MEKELLE UNIVERSITY

School of Earth Sciences

HYDROMETEOROLOGICAL STATIONS DISTRIBUTION AND PARAMETERS TREND IN TIGRAY

MSC. THESIS

BY

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DECLARATION

This is to certify that the thesis entitled "HYDROMETEOROLOGICAL STATIONS DISTRIBUTION AND PARAMETER TRENDS IN TIGRAY" is submitted in partial fulfilment of the requirements for the Degree of Master of Science in Hydrogeology to the School of Earth Science, Mekelle University.

This thesis has been carried out by Ms. Mebrat Amare Suhul, ID No. CNSC/PS4004/09, under the supervision of Dr. Ermiyas Hagos (Principal Advisor) and Dr.Tesfamichael Gereyohannes (Co-Advisor). It is an original and authentic work conducted during the 2017 E.C./2025 G.C. academic year. The contents of this thesis have not been previously presented or published for the award of any degree, and all sources of materials used have been duly acknowledged and properly referenced.

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We, the undersigned, members of the Board of Examiners, have evaluated the thesis presented by **Ms. Mebrat Amare Suhul**, entitled **"Hydrometeorological Stations Distribution and Parameters Trend in Tigray,"** submitted in partial fulfillment of the requirements for the Degree of Master of Science in Hydrogeology. We confirm that the candidate's oral presentation and the final thesis manuscript have been examined and found to be acceptable. This thesis is hereby approved.

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ABSTRACT

The effective management of water resources in Ethiopia's topographically complex Tigray Region is critically dependent on a robust hydro-meteorological observation distribution. However, the existing distribution suffers from severe deficiencies in spatial coverage and operational integrity, creating significant uncertainty for water resource planning. This thesis provides a systematic evaluation of the hydro-meteorological distribution in Tigray, analyzes long-term trends in key climatic and hydrological parameters, and proposes a data-driven framework for its optimization.

The study employed a mixed-methods design, integrating Geographic Information Systems (GIS) to assess spatial adequacy against World Meteorological Organization (WMO) standards, non-parametric statistical tests (Mann-Kendall, Sen's Slope) to analyze long-term (1960–2024) data, and field verification to assess operational status.

Results reveal a network in critical failure. The conventional station network meets only 51% of the WMO minimum requirement, with precipitation stations achieving just 17% of the necessary coverage. This spatial gap is compounded by an operational collapse, with only 13% of the required stations currently functional, creating vast unmonitored areas. The streamflow gauging network is similarly sub-optimal, while the modern Automatic Weather Station (AWS) network is nascent. Trend analysis identified no significant long-term change in regional rainfall or streamflow.

In conclusion, the existing monitoring infrastructure is structurally imbalanced, spatially biased, and operationally crippled, rendering it unfits to support reliable water resource assessment or climate-resilient development. This thesis culminates in a strategic roadmap with prioritized recommendations for the phased expansion and modernization of the network to build a scientifically robust observational foundation for the region.

Keywords: Hydro-meteorological distribution, distribution optimization, Gap analysis, Trend analysis, Water resource management, Tigray, Ethiopia.

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LIST OF ABBREVIATIONS AND ACRONYMS

AWS- Automatic Weather Stations

DEM - Digital Elevation Model

E – Easting, N - Northing

FAO - Food and Agriculture Organization

ITCZ - Inter-Tropical Convergence Zone

IMO- International Meteorological Organization

M – Meters

m.a.s.l - Mean above sea level

NMA- National Meteorological Agency

(NMHSs)- National Meteorological and Hydrological Services

WMO -World Meteorological Organization

1 INTRODUCTION

1.1 Background

Adequate and accurate hydrometeorological data, according to Feloni et. al (2018) are very important for performing a range of hydrologic purposes, including water resources management, assessment of the impacts of climate change, and flood forecasting and warning. The rational prevention of natural disasters, such as floods and droughts, is strongly connected with a forecasting technology which cannot be achieved without hydrometeorological observations. The existence of an optimum network of instruments is required in order to be able to model, predict, and plan for catastrophic events which have obvious negative impacts on public health and socioeconomic aspects; however, this entails large installation and operational costs. Hydrometeorological stations are equipped with instruments that measure a wide range of meteorological and hydrological variables including precipitation, humidity, wind speed and water levels. These stations are strategically located across different geographical regions to capture local weather patterns and hydrological processes accurately. By continuously monitoring these parameters, hydrometeorology stations provide valuable data for weather forecasting, flood forecasting and drought monitoring. Analysis of hydrometeorological records enables scientists to understand the complex interaction between the atmosphere, hydrosphere and the lithosphere. Furthermore, analysis of these hydrometeorological data enables researchers to identify trends and patterns that help understand climate change, water availability and ecosystem dynamics.

Building on this foundation, effective water resource management, climate monitoring, and disaster risk reduction are fundamentally dependent on the availability of reliable hydrometeorological data. Station-based ground observations are widely regarded as the most accurate source for localized analysis, providing the high-resolution measurements essential for calibrating and validating remotely sensed data (WMO, 2010). The precision and reliability of in-situ measurements are particularly vital in regions with complex topography or distinct microclimates, where satellite-based systems may be compromised by signal obstruction or atmospheric interference (Bartsotas et al., 2018; Gebremedhina et al., 2021). Consequently, a well-maintained network of ground stations remains an indispensable component of modern environmental monitoring infrastructure.

However, despite their critical importance, hydrometeorological station networks worldwide often suffer from significant deficiencies. Global assessments have identified common challenges, including inadequate spatial coverage, uneven distribution of stations, and inconsistencies in data quality arising from suboptimal siting and infrastructure (Briceño et al., 2021). These limitations compromise the integrity of environmental analyses and undermine evidence-based decision-making. The establishment of a robust and strategically designed observation network is therefore a prerequisite for sustainable land and water management, particularly in nations prone to hydro-climatic hazards.

Historically, the foundation of formal meteorological observation is rooted in international collaboration, beginning with the International Meteorological Organization (IMO) in 1873, which evolved into the World Meteorological Organization (WMO) in 1950. As a specialized agency of the United Nations, the WMO establishes the technical standards and guidelines for the planning, instrumentation, and operation of meteorological networks globally. In a similar vein, in Ethiopia, the establishment of meteorological stations began in the 19th century, initially driven by religious missionaries and European travelers. A more systematic expansion occurred later, primarily to support aviation safety. Over time, the network grew to serve agricultural planning and river basin master plan studies, a process that was largely uncoordinated until the establishment of the National Meteorological Agency (NMA) in 1980. The NMA has since overseen a centrally coordinated expansion, driven further by the need for national drought monitoring (NMA, 2020).

Specifically, within the Tigray Region of Ethiopia, meteorological observations commenced in 1960 at Mekelle Airport. As of 2020, the NMA manages a national network of 1,539 functional stations, which are categorized according to WMO guidelines as Principal (Class I), Synoptic (Class II), Ordinary (Class III), and Precipitation (Class IV) stations. While all station types contribute valuable data, it is crucial to note that the effective management of water resources requires a holistic approach that integrates both atmospheric and terrestrial water cycle measurements.

Beyond just rainfall and temperature, hydrometeorological analysis extends to include critical hydrological variables, most notably streamflow. Streamflow data are indispensable for understanding the intricate relationship between climate inputs and hydrological responses, such as runoff and river discharge (Chu et al., 2020; Adnan et al., 2020). These data are vital for the operational management of water supply systems, flood and drought mitigation, and the long-term reconstruction of water availability patterns (Horner et al., 2022; Mohammadi et al., 2020).

Consequently, the sustainable management and strategic planning of water resources are critically reliant on the availability of accurate and continuous streamflow data. However, hydrological monitoring networks are facing a decline globally, a challenge particularly acute in developing nations due to persistent financial and logistical constraints.

This critical issue is exemplified by the situation in Ethiopia. The national streamflow network, managed by the Ministry of Water and Energy (MoWE), comprises 541 gauging stations, with only 490 being operational. This number falls considerably short of the World Meteorological Organization (WMO) minimum recommendation benchmark of 674 to 1796 stations for the country. This deficiency is compounded by a systemic problem: hydrological agencies often lack the research-based evidence needed to articulate the value of monitoring activities in socio-economic terms, making it difficult to secure sustained funding.

Given this context, merely assessing the physical distribution of stations is insufficient. To develop resilient water management and climate adaptation strategies, it is crucial to conduct a comprehensive trend analysis of key hydrometeorological parameters. Specifically, analyzing long-term historical data for trends and variability in rainfall, temperature, and streamflow provides critical insights into how the regional climate is changing and its subsequent impact on water availability. This analytical step is essential for moving beyond a static assessment of the network to a dynamic understanding of the resources it is meant to monitor. Ultimately, improved collaboration between meteorological science and water management, informed by robust trend analysis, is vital for a sustainable future (WMO-No. 168, 2009).

1.2 Problem Statement

The effective management of water resources is inseparably linked to the availability and quality of hydro-meteorological data. As the World Meteorological Organization (WMO) emphasizes, planning water resource systems relies on long-term climate information, while their daily operation depends on current weather data. A comprehensive understanding of a region's water balance—encompassing precipitation, temperature, and river flow—is therefore a prerequisite for sustainable development. Inadequate information on any of these elements severely constrains the ability to accurately assess and allocate available water resources (WMO, 2010).

This fundamental dependency on robust data is particularly acute in the Tigray Region of Ethiopia. The region is characterized by significant topographic complexity and is subject to large spatial and temporal variations in temperature and precipitation due to its geographical location and proximity to major climate drivers (Fazzini et al., 2015). In such variable terrain, which includes both highlands and lowlands, a dense network of ground-based monitoring stations is essential for capturing the true basin-wide hydro-meteorological patterns and avoiding significant assessment errors (Bewket & Conway, 2007; Mekasha et al., 2014).

Despite this critical need, the existing hydro-meteorological monitoring network in Tigray is fundamentally inadequate to meet the region's scientific and planning requirements. Recent assessments confirm that the network suffers from severe, multifaceted deficiencies (Haile et al., 2022; Taye et al., 2023). These problems include:

1. **Insufficient Density and Uneven spatial distribution:** The number of stations is well below international recommendations, and their placement leaves critical areas, particularly in mountainous and remote lowland zones, entirely unmonitored.
2. **Poor Operational Integrity:** A significant portion of existing stations are non-functional or suffer from persistent data gaps due to equipment failure, lack of maintenance, and logistical constraints.
3. **Lack of Data Standardization:** The data that are collected often lack consistency in observed parameters and formats, limiting their interoperability and utility for comprehensive regional analyses.

While previous studies have acknowledged data challenges in Ethiopia, a critical research gap persists for the Tigray Region. Specifically, there has been no systematic evaluation of the existing network's adequacy against WMO standards, nor an optimization analysis guided by the region's unique topographic and climatic characteristics. Moreover, a significant lack of region-specific research concurrently assesses both the operational functionality of existing stations and analyzes the long-term trends of key hydrometeorological parameters from available fragmented records.

Consequently, this confluence of an inadequate network and a gap in analytical research creates significant uncertainty, which directly undermines strategic water resource planning, climate change adaptation efforts, and the development of reliable early warning systems. Without a foundational, evidence-based assessment of the current network and a clear roadmap for its optimization, decision-making will continue to be based on fragmented and potentially unrepresentative data. Therefore, this thesis aims to address this critical need by evaluating the existing hydro-meteorological network in Tigray and proposing an optimized configuration that can effectively support climate-resilient water management for the region.

1.3 Research Questions

How can the hydro-meteorological monitoring distribution in Tigray be systematically evaluated and optimized to provide the necessary data for effective and climate-resilient water resource management?

To address this primary question, the research will answer the following four specific and sequential sub-questions:

1. What is the current state of the hydro-meteorological monitoring network in Tigray regarding station distribution, data availability, and adherence to established quality standards?
2. What are the significant spatial and temporal trends in key meteorological and hydrological parameters within the Tigray region over recent decades?
3. What constitutes an optimized hydro-meteorological monitoring network for Tigray in terms of station density, location, and type, according to geostatistical analysis and World Meteorological Organization (WMO) guidelines?
4. How do the identified gaps and deficiencies in the current hydro-meteorological data network impact the reliability of water resource assessment, strategic planning, and academic research in Tigray?

1.4 Objectives

1.4.1 General Objective

The main objective of the study is to evaluate the hydro metrological stations (their quantities, standards and distribution) and analyze key climatic and hydrological trends in Tigray, with the ultimate aim of providing an evidence-based framework for network optimization to support sustainable water resource management.

1.4.2 Specific Objective

- To assess the hydrometeorological stations in terms of temporal and spatial coverage, completeness of parameters.
- To determine the optimum number, type, geographic location of the meteorological station network in Tigray.
- To analyse the spatial variation and temporal trend of the hydrometeorological parameters in Tigray.
- To investigate the relationship between observed trends in climatic variables (precipitation, temperature) and hydrological response (streamflow).

1.5 Scope of the study

This study provides a systematic evaluation of the hydro-meteorological monitoring infrastructure within the Tigray Region of northern Ethiopia. The research is thematically focused on three core components: a comprehensive assessment of the existing station network, a statistical analysis of long-term hydro-climatic trends, and the development of an evidence-based design for an optimized network.

Geographically, the study is delimited to the administrative boundaries of the Tigray Region, located between latitudes 12°–15° N and longitudes 36°30'–40°30' E, an area of approximately 52,610 km^2.

Analytically, the scope includes the evaluation of both meteorological and hydrological stations based on their spatial density, operational status, and the completeness of observed parameters. This assessment will be benchmarked against World Meteorological Organization (WMO) guidelines, while also incorporating the region's unique topographic and climatic characteristics.

The research will analyze historical time-series data for key variables, including precipitation, temperature, and streamflow, to identify significant temporal trends and spatial patterns. This analysis will be conducted using a combination of statistical methods and geospatial tools, such as Geographic Information Systems (GIS).

Finally, it is important to define the delimitations of this study. While the research will propose an optimized network configuration, the physical implementation, detailed engineering design, and associated cost-benefit analysis fall outside its scope. The hydrological analysis will focus on trend detection and statistical relationships rather than complex, process-based catchment modeling. The study's primary output is a technical and data-driven framework intended to inform, rather than execute, future water resource planning and infrastructure investments in the region.

1.6 Significance of the study

The findings of this research are expected to make substantial contributions to water resource management, scientific knowledge, and regional policy in Tigray, a region were water scarcity and climate variability present persistent threats to socio-economic development. At a practical level, this study addresses a critical information gap that currently constrains effective water management. By providing a rigorous evaluation of the existing monitoring network and delivering an evidence-based design for its optimization, the research offers a foundational tool for decision-makers. The trend analyses and interpolated spatial maps of key hydro-climatic variables will directly support more accurate water availability assessments, drought monitoring, and agricultural planning. This moves the basis of decision-making from assumption-based to evidence-based, which is vital for building climate resilience in a vulnerable region. In addition to these practical applications, this research contributes a valuable and much-needed baseline assessment of the hydro-meteorological conditions in Tigray. The analysis of long-term data trends provides crucial insights into the regional impacts of climate change, while the evaluation of the station network quantifies the data uncertainty that underpins previous and future scientific studies. Furthermore, the methodological framework, which integrates WMO standards, geospatial analysis, and climatic considerations, establishes a robust and replicable approach for similar assessments in other data-scarce regions with complex topography. Consequently, the study's findings have direct and actionable policy implications. By identifying specific gaps and proposing an optimized network, this research provides the technical justification needed to guide and prioritize strategic investments in hydro-meteorological infrastructure. The results can inform the development of regional climate adaptation strategies, support national development goals, and strengthen the case for modernizing data collection and dissemination systems. Ultimately, this thesis serves as a foundational blueprint for building the observational capacity required for long-term environmental sustainability and economic security in Tigray.

2 DESCRIPTIONS OF THE STUDY AREA

2.1 Location and Accessibility

The Tigray region, located in northern Ethiopia between latitudes 12°-15° N and longitudes 36°30' - 40°30' E, spans an area of approximately 52,610 square kilometres. Tigray shares borders with Eritrea to the north, Sudan to the west, the Amhara Regional State to the southwest, and the Afar Regional State to the east. The research is conducted across 109 districts within the Tigray region: The capital city of Tigray, Mekelle, is situated approximately 770 kilometres from Addis Ababa, the capital of Ethiopia (Figure 1). The Tigray regional state is accessible through the all- weather Asphalt roads running Addis Ababa – Dessie-Alamata, Addis Ababa – Semera- Mekelle, Adddi Ababa Gonder –Mia Tsebri and Addis Ababa- Gonder Humera. Most meteorological stations within the study area are accessible via asphalt roads from the capital city, Mekelle, to the major zones, including Adigrat, Axum, Shire, Humera, and Maichew. Similarly, most stations located in wereda administrative centers are also connected by asphalt roads. In contrast, stations situated within Tabia (local) administrative areas are primarily accessible by dry-weather roads.

2.2 Physical and Environmental Setting

2.2.1 Climate

The climate of the Tigray Region is complex, governed primarily by the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ) and profoundly modulated by the region's diverse and rugged topography (Beltrando & Camberlin, 1993). This interaction results in significant spatial and temporal variability in rainfall and temperature, causing the region's climate to be overwhelmingly dry, with quantitative classification confirming that the majority is semi-arid (81.46%) or arid (16.91%), and only a small fraction (1.63%) is dry sub-humid (Haftom et al., 2019). The region exhibits two principal rainfall regimes: the western and central parts predominantly experience a uni-modal pattern with a single, concentrated rainy season known as Kiremt (June to early September), while the southern and eastern highlands typically experience a bi-modal pattern that includes both the main Kiremt rains and a shorter, secondary Belg season (March to May).

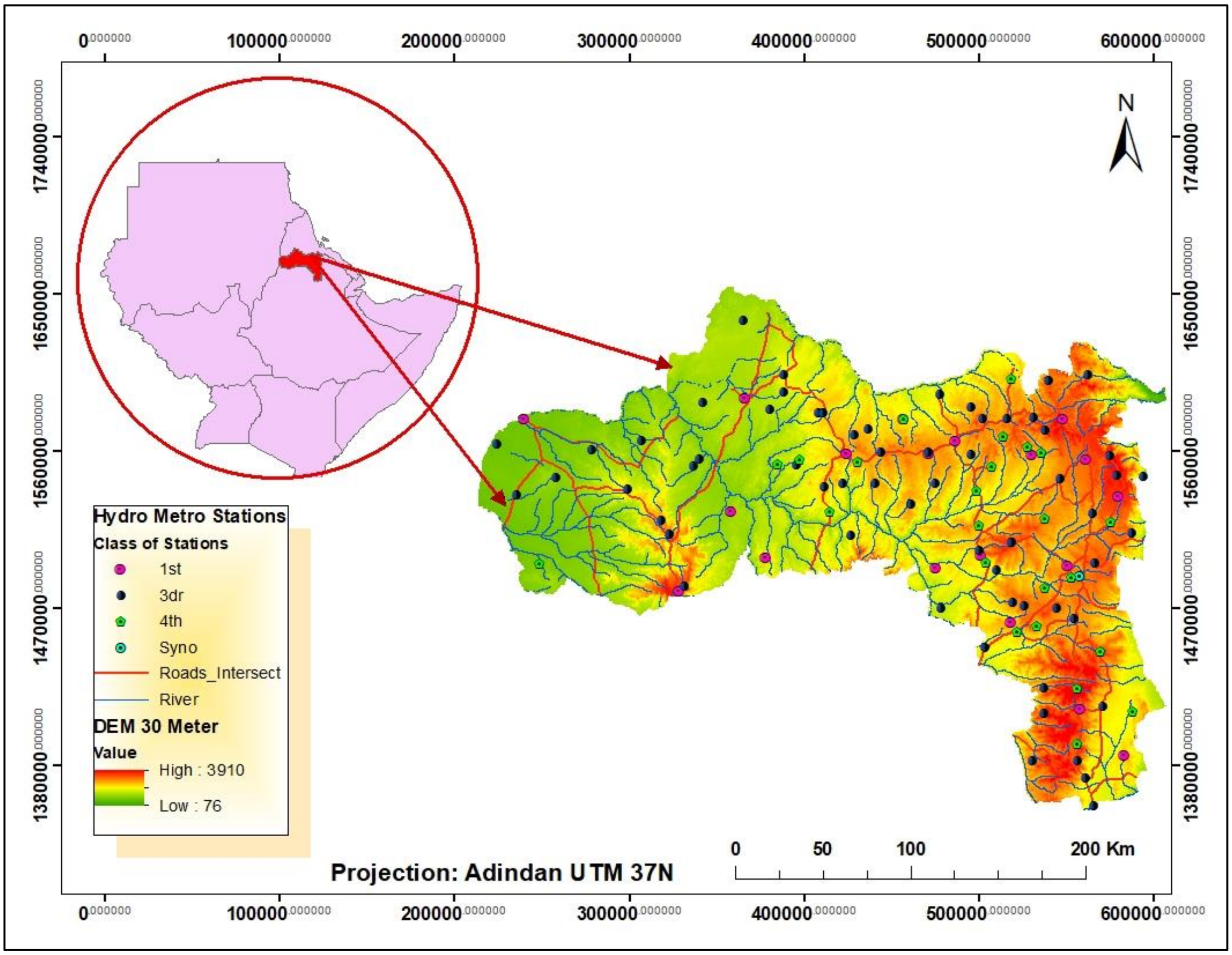


Figure 1. Location Map of the study area, the Tigray Region

These rainy seasons are separated by a long dry period called Bega, which extends from October to January. Further classification of the study area's climate is based on the Traditional Ethiopian Agro-Climatic Zonation system, which establishes a strong correlation between altitude and temperature and is highly relevant for Ethiopia's topographically diverse landscape (Hurni, 1998). Based on elevation data, five distinct agro-climatic zones were identified within the study area, which can be described in order of increasing elevation. The Tropical/Desert (Kola) zone encompasses the lowest elevations (below 500 to 1500 meters), characterized by hot and arid to semi-arid conditions, and is geographically dominant in the western portion of the study area. Adjacent to this is the Sub-tropical (Woina Dega) zone, situated at mid-altitudes between 1500 and 2300 meters. The Temperate (Dega) zone represents the cool highlands, found at elevations from 2300 to 3300 meters in the eastern and central-southern mountain ranges. Finally, the Afro-

Alpine (Wurch) zone occupies the highest mountain peaks at altitudes exceeding 3300 meters, existing as a cold, high-altitude moorland ecosystem in small, isolated patches on the highest massifs in the eastern part of the region.

2.2.2 Topography and Physiography

The topography of the Tigray Region is a defining feature of its physical landscape, exhibiting dramatic variations in elevation that fundamentally control the region's climate, hydrology, and land use patterns. Figure 2. presents the Digital Elevation Model (DEM) for the study area, which shows an elevation range spanning from as low as 76 meters above sea level in the western lowlands to a maximum of 3910 meters in the south-eastern highlands. The map reveals a clear and significant topographic gradient, with elevation generally increasing from west to east. This gradient effectively divides the region into three distinct topographic zones, which align closely with the slope classifications identified previously.

The Western Lowlands: The western part of Tigray is characterized by expansive, low-lying plains and plateaus, with elevations predominantly below 1500 meters (shown in green). This area corresponds directly to the land classes identified as having 'Level' and 'Gentle' slopes, which collectively account for approximately 38% of the region's total surface. These relatively flat lands are the agricultural heartland of the region but are also subject to the highest temperatures.

The Central Highlands: Moving eastward, the landscape transitions into a vast, highly dissected central highland plateau, where elevations typically range from 1500 to over 2500 meters (shown in yellow and light orange). This zone, which constitutes the largest portion of the study area, is characterized by a complex network of hills, valleys, and tablelands. Spatially, it aligns with the areas dominated by 'Moderate' and 'Strong' slopes, which together cover over 45% of the region.
The Eastern Escarpment and Mountain Ranges: The eastern and south eastern boundaries of the region are defined by rugged and imposing mountain ranges and a steep escarpment. It is here that the highest elevations are found, frequently exceeding 3000 meters (shown in deep orange and red). This terrain directly corresponds to the areas classified with 'Very Strong' and 'Extreme' slopes, which, while covering only 16% of the land area, represent the most topographically extreme and inaccessible parts of Tigray.

This pronounced topographic heterogeneity is of paramount importance to this study. The significant elevation range creates strong climatic gradients, particularly in temperature and orographic precipitation. Furthermore, the interplay between elevation and slope governs hydrological processes such as runoff generation, river network formation, and soil erosion, while also posing significant challenges to the establishment and maintenance of a representative hydro-meteorological monitoring network.

