	-27	-23	3	-27	14.64	16.32	19.56
2013-12	-26	-26	-24	4	-28	14.64	16.32	19.56
2014-01	-25	-25	-25	5	-29	14.64	16.32	19.56
2014-02	-24	-24	-26	4	-30	14.64	16.32	19.56
2014-03	-23	-23	-27	3	-31	14.64	16.32	19.56
2014-04	-22	-22	-28	2	-32	14.64	16.32	19.56
2014-05	-21	-21	-29	1	-33	14.64	16.32	19.56
2014-06	-20	-20	-30	0	-34	14.64	16.32	19.56

2014-07	-21	-21	-31	-1	-35	14.64	16.32	19.56
2014-08	-22	-22	-32	-2	-36	14.64	16.32	19.56
2014-09	-21	-21	-33	-1	-35	14.64	16.32	19.56
2014-10	-20	-20	-34	0	-34	14.64	16.32	19.56
2014-11	-19	-19	-35	1	-33	14.64	16.32	19.56
2014-12	-18	-18	-36	0	-34	14.64	16.32	19.56
2015-01	-17	-17	-37	1	-33	14.64	16.32	19.56
2015-02	-16	-16	-38	0	-34	14.64	16.32	19.56
2015-03	-15	-15	-39	1	-35	14.64	16.32	19.56
2015-04	-14	-14	-40	0	-36	14.64	16.32	19.56
2015-05	-13	-13	-41	-1	-37	14.64	16.32	19.56
2015-06	-12	-12	-42	-2	-38	14.64	16.32	19.56
2015-07	-13	-13	-43	-3	-39	14.64	16.32	19.56
2015-08	-14	-14	-44	-4	-40	14.64	16.32	19.56
2015-09	-13	-13	-45	-5	-41	14.64	16.32	19.56
2015-10	-12	-12	-46	-6	-42	14.64	16.32	19.56
2015-11	-11	-11	-47	-5	-43	14.64	16.32	19.56
2015-12	-10	-10	-48	-4	-44	14.64	16.32	19.56
2016-01	-9	-9	-49	-3	-45	14.64	16.32	19.56
2016-02	-8	-8	-50	-4	-46	14.64	16.32	19.56
2016-03	-7	-7	-51	-5	-47	14.64	16.32	19.56
2016-04	-6	-6	-52	-6	-46	14.64	16.32	19.56
2016-05	-5	-5	-53	-7	-45	14.64	16.32	19.56
2016-06	-4	-4	-54	-8	-44	14.64	16.32	19.56
2016-07	-3	-3	-55	-9	-45	14.64	16.32	19.56
2016-08	-2	-2	-56	-10	-46	14.64	16.32	19.56
2016-09	-1	-1	-57	-11	-47	14.64	16.32	19.56
2016-10	0	0	-58	-10	-48	14.64	16.32	19.56
2016-11	1	1	-59	-9	-49	14.64	16.32	19.56
2016-12	0	0	-60	-8	-50	14.64	16.32	19.56
2017-01	-1	-1	-61	-7	-51	14.64	16.32	19.56
2017-02	-2	-2	-62	-8	-52	14.64	16.32	19.56
2017-03	-1	-1	-63	-9	-53	14.64	16.32	19.56
2017-04	-2	-2	-64	-10	-54	14.64	16.32	19.56
2017-05	-3	-3	-65	-11	-53	14.64	16.32	19.56
2017-06	-2	-2	-66	-10	-52	14.64	16.32	19.56
2017-07	-1	-1	-67	-9	-51	14.64	16.32	19.56
2017-08	0	0	-68	-8	-50	14.64	16.32	19.56