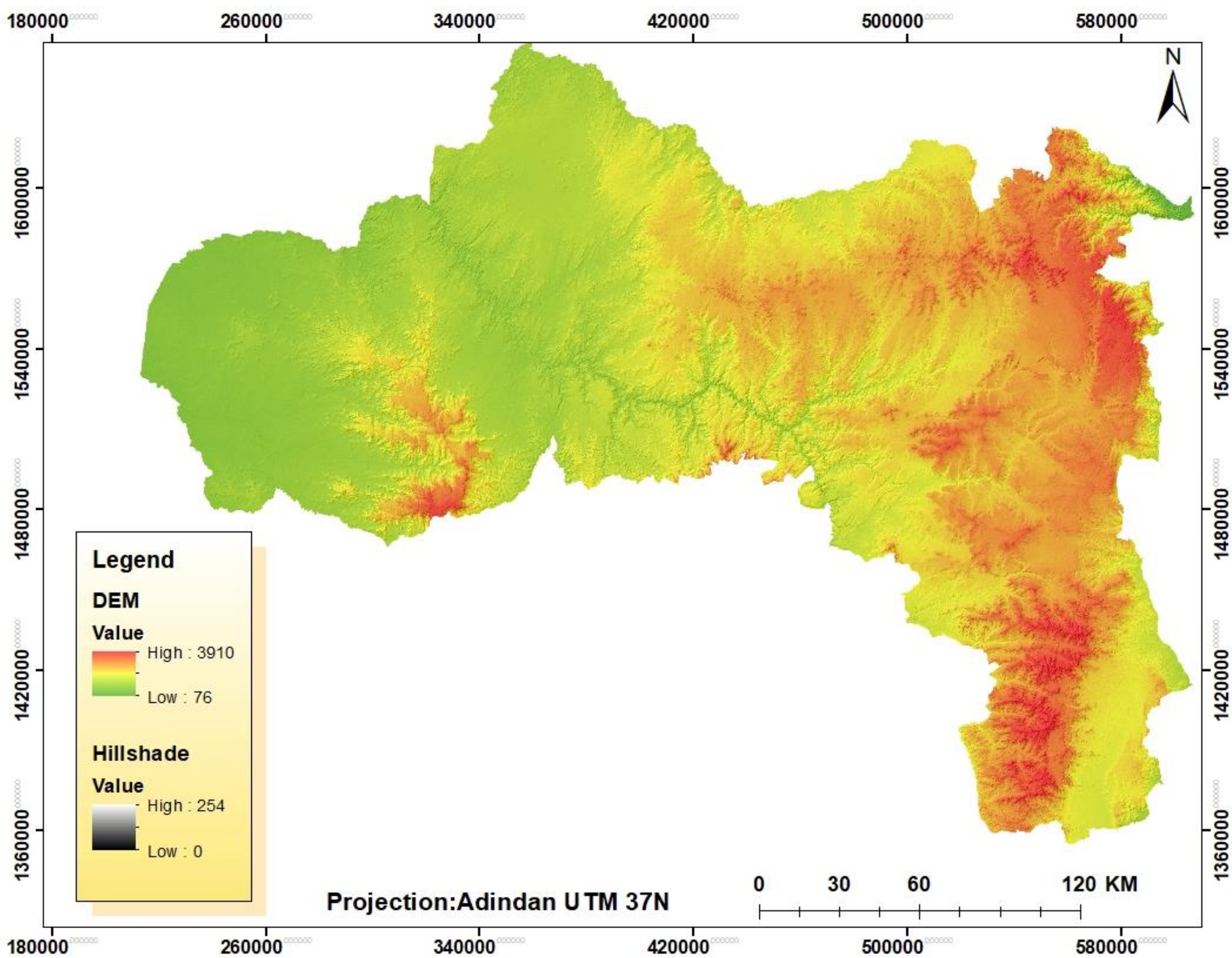


Figure 2: Topographic map of Tigray Region

2.2.3 Slope

The topography of the Tigray Region is highly complex and heterogeneous, a critical factor influencing its hydro-climatic characteristics and water resource dynamics. Figure 3 illustrates the spatial distribution of slope, derived from a Digital Elevation Model (DEM), while Table1 provides a quantitative breakdown of the slope classifications across the study are

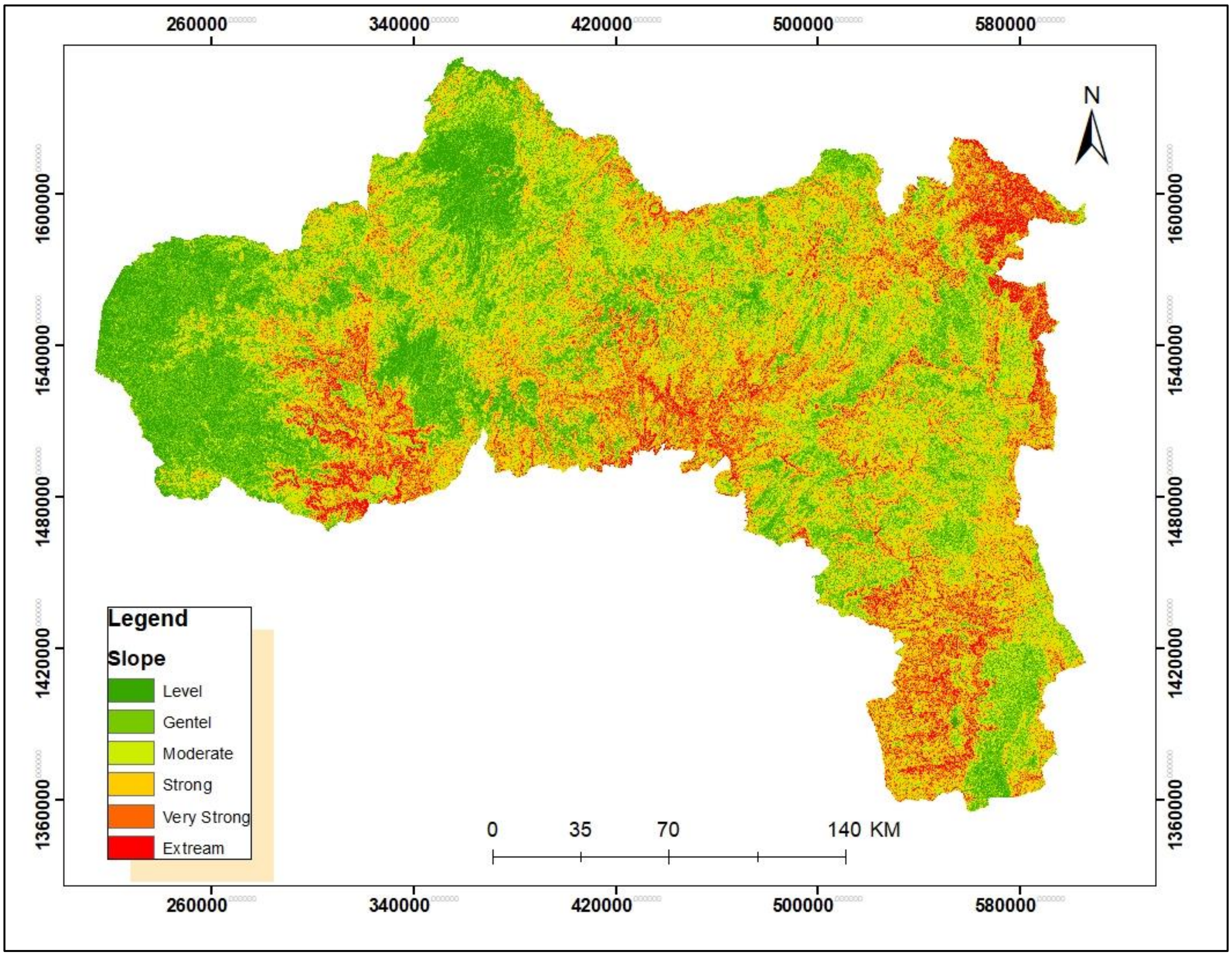


Figure 3. Slope map of Tigray classified based on FAO standard.

Table 1: Slope Classification and Areal Coverage in the study area Tigray

NO	Slope Classification (°)	Slope Classification	Coverage Area (KM²)	Weighted (%)
1	0-2	Level	7367.271	14.00359
2	2-5	Gentle	12756.86	24.24803
3	5-10	Moderate	11662.63	22.16813
4	10-20	Strong	12245.38	23.2758

5	20-30	Very Strong	5822.639	11.06758
6	>30	Extreme	2755.106	5.23686

A visual analysis of the map reveals a pronounced east-west topographic gradient. The western part of the region is predominantly characterized by flatter terrain. Quantitatively, as detailed in Table1, 'Level' and 'Gentle' slopes (0-5°) collectively account for approximately 38% of the region's total land area, corresponding to the extensive lowland plains and plateaus visible on the map.

In stark contrast, the majority of the landscape (over 60%) is defined by more rugged terrain. 'Moderate' (5-10°) and 'Strong' (10-20°) slopes are the most widespread of these categories, together covering over 45% of the region. These slopes form the complex topography of the central highlands. Most critically, areas classified as 'Very Strong' and 'Extreme' (>20°), while constituting a smaller portion of the total area (approximately 16% combined), are spatially concentrated along the eastern escarpment and in the deeply incised river valleys of the south-central highlands.

This quantitative and spatial distribution of slope is of fundamental importance to this study. The prevalence of steep gradients promotes rapid surface runoff, increases soil erosion potential, and influences groundwater infiltration rates. Furthermore, this rugged terrain contributes to the formation of distinct microclimates and poses significant logistical challenges for the placement and maintenance of hydro-meteorological monitoring stations. Therefore, a comprehensive understanding of the region's slope distribution is essential for evaluating the existing monitoring network and for proposing an optimized design that can adequately capture this spatial heterogeneity

2.2.4 Soil

The soil profile of the Tigray Region is a complex mosaic shaped by the interplay of varied parent geology, rugged topography, a semi-arid to sub-humic climate, and a long history of agricultural land use. The region's major soil groups can be broadly categorized based on their agricultural potential and their prevalence across different agro-ecological zones. Figure 4 illustrates the major soil groups.

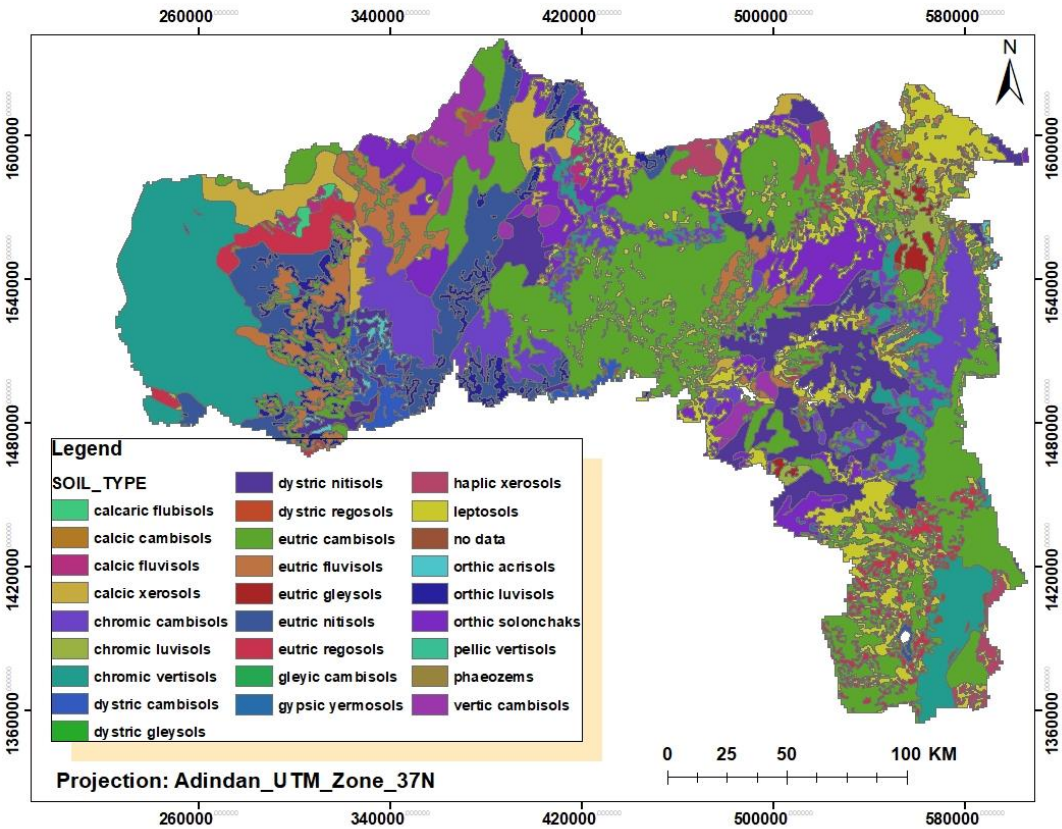


Figure 4 : Soil Map of Tigray (Ministry of Agriculture of Ethiopia 2019) 1:200 000 scale.

2.2.5 Geological and Structural setting

The Tigray Region is geologically diverse, representing a significant portion of the northern Ethiopian highlands. The region's geology spans from the Precambrian basement complex to Cenozoic volcanic formations, with a well-defined stratigraphic succession. The area lies within the broader East African Orogen, influenced by the convergence and later separation of the Arabian and African plates, which played a major role in shaping its complex structural and lithological setting. The Precambrian basement, part of the Arabian-Nubian Shield, consists of deformed and metamorphosed rocks such as schists, gneisses, and granites, dating back to 830–650 Ma. Overlying this basement are Paleozoic to Mesozoic sedimentary formations, including the Enticho and Adigrat sandstones, Edaga Arbi Glacials, Antalo limestones, and Agula shales. These units reflect environments ranging from glacial deposition to shallow marine conditions (Beyth, 1972; Bosellini et al., 1997).

The Cenozoic volcanic rocks, dominated by flood basalts (Trap series), Mekelle Dolerites, and Axum-Adwa plugs, mark extensive volcanic activity during the Tertiary period. These formations are especially prominent in the Tekeze River basin and around Mekelle. Structurally, Tigray is affected by three major tectonic systems: (1) Neoproterozoic thrusts and folds from the East–West Gondwana collision, (2) NW–SE fault systems related to the breakup of Gondwanaland, and (3) N–S to NNW–SSE trending faults linked to the development of the Afar Depression during the Miocene to present (Corti, 2009; Audin et al., 2004). These structures control the orientation of valleys, river basins, and lithological boundaries, making Tigray one of the most geologically dynamic regions in Ethiopia. Figure 5 illustrates the Geological Map of Tigray.

2.2.6 Land use land cover

The land use and land cover (LULC) map of the Tigray region (Figure 6) offers significant insights into the study area's environmental landscape. Complementing this visual representation, the data presented in Table 2 quantitatively confirms and provides a more detailed understanding of the LULC distribution.

Dominant Landscape Features: The region is overwhelmingly dominated by a trio of interconnected land cover types. Shrubland is the single largest class, covering 20,529.90 km^2 (39.83%). This is closely followed by Cultivation at 15,010.28 km^2 (29.12%) and Grassland at 11,658.75 km^2 (22.62%). Together, these three classes constitute 91.57% of the entire landscape. This numeric evidence strongly supports the visual impression of a region primarily defined by agriculture and livestock grazing, where natural vegetation has been modified into a mix of farmland, pasture, and secondary shrub growth.

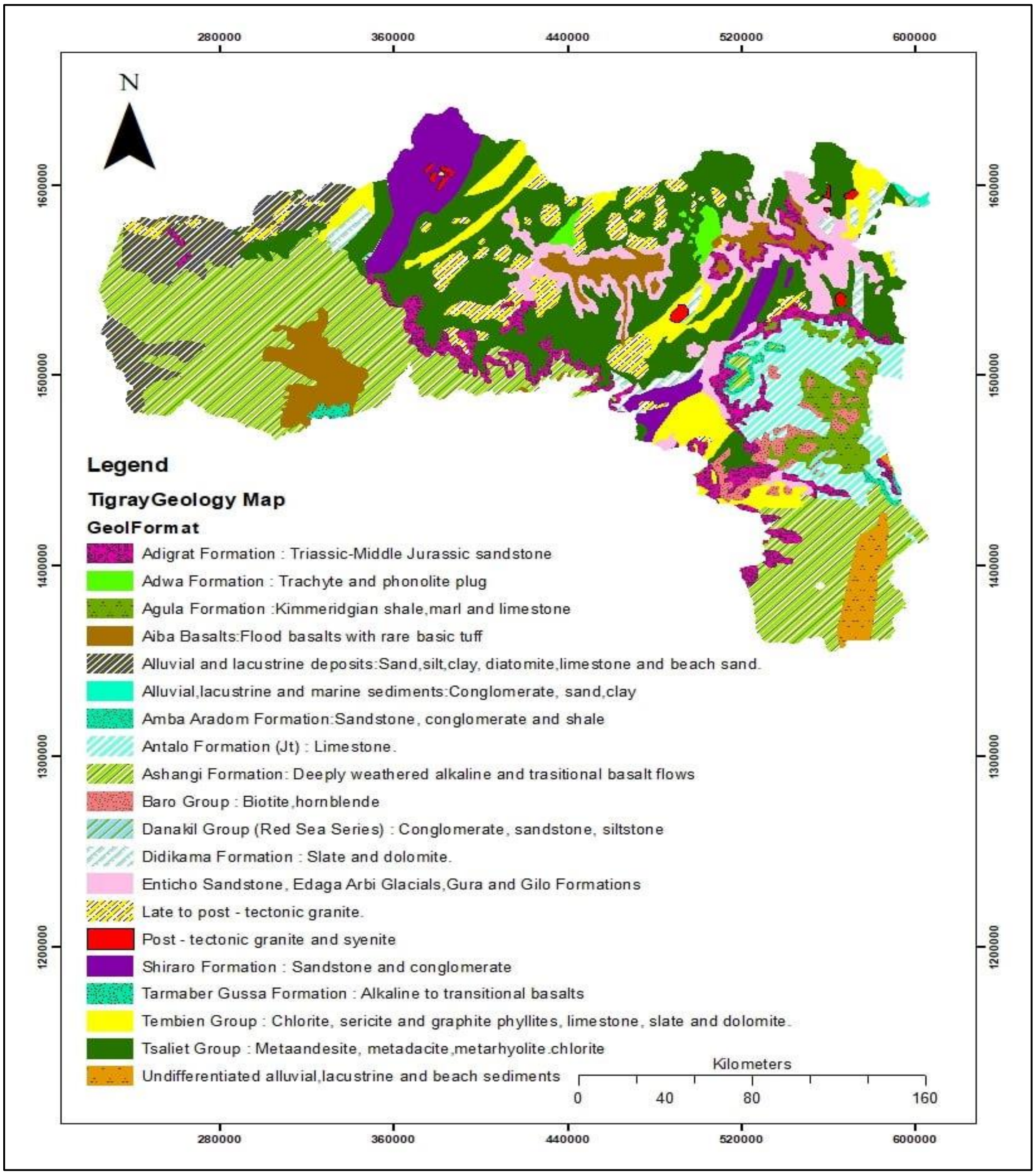


Figure 5: Geological Map of Tigray (Geological Survey of Ethiopia 2005.) 1:250 000 scale

Secondary Land Covers: Land covers with a moderate but still significant presence include Woodland (4.53%) and Bare land (3.44%). These are visible on the map as substantial patches but are not the primary features of the landscape. They likely represent open woodlands, degraded areas, and rocky outcrops scattered throughout the region.

Scarce and Trace Land Covers: A striking finding from the data is the extreme scarcity of several critical ecosystems and land use types.

Natural Forest covers a critically low 0.26% of the area. This minuscule percentage highlights the extensive historical deforestation in the region.

Water bodies are also very limited, making up only 0.17% of the surface, which aligns with the near-absence of large lakes or rivers on the map.

Land covers associated with specialized conditions or intensive development are virtually non-existent. Urban areas (0.008%), Plantations (0.007%), Afro-alpine zones (0.016%), and Wetlands (0.002%) collectively make up less than 0.04% of the total area. This indicates a landscape with low urbanization and a near-total absence of large-scale plantations or wetlands. Figure 7: see Land use land cover map of Tigray region.

Table 2: Area and Percentage Distribution of Land Use/Land Cover in Tigray

ID	LULC Class	Area (km²)	Coverage (%)
2	Cultivation	15010.28	29.121%
3	Grassland	11658.75	22.619%
4	Shrubland	20529.90	39.830%
5	Water	85.32	0.166%
6	Bare land	1774.87	3.443%
7	Woodland	2335.45	4.531%
8	Natural Forest	132.26	0.257%
9	Plantation	3.63	0.007%
10	Urban	4.04	0.008%
11	Afro-alpine	8.47	0.016%
12	Wetland	1.21	0.002%
	Total		**100%**

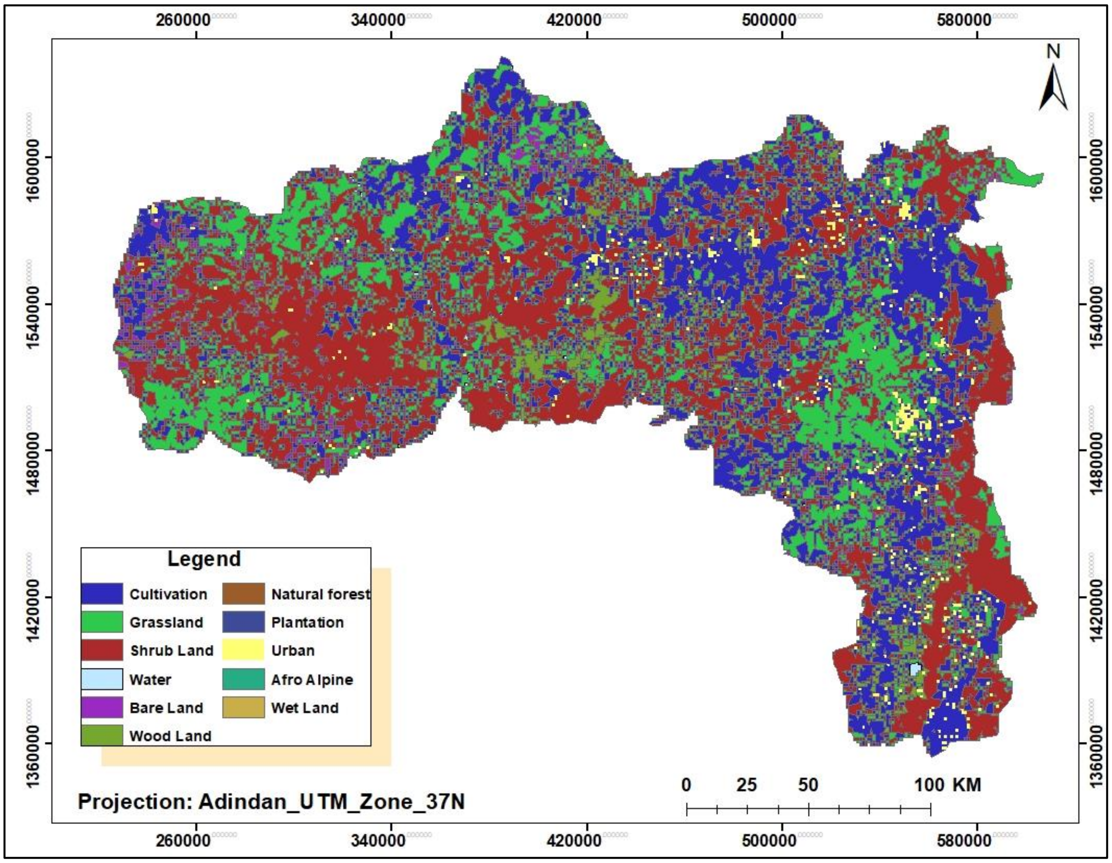


Figure 6 : Land use land cover map of Tigray region (from Ethiopian Environmental Protection Authority 2018).

Generally: The combined analysis of the map and data reveals that Tigray is a landscape heavily transformed by human use. The environment is dominated by a complex interspersion of shrubland, cultivated fields, and grasslands, which together account for over 90% of the land. Conversely, natural ecosystems such as forests and wetlands are present in only trace amounts, pointing to significant environmental challenges related to land degradation, biodiversity loss, and water resource management.

2.2.7 Hydrogeology

The hydrogeology of the Tigray Region is diverse and strongly influenced by its complex geological setting, characterized by fractured volcanic, sedimentary, and basement formations. Groundwater studies in the region are limited and mostly localized around urban centers such as Mekelle and small catchments within the Geba River Basin. whereas studies such as Geba basin by Tesfamichael et al. (2017) are rare.

Groundwater in Tigray is primarily stored in fractured dolerites, limestones, sandstones, and shallow alluvial deposits. Aquifers in doleritic sills, such as those in the Aynalem Valley near Mekelle, were previously identified as key sources of potable water (DEVCON, 1992; WWDSE, 2006). However, groundwater levels in the Aynalem well-field have shown a continuous decline, indicating unsustainable abstraction rates (Hussien, 2000; Tesfamichael, 2009; Ermias et.al 2015).

Hydraulic conductivity varies widely across lithological units, with values ranging from <0.1 m/d in formations such as Agula Shale and Amba Aradam Sandstone, to >70 m/d in fractured limestones and meta-limestones (Chernet & Eshete, 1978; Tesfamichael et al., 2017). This variability reflects the importance of secondary porosity from fracturing and dissolution. Recharge estimates for the Geba basin range from 6% to 20% of annual rainfall, with the highest recharge zones located in the highland areas (Tesfamichael, 2009; Ermias et.al 2015; Yihdego, 2003). Depth to groundwater ranges from 0 to over 200 m, with shallow water tables (<50 m) occurring in the northern and eastern parts of the basin, such as Senkata, Atsbi, and Wukro. (Tesfamichael, 2017).

The study by Ermias et.al (2015), investigated the complex geological and structural controls on groundwater flow and hydrochemistry in the Mekelle Outlier of Northern Ethiopia. By integrating litho-stratigraphy, structural geology, hydrochemistry, and isotopic analysis ($\delta^{18}O$, $\delta^{2}H$, tritium), the research developed a comprehensive conceptual model of the region's groundwater systems. The study identified two primary types of aquifer systems. A high-yield, semi-regional aquifer system exists within the Adigrat Sandstone and the lower Antalo Limestone, with borehole yields reaching up to 60 L/s. In contrast, the basement rocks, dolerites, and the clay-rich Agula Shale host low-yield, localized aquifers (typically < 5 L/s).

A critical finding was the profound control of geological structures on water flow; borehole yields and spring discharges were significantly higher along major faults, fractures, and at the contact zones between sedimentary rocks and dolerite intrusions (12-40 L/s).

Isotopic and chemical data established a clear recharge-discharge framework. The surrounding highlands act as primary recharge zones, characterized by isotopically depleted water with low dissolved-ion concentrations. Groundwater flows from these highlands and discharges into the major river valleys of Giba, Illala, and others. Isotopic analysis confirmed the groundwater is of modern meteoric origin, and tritium data indicated a relatively short residence time, with a mixture of pre- and post-1952 recharge. The study also identified complex surface-groundwater interactions, including seasonal interflow and localized aquifer recharge from rivers and micro-dams. Ultimately, the research synthesizes these findings into a three-tiered conceptual model for the region, comprising shallow/local, intermediate, and deep/semi-regional groundwater flow systems, providing a robust hydrogeological framework for water resource management. In Irob, groundwater occurs in shallow metavolcanic and metasedimentary aquifers, with yields between 0.09 and 0.98 L/s. These aquifers are generally low in productivity due to limited porosity and deep fracture infill (Abadi et al., 2024; Briški et al., 2020).

In the Raya Valley of southern Tigray, groundwater is the main water source, Almaw et al. (2014) applied an integrated RS-GIS-AHP approach to map groundwater potential zones. Their analysis revealed that about 28% of the study area (770 km^2) had 'very good' groundwater potential, while 23% was classified as 'good', 22% as 'moderate', 25% as 'poor', and only 2% as 'very poor'. The validation of this map using yield data from 80 boreholes showed a 74% agreement, indicating reliable results. The most influential factor in determining GP was lithology, with a mean effective weight of 52%, followed by drainage density and geomorphology. Sensitivity analyses confirmed that the GP map was most sensitive to the lithology layer, with a variation index of 6.5% when removed Ayele et al.; (2014). Overall, groundwater availability in Tigray is constrained by geological heterogeneity, limited recharge, and increasing demand, necessitating careful management and site-specific hydrogeological assessments. Figure 7, Shows Hydrogeological Map of the study area.

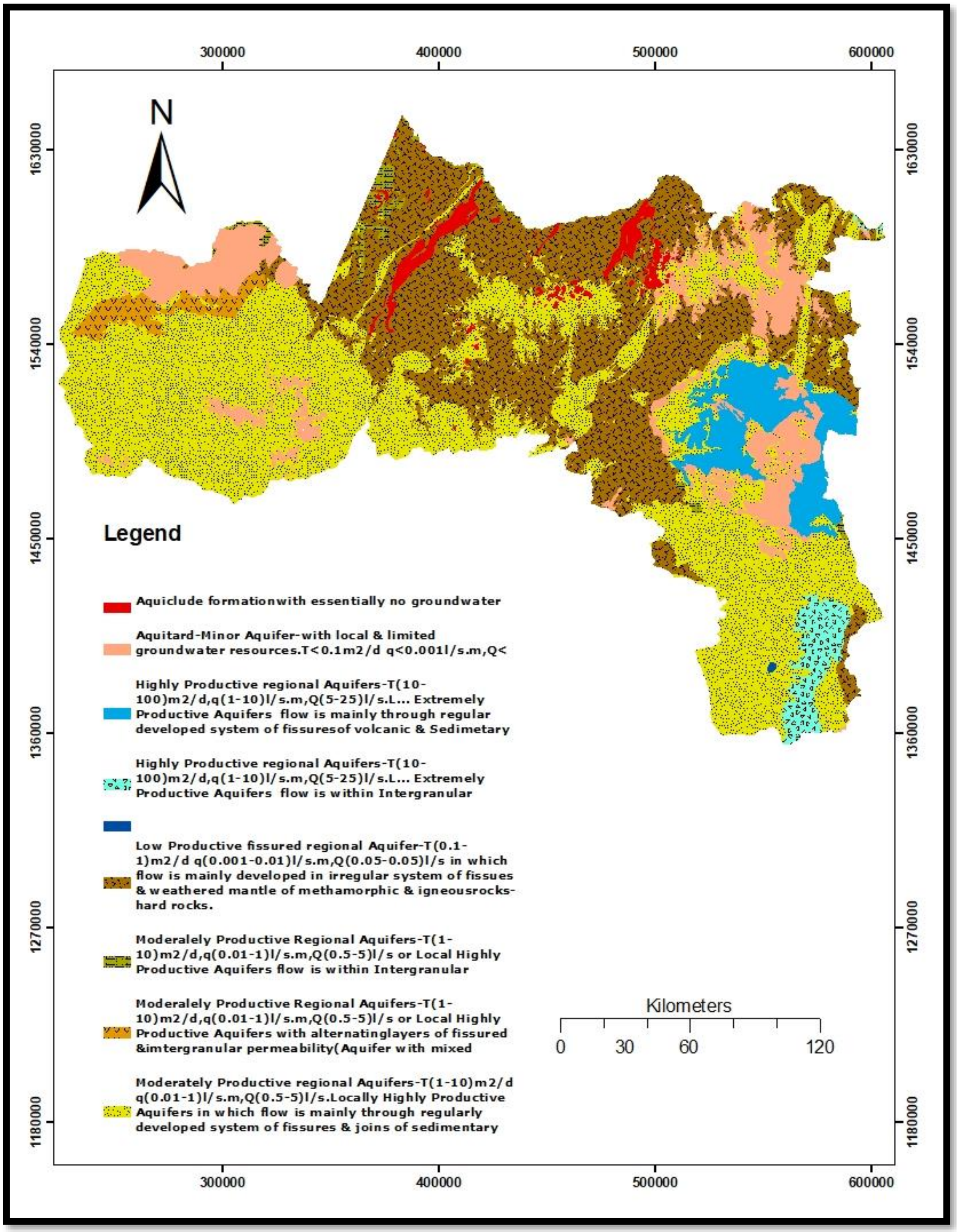


Figure 7 : Aquifer productivity Map of Tigray, source dataset (A synopsis of the Regional Geology and Hydrogeology of Ethiopia. Czech Geological Survey, Praque, 364 p. by Verner K., et al. (2025). 1: 1200, 000 scale

2.2.8 Hydrology and Drainage Systems

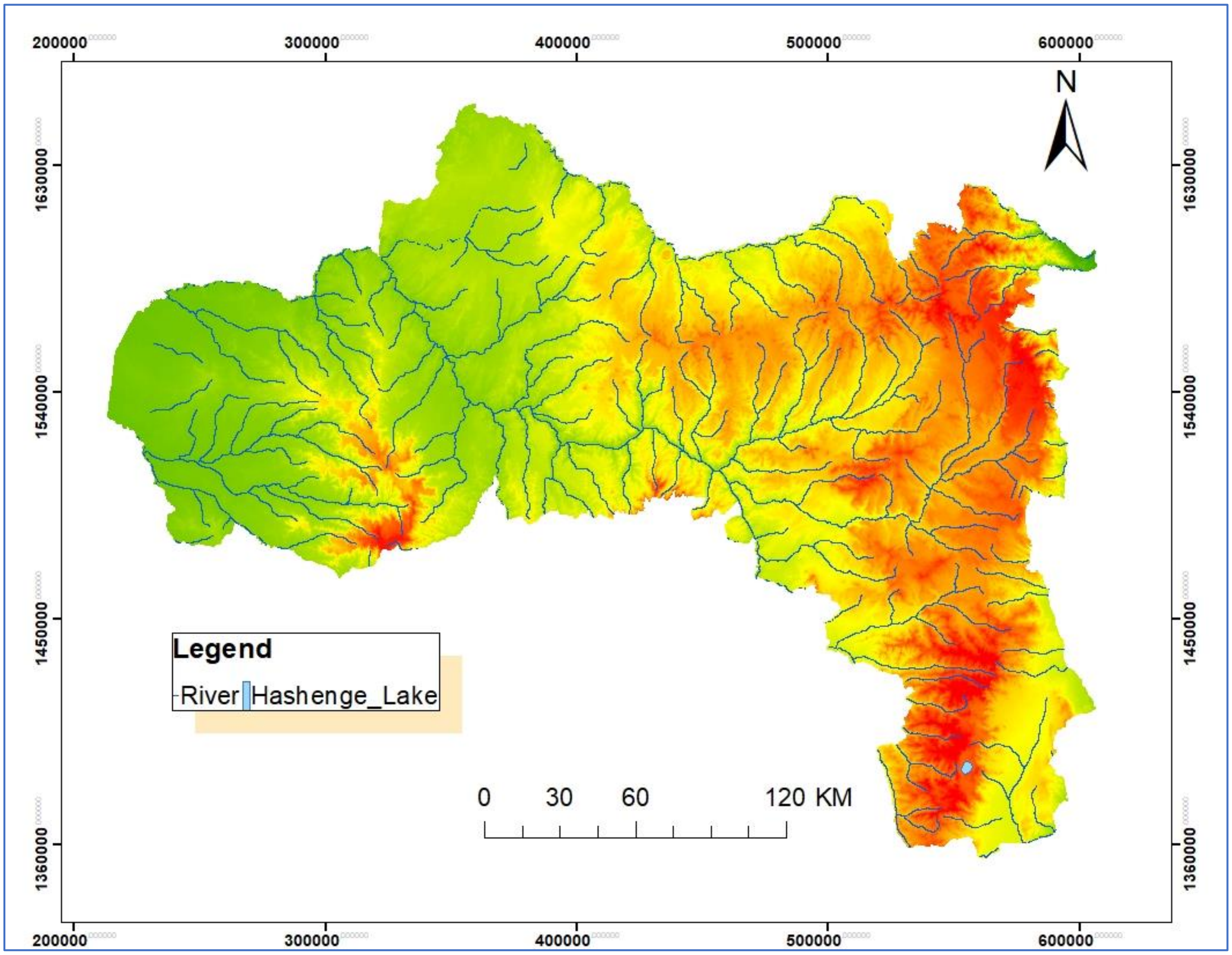


Figure 8 : Tigray River network map

The hydrology of the Tigray Region is fundamentally governed by its complex topography, geology, and climatic conditions. The region's intricate hydrographic network, depicted in Figure 8. overlaid on a Digital Elevation Model (DEM), illustrates the strong topographical control on drainage patterns and basin morphology. The region is characterized by a well-developed and dense drainage network, a feature particularly prominent in the central and eastern highlands. The steep topographic gradients in these areas promote rapid surface runoff and fluvial incision, which in turn contribute to the region's high susceptibility to soil erosion and significant sediment yields (Nyssen et al., 2008; Haregeweyn et al., 2006).

The drainage patterns vary spatially across the region, reflecting underlying geological structures and lithological variations. The dendritic pattern is the most dominant, widely observed in the central and western parts of the region where its tree-like form is characteristic of drainage over areas with relatively uniform lithology (Abay et al., 2011). In contrast, a trellis pattern is common in areas influenced by structural controls, such as folded and faulted terrain, and is particularly evident along escarpments (Gebreyohannes et al., 2013). Additionally, radial drainage patterns are found around prominent volcanic centers like Mount Tsibet, where streams radiate outwards from a central high point, while parallel drainage systems develop where streams are constrained by linear, structurally controlled features like major faults. The drainage density—the total length of streams per unit area—is a critical hydrological parameter that varies significantly across Tigray, primarily controlled by lithology, slope, soil type, and land cover. Quantitative studies in selected watersheds have reported drainage density values ranging from 0.4 km/km^2 in flatter areas with higher infiltration capacity to over 2.5 km/km^2 in steep, less-vegetated highlands with impermeable rock types, with these higher values being typically indicative of degraded landscapes with high runoff generation potential (Gebreyohannes et al., 2013).

2.2.9 Major Drainage Basins

The Tigray Region is transected by a major north-south trending hydrological divide that separates its surface waters into two principal drainage systems (MoWE, 2013), as depicted in Figure 9.

The Tekeze River Basin: This basin dominates the western two-thirds of the region. Its rivers, including major systems like the Tekeze, Mereb, and Giba, generally flow westward and northwestward. These rivers form the headwaters of the Tekeze River, a major tributary of the Atbara River, which is part of the larger Nile River system (Conway et al., 2000). The basin captures runoff from the expansive central highlands and is therefore critical for local water supply, agriculture, and downstream international water dynamics.

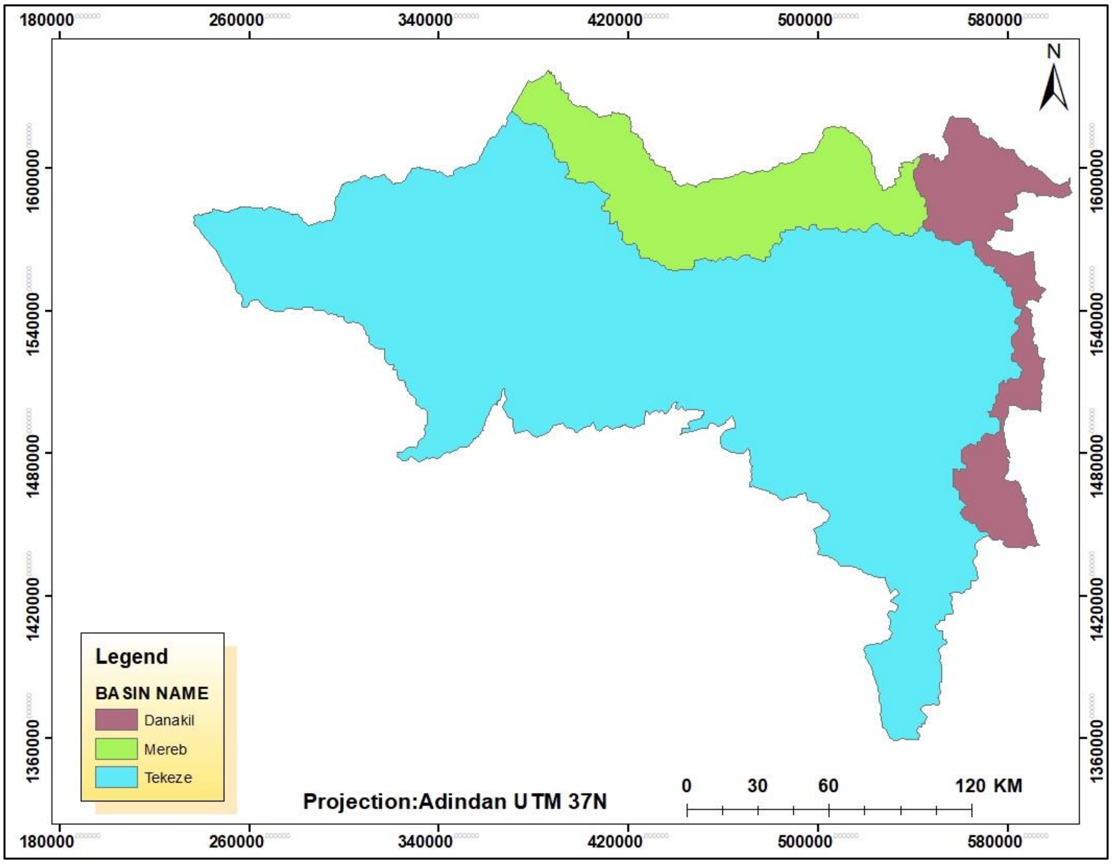


Figure 9: Major drainage basins within the study area of Tigray.

The Danakil (Afar) Basin: The eastern portion of Tigray drains eastward towards the endorheic (internally draining) Danakil Basin in the Afar Depression. The rivers in this system are typically shorter and have steeper gradients as they descend from the eastern escarpment. Consequently, their flow is often ephemeral, dependent on seasonal rainfall (Tesfaye et al., 2011).

The Mereb River Basin: Originating in the central highlands of Tigray, the Mereb River basin (also known as Gash River in Eritrea and Sudan) flows northward, demarcating a significant portion of the border between Ethiopia and Eritrea before turning westward (Nyssen et al., 2005; Seleshi & Zanke, 2004). Unlike the Tekeze, the Mereb is typically ephemeral in its lower reaches, only contributing flow to the Atbara River during peak flood seasons (Setegn et al., 2008). This basin is vital for cross-border water resources and agricultural activities in its upper and middle courses.

3 LITERATURE REVIEW

Effective water resource management and climate monitoring depend on reliable, accurate, and comparable data, for which the World Meteorological Organization (WMO) provides the international framework through its comprehensive guidelines, including the Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8, 2006) and the Guide to Hydrological Practices (WMO-No. 168, 2009). These WMO standards serve as the primary international benchmark against which national and regional observation networks are evaluated. To apply these standards, modern approaches to network planning increasingly leverage geospatial technologies, as demonstrated by Rojas Briceño et al. (2021), who used the Analytic Hierarchy Process (AHP) and GIS to generate a suitability map for optimal weather station placement. This highlights the power of combining expert-based decision-making with spatial analysis to enhance network reliability. The need for such robust networks is particularly acute given that climate variability and change are pressing concerns in Ethiopia. Research across the Tigray region consistently indicates a significant warming trend, while rainfall trends are less conclusive and are primarily characterized by high interannual variability, delayed onset, and an increased frequency of dry spells (Hadgu et al., 2013; Hayelom et al., 2017; Berhe et al., 2021). The reviewed literature thus establishes two key points: first, that internationally recognized standards and advanced geospatial methods exist for designing and evaluating observation networks; and second, that the Tigray region is experiencing significant climatic shifts that necessitate robust monitoring. However, a critical gap remains, as there has been no comprehensive, systematic assessment of the current hydrometeorological observation network in Tigray evaluated against WMO standards and contextualized within the region's complex topography. Therefore, this thesis aims to fill this gap by conducting a rigorous spatial adequacy analysis of the station network and a temporal analysis of its data, providing an evidence-based foundation to guide the strategic improvement and modernization of the region's monitoring infrastructure.

4 MATERIALS AND METHODS

4.1 Research Design

This study employs an integrative, mixed-methods research design to provide a comprehensive assessment of the hydrometeorological observation network and analysis of hydrometeorological trend analysis in the study area. The methodology combines quantitative analysis of spatial and temporal data with qualitative field-based verification. The approach is structured around three core components:

1. **Spatial Adequacy Assessment:** Evaluating the existing station network against World Meteorological Organization (WMO) benchmarks and the region's physiographic characteristics using Geographic Information Systems (GIS).
2. **Hydrometeorological Trend and Variability Analysis:** Analyzing long-term time-series data for rainfall, temperature, and streamflow using robust non-parametric statistical methods.
3. **Field Verification:** Ground-truthing the status, functionality, and classification of stations to validate the office-based analysis.

This multi-faceted design ensures that the study's conclusions are grounded in international standards, empirical data, and real-world operational realities.

4.2 Data Sources and Materials

A variety of data, software, and field instruments were utilized to achieve the research objectives. These materials were selected based on their relevance for analyzing hydrometeorological trends and assessing the spatial distribution of the observation network

4.2.1 Hydrometeorological Data

Long-term historical hydrometeorological data were acquired from national and global repositories. Data scarcity and quality issues necessitated a rigorous acquisition, selection, and pre-processing phase.

Meteorological Data: Monthly rainfall and daily temperature records (1960–2024) were primarily obtained from the Ethiopian National Meteorological Agency (NMA). An initial collection of 108 stations within Tigray provided the dataset for broad spatial distribution analysis, aligning with World Meteorological Organization (WMO) network considerations.

For robust trend analysis, a subset of 30 rainfall stations was meticulously selected from the 108 based on record length (>30 years), data completeness (<10% missing), and spatial representativeness. For generating interpolated rainfall and temperature maps, a larger subset of approximately 80 stations with suitable data was utilized to capture spatial variations.

Daily temperature data were supplemented from the Global Historical Climatology Network (GHCN)) were retrieved from the NOAA website: https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-monthly and Additional climate data were consulted from Climate-Data.org (1991–2021) on January 15, 2025.

Streamflow Data: Time-series discharge data (up to 2019) were collected from the Ethiopian Ministry of Water and Energy (MoWE). While 61 river gauging stations are reportedly present across the Tigray Region (representing the full network considered for WMO distribution analysis), historical records suitable for robust analysis were available for only six river gauging stations. These six stations were: Yechila, Tekeze at Embamadre, Ilala, Ketin Gereb (Maichew), Gando near Korem, and Genfel.

4.2.2 Geospatial Data and Software

The foundational geospatial dataset for this research was a 30-meter resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), acquired from the U.S. Geological Survey (USGS) Earth Explorer. This DEM served a crucial role in classifying the study area into various physiographic zones based on elevation. For other geospatial data processing, including the interpolation of rainfall and temperature values, the Kriging method was employed. Geospatial Software: All spatial analysis, network evaluation, and the production of thematic maps were primarily performed using ArcGIS 10.5. Google Earth facilitated preliminary visualization and location verification. Statistical analyses, such as the Mann-Kendall (MK) test, were conducted using Microsoft Excel with the XLSTAT add-in.

4.2.3 Field Equipment

Global Positioning System (GPS): A handheld GPS unit was used during fieldwork to accurately record the geographic coordinates and elevation of each visited station.

Digital Camera and Notebooks: A camera provided photographic evidence of station conditions, while notebooks and checklists were used for systematic recording of on-site observations

4.2.4 Types of Meteorological stations

This study utilizes meteorological data from two primary station types: conventional (manual) surface stations and Automatic Weather Stations (AWS). These stations vary in instrumentation, observation frequency, and data transmission methods, but both play a crucial role in capturing key atmospheric variables essential for climatological and hydrological analysis.

4.2.5 Conventional (Manual) Surface Stations

Conventional stations are operated manually and classified by the World Meteorological Organization (WMO) into four main categories:

- **Class I – Principal Stations**: These are comprehensive observation sites equipped to measure a wide range of meteorological variables. Parameters recorded include maximum and minimum air temperature, rainfall, soil temperature at various depths, wet and dry bulb temperatures, sunshine duration, and readings from self-recording instruments such as thermographs (temperature), hygrographs (humidity), and actinographs (solar radiation).
- **Class II – Synoptic Stations**: Designed for detailed synoptic weather reporting, these stations observe key variables like present and past weather conditions, wind speed and direction, cloud cover (amount and type), cloud base height, visibility, air temperature, humidity, and atmospheric pressure. Additional parameters may include pressure tendency, ground condition, and precipitation.
- **Class III – Ordinary Stations**: These stations mainly record basic climate elements such as rainfall and temperature.
- **Class IV – Precipitation Stations**: These are the most basic stations, focused solely on measuring daily rainfall totals (24-hour accumulation).

Observations at manual stations follow standard synoptic reporting schedules: typically, eight times per day in extratropical regions and four times per day in tropical regions, aligning with the main synoptic hours (00, 06, 12, and 18 UTC).

4.2.6 Automatic Weather Stations (AWS)

AWS are equipped with electronic sensors that continuously monitor and record meteorological variables including air temperature, wind speed and direction, relative humidity, rainfall, and global radiation. These stations automatically collect data every minute, and summary statistics are typically recorded at 15-minute intervals.

AWS are connected via GPRS telemetry, enabling real-time data transmission to a central database, depending on connection quality. Data is also stored locally at remote sites for up to six months. At the base station, a gateway and HSQL database server manage, process, and visualize spatial and temporal data through integrated network systems.

4.3 Meteorological Station Distribution Analysis

The analysis of the spatial distribution and adequacy of meteorological stations in the study area was based on two key methodological considerations: (i) compliance with the World Meteorological Organization (WMO) standards, and (ii) topographic and climatic analysis using GIS-based classification. These combined approaches were essential for evaluating whether the existing meteorological network meets international standards and for identifying potential gaps in spatial coverage across different terrain types.

4.3.1 Consideration of the WMO Standard

The first approach employed in this study is grounded in international guidelines provided by the World Meteorological Organization (WMO). The WMO sets recommended station densities and interstation distances for various meteorological parameters, based on the terrain type—such as highlands, plains, and arid zones. These standards serve as benchmarks for assessing the adequacy of meteorological networks at regional and national levels.

This study adopts the WMO criteria to assess whether the current distribution of meteorological stations in the region fulfills the minimum spatial requirements necessary for effective climate monitoring. The assessment was guided by recommendations from key WMO documents (e.g., WMO No. 168 and WMO No. 1185), which define optimal interstation distances for parameters such as rainfall, temperature, wind, and solar radiation (Table 2). These standards were used to determine both the required number of stations and their spatial arrangement, depending on the physiographic characteristics of the area.

The conceptual basis for these standards is that meteorological stations should be spaced such that each capture distinct climatic conditions without redundancy. According to Stringer (1972), station spacing should ensure that interpolation errors in estimating climatic conditions between stations are within acceptable limits—ideally comparable to instrumental error. Godske (1969) proposed that correlation coefficients between adjacent stations should typically fall between 0.8 and 0.95 in most synoptic situations, with 0.7 as the minimum acceptable threshold to avoid missing significant local climate variations. Thus, the evaluation of existing stations also considered whether station density and spacing were sufficient to account for local topo-climatic diversity.

4.3.2 GIS-Based Topographic and Climatic Considerations

The second methodological component involves the use of Geographic Information Systems (GIS) to assess meteorological station distribution in relation to topographic and climatic variability. The region was categorized into three major physiographic zones based on elevation and climatic characteristics:

- Arid Zones: Areas with elevation below 500 meters above sea level (masl)

- Plain Zones: Areas between 500 and 1500 masl
- Mountainous Zones: Areas above 1500 masl

This classification facilitated a spatially differentiated analysis of station coverage. Using digital elevation models (DEMs) and GIS tools, each zone was mapped and overlaid with the existing meteorological station network. This allowed for a comparison between the current station density and the WMO-recommended standards for each physiographic class. The aim was to identify which areas are underrepresented and require the establishment of new stations, particularly for fourth-class (rain gauge), third-class (ordinary), and higher-class (first and second) meteorological stations.