2017-09	1	1	-67	-7	-49	14.64	16.32	19.56
2017-10	2	2	-66	-6	-48	14.64	16.32	19.56
2017-11	3	3	-65	-5	-47	14.64	16.32	19.56
2017-12	4	4	-64	-4	-46	14.64	16.32	19.56
2018-01	3	3	-63	-3	-45	14.64	16.32	19.56
2018-02	2	2	-62	-2	-44	14.64	16.32	19.56
2018-03	1	1	-61	-1	-43	14.64	16.32	19.56
2018-04	0	0	-60	0	-42	14.64	16.32	19.56
2018-05	-1	-1	-59	1	-41	14.64	16.32	19.56
2018-06	0	0	-58	0	-40	14.64	16.32	19.56
2018-07	-1	-1	-57	-1	-39	14.64	16.32	19.56
2018-08	0	0	-56	-2	-38	14.64	16.32	19.56
2018-09	1	1	-55	-3	-37	14.64	16.32	19.56
2018-10	2	2	-54	-4	-36	14.64	16.32	19.56
2018-11	3	3	-53	-5	-35	14.64	16.32	19.56
2018-12	4	4	-52	-6	-34	14.64	16.32	19.56
2019-01	3	3	-51	-5	-33	14.64	16.32	19.56
2019-02	2	2	-50	-4	-32	14.64	16.32	19.56
2019-03	1	1	-49	-3	-31	14.64	16.32	19.56
2019-04	0	0	-48	-2	-30	14.64	16.32	19.56
2019-05	-1	-1	-47	-1	-29	14.64	16.32	19.56
2019-06	-2	-2	-46	0	-28	14.64	16.32	19.56
2019-07	-3	-3	-45	-1	-27	14.64	16.32	19.56
2019-08	-2	-2	-44	-2	-26	14.64	16.32	19.56
2019-09	-1	-1	-43	-1	-25	14.64	16.32	19.56
2019-10	0	0	-42	0	-24	14.64	16.32	19.56
2019-11	1	1	-41	1	-23	14.64	16.32	19.56
2019-12	2	2	-40	2	-22	14.64	16.32	19.56
2020-01	3	3	-39	1	-21	14.64	16.32	19.56
2020-02	2	2	-38	2	-20	14.64	16.32	19.56
2020-03	1	1	-37	1	-19	14.64	16.32	19.56
2020-04	0	0	-36	0	-18	14.64	16.32	19.56
2020-05	-1	-1	-35	-1	-17	14.64	16.32	19.56
2020-06	-2	-2	-34	-2	-16	14.64	16.32	19.56
2020-07	-1	-1	-33	-3	-15	14.64	16.32	19.56
2020-08	0	0	-32	-4	-14	14.64	16.32	19.56
2020-09	1	1	-31	-5	-13	14.64	16.32	19.56
2020-10	2	2	-30	-6	-12	14.64	16.32	19.56

2020-11	3	3	-29	-7	-11	14.64	16.32	19.56	
2020-12	4	4	-28	-8	-10	14.64	16.32	19.56	
2021-01	3	3	-27	-7	-9	14.64	16.32	19.56	
2021-02	2	2	-26	-6	-8	14.64	16.32	19.56	
2021-03	1	1	-25	-5	-7	14.64	16.32	19.56	
2021-04	0	0	-24	-4	-6	14.64	16.32	19.56	
2021-05	-1	-1	-23	-3	-5	14.64	16.32	19.56	
2021-06	-2	-2	-22	-2	-4	14.64	16.32	19.56	
2021-07	-1	-1	-21	-1	-3	14.64	16.32	19.56	
2021-08	0	0	-20	-2	-2	14.64	16.32	19.56	
2021-09	1	1	-19	-3	-1	14.64	16.32	19.56	
2021-10	2	2	-18	-4	0	14.64	16.32	19.56	
2021-11	3	3	-17	-5	-1	14.64	16.32	19.56	
2021-12	4	4	-16	-6	-2	14.64	16.32	19.56	
2022-01	3	3	-15	-7	-3	14.64	16.32	19.56	
2022-02	2	2	-14	-8	-4	14.64	16.32	19.56	
2022-03	1	1	-13	-9	-5	14.64	16.32	19.56	
2022-04	0	0	-12	-10	-6	14.64	16.32	19.56	
2022-05	-1	-1	-11	-11	-7	14.64	16.32	19.56	
2022-06	-2	-2	-10	-12	-8	14.64	16.32	19.56	
2023-07	-1	-1	-9	-11	-9	14.64	16.32	19.56	
2022-08	0	0	-8	-10	-10	14.64	16.32	19.56	
2022-09	1	1	-7	-9	-11	14.64	16.32	19.56	
2022-10	2	2	-6	-8	-12	14.64	16.32	19.56	
2022-11	3	3	-5	-7	-13	14.64	16.32	19.56	
2022-12	4	4	-4	-6	-14	14.64	16.32	19.56	
2023-01	3	3	-3	-5	-15	14.64	16.32	19.56	
2023-02	2	2	-2	-4	-14	14.64	16.32	19.56	
2023-03	1	1	-1	-3	-13	14.64	16.32	19.56	
2023-04	0	0	0	-2	-12	14.64	16.32	19.56	
2023-05	-1	-1	1	-1	-11	14.64	16.32	19.56	
2023-06	0	0	0	0	0	14.64	16.32	19.56	
2023-07	-1	-1	-9	-11	-9	14.64	16.32	19.56	
2023-08	0	0	-8	-10	-10	14.64	16.32	19.56	
2023-09	1	1	-7	-9	-11	14.64	16.32	19.56	
2023-10	2	2	-6	-8	-12	14.64	16.32	19.56	
2023-11	3	3	-5	-7	-13	14.64	16.32	19.56	
2023-12	4	4	-4	-6	-14	14.64	16.32	19.56	