This GIS-based analysis also supported decision-making for the optimal placement of future stations, ensuring that each physiographic zone is adequately represented, and that data collected from the network is spatially and climatically representative.

The following table (Table 3) summarizes the minimum recommended interstation distances and coverage areas for various meteorological parameters in different physiographic zones, as outlined in WMO documentation

Table 3: WMO Station Network Standards

Meteorological Parameter	**High Land (km / sq km**	**Plain (km / sq km**	**Arid areas (km / sq km**	**References**
Rainfall	250 sq km	575 sq km	10,000 sq km	WMO No. 168
Self-recording rainfall	2500 sq km	5750 sq km	100,000 sq km	WMO No. 1185
Air Temperature	30km	60km	—	WMO No. 168
Wind	20km	70km	—	WMO No. 168
Sun shine duration	60km	120km	—	WMO No. 168
Radiation	50km	80km	—	WMO No. 168
Synoptic Station	200km	—	—	WMO No. 168

This methodology ensures that the planning and evaluation of the meteorological station network in the region are scientifically justified, internationally benchmarked, and spatially inclusive of the region's diverse topography and climate zones.

4.3.3 Modernization Efforts: Integration of Automatic Weather Stations (AWS)

The transition to Automatic Weather Stations (AWS) represents a critical pathway for modernizing hydrometeorological observation networks, offering significant advantages in data resolution, reliability, and operational efficiency over conventional stations.

While the WMO provides clear density guidelines for conventional stations, standards for AWS networks are more flexible and evolving. Therefore, to establish a meaningful target for expansion, this study proposes a pragmatic benchmark: the AWS network should, at a minimum, be equivalent in density to the requirement for Third Class conventional stations. This benchmark is justified because the primary function of Third-Class stations—collecting climatological data for agricultural and hydrological purposes—is a role for which modern AWS are exceptionally well-suited. An AWS network of this size would provide the high-resolution, real-time data necessary for effective water resource management and climate adaptation planning.

4.4 Hydrometeorological Station Distribution Analysis

The spatial sufficiency of hydrometeorological stations in the Tigray Region is evaluated using WMO (2008) recommended minimum station densities, taking into account topographic classifications derived from elevation data. Tigray consists of three main elevation zones: highlands (>1500 m), plains (500–1500 m), and lowland arid zones (<500 m). According to WMO standards, highland regions require 1 station per 250–1,000 km², plains 1 per 1,000-2,500 km², and arid zones 1 per 10,000-20,000 km². Based on these criteria, the region requires a minimum of 37–134 meteorological stations to ensure adequate spatial coverage. Particular attention is needed in highland areas, which dominate the landscape and exhibit significant climatic variability. Station distribution was compared with these thresholds to assess observational infrastructure sufficiency.

streamflow monitoring stations varies depending on regional characteristics. For instance:

- **Mountainous regions**: 1 station per 250–1,000 km²
- **Flat lowland areas**: 1 station per 1,000–2,500 km²
- **Arid/semi-arid zones**: 1 station per 10,000–20,000 km²

4.5 Hydrometeorological Parameter Trend

This study utilized long-term hydrometeorological data to analyze trends in rainfall, temperature, and streamflow. The datasets were acquired from national and global sources to ensure comprehensive temporal coverage. A summary of the data sources and periods of record is presented in Table 4.

Table 4: Summary of Hydrometeorological Data Sources and Periods

Parameter	**Data Source**	**Period**
Rainfall	Ethiopian National Meteorological Agency (NMA)	1960–2024
	Global Historical Climatology Network (GHCN)	1991–2021
Temperature	Ethiopian National Meteorological Agency (NMA)	1960–2024
	Global Historical Climatology Network (GHCN)	1991–2021
Streamflow	Ethiopian Ministry of Water and Energy (MoWE)	1962–2019

Prior to trend analysis, the raw daily records were processed to compute consistent monthly and annual time series for each parameter. This aggregation is essential for the examination of long-term climatic patterns.

4.5.1 Data Pre-processing and Handling of Missing Data

A critical step prior to trend analysis was the robust management of gaps within the daily time series for rainfall, temperature, and streamflow. A hierarchical data infilling strategy was adopted to ensure the highest possible data quality while pragmatically addressing the limitations of the available records. This approach prioritized the use of the most statistically robust method possible for any given data gap.

The hierarchy of methods was as follows:

1. **Primary Method: Liner Regression Infilling**

The preferred and primary method for data imputation was linear regression using a highly correlated neighboring reference station. This technique is superior as it preserves the natural day-to-day variance and captures specific hydro-climatic events. The procedure involved:
a. Identifying a suitable reference station with a complete, overlapping record.
b. Developing a linear regression model between the target and reference stations and validating it with a strong coefficient of determination (R^2 > [e.g., 0.85]).
c. Using the validated model to predict and fill missing daily values.

This method was used for all gaps where a valid reference station and a strong statistical relationship were present.

2. **Secondary Method: Monthly Mean Replacement**

In instances where the primary regression method was not feasible, a secondary imputation method was employed. The most common reason for this was the absence of concurrent data from the reference station. For these specific gaps, the Monthly Mean Replacement method was used. This involved calculating the arithmetic mean of all available daily values for a specific month within a given year and using this mean to fill the gaps. While this method reduces daily variance, it was deemed the best available alternative to maintain the seasonal integrity of the time series when regression was not possible.

All imputation decisions were logged to maintain a transparent record of the data preparation process. As a final quality control measure, any year where more than 20% of the data was composed of imputed values (from either method) was excluded from the final trend analysis to prevent excessive uncertainty (WMO, 2008).

4.5.2 Trend Analysis Methodology

To identify, quantify, and assess the statistical significance of long-term trends in the prepared time series, this study employed a combination of non-parametric methods. The primary methods were the Mann-Kendall (MK) Test for trend detection and Sen's Slope Estimator for trend magnitude.

The selection of the Mann-Kendall test was deliberate. Hydrometeorological data often violate the assumptions of parametric tests (e.g., linear regression), such as the requirement for normal distribution. The MK test is a non-parametric, rank-based method that is robust to such violations, less sensitive to outliers, and can accommodate missing values within a time series (Mann, 1945; Kendall, 1975; Helsel & Hirsch, 2012). The test produces a standardized Z-statistic, where a positive value indicates an upward trend and a negative value indicates a downward trend. The statistical significance of the trend is determined by the p-value. For this study, a trend was considered statistically significant at the 95% confidence level if the p-value was less than 0.05 (Hirsch et al., 1982).

While the MK test confirms the presence and significance of a trend, the Sen's Slope Estimator quantifies its magnitude. This method calculates the median of all slopes between data pairs, providing a robust estimate of the rate of change over time (Sen, 1968). The result is expressed in the units of the variable (e.g., m^3/s per year), providing a clear measure of the trend's steepness.

For supplementary analysis and visualization, linear regression and moving averages were also applied to compare results and highlight underlying long-term patterns. However, the conclusions of this thesis are based primarily on the robust, non-parametric results from the MK test and Sen's Slope Estimator.

Mann–Kendall Test Statistic

For a time, series $x_1, x_2, \ldots, x_n$:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right)$$

were

$$\operatorname{sgn}\left(x_j - x_i\right) = \begin{cases} +1 & \text{if } \left(x_j - x_i\right) > 0, \\ 0 & \text{if } \left(x_j - x_i\right) = 0, \\ -1 & \text{if } \left(x_j - x_i\right) < 0. \end{cases}$$

The variance of S (when there are no ties) is:

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5)}{18}$$

If ties exist (equal values), correction terms are added.

The standardized test statistic is:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ \dfrac{S+1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S < 0. \end{cases}$$

A positive Z indicates an **upward trend**, a negative Z indicates a **downward trend**. Significance is tested against standard normal distribution.

Sen's Slope Estimator

For all data pairs $\left(x_j, x_k\right)$ where $j > k$:

$$Q_{jk} = \frac{x_j - x_k}{j - k}$$

The Sen's slope estimator $\hat{\beta}$ is the **median** of all Q_{jk}:

$$\hat{\beta} = \operatorname{Median}\left(Q_{jk}\right), \quad \forall\, j > k$$

The intercept can be estimated as:

$$\hat{\alpha} = \operatorname{Median}\left(x_i - \hat{\beta} \cdot i\right)$$

Thus, the fitted trend line is:

$$x_t = \hat{\alpha} + \hat{\beta} \cdot t$$

4.5.3 Software Implementation

All data management, statistical analyses, and visualizations were carried out using Microsoft Excel and the XLSTAT software add-in, which provides modules for performing the Mann-Kendall test and Sen's Slope computations.

4.6 Geospatial Analysis and Mapping Tools

For spatial analysis and visualization, ArcGIS software is employed to perform various geospatial tasks, including spatial interpolation, elevation analysis, and map production. Interpolation techniques were applied to estimate values at unsampled locations based on available point data, enabling a more comprehensive representation of spatial patterns. Elevation analysis is conducted in accordance with World Meteorological Organization (WMO) standards to assess the influence of topography on climatic parameters. The resulting spatial datasets were used to generate thematic maps illustrating the distribution of meteorological variables across the study area.

5 RESULTS AND DISCUSSIONS

5.1 Hydrometeorological Stations distribution and Gap analysis

The spatial inventory of the hydrometeorological network in the Tigray Region, based on the 2025 dataset, revealed a total of 108 monitoring stations with varied observational capacities. Classification under the WMO framework delineated a clear hierarchical structure: 18 Class I (Principal), 1 Class II (Synoptic), 63 Class III (Ordinary), and 26 Class IV (Precipitation) stations (Figure 12). A key finding is the network's heavy skew towards stations with limited observational scope; Class III and Class IV stations together account for a significant majority

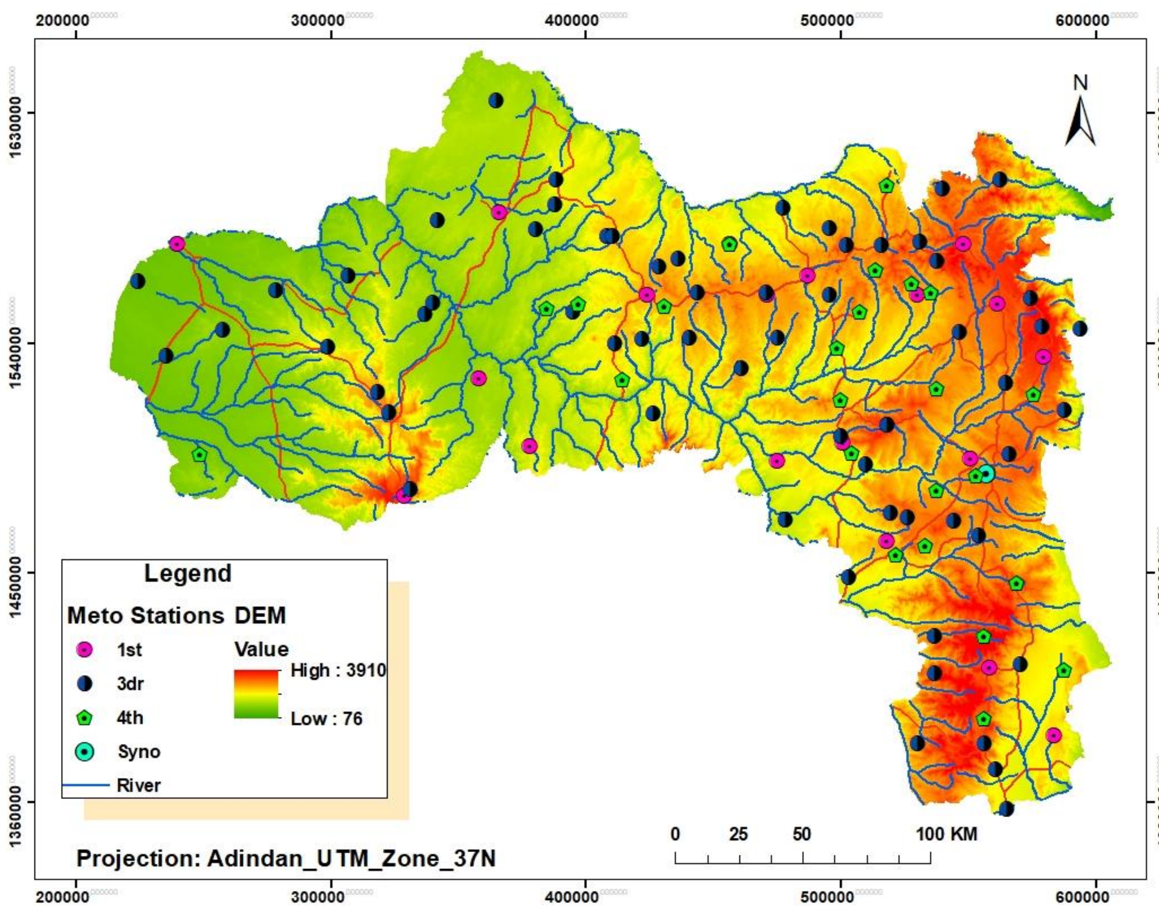


Figure 10: Spatial distribution of hydrometeorological stations in the Tigray Region. (Data source: NMA, 2025).

Figure 11 illustrates the spatial distribution of the 108 identified hydrometeorological stations across the Tigray Region, superimposed on a Digital Elevation Model (DEM) that highlights the area's complex topography. The station network is visually dispersed across the region, though with notable variations in density.

A primary observation is the relationship between station location and topography. Stations are distributed across all elevation zones, from the lower-lying western areas (indicated in green) to the mountainous highlands and plateaus in the central, eastern, and southern parts (indicated in yellow, orange, and red). Many stations, particularly the more numerous Class III (Ordinary) and Class IV (Precipitation) types, appear to be situated within river valleys and along major drainage networks, which is logical for hydrologically-focused monitoring. However, there are apparent spatial gaps in coverage, especially in the far western lowlands and some of the highest-elevation mountain ridges.

The distribution of station types further reveals critical aspects of the network's capacity. The 18 Class I (Principal) stations are scattered relatively broadly, serving as anchor points for comprehensive data collection. In contrast, the single Class II (Synoptic) station provides only one point of high-frequency, multi-parameter data for the entire region. The network is numerically dominated by Class III (63 stations) and Class IV (26 stations), whose primary function is rainfall and basic temperature measurement.

Implication for gap analysis: The observed spatial arrangement immediately suggests the presence of geographical gaps, where large areas lack instrumental coverage. This is particularly concerning for accurately capturing the spatial variability of precipitation, which is heavily influenced by the region's diverse topography. Furthermore, the qualitative composition of the network points to a significant functional gap. The heavy reliance on lower-class stations implies a regional deficit in crucial parameters such as wind speed, solar radiation, and humidity, which are essential for robust hydrological modeling, evapotranspiration estimates, and drought monitoring. The patterns shown in Figure 9 therefore form the basis for the quantitative gap analysis undertaken in this study to identify and prioritize these underserved areas.

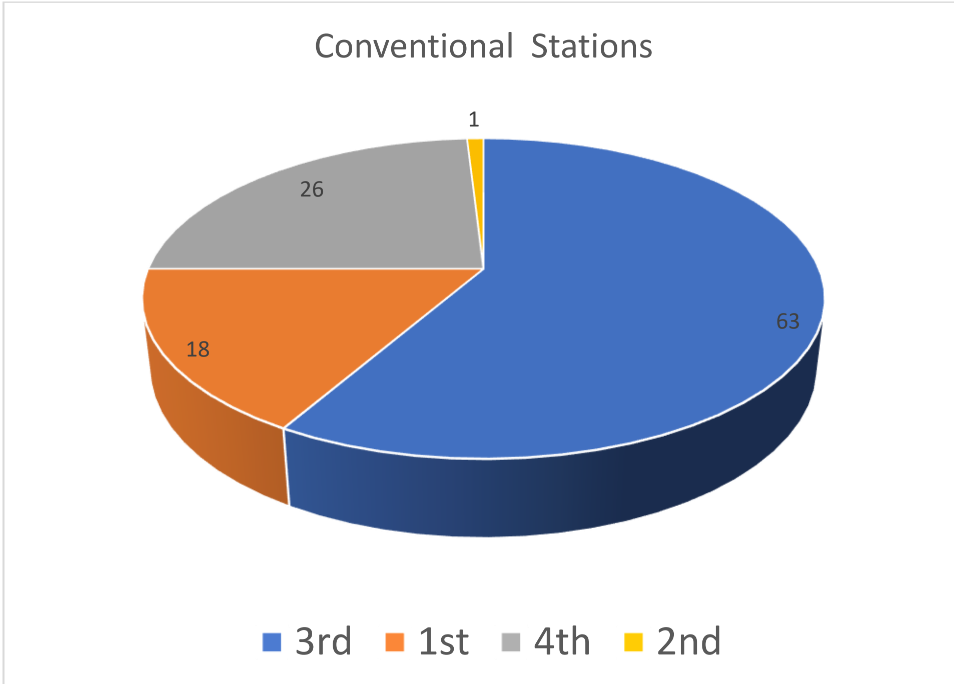


Figure 11: Distribution of conventional meteorological stations in Tigray by class, based on NMA data.

5.1.1 Topographic analysis of Tigray

As topography is a primary consideration for designing meteorological station networks, a GIS-based analysis was conducted to quantify the elevation characteristics of the Tigray Region. Using a Digital Elevation Model (DEM), the study area was classified into three distinct elevation zones, as illustrated in Figure 13. The analysis of the region's total area reveals the following distribution:

- Highlands (>1500 m): The majority of the region, 51.5%, is classified as highlands, situated at altitudes above 1500 meters.
- Plains / Midlands (500–1500 m): A substantial 48.37% of the area consists of plains and mid-altitude terrain, located between 500 and 1500 meters.
- Lowlands (<500 m): A marginal 0.13% of the land area is classified as lowlands, with an elevation below 500 meters.

This physiographic classification into highlands, plains, and lowlands provides the framework for the subsequent gap analysis, the results of which are presented in Table 5.

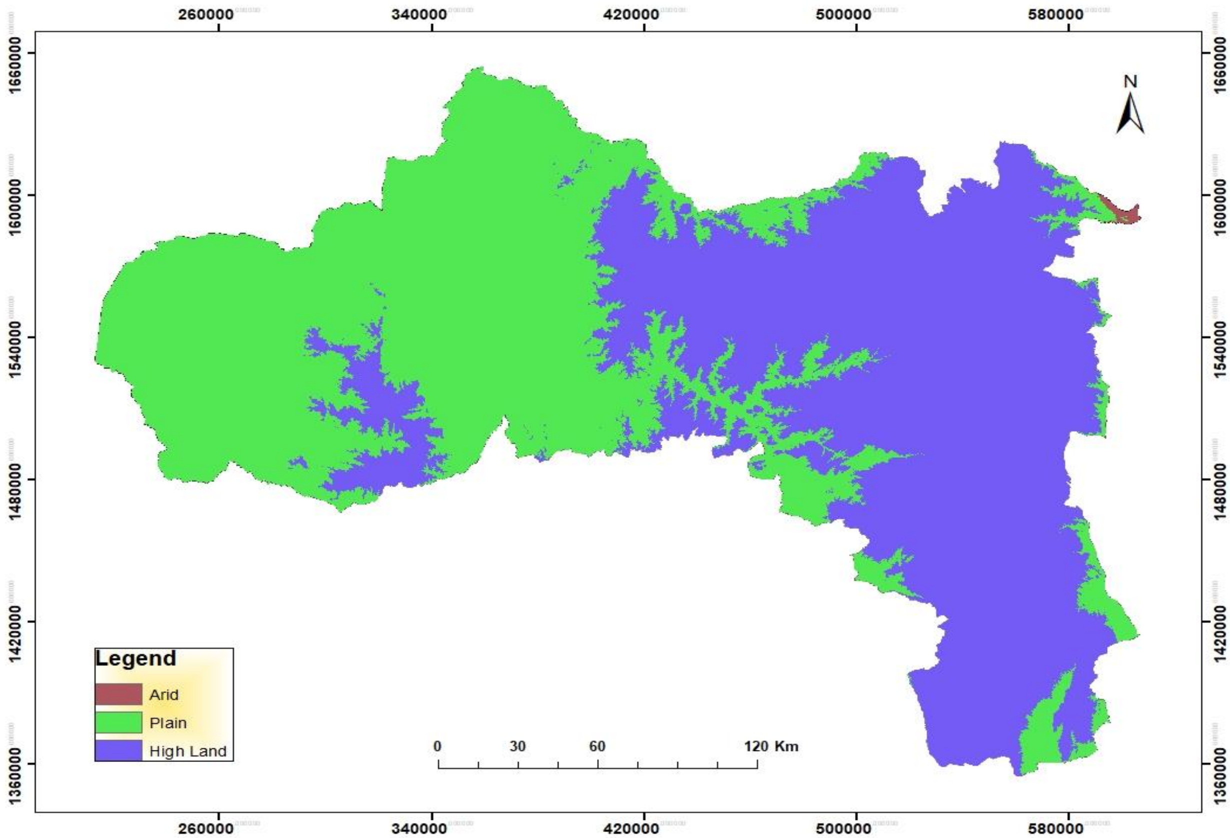


Figure 12: Topography map of Tigray based on WMO Standard

Table 5: Computed areas for different physiographic topographies (On Regional basis WMO standard)

Elevation(m)	Area_km²	Percent (%)
<500	70	0.13%
500-1500	25444	48.37%
>1500	27096	51.50%
Total	52610	100.00%

5.1.2 Benchmarking the distribution Against WMO Standards

To conduct a quantitative gap analysis, the existing station network was evaluated against the minimum density standards set by the World Meteorological Organization (WMO). The WMO recommends station densities that vary with topography, acknowledging that meteorologically complex terrain requires denser monitoring. The standards applied to the three physiographic zones of the Tigray Region are:

- **Highlands (>1500 m):** Mountainous areas requiring the highest density to capture complex weather patterns.
- **Plains / Midlands (500–1500 m):** Areas with moderate topographic variability.
- **Lowlands (<500 m):** Arid, flat areas where weather phenomena are generally more uniform.

Based on the region's total area of 52,610 km² and its topographic distribution, the ideal number of stations required to meet WMO standards was calculated for each class. The results of this calculation are presented in Table 7.

Table 6 : Required Number of Meteorological Stations in Tigray Based on WMO Topographic Standards

Elevation Zone	**Area (km²)**	**Percent (%)**	**Required Class IV (Precipitation)**	**Required Class III (Ordinary)**	**Required Class I (Principal)**	**Required Class II (Synoptic)**
Lowlands (<500 m)	70	0.13%	70/10000=0.007	70/3600=0.02	70/100000=0	70/40000=0
Plains (500–1500 m	25,444	48.37%	25444/575=45	25444/3600=7	25444/5750=5	25444/40000=1
Highlands (>1500 m)>1500	27.096	51.50%	27096/250=109	27096/900=31	27096/2500=11	27096/40000=1
Total Required Stations	52,610	100.00%	154	38	16	2

Note: The required station number is calculated by dividing the area of each zone by the WMO-recommended area per station for that topography and class. Values are rounded to the nearest whole number. The total requirement is the sum from all zones.

To develop a network design that is responsive to the region's diverse landscape, the study area was stratified into three elevation zones. This approach aligns with WMO recommendations to increase station density in areas of complex topography where weather patterns are most variable. The specific station requirements calculated for each zone are detailed in Table 7.

Table 7 : Required Meteorological Station Density by Topographical Elevation Zone

Elevation Zone	**Area (km²)**	**Percent (%)**	**Required** Class IV **(Precipitation)**	**Required** ClassIII **(Ordinary)**	**Required** ClassI **(Principal)**	**Required ClassII (Synoptic)**	**Total Required**
Lowlands (<500 m)	70	0.13 %	0.007	0.02	0	0	0
Plains (500–1500 m	25,444	48.37%	45	7	5	1	58
Highlands (>1500 m)>1500	27.096	51.50%	109	31	11	1	152
Total Required Stations	52,610	100.00%	154	38	16	2	210

5.1.3 Quantitative and Spatial Gap Analysis

A thorough comparison of the existing network (108 stations) with the WMO-recommended network (Table 8) reveals significant quantitative and qualitative gaps.

1. **Quantitative Gap Analysis (Comparison of Station Numbers):**

A class-by-class comparison highlights the network's key deficiencies and imbalances:

- Principal (Class I) Stations: The existing network includes 18 Class I stations, which slightly exceeds the WMO requirement of 16 stations. From a purely numerical standpoint, the coverage for comprehensive, multi-parameter monitoring appears adequate.
- Synoptic (Class II) Stations: A deficit exists, with one operational synoptic station against a calculated requirement of two. This limits the availability of high-frequency data for regional forecasting.

  Ordinary (Class III) Stations: The network contains a notable optimum of Class III stations, with 63 existing stations compared to a WMO standard of 38.
- Precipitation (Class IV) Stations: The most critical finding of this analysis is the severe deficit in precipitation stations. The region requires an estimated 152 Class IV stations to

adequately capture rainfall variability, but only 26 are currently operational. This represents a shortfall of 130 stations, or meeting only 17% of the WMO standard.

2. **Spatial Distribution and Evenness:**

- Uneven Geographic Distribution: A qualitative review of the station map (Figure 8) clearly indicates that the network lacks spatial evenness. Stations are visibly clustered in the central and eastern highlands, which, while topographically complex, leaves vast areas in the western lowlands and northern territories critically under-monitored.
- Implication of Surplus and Deficit: The surplus of 63 Class III stations is problematic if they are clustered in already well-observed areas, offering redundant data rather than expanding spatial coverage. Conversely, the severe deficit of 130 Class IV rain gauges is the most significant issue for hydrometeorological analysis. Given that rainfall is highly variable in mountainous terrain, the current sparse and uneven network cannot reliably capture local rainfall extremes, calculate accurate basin-wide precipitation, or support effective flash-flood and drought forecasting.
- In conclusion, while the network meets the standard for Class I stations, it is fundamentally imbalanced. The critical shortage and poor spatial distribution of rain gauges (Class IV) represent the most significant weakness of the hydrometeorological infrastructure in the Tigray Region, directly impacting the reliability of any water resource assessment or management strategy.

5.1.4 Gap Analysis of the study area Meteorological station distribution

To evaluate the adequacy of the region's meteorological observation infrastructure, a gap analysis was conducted by benchmarking the current network of conventional stations against the minimum density guidelines established by the World Meteorological Organization (WMO). These international standards are essential for ensuring that collected data are representative, reliable, and comparable, and adherence to them is a foundational step toward developing a world-class meteorological infrastructure capable of supporting robust, evidence-based planning and enhancing regional climate resilience. The quantitative results of this gap analysis, based on WMO standards for the year 2025 and presented in Table 8, reveal significant imbalances and critical deficiencies within the network. While the network meets or exceeds standards for certain station types, it suffers from a substantial overall deficit, achieving only 51% of the total required coverage as per WMO guidelines.

Table 8: Gap Analysis of Conventional Meteorological Stations Based on WMO Standards

Station Class	**Existing Stations**	**Required Stations (WMO Standard)**	**Coverage (%)**	**Numerical Gap (Stations Required/ Surplus)**
First Class	18	16	112.5%	0
Second Class	1	2	50%	1
Third Class	63	38	165%	0
Fourth Class	26	154	16.8%	128
Total	**108**	**210**	**51%**	**129**

A notable strength of the current network is its full compliance with the standards for First Class stations; with 18 stations existing against a requirement of 16, the region achieves 100% coverage, indicating a robust foundation for capturing large-scale synoptic data vital for national forecasting. However, the analysis also reveals a critical gap in Second-Class station coverage, with only one of the two WMO-required stations operational. This 50% deficit is misleadingly simple, as the severity is magnified by the vast territory the single station must cover—approximately 200 km—leaving a significant data void. Although numerically manageable, closing this gap is crucial as these stations are designed to supplement the primary network, and the current situation results in large, unmonitored regions. In stark contrast to this deficit, the analysis shows a significant surplus of Third-Class stations, with 63 operational against a requirement of 38, or 165% coverage. While seemingly beneficial, this excess of 25 stations points to a potential inefficiency in resource allocation, suggesting a historical deployment strategy that may not align with current standards or needs. This over-saturation, especially when viewed alongside the critical gap in the Second-Class network, suggests the network is a mixture of unmonitored expanses and areas of inefficient over-monitoring, warranting a deeper audit to determine if these assets could be relocated, upgraded, or decommissioned.

The most critical finding of this analysis, however, is the severe deficit in Fourth Class stations. The region has only 26 of the 154 stations required, representing a coverage of merely 16.8% and leaving a staggering gap of 130 stations. These stations are fundamental for capturing data on local-scale phenomena essential for hydrology (local rainfall patterns for flood risk), agriculture (microclimates for crop management), and disaster risk reduction (granular data for early warnings). The profound lack of these stations severely compromises the region's ability to conduct evidence-based local planning and build effective climate resilience, as variability in weather and climate at the local scale is not being adequately captured.

In summary, the regional meteorological network is imbalanced. It is relatively well-equipped for monitoring large-scale weather patterns (First Class) but is critically deficient in its capacity to observe local-scale conditions (Fourth Class), and the surplus in Third Class stations suggests a potential for optimization. To elevate the region's meteorological infrastructure to a world-class standard, strategic investment must be prioritized to address the critical 128-station deficit in the Fourth-Class category. Concurrently, the gap in Second Class stations should be filled, and the distribution of Third-Class stations should be reviewed to maximize their utility and efficiency. Failure to address these gaps, particularly at the local level, will continue to hamper efforts in climate change adaptation, water resource management, agricultural productivity, and disaster preparedness.

5.1.5 Assessment of the Operational Functionality of the Study area Meteorological distribution

Following the initial gap analysis based on WMO standards, a further assessment was conducted to determine the current operational status of the conventional meteorological stations in Tigray. This assessment, based on data provided by the National Meteorological Agency (NMA), Mekelle Branch, and supplemented by field verifications up to February 2025, reveals a critical degradation of the region's meteorological infrastructure.

The primary finding is that only 28 conventional meteorological stations are currently functional. This represents a mere 13% of the 210 stations required to meet the minimum WMO density standard for the region. This severe reduction in operational capacity has profound implications for data collection, weather forecasting, and climate services across Tigray. The detailed breakdown of this functionality gap is presented in Table 9, with the disparity visualized in Figure 12 and the spatial inadequacies illustrated in Figure 13.

The functional status of the network was evaluated against the WMO requirements for each station class. The results, summarized in Table 9, highlight the scale of the challenge.

Table 9 : Functional Status of Conventional Meteorological Stations vs. WMO Requirements (February 2025)

Station Class	**Required Stations (WMO Standard)**	**Existing Functional Stations**	**Functional Coverage (%)**	**Numerical Deficit (Stations Required)**
First Class	16	8	50%	8
Second Class	2	1	50%	1
Third Class	38	13	34.2%	25
fourth Class	154	6	3.9%	148
Total	**210**	**28**	**13.3%**	**182**

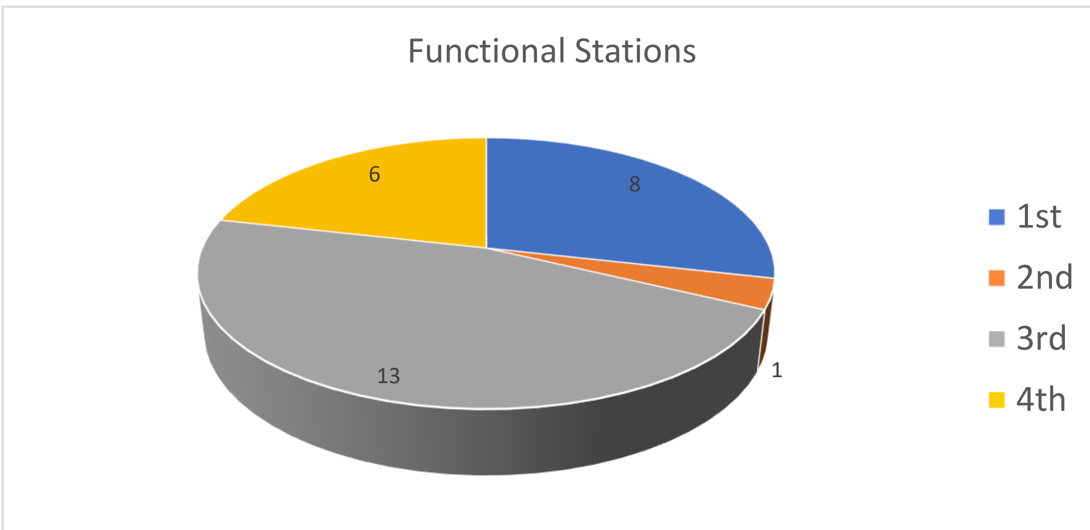
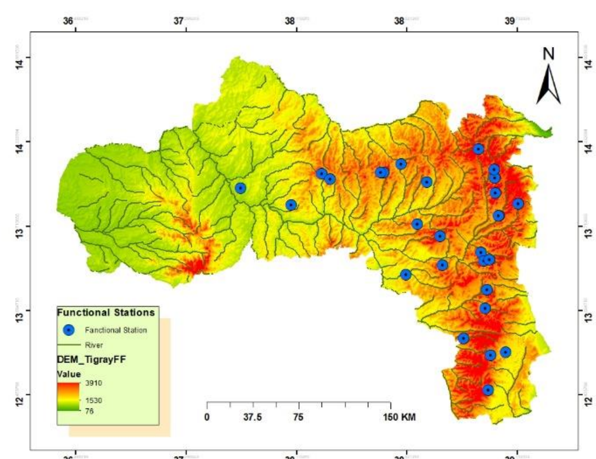


Figure 13 : Functional Meteorological Stations distribution in Tigray by Class (2025).



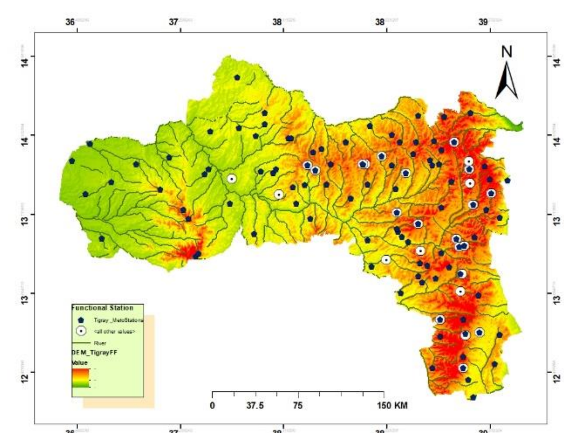


Figure 14 : Spatial Distribution of Functional Conventional Meteorological Stations in Tigray (2025)

The data presented in Table 9 and the accompanying figures paint a stark picture of a meteorological network in a state of systemic collapse. The discussion below analyzes these findings by station class and spatial distribution to explore the full implications of this operational failure.

The decline in functionality affects all station classes, but the impact is most severe at the local level.

- Fourth Class Network Collapse: The most alarming finding is the near-total loss of the Fourth-Class network, with only 6 of the required 154 stations (a mere 3.9%) operational. This constitutes a deficit of 148 stations. As these stations are the primary source of granular data for agriculture, hydrology, and local disaster risk management, their absence creates a critical data vacuum. It cripples the region's ability to monitor microclimates, manage water resources for irrigation, and issue timely warnings for localized hazards like flash floods.
- Significant Decline in Third- and First-Class Stations: The Third-Class network, essential for climatological records, is operating at only 34% capacity, with a deficit of 25 stations. This loss jeopardizes the continuity and integrity of long-term climate data. Furthermore, the First-Class synoptic network, which forms the backbone of national weather forecasting and international data exchange, is functioning at only 50% capacity. The non-operation of 8 of these critical stations severely compromises the accuracy of regional forecasts and the region's contribution to global weather models.

As starkly illustrated in Table 9, the gap between the required standard and the on-the-ground reality is immense across all categories. The operational network is a skeleton of the required system, fundamentally incapable of serving its intended purpose.

Beyond the numerical deficit, the geographical placement of the few remaining functional stations is a major concern. As shown in the spatial distribution map in Figure 15, the 28 operational stations are not evenly distributed across the region. A visual inspection of the map reveals:

- Geographic Clustering: A significant concentration of functional stations is observed around the regional capital, Mekelle, and other major administrative centers. This is likely due to better accessibility for maintenance and more reliable power infrastructure.
- Vast Data Deserts: Consequently, vast rural and remote areas, particularly in the western, northern, and eastern peripheries of Tigray, are left as "data deserts" with no ground-based meteorological monitoring. These are often the very areas most vulnerable to climate variability, with economies heavily reliant on rain-fed agriculture and pastoralism.
- Topographical Bias: The functional network likely under-represents the region's diverse topography. Key highland and mountainous areas, which are critical for understanding orographic rainfall and water origination, appear to be largely unmonitored.

This inequitable spatial distribution means that the data being collected is not representative of the region as a whole. It is biased towards urban and accessible lowland areas, leading to a distorted understanding of regional weather patterns and climate risks.

Overall Implications for Regional Resilience and Planning**:** In summary, the operational meteorological network in Tigray is critically deficient both in number and in spatial coverage. With only 13% of the required stations functional, the region's capacity for evidence-based decision-making is profoundly compromised. This systemic failure directly undermines efforts in:

- Climate Change Adaptation: Without reliable local data, planning for climate resilience becomes an exercise in guesswork.
- Food Security: The inability to provide tailored agrometeorological advisories to farmers hampers agricultural productivity.
- Disaster Risk Reduction**:** The lack of a dense observation network renders early warning systems for floods and droughts ineffective.

The challenge is therefore not simply one of repairing existing stations, but of strategically rebuilding a resilient and representative network from the ground up. This will require significant investment and a clear prioritization plan that addresses the most critical gaps in the Fourth-Class network and ensures equitable geographic coverage across all of Tigray.

5.1.6 A Geographically Stratified Framework for distribution Analysis

To conduct a robust analysis of the Tigray Region's meteorological network, a geographically stratified framework was established. This approach aligns with World Meteorological Organization (WMO) guidelines, which mandate higher station densities in areas of complex topography where weather and climate patterns exhibit the greatest spatial variability (WMO-No.8, 2006, and No.168, 2009 standard). The region was delineated into three primary elevation zones, and the minimum station requirements for each zone were calculated. This methodology ensures that the network assessment is directly proportional to the landscape's meteorological complexity.

The results of this stratification, which define the "ideal" or required network, are presented in Table 10 The data underscore the profound influence of geography on the region's observational needs, with the Highlands (>1500 m) requiring 72% of the total necessary stations to capture its complex orographic effects.

Table 10. Required Meteorological Station Density by Topographical Elevation Zone (WMO Standard)

Elevation Zone	**Area (km²)**	**Percent (%)**	**Required ClassI (Principal)**	**Required Class II (Synoptic)**	**Required Class III (ordinary)**	**Required Class IV (Precipitation)**	**Total Required**
Highlands (>1500 m)	27.096	51.50 %	11	1	31	109	152
Plains (500–1500 m)	25,444	48.37 %	5	1	7	45	58
Lowlands (<500 m)	70	0.13%	0	0	0	0	0
Total Required Stations	52,610	100.00 %	16	2	38	154	210

An inventory of the currently operational stations was conducted and categorized within the same elevation framework. The geographic distribution of the "observed" or existing network is detailed in Table 11. This inventory reveals a strong concentration of infrastructure in the Highlands, which is broadly appropriate, but also exposes significant imbalances when compared against the WMO requirements.

Table 11 :Observed Meteorological Station Distribution by Topographical Elevation Zone

Elevation Zone	**Area (km²)**	**Percent (%)**	**ClassI (Principal)**	**Class II (Synoptic)**	**Class III (Ordinary)**	**Class IV (Precipitation)**	**Total Observed**
Highlands (>1500 m)	27.096	51.50%	11	1	44	22	**78**
Plains (500–1500 m)	25,444	48.37%	6	0	17	4	**27**
Lowlands (<500 m)	70	0.13%	1	0	2	0	**3**
Total Required Stations	52,610	100.00%	**18**	**1**	**63**	**26**	**108**

Gap Analysis and Strategic Proposals for Network Optimization

By comparing the required network (Table 10) with the observed network (Table 11), a detailed gap analysis was performed. The results, summarized in (Table 12) and discussed below, form the basis for the strategic recommendations aimed at creating a balanced, efficient, and geographically coherent network.

Table 12: Comprehensive Gap Analysis by Station Class and Elevation Zone

Station Class	**Elevation Zone**	**Required**	**Observed**	**Surplus / (Deficit)**	**Key Geographic Finding & Proposal**
1st-Class	Highlands	11	11	0	Sufficient. No new stations proposed.
	Plains	5	6	1	Sufficient.
	Lowlands	0	1	1	Sufficient.
2nd-Class	Highlands	1	1	0	Sufficient.
	Plains	1	0	-1	Critical geographic void. Propose 1 new station.

Station Class	Elevation Zone	Required	Observed	Surplus / (Deficit)	Key Geographic Finding & Proposal
3rd-Class	Highlands	31	44	13	Significant surplus suggests inefficiency. No new stations proposed; recommend rationalization.
	Midlands/Plains	7	17	10	Significant surplus suggests inefficiency.
	Lowlands	1	2	1	Minor surplus.
4th-Class	Highlands	109	22	-87	Profound deficit in critical water-source region. Propose strategic, high-density expansion.
	/Plains	45	4	-41	Severe deficit in key agricultural zones.

First-Class Stations: Confirmation of Adequate Coverage

- **Finding:** The network is numerically sufficient (18 observed vs. 16 required) and geographically well-distributed, meeting the specific requirements for all elevation zones.
- **Proposal:** No new First-Class stations are proposed.

Second-Class Stations: Addressing a Critical Geographic Void

- **Finding:** The network has a 50% deficit (1 observed vs. 2 required). Critically, this deficit is spatial: the requirement for a station in the Plains/Midlands zone is entirely unmet, creating a major geographic gap in the synoptic network.
- **Proposal:** The establishment of one (1) new Second-Class station is proposed, to be strategically sited within the unmonitored Plains/Midlands zone.

Third-Class Stations: A Paradox of Surplus and Spatial Inefficiency

- **Finding:** A massive numerical surplus of 25 stations exists regionally (63 observed vs. 39 required). This surplus is present across all elevation zones and points to a historical legacy of inefficient deployment, likely resulting in geographic clustering and data redundancy.

- **Proposal:** No new Third-Class stations are proposed. A future study focused on the rationalization of this network (relocating or upgrading stations) is strongly recommended to improve spatial efficiency.

Fourth-Class Stations: A Proposal for Strategic, High-Density Expansion

- **Finding:** A profound regional deficit of 128 stations exists (26 observed vs. 154 required). This gap is most severe in the Highlands (deficit of 87) and the Midlands (deficit of 41), the very zones critical for water resources and agriculture.
- **Proposal**: The establishment of 130 new Fourth-Class stations is proposed. Their implementation must follow a spatial optimization strategy prioritizing geographically critical locations, such as unmonitored watersheds and key agricultural areas identified in this study.

A Geographically-Informed Roadmap for Network Enhancement

In conclusion, the proposals outlined in this chapter are designed not merely to meet numerical quotas but to engineer a spatially coherent and geographically intelligent meteorological network. By grounding the analysis in the region's unique topography, these data-driven recommendations form a strategic roadmap for rectifying critical geographic gaps and systemic inefficiencies. The targeted implementation of the proposed stations will fundamentally strengthen the region's capacity for climate monitoring, water resource management, and disaster risk reduction.

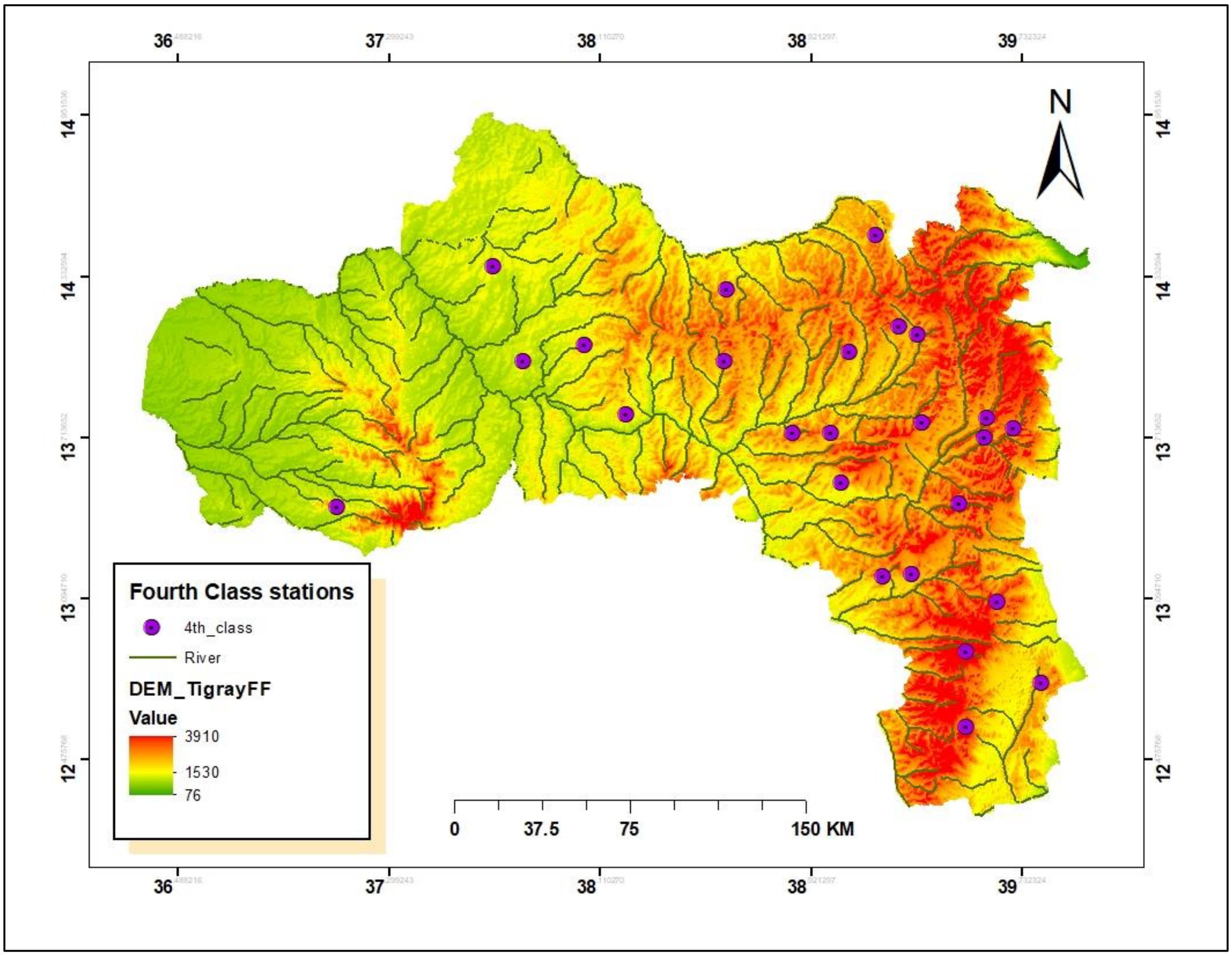


Figure 15: Fourth class Station spatial distribution map (most sever deficits class)

Figure 15 displays the geographical layout of the meteorological stations used in this study. The stations are distributed across the varied topography of the region. However, it is crucial to note that all are 'Fourth-Class' stations, a classification which signifies a severe deficiency in data.

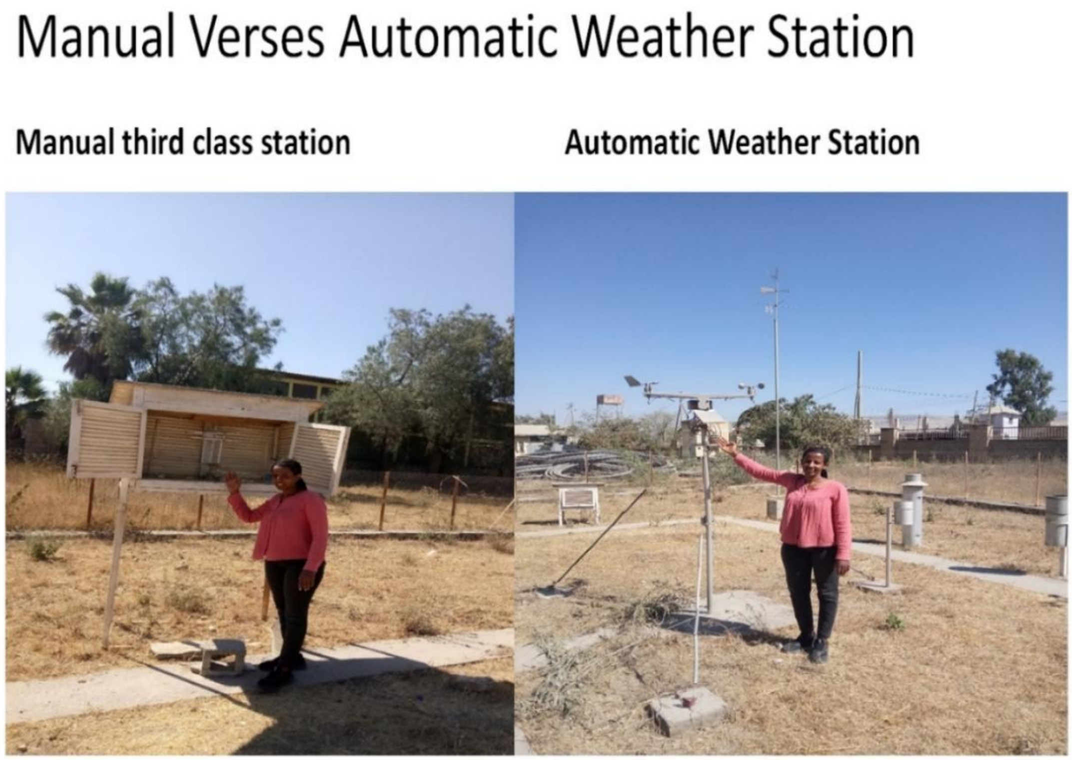


Figure 16: manual verses Automatic stations in Mekelle Observatory.

Figure 16 illustrates a comparison between manual and automatic weather stations within the study area. Manual stations require periodic human observation and recording, which may result in gaps or inconsistencies in the data. In contrast, Automatic Weather Stations (AWS) continuously measure and store meteorological parameters such as rainfall, temperature, humidity, and wind speed with higher temporal resolution. This comparison highlights the advantage of AWS in improving data accuracy, consistency, and accessibility, thereby strengthening the reliability of climate trend analysis in the region.

Figure 17: Principal (first class) stations which measures rainfall self-recording and relative humidity instruments in Mekelle Observatory.

Figure 17 depicts the principal (first-class) meteorological station at Mekelle Observatory, equipped with self-recording instruments for rainfall and relative humidity. In addition to these, first-class stations are generally capable of measuring temperature, solar radiation, and wind speed. This photograph is presented as a representative example of such stations in the study area. As a first-class station, it provides high-quality and continuous observations that serve as a benchmark for climate monitoring in the region. The availability of these detailed records is essential for validating data from other stations and for supporting long-term hydrometeorological trend analysis.

5.1.7 Analysis of the Automatic Weather Station (AWS) Network

The transition to Automatic Weather Stations (AWS) represents a critical pathway for modernizing meteorological observation networks, offering significant advantages in data resolution, reliability, and operational efficiency over conventional stations. This section assesses the current status of the AWS network in Tigray and proposes a strategic plan for its expansion. An inventory of the region's automated observation infrastructure revealed a total of only twenty-seven (27) functional Automatic Weather Stations, a number that is critically insufficient for a region characterized by complex topography and highly variable microclimates. While the WMO provides clear density guidelines for conventional stations, standards for AWS networks are more flexible; therefore, to establish a meaningful target, this study proposes a pragmatic benchmark: the AWS network should, at a minimum, be equivalent in density to the requirement for Third Class conventional stations, which for the Tigray region is 38 stations. This benchmark is justified because the primary function of Third-Class stations—collecting climatological data for hydrological and agricultural purposes—is a role for which modern AWS are exceptionally well-suited. Comparing the existing twenty-seven AWS to this proposed benchmark of 38 reveals a minimum deficit of 33 stations, a significant gap representing a missed opportunity to leverage modern technology for enhanced climate resilience. A robust AWS network is essential for capturing the fine-scale meteorological phenomena that conventional stations often miss, which is particularly important in a topographically diverse region like Tigray. Therefore, this study advocates for a strategic and ambitious expansion of the AWS network, recommending that AWS be established as the new standard, particularly in areas that currently lack any form of meteorological station. Based on this analysis, the study proposes the establishment of 49 new Automatic Weather Stations. This forward-looking proposal exceeds the minimum benchmark of 38 stations and is designed to create a state-of-the-art observational network capable of supporting advanced agrometeorological modelling, precise water resource management, and highly localized disaster early warning systems, with specific proposed locations detailed in Table 13. In summary, while the current AWS network is nascent, its expansion is the most effective path toward elevating the region's meteorological infrastructure, and the proposed deployment of 49 new stations is a critical investment in the region's future, forming the foundation for evidence-based policy and sustainable development in the face of climate change.

Figure 18 : Automatic Weather Station (AWS) in Mekelle Observatory

Figure 18 presents the Automatic Weather Station (AWS) installed at the Mekelle Observatory. The station is designed to automatically measure and record essential meteorological parameters, including rainfall, temperature, relative humidity, wind speed, and solar radiation. The meteorological monitoring infrastructure in the Tigray Region has undergone a significant and recent expansion. According to data from the National Meteorological Agency (NMA), the majority of the current Automatic Weather Station (AWS) network was deployed in the last two years. Specifically, ten stations were commissioned in 2024 and seven in 2023. These additions complement the ten initial stations established between 2019 and 2022. This modernized network, totaling 27 stations, features a centralized data collection and control system managed from Addis Ababa, enhancing real-time monitoring capabilities for the region. The distribution of AWS stations across the study area is highly uneven, as shown in Figure 19, with a strong concentration in higher elevation areas.

Highland/Mountainous Zone (>1500 masl): This zone, represented in brown on the map, contains the vast majority of the monitoring stations. With 23 out of 27 stations (approximately 85% of the total), this area is densely monitored. The stations are spread throughout the large mountainous region in the eastern half of the map and the smaller mountain ranges in the west.

Plain Zone (500–1500 masl): The plain, colored yellow, is a significant portion of the total area but is sparsely monitored. There are only 4 stations located in this zone, primarily scattered across the western and central parts of the map.

Lowland/Arid Zone (<500 masl): The areas identified as "Arid" on the map (teal color), which correspond to the lowlands, have zero stations. These regions, located in the far southeast and northeast, are completely lacking weather monitoring coverage from this network.

In summary, the AWS network is heavily biased towards monitoring the highland and mountainous topography, with significantly less coverage in the plains and no coverage in the low-lying arid regions.

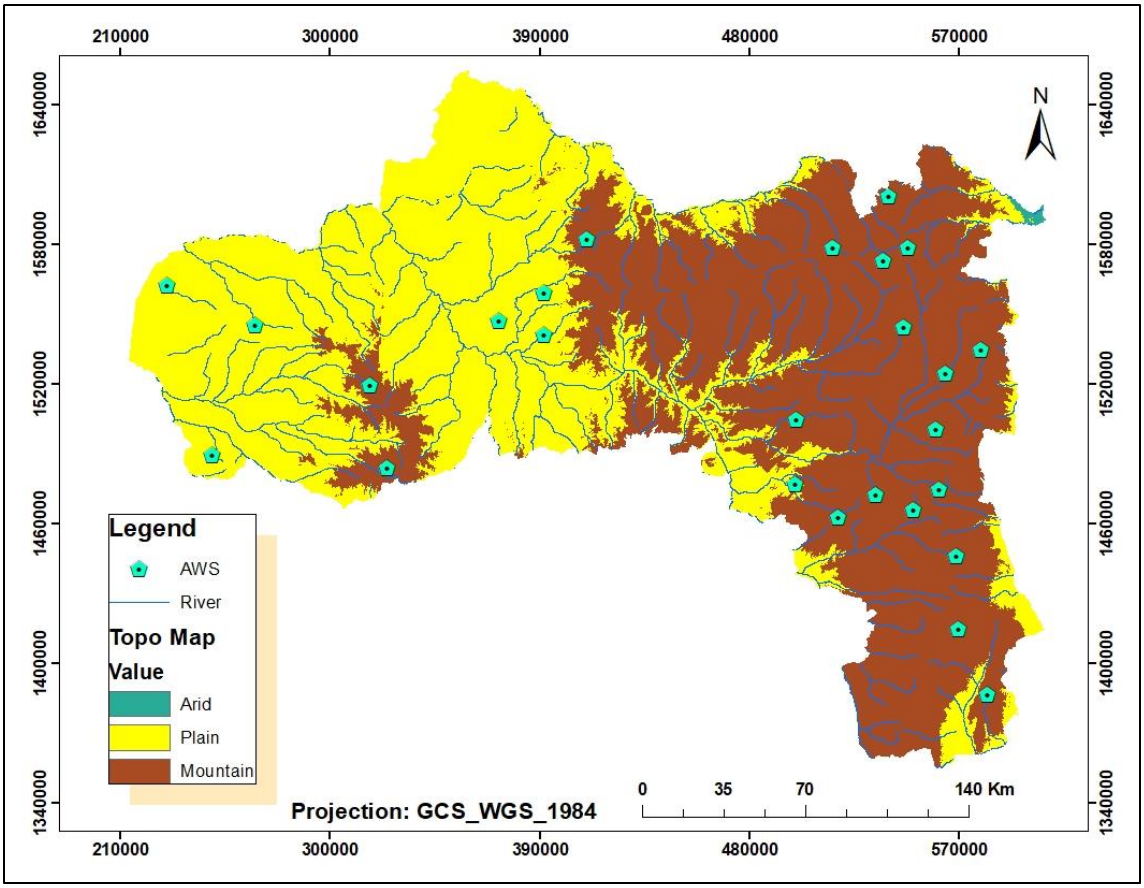


Figure 19: Spatial Distribution of Existing Automatic Weather Stations (AWS).

Table 13: Summary of Proposed AWS Network Expansion

Type of Stations	Observed Station	Computed values to meet the standard	Observed Station coverage (%)	Total Required
AWS	27	49	55%	28
Total	**27**	**49**	55%	28

5.1.8 Stream flow Stations Gap Analysis

The analysis is broken down into three parts:

1. **Calculation of Required Stations:** Determining the minimum and maximum number of stations needed for the region based on WMO standards and the area of each topographic zone.
2. **Assessment of Existing Stations:** Evaluating the current network based on the provided station list.

3. **Comparison and Conclusion:** Comparing the required number of stations with the existing number to assess the network's sufficiency and identify gaps.

1. Calculation of Required Station Density (Based on WMO Standards)

First, I calculate the area of each topographic zone and then determine the required number of stations for each.

- **Total Area:** 52,610 km²

Table 14 : Required stream flow gauging station Density (Based on WMO NO 168 Standards)

Topographic Zone	Percentage of Area	Calculated Area (km²)	WMO Density (km²/station)	Required Stations (Range)
High Land (>1500m)	51.50%	27,094 km²	250 - 1,000	27 – 108
Plain (500–1500m)	48.40%	25,463 km²	1,000 - 2,500	10-25
Arid (<500m)	0.10%	53 km²	10,000 - 20,000	0 – 1
Total	**100%**	**52,610 km²**	---	**37 – 134**

- **High Land:** 27,094 km² / 1,000 = 27 stations (minimum); 27,094 km² / 250 = 108 stations (optimum).
- **Plain:** 25,463 km² / 2,500 = 10 stations (minimum); 25,463 km² / 1,000 = 25 stations optimum).
- **Arid:** The area is too small to require a dedicated station based on this density standard, but one could be justified for monitoring this unique environment.

2. Assessment of Existing Stations

Next, I classify the 61 existing stations from the table based on their altitude to see how they are distributed across the topographic zones.

Table 15 : Existing Stream flow Stations distribution

No	Number of Station	Altitude (m)	Topographic Zone
1	39	>1500	High Land

2	22	500-1500	Plain
3	-	<500	Arid

Comparison, Result, and Completed Text: As the research over all aim is optimize the streamflow station of the study area based on the WMO standards so the analysis is foxed on optimum standard or values.

Table 16. Sufficiency Assessment:

Topographic Zone	**Required Stations (Min - optimum)**	**Existing Stations (Counted)**	**Assessment**
High Land	27 – 108	39	Severely Insufficient. The highland zone is the largest and most climatically complex, yet it is critically under sampled.
Plain	10 – 25	22	Insufficient. the number of stations falls short of the optimum requirement of 25.
Arid	0 – 1	0	Acceptable by Density, but a Gap. While the area is small, having no station means this unique climatic zone is not monitored at all.
Total	37 – 134	61	Insufficient. The total number of stations 61 is significantly below the absolute optimum required for the region (134).

Visual and Spatial Analysis: The stations are listed by basin (Tekeze, Denakille, Mereb). A critical finding of this study is twofold, revealing both a systemic and a relative failure in the region's hydrometeorological monitoring. First, when evaluated against World Meteorological Organization (WMO) standards, the entire network is critically deficient, with no single basin, including the most monitored Tekeze River Basin (n=49), meeting the recommended optimum station density. Second, within this context of overall inadequacy, there is a profound internal imbalance. The Danakil (n=7) and Mereb (n=5) basins are not only under-equipped in absolute terms but are also disproportionately under-observed compared to the Tekeze basin. This dual challenge—a systemically inadequate network further weakened by severe spatial bias—poses a significant and fundamental obstacle to effective, region-wide water resource management.

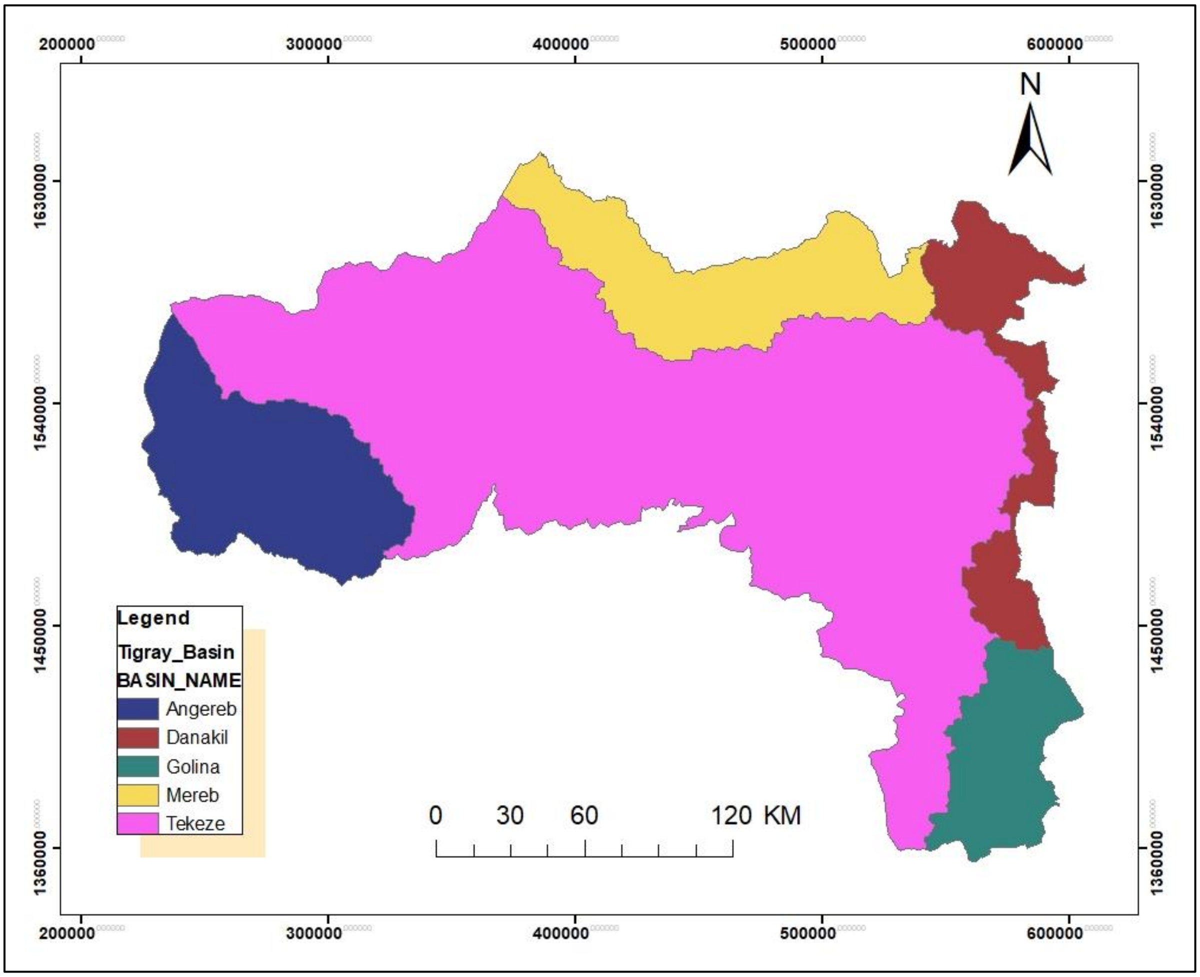


Figure 20. Tigray Basins map

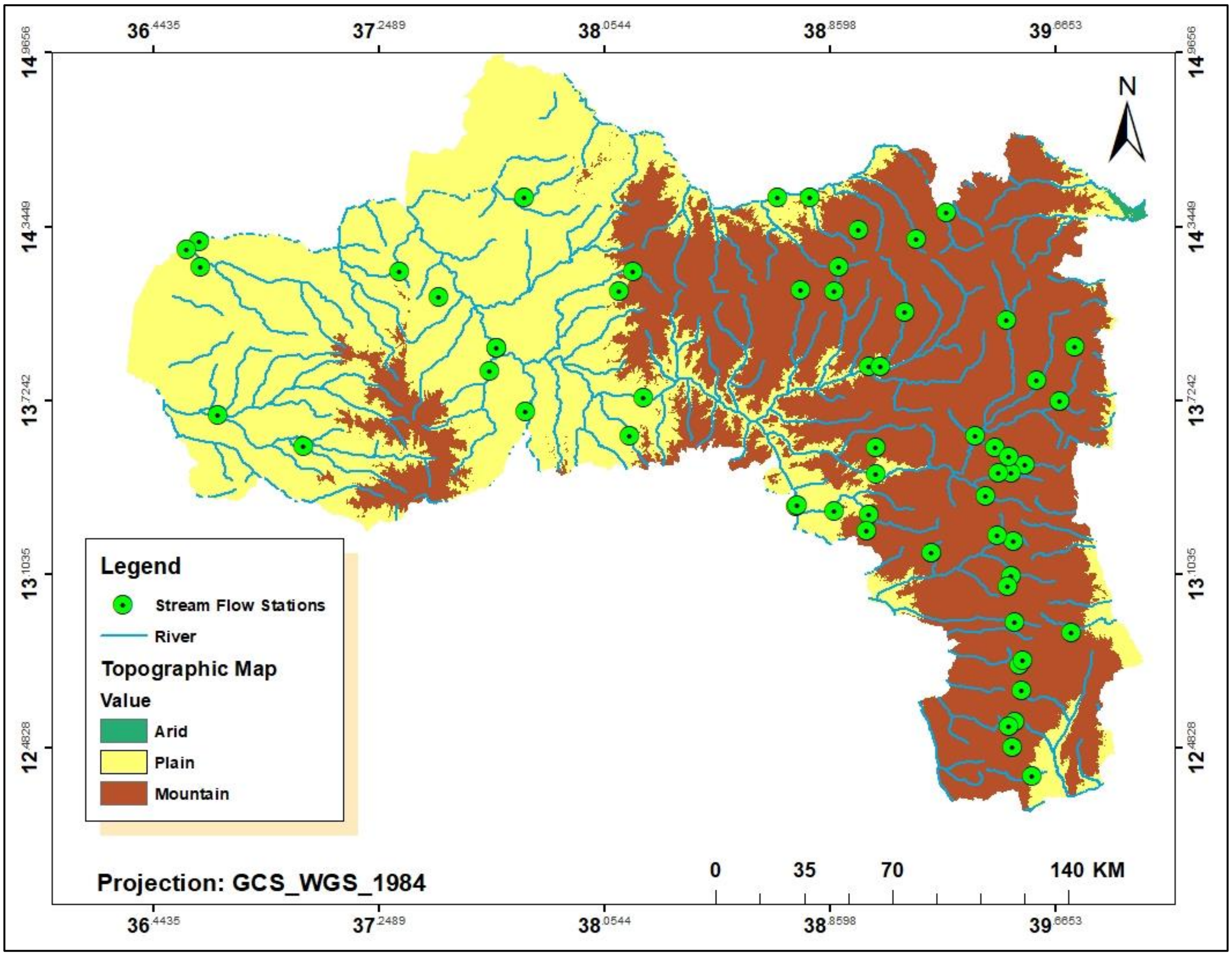


Figure 21. Stream/River flow station distribution map of the study area

Table 17. Optimum, Existing and Additional stream/river flow stations (I-IV class)

Name of Basins	Optimum gauge Stations	Existing gauges	Additional required gauge	Existing Coverage in %
Tigraybasin (Angereb, Danakil,Golina,Mereb Gash and Tekeze)	134	61	73	45.5%

Table 18. Minimum, Existing and Additional stream/river flow stations (I-IV class)

Name of Basins	Minimum gauge Stations	Existing gauges	Additional required gauge	Existing Coverage in %

Tigraybasin (Angereb, Danakil, Golina,Mereb Gash and Tekeze)	37	61	-	100%

5.2 HYDROMETROLOGICAL PARAMETER TREND

This section presents and discusses the findings of the hydrometeorological trend analysis for the river basins within the Tigray Region. The analysis focuses on identifying statistically significant trends in key climatic parameters, primarily rainfall and temperature, using long-term station data. The results are contextualized within the broader framework of climate change impacts in Ethiopia and are compared with findings from previous studies.

The Context of Climate Change and Water Resources in Ethiopia: Ethiopia's vulnerability to climate change and variability is well-documented, with a marked increase in the frequency and intensity of climate-related impacts over the past four decades. Observational evidence points to a decline in vital water resources, including lakes and rivers. While increasing demand from a growing population is a contributing factor, climate change exerts significant pressure on water availability (Bayisa et al., 2019). The nation's economy and livelihoods are highly sensitive to shifts in precipitation and temperature, which can negatively affect water availability, stability, access, and utilization. Consequently, concerns are growing that future river flows will be insufficient to meet demand, making climate risk a critical challenge that necessitates urgent and strategic mitigation measures (Bayisa et al., 2019).

While global climate models confirm long-term shifts in temperature and precipitation, these changes are not spatially uniform. Instead, they manifest with significant regional and local variations (Parry et al., 2007). This highlights the necessity of conducting localized studies to understand specific impacts. For instance, the National Meteorological Agency (NMA, 2007) reported that while average annual rainfall remained relatively stable across Ethiopia, the mean annual temperature increased by 1.3°C between 1960 and 2006 (McSweeney et al., 2008). In contrast, other studies have identified a decline in rainfall during the main rainy season (June to September) in specific northern, central, and southwestern regions (Wing et al., 2008; Baley, 2014). This high inter-annual and decadal variability makes the identification of long-term rainfall trends challenging and underscores the importance of historical trend analysis for effective water resource management (NMA, 2020).

5.2.1 Trend Analysis of Hydrometeorological Parameters

To address the inconsistencies in previous findings and account for the region's complex topography, this study employed station-based data for trend analysis. The use of point-based station data is critical in basins with high topographic variability, as areal averaging or reliance on satellite-based gridded data can mask localized trends and produce inconsistent results (Bewket & Conway, 2007; Mekasha et al., 2014). For example, conflicting rainfall trends have been reported in the Awash River basin when comparing station-based analyses (Tadese et al., 2019) with those using satellite data (Mulugeta et al., 2019). Therefore, a robust network of ground stations is indispensable for comprehensive hydro-meteorological planning and management (Cheung et al., 2008).

The non-parametric Mann-Kendall (MK) test was used to detect monotonic trends in the time-series data of rainfall and temperature. This method is widely applied in hydro-climatic studies due to its robustness; it does not require the data to be normally distributed, is less sensitive to outliers or sudden breaks, and can handle missing values (Helsel & Hirsch, 1992; Asfaw et al., 2018). Its successful application in numerous Ethiopian and regional studies confirms its suitability for this analysis (e.g., Alemu & Bawoke, 2020; Gebremicael et al., 2017; Kiros et al., 2016).

5.2.2 Precipitation and streamflow Trends

This subtitle presents the results of the temporal trend analysis for key hydrometeorological parameters—precipitation and streamflow—within the river basins of the Tigray Region. Understanding the relationship between these parameters is fundamental for water resource assessment and prediction (Chu et al., 2020; Adnan et al., 2020). The analysis employs the non-parametric Mann-Kendall test to identify statistically significant trends and Sen's Slope estimator to quantify their magnitude. The findings are then discussed in the context of regional hydro-climatology, data limitations, and their implications for water resource management.

Data Acquisition and Pre-processing:A robust analysis of hydrometeorological trends requires long-term, high-quality data. However, data scarcity and quality issues are persistent challenges in the study region, necessitating a rigorous data selection and pre-processing phase.

Monthly rainfall data were initially collected from 108 rain gauge stations managed by the Ethiopian National Meteorological Agency (NMA). These stations are strategically located within the geographical confines of the Tigray region, specifically covering areas that fall under the Danakil, Tekeze, and Mereb-Gash basins within Tigray's political boundary. Data collection was strictly limited to stations situated within the Tigray region, even for basins that extend beyond its administrative borders.The records varied significantly in length (5 to 60 years) and quality. Many stations, particularly older ones established since the 1960s, exhibited large temporal discontinuities due to periods of civil conflict in the 1980s, the Ethio-Eritrea conflict in the 1990s, and the recent regional conflict.

Furthermore, the station network suffers from an uneven spatial distribution, with a concentration in highland areas and along major transportation routes. Approximately 60% of the stations were installed recently and possess records shorter than 15 years, rendering them unsuitable for long-term trend analysis, which ideally requires a minimum of 30 years of data (WMO, 2008; Taye et al., 2023).

To address these limitations, a subset of **30 stations** Adigrat, Maichew, Adwa, Shire, Senkata, Samre, Sheraro, Atsbi, Axum, Chercher, Maitsebrie, Humera, Dongolat, Abi-adi, Adigudom, Adigoshu, Adishu, Alamata, Asgede, Badme, Bizet, Dewhan, Hashenge, Hawzen, Korom, Mekonie, Zalanbesa, Waja, Mekelle are selected for this study. The selection is based on three primary criteria: (i) length of record, (ii) completeness of the data (percentage of missing values), and (iii) contribution to the spatial representativeness of the network. While some literature suggests a missing data threshold of 5% for statistical analysis (Schafer, 1999), a threshold of up to 10% is considered acceptable in data-scarce regions like Ethiopia,Tigray (Bennett, 2001; Mohammed et al., 2018). Given the robustness of the Mann-Kendall test to missing values (Helsel & Hirsch, 1992), this approach was deemed appropriate. The quality of the selected time series was further assessed through visual inspection and homogeneity testing.

Acquiring recent and complete streamflow data is a well-documented challenge in Ethiopia. A systematic review by Taye et al. (2023) revealed an average gap of nine years between the end year of streamflow data and the year of publication in hydrological studies. This study encountered similar constraints, relying on historical records for key gauging stations within the region. Data from six rivers—Yechila, Tekeze at Embamadre, ilala, ketin Gereb(Maichew), Gando near korem, Genfel—were available for analysis, with records ending between 1995 and 2019.

Table 19. Annual Mean Rainfall of Tigray based on NMA data

Year	**Mean RF**
1960	678.3
1962	747.2
1963	605.3
1964	722.81
1965	525.2
1966	473.5
1967	682.14
1968	451.57
1969	613.9
1970	705.701
1971	689.9637
1972	695.0751
1973	686.8903
1974	693.3413
1975	713.4344
1976	710.8344
1977	716.5586
1978	697.0723
1979	696.7655
1980	705.593
1981	705.583
Year	Mean RF
1983	698.832
1984	683.6896
1985	691.0033
1986	698.7298
1987	721.1084
1988	682.8721
1989	695.2801
1990	694.1323
1991	693.0108
1992	686.6718
1993	678.5574
1994	722.523
1995	721.582
1996	708.8931
1997	697.1034
1998	795.1102
1999	724.8058
2000	680.3972
2001	709.8486
2002	590.8332
2003	654.2743
Year	Mean RF
2005	695.929
2006	747.3087
2007	720.7276
2008	599.7925
2009	635.1686
2010	746.4366
2011	678.05
2012	697.8129
2013	693.7248
2014	697.6763
2015	628.6222
2016	701.84
2017	695.28
2018	683.88
2019	697.62
2020	613.5
2023	693.4
2024	678.5

Year	Mean RF
1982	690.5555

Year	Mean RF
2004	670.9536

Year	Mean RF

Temporal Trend Analysis of Annual Rainfall (1960–2024): This section presents the findings from the statistical trend analysis of the Mean Rainfall time-series data. To investigate the presence of a monotonic trend, the non-parametric Mann-Kendall (MK) test was employed, complemented by the Sen's Slope estimator to quantify the magnitude of any detected trend. The analysis was conducted on the full dataset (1960-2024) and two subsequent sub-periods (1970-2024 and 1985-2024) to assess the robustness of the findings over different time scales.

The significance level (α) for hypothesis testing was set at 0.05. The null hypothesis (H_0) posits no monotonic trend in the data, while the alternative hypothesis (H_1) posits the existence of a significant trend.The results of the Mann-Kendall analysis for all three periods are summarized in Table 20.

Table 20: Mann-Kendall Trend Test Results for Regional Mean Annual Rainfall (1960-2024).

Time Period	**Data Source**	**Mann-Kendall's Z-statistic**	**p-value**	**Sen's Slope (mm/year)**	**Trend Significance (at α =0.05**
1960–2024	NMA	0.396	0.692	0.177	Not Statistically Significant
1970-2024	NMA	-0.32	0.749	-0.150	Not Statistically Significant
1985-2024	NMA	-0.490	0.624	-0.312	Not Statistically Significant

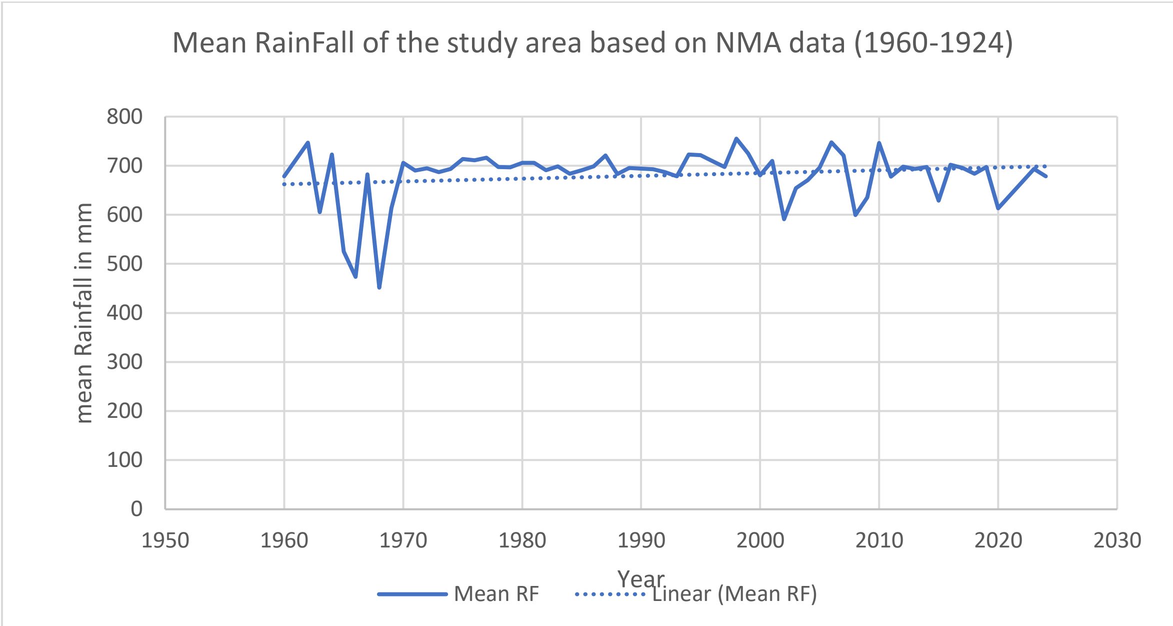


Figure 22: Mean Rainfall of the study area from 1960-2024

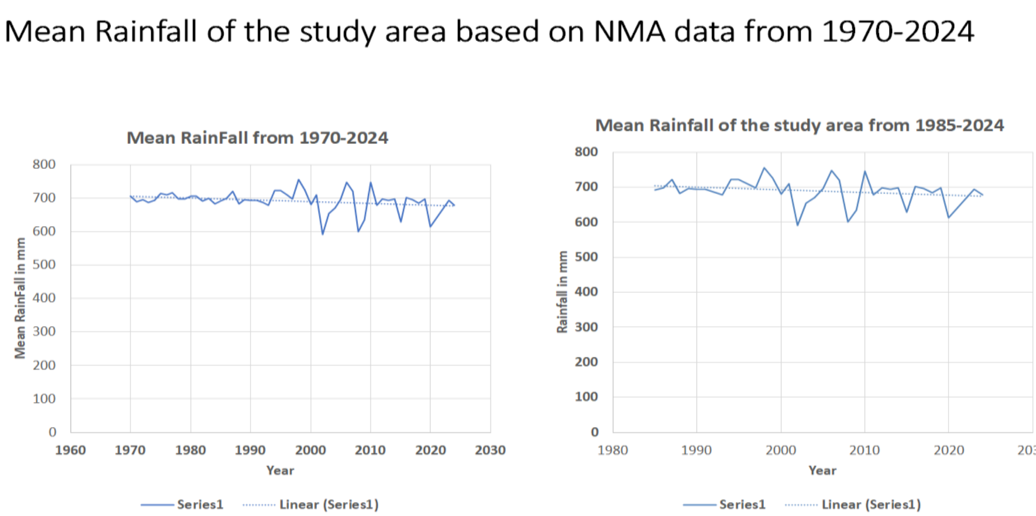


Figure 23: Mean Rainfall of the study area from 1970-2024 extended

For the complete time series from 1960 to 2024, the analysis yielded a positive Z-statistic of +0.396, indicating a very slight increasing tendency. However, the corresponding p-value of 0.692

is substantially greater than the significance threshold of 0.05. The Sen's Slope estimator calculated a median rate of change of +0.177 units per year, a magnitude that is statistically negligible. When the analysis was constrained to the period 1970-2024, the Z-statistic shifted to a negative value of -0.320, with a p-value of 0.749. Similarly, for the most recent period of 1985-2024, the Z-statistic was -0.490 with a p-value of 0.624. In both sub-periods, the trend direction became weakly negative, but the p-values remained high, indicating a lack of statistical significance. In all three analytical scenarios, the null hypothesis (H_0) of no trend could not be rejected. The results consistently demonstrate the absence of a statistically significant monotonic trend in the Mean RF data.

Discussion: The primary finding of this study is the conspicuous absence of a statistically significant long-term trend in Mean RF for the study area, a conclusion that holds true across multiple timeframes spanning from 1960 to 2024. This suggests that despite evident inter-annual and decadal variability, the central tendency of annual rainfall has remained stationary over the past six decades.

The Mann-Kendall analysis revealed that while the direction of the non-significant trend fluctuated depending on the start year—from a slight positive tendency in the full 62-year dataset to a slight negative tendency in the more recent 53- and 38-year periods—none of these approached statistical significance. This inversion in the sign of the Z-statistic highlights that the time series is dominated by stochastic fluctuations rather than a persistent, underlying directional signal. The magnitude of the change, as quantified by Sen's Slope, was negligible in all cases, reinforcing the conclusion of long-term stability. This finding implies that historical rainfall averages remain a robust baseline for the region.

In summary, this thesis finds that the Mean RF in the study area has demonstrated remarkable stability over the long term. The time series is characterized by significant natural variability but lacks a statistically significant directional trend. This conclusion provides a foundational piece of evidence for sustainable water management and serves as a basis for more detailed future investigations into the nuanced impacts of climatic variability in the region.

Monthly variability of rainfall

Following the analysis of long-term rainfall variability and trends, this section focuses on the monthly variability of rainfall across the study period. Monthly rainfall across most meteorological stations in the Tigray Region exhibits significantly higher temporal variability compared to annual timescales. The region receives the majority of its annual rainfall during the main rainy season, which extends from June to September. This seasonal precipitation is largely driven by the northward migration of the Intertropical Convergence Zone (ITCZ), bringing Equatorial westerly winds from the Atlantic Ocean and moist southerly flows from the Indian Ocean. In contrast, the dry season, which spans from October to May, is characterized by very limited rainfall. During this period, the region is predominantly influenced by dry northeasterly trade winds originating from the Arabian Peninsula, which suppress precipitation. The Tigray Region exhibits a unimodal rainfall pattern, with a distinct peak in August. As illustrated in Figure 24 and Table 21, August records the highest mean monthly rainfall, averaging approximately 340.5 mm. On the other hand, December experiences the lowest rainfall, with a mean value of only 5.5 mm. These findings are consistent with satellite-based and station-level climate data analyses, confirming the strong seasonal concentration of rainfall in the region

Table 21. Tigray mean monthly Rainfall data from 1991-2021 (based on climate data)

Month	**Mean Rain Fall**
JAN	8.84
FEB	19.97
MAR	54.45
APR	99.34
MAY	98.35
JUN	78.17
JUL	340.15
AUG	381.77
SEP	75.22
NOV	26.95
OCT	28.96
DEC	5.5

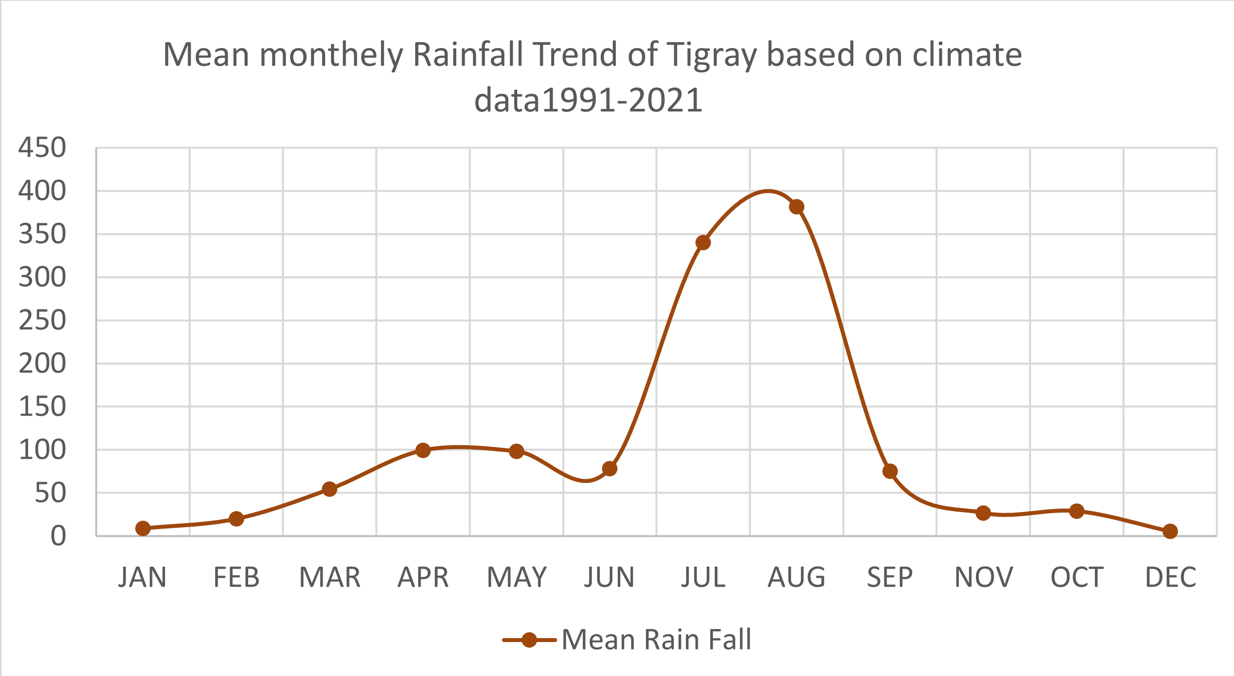


Figure 24. Rainfall trend of Tigray from 1991-2021 (based on climate data)

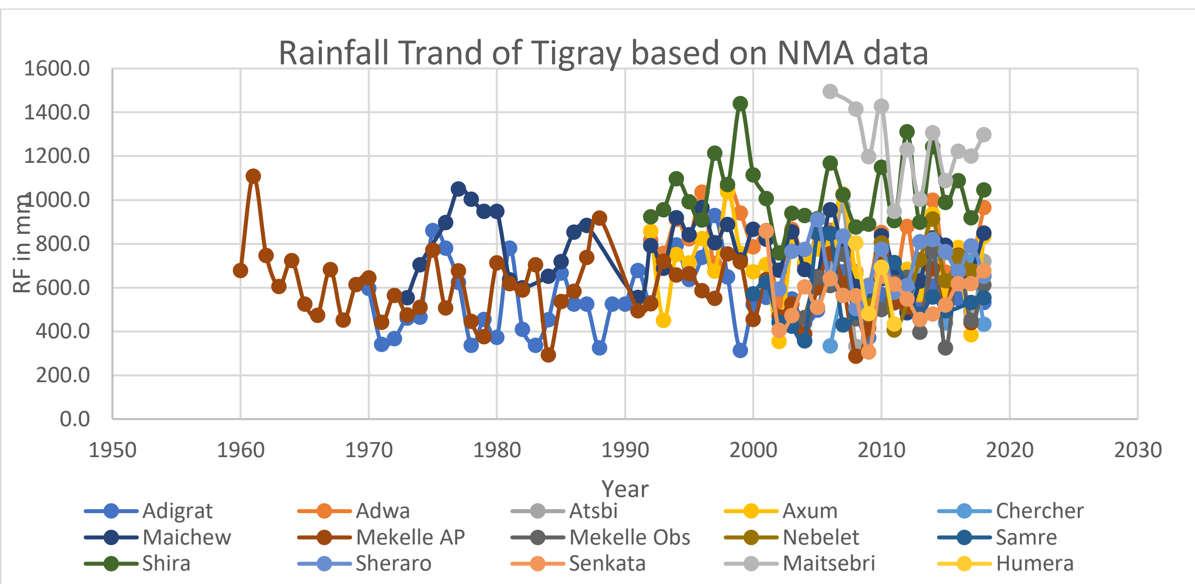


Figure 25.Rainfall trend of Tigray based on NMA data

The chart (Figure 25) shows the rainfall trend of Tigray based on NMA data over several decades, from a 1960 to 2018, across meteorological stations.

Key Observations from the Trend Analysis:

Fluctuations in Rainfall:

- There is high variability in rainfall across the years and among different stations.
- stations Shira and Atsbi show higher peaks in certain years, especially after 1990.
- In earlier decades (1960s–1970s), the trend appears relatively stable but lower, with a few spikes.

General Long-Term Trend:

- Despite yearly fluctuations, an overall slightly increasing trend can be observed.
- The early decades (1960s–1970s) had more stable and moderate rainfall, whereas recent decades (1990s onward) have more variability.

As illustrated in Figure 32, the study area exhibits a pronounced spatial pattern in mean annual rainfall. The primary trend is a distinct east-to-west gradient, with precipitation increasing across the region. The eastern and southern parts of Tigray are the most arid, characterized by mean annual rainfall totals below 700 mm. In contrast, the western half of the region is significantly wetter, with totals exceeding 1000 mm in its southern areas. Within this wetter western zone, a secondary north-to-south gradient is also apparent, where rainfall decreases progressively from north to south.

5.2.3 Spatial Distribution of Mean Annual Rainfall

Figure 31 presents the spatial distribution of mean annual rainfall across the study area, based on interpolated data from meteorological stations. The map highlights a complex and highly variable rainfall pattern, with distinct wet and dry zones corresponding closely to the region's topography.

Rainfall Patterns

The analysis of the map reveals a non-uniform rainfall distribution with a wide range, from approximately 327 mm to 1,238 mm per year. The key spatial patterns are as follows:

- **Wettest Regions:** The highest mean annual rainfall, exceeding 1,100 mm/year (represented in dark green), is concentrated in a specific area in the south-central highlands. Surrounding this core, a broader zone receives high rainfall, ranging from 898 to 1,100 mm/year (orange). These high-precipitation zones are geographically associated with the region's major mountain ranges and high-altitude plateaus.
- **Driest Regions:** The lowest rainfall, with values between 326 mm and 702 mm/year (Rade and medium yellow shades), is predominantly found in the eastern and northeastern parts of the study area. Another pocket of low rainfall is evident in the northwestern corner. These areas generally correspond to the lower-lying plains and deep river valleys, which lie in the rain shadow of the highlands.
- **Transitional Zones:** A significant portion of the central part of the study area experiences moderate rainfall, ranging from 702 to 898 mm/year (light grey). This zone acts as a transition between the wet highlands and the arid lowlands.

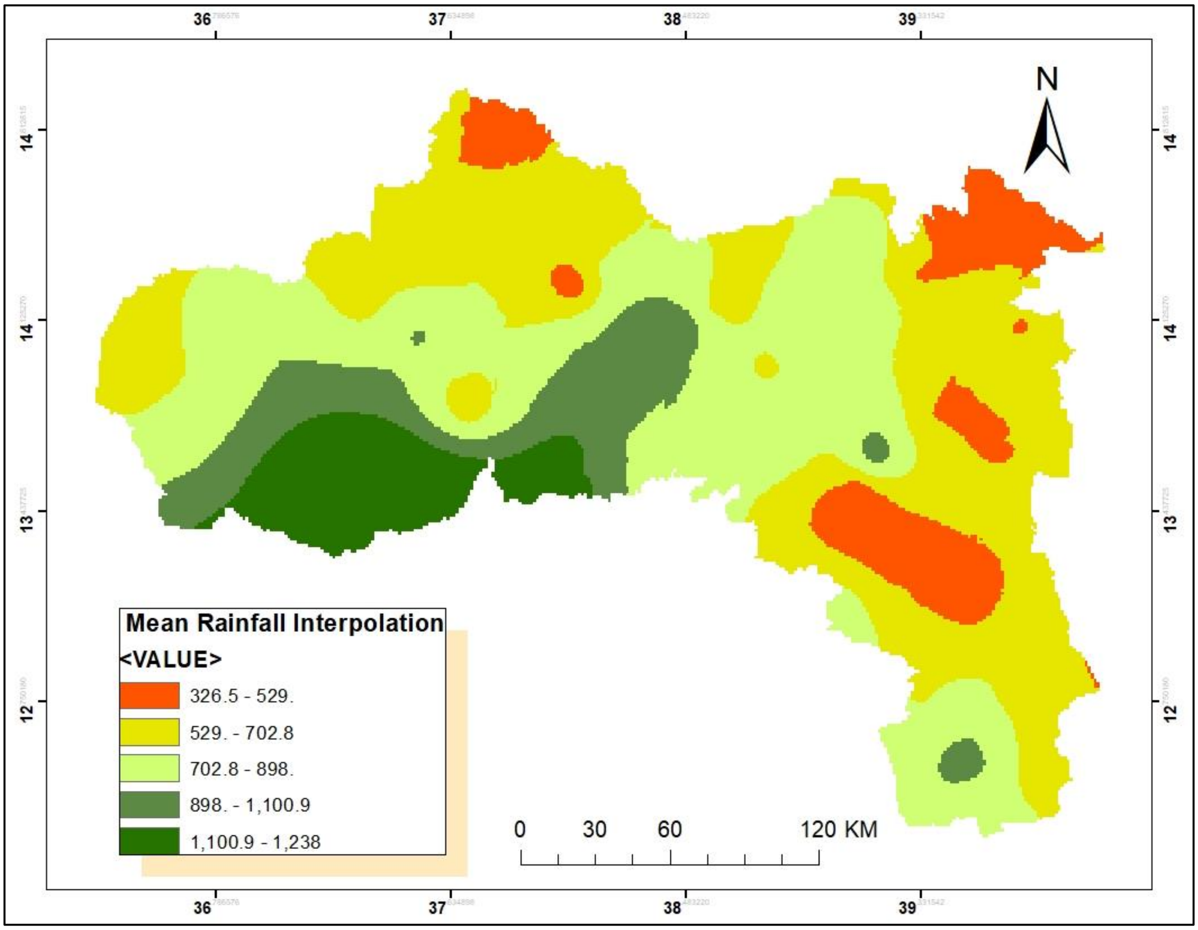


Figure 26. Spatial distribution of mean annual rainfall (mm) across the study area based on NMA data from 1985-2024G.C

Orographic Influence and Hydrological Significance

The observed spatial pattern of rainfall is primarily a result of orographic effects, where topography significantly influences precipitation.

- **Orographic Precipitation and Rain Shadows:** The highlands act as a natural barrier to moisture-laden air masses, forcing them to ascend, cool, and release their moisture as
- orographic rainfall. This process, which is the key determinant of rainfall patterns across Ethiopia, explains the high precipitation totals observed in the south-central and other elevated parts of the region (Conway, 2000; Seleshi & Zanke, 2004). Conversely, the lowlands in the east and northwest lie in a rain shadow, receiving substantially less rainfall

as the descending air becomes warmer and drier. This mechanism is the primary driver of the region's starkly contrasting climatic and ecological diversity (Nyssen et al., 2014).

- **Implications for Water Resources ("Water Towers"):** The high-rainfall highland areas function as the region's "water towers," a concept recognized for mountain systems globally due to their disproportionate contribution to river discharge (Viviroli et al., 2007). They are the primary sources of runoff that feeds major rivers like the Tekeze, and they are critical zones for groundwater recharge (Tadesse et al., 2017). The health and stability of these highland ecosystems are therefore essential for the water security of the entire downstream basin. The spatial correlation between the wettest zones on this map and the headwaters of major rivers underscores this critical hydrological linkage.
- **Vulnerability to Drought:** The areas receiving the lowest rainfall (eastern and northwestern parts) are inherently more vulnerable to drought and water scarcity. These semi-arid zones rely on a smaller and often more variable amount of precipitation, making their rain-fed agricultural and pastoral systems highly susceptible to climatic shocks (Hadgu et al., 2013; Viste et al., 2013). The significant decrease in streamflow observed for the Suluh River (Section 4.3.3), which is located in the drier eastern part of the region, is consistent with the heightened vulnerability of such low-rainfall zones to hydro-climatic stress.

In summary, the heterogeneous distribution of rainfall is a defining feature of the study area's climatology. This topographically controlled pattern dictates the availability of surface and groundwater resources, shaping agricultural practices and determining the relative vulnerability of different parts of the region to hydro-climatic variability and change (Nyssen et al., 2014).

5.2.4 Stream flow Trend Analysis

Trend analysis was conducted on the mean annual flow for six key rivers in the study area.

- **Yechila River (1962–2005):** The Mann-Kendall test for the Yechila River's 44-year record showed no statistically significant trend ($p = 0.592$), as depicted in Figure 27. The Sen's Slope of 5.523 $m^3/s/year$ was not statistically different from zero.

- **Tekeze River at Embamadre (1968–2000):** Similarly, the Tekeze River at the Embamadre gauging station exhibited no significant trend in its annual mean flow over the 33-year period ($p = 0.471$) (Figure 28).

Table 22 and 17 summarizes the selected stations, mean annual rainfall, coordination of Tigray river basin

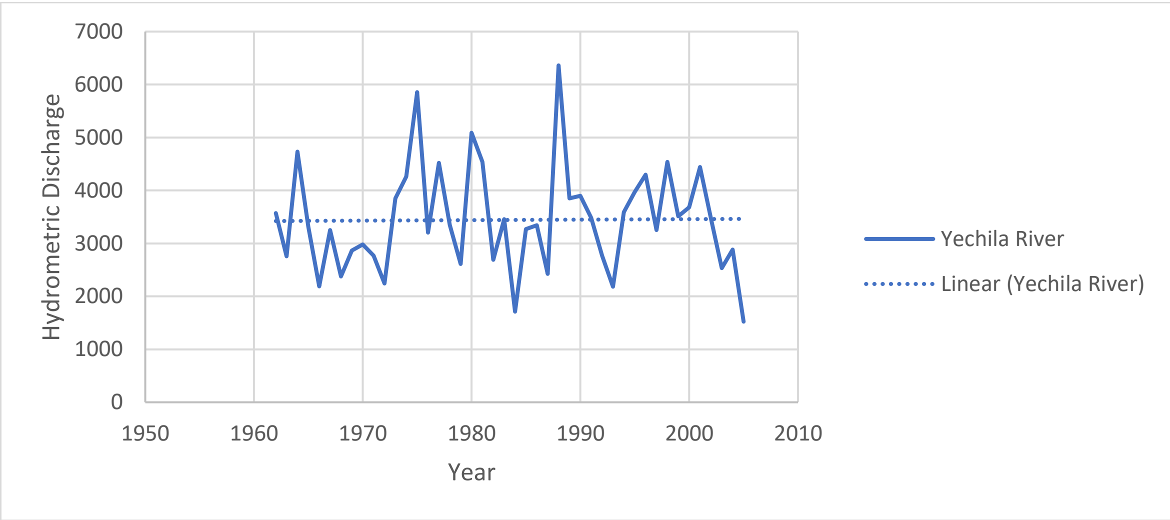


Figure 27.Yechiela river discharge trend (yechila river mean flow from (1962–2005):

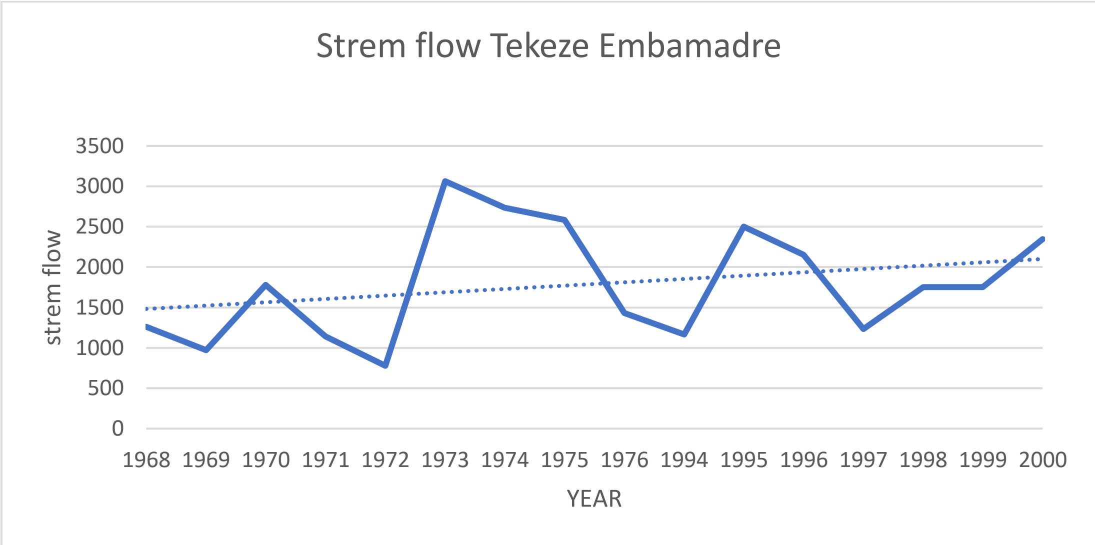


Figure 28. Tekeze Embamadre river discharge trend (TK river annual mean flow) from (1968–2000)

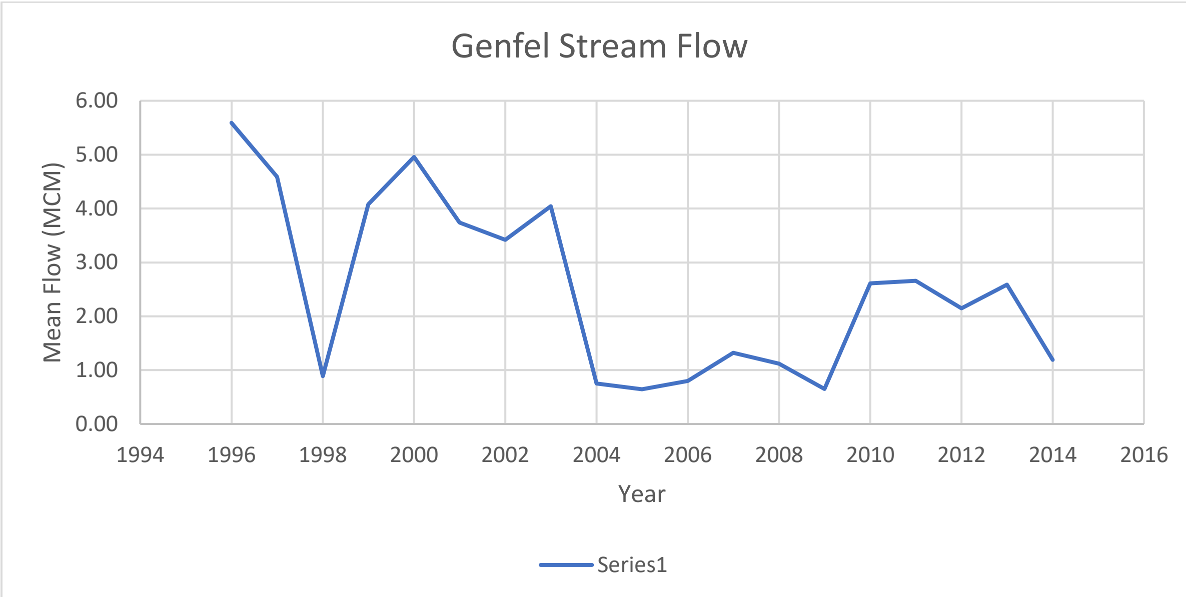


Figure 29: Genfele Stream Flow from 1996-2014

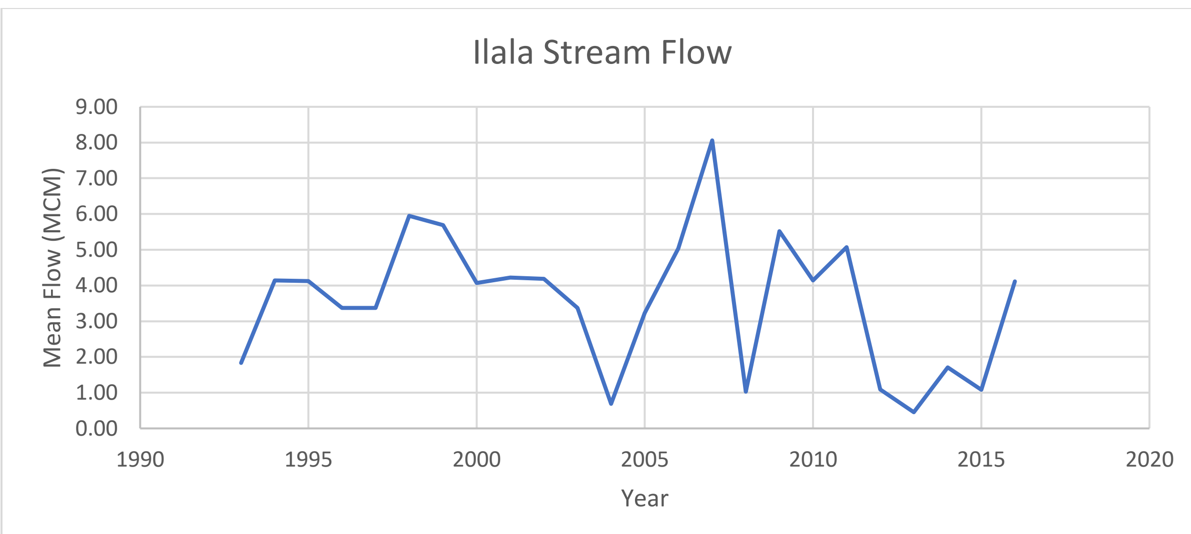
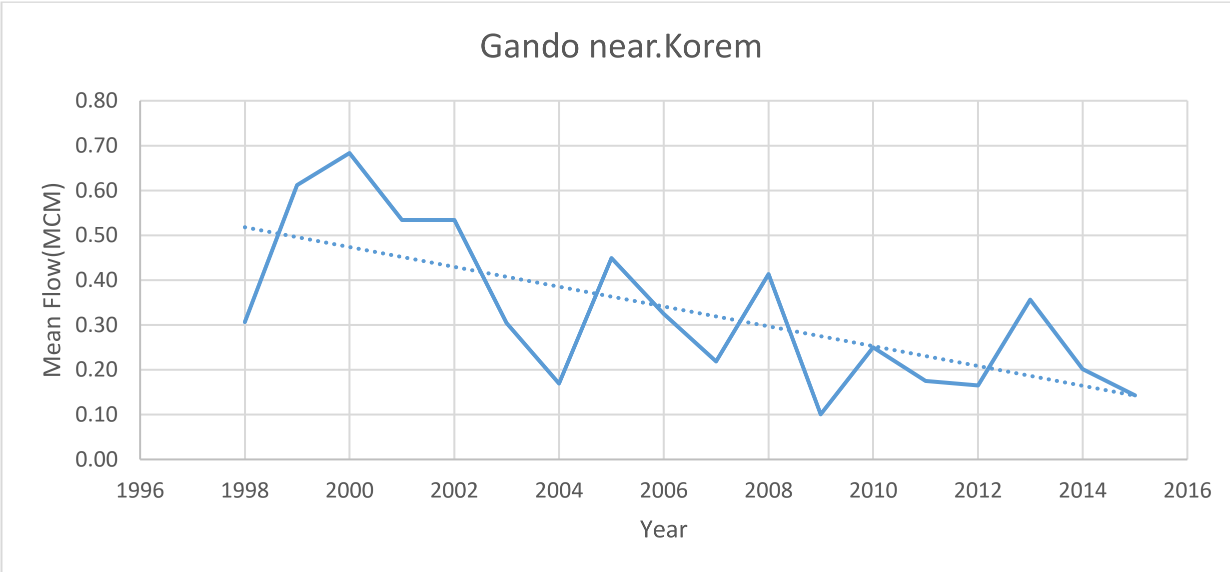


Figure 30: Ilala Stream Flow from 1993-2016



Stream Flow of Gando near korem from 1998-2015

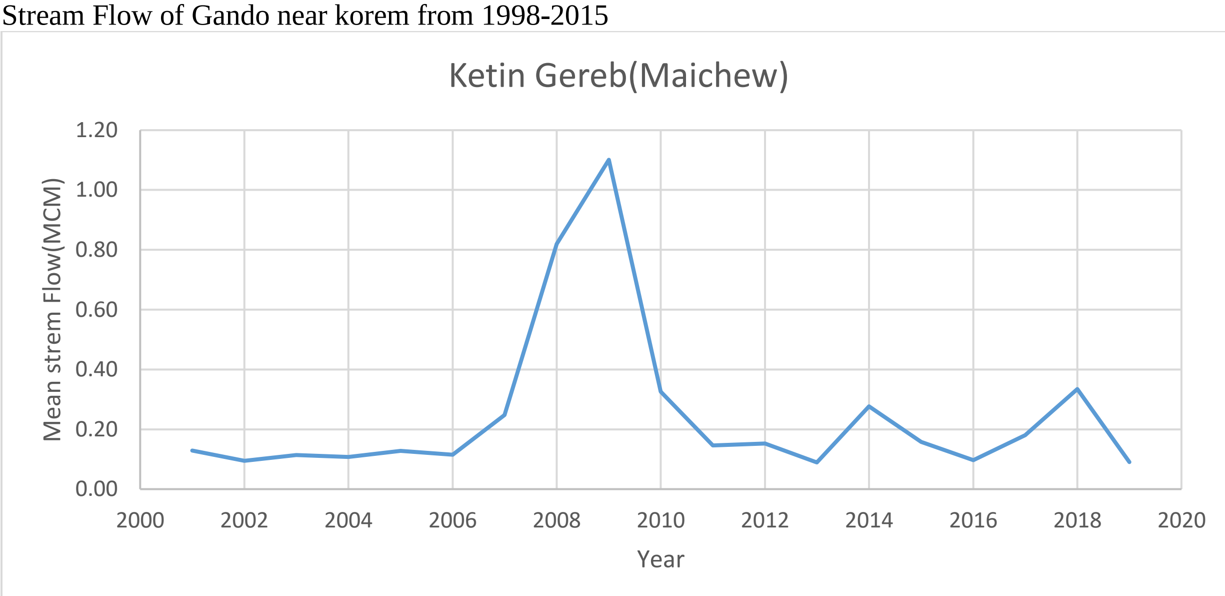


Figure 31: Ketin Gereb (Maichew) Mean Stream Flow 2001-2019

Trend Analysis of Seasonal Streamflow (June-August)

This section details the results of a trend analysis conducted on historical and recent seasonal streamflow data from several river gauging stations within the study area. The primary objective was to identify and quantify any statistically significant long-term changes in river discharge. The analysis employed the non-parametric Mann-Kendall (MK) test to detect monotonic trends and the Theil-Sen's Slope estimator to quantify the magnitude of such trends. A significance level (α) of 0.05 was used for all statistical tests, meaning p-values less than 0.05 were considered indicative of a statistically significant trend.

Analysis of Historical Streamflow Data

A trend analysis was performed on long-term historical datasets for two key rivers in the study area: Yechila and Tekeze (at Embamadre). The findings for each station are consolidated in Table 22.

Table 23: Mann-Kendall Trend Test Results for Historical Mean Seasonal (June-August) Streamflow

River / Station	Analysis Period	Kendall's Tau (τ)	p-value	Sen's Slope (m^3/s/year)	Trend Interpretation (α = 0.05)
Yechila River	1962–2005	0.057	0.592	5.523	No Significant Trend
Tekeze River (at Embamadre)	1968–2000	0.142	0.471	16.186	No Significant Trend

Interpretation of Historical Trends:

The analysis of mean Seasonal flow for both the Yechila River (1962–2005) and the Tekeze River at Embamadre (1968–2000) revealed no statistically significant trends.

For the Yechila River, the MK test indicated a very weak positive signal (τ = 0.057) that was not statistically significant (p = 0.592). Similarly, the Tekeze River showed a weak positive tendency (τ = 0.142) that was also not significant (p = 0.471). In both cases, the p-values were substantially greater than the 0.05 significance level, meaning the null hypothesis (H_0) of no trend could not be rejected. The confidence intervals for the Sen's Slope estimates for both rivers contained zero, confirming that the observed minor fluctuations are not statistically discernible from random inter-annual variability. This suggests a broadly stable flow regime for these major rivers during their respective periods of record.

Analysis of Recent Streamflow Data (1993-2019)

A second trend analysis was performed on more recent but sparser datasets from four catchments: Genfel, ilala, Gando nr.Korem, and Kettin-Gereb at Maichew. The results are summarized in Table 24.

Table 24: Mann-Kendall Trend Analysis for Recent Streamflow (1993-2019)

Station Name	Data Points (n)	Z-Statistic	p-value	Sen's Slope (Trend Magnitude)	Trend Interpretation (α = 0.05)
Genfel	16	-1.14	0.254	-0.11	No Significant Trend
ilala	12	0.38	0.704	0.09	No Significant Trend
Gando nr.Korem	15	-0.04	0.968	-0.001	No Significant Trend
Kettin-Gereb(Maichew)	15	0.92	0.358	0.005	No Significant Trend

Interpretation of Recent Trends:

Consistent with the historical data from the larger rivers, the analysis of all four recent datasets from 1993 to 2019 did not reveal any statistically significant trends. While some stations showed slight tendencies (e.g., a minor decreasing tendency at Genfel and a minor increasing tendency at Kettin-Gereb), none of these patterns were strong enough to be distinguished from random chance, as indicated by their high p-values.

Discussion

The trend analyses of streamflow data, encompassing both long-term historical records and more recent datasets, consistently point toward hydrological stability within the analyzed catchments. Across all examined rivers and time periods, there was no statistical evidence of significant, monotonic increases or decreases in mean annual streamflow.

This finding of stable streamflow aligns well with regional meteorological studies that have reported generally stable long-term rainfall patterns for the broader region (e.g., NMA, 2007). The fluctuations observed in streamflow time-series plots appear to be characteristic of the region's semi-arid climate, reflecting inter-annual variability rather than a persistent directional change. The fact that this stability is observed in both large river systems (Yechila, Tekeze) and, to the extent the data allows, in river (Genfel, Kettin-Gereb at Maichew) suggests that, at the scale of this investigation, rainfall remains the primary driver of river discharge, and widespread systemic shifts have not occurred.

In summary, based on the available data, the streamflow regimes of the analyzed rivers in the Tigray Region appear to have been broadly stable. This hydrological stability is consistent with the lack of a significant trend in regional rainfall. Nonetheless, careful monitoring remains crucial to detect potential future changes and to understand the impacts of localized human activities on water resources.

5.2.5 Temperature Trends

Monthly trend analysis on climate data: The trend graph shows that Temperate has considerable seasonal variations. It maintains two peaks with a minimum in August. The August minimum is due to the fact that August month is the core rainy month that is characteristic of incessant cloud formation thereby depleting the amount of temperature reaching the earth's surface. In the case of Air temperature and sunshine hour, the first peak lasts between February and May, while the second peak is found between November and December.

The months from Jan to Jun temperate increases but Jul and August decrease Temp then Seb, Nov increase and decalin in Oct and December. Mean Maximum temperate observe on Jun 22.08°c and Mean Minimum Temperature on December16.35 °c most north part of the region is characterized by high temperate area where as eastern part is characterized by cold climate condition. (Satellite-based or based on climate data analysis of temperature trend)

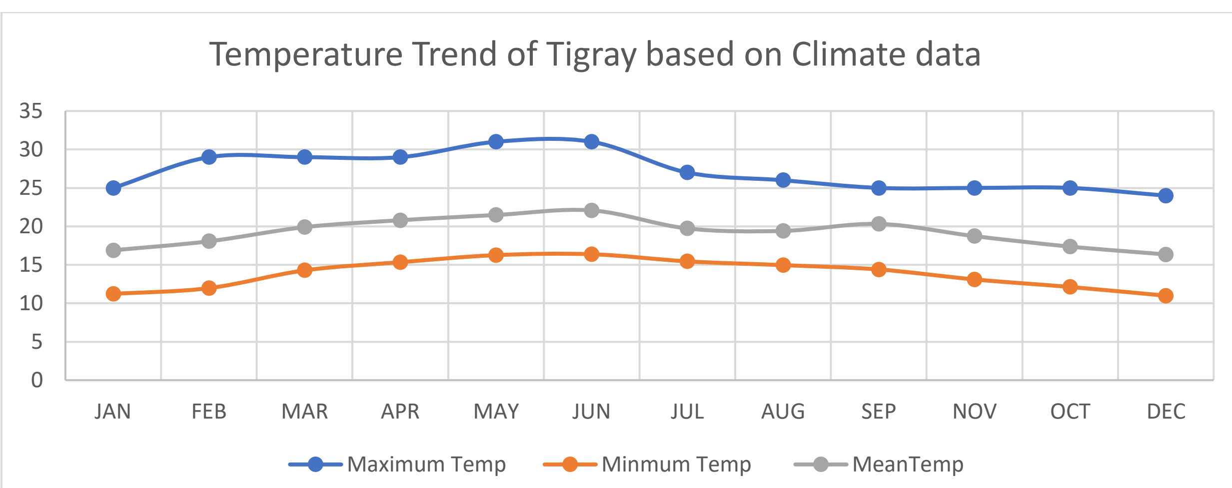


Figure 32. Temperature trend of Tigray from 1991-2021 (based on climate data)

Table 25. Tigray Temperature data from 1991-2021 (based on climate data)

Month	Maximum Temp	Minimum Temp	Mean Temp
JAN	25	11.22	16.89
FEB	29	11.97	18.06
MAR	29	14.28	19.9
APR	29	15.34	20.8
MAY	31	16.26	21.48
JUN	31	16.38	22.08
JUL	27	15.45	19.73
AUG	26	14.96	19.41
SEP	25	14.4	20.32
NOV	25	13.1	18.73
OCT	25	12.12	17.37
DEC	24	10.99	16.35

Station -based or based on NMA data analysis of temperature trend from 1985-2024

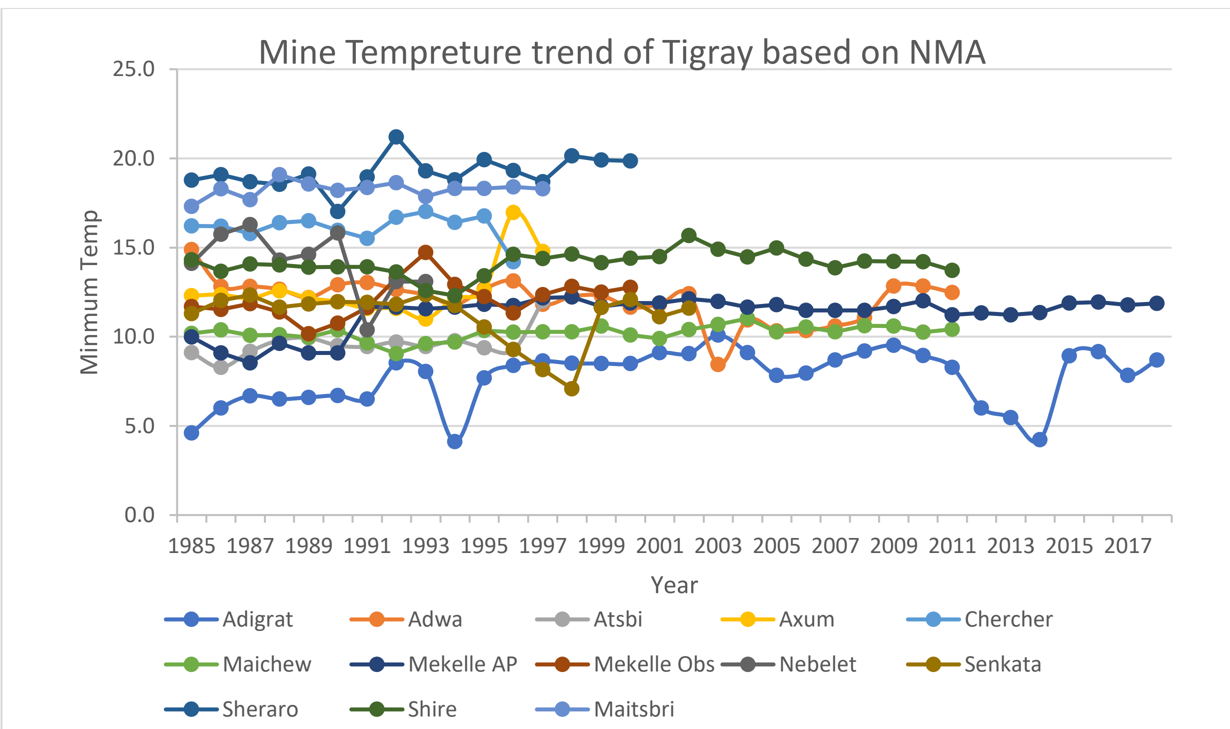


Figure 33. Minimum Temperature trend of Tigray based on NMA

Trend analysis of Mean Temperature in Tigray (based on NMA data)

The graph presents the mine temperature trends for different meteorological stations in Tigray over the period 1985–2024. The key observations from the trend analysis are:

Stations with Increasing Trends:

Mekelle AP and Sheraro display an increasing trend in minimum temperature, suggesting a warming trend in these locations, Shire and Neblet, also show an overall gradual increase in temperature.

Stations shows Decreasing Trends: Chercher has a noticeable decreasing trend, particularly after 2000, where temperatures drop significantly. Adigrat also exhibits fluctuations with a slight downward trend in the later years.

Fluctuations and Variability: Axum, Adwa, and Maichew demonstrate significant interannual variability, with noticeable spikes and dips in temperature. Whear as Senkata, show relative stability with minor fluctuations.

Abrupt Changes and Anomalies:

Some stations experience abrupt drops, such as Chercher in the early 1990s and again around 2013.Periods of high variability can be observed around the late 1990s and early 2000s, indicating potential climatic shifts.

Implications for Climate Change and Local Adaptation

The overall trend suggests that some areas in Tigray are experiencing warming, which could have implications for agriculture, water resources, and biodiversity. The decreasing trends in certain areas might indicate localized microclimatic effects or changes in weather patterns.

The variability and abrupt shifts could be linked to extreme weather events, land-use changes, or global climatic influences such as El Niño and La Niña.

Mann-Kendall Trend Analysis Results for Chercher Station (2007-2024)

- Kendall's Tau (τ): 0.147

A positive value suggests a slight increasing trend in minimum temperature.

- p-value: 0.532

Since the p-value is greater than 0.05, the trend is not statistically significant at the 95% confidence level.

- Sen's Slope Estimate: 0.057°C per year

Indicates a small annual increase in minimum temperature.

Interpretation

The minimum temperature at Chercher station shows a weak increasing trend. However, the trend is not statistically significant, meaning we cannot confidently say that the temperature is increasing due to long-term climate patterns—it could be due to natural variability. The estimated Sen's slope (0.057°C per year) suggests a gradual warming over the study period. The analysis is to determine if there is a statistically significant monotonic (consistently increasing or decreasing) trend in the mean annual temperature data from 1985 to 2024. The analysis employs the non-parametric Mann-Kendall (MK) test for trend detection and the Theil-Sen's Slope estimator to quantify the magnitude of the trend.

5.2.6 Spatial Distribution of Mean Annual Temperature

Figure 34. illustrates the spatial distribution of mean annual temperature across the study area, interpolated from NMA data. The map reveals a distinct and highly variable temperature regime, strongly governed by the region's topography.

Temperature Patterns

The analysis of the spatial temperature patterns reveals several key features:

- **Overall Gradient:** A clear temperature gradient is observable across the region, generally trending from the hot western lowlands to the cooler eastern highlands. Mean annual temperatures range from a low of 13.7°C to a high of 29.7°C.
- **Coolest Regions:** The coolest areas, with mean annual temperatures between 13.7°C and 17.3°C (represented by dark and light green shades), are concentrated in distinct, isolated pockets. The most prominent cool zones are located in the south-central part of the study area and along the eastern escarpment. These locations correspond to the highest-altitude areas within the region.
- **Hottest Regions:** The highest mean annual temperatures, ranging from 26.3°C to 29.7°C (pink and light lavender shades), are found in the expansive western portion of the study area. This zone represents the lowest-lying areas, indicating a strong inverse relationship between temperature and elevation.
- **Transitional Zones:** A