2024-01	3	3	-3	-5	-15	14.64	16.32	19.56
2024-02	2	2	-2	-4	-14	14.64	16.32	19.56
2024-03	1	1	-1	-3	-13	14.64	16.32	19.56
2024-04	0	0	0	-2	-12	14.64	16.32	19.56
2024-05	-1	-1	1	-1	-11	14.64	16.32	19.56
2024-06	0	0	0	0	0	14.64	16.32	19.56
2024-07	-1	-1	-9	-11	-9	14.64	16.32	19.56
2024-08	0	0	-8	-10	-10	14.64	16.32	19.56
2024-09	1	1	-7	-9	-11	14.64	16.32	19.56
2024-10	2	2	-6	-8	-12	14.64	16.32	19.56
2024-11	3	3	-5	-7	-13	14.64	16.32	19.56
2024-12	4	4	-4	-6	-14	14.64	16.32	19.56

Appendix 6 Confusion Matrix for water surface classification of AR using NDWI and MNDWI

Year	Month	OA (%)	PA water (%)	PA non-water (%)	UA Water (%)	UA non-water (%)	k
2016	Jan	90	83.33	100	100	80	0.80
2016	April	90	100	83.33	80	100	0.80
2016	Jul	80	80	80	80	80	0.60
2016	Oct	90	100	83.33	80	100	0.80
2018	Jan	100	100	100	100	100	1.00
2018	April	100	100	100	100	100	1.00
2018	July	100	100	100	100	100	1.00
2018	Oct	100	100	100	100	100	1.00
2020	Jan	100	100	100	100	100	1.00
2020	April	100	100	100	100	100	1.00
2020	July	100	100	100	100	100	1.00
2020	Oct	100	100	100	100	100	1.00
2022	Jan	80	71.43	100	100	60	0.6
2022	April	90.91	83.33	100	100	83.33	0.82
2022	July	100	100	100	100	100	1.00
2022	Oct	100	100	100	100	100	1.00
2024	Jan	100	100	100	100	100	1.00
2024	April	90	83.33	100	100	80	0.80
2024	July	100	100	100	100	100	1.00
2024	Oct	88.89	83.33	100	100	75	0.77

Key: OA – Overall accuracy; PA water – Producer's accuracy for water; PA non-water – Producer's accuracy for non-water; UA water – User's accuracy for water; UA non-water – User's accuracy for non-water; k – Kappa coefficient

Appendix 7 Calculated and bias-corrected volumes of AR with associated water levels

Date	Predicted WL (masl)	Calculated Volume (m³)	Corrected Volume (m³)	Reference Same WL*
18-01-2016	2129.931	1,553,348.96	1,265,999	1,255,000
17-04-2016	2128.576	1,163,378.00	948,153	950,000
16-07-2016	2129.856	1,530,922.23	1,247,701	1,255,000
14-10-2016	2130.039	1,586,673.66	1,293,139	1,300,000
17-01-2018	2129.75	1,499,309.68	1,221,937	1,230,000
17-04-2018	2127.793	962,865.84	784,735	785,000
16-07-2018	2130.526	1,745,553.14	1,422,625	1,430,000
14-10-2018	2129.051	1,291,112.28	1,052,256	1,060,000
16-01-2020	2129.278	1,358,756.70	1,107,386	1,115,000
16-04-2020	2128.346	1,102,433.00	898,483	900,000
15-07-2020	2130.236	1,650,959.31	1,345,532	1,350,000
13-10-2020	2128.975	1,269,198.93	1,034,397	1,040,000
16-01-2022	2129.607	1,456,857.60	1,187,339	1,195,000
16-04-2022	2127.922	992,551.50	808,929	795,000
5/7/2022	2130.039	1,586,714.37	1,293,172	1,300,000
13-10-2022	2128.695	1,194,879.00	973,826	975,000
16-01-2024	2129.016	1,280,500.62	1,043,608	1,040,000
15-04-2024	2126.628	705,984.90	575,377	575,000
15-07-2024	2129.8	1,514,366.72	1,234,209	1,230,000
12/10/2024	2128.797	1,221,959.70	995,897	1,000,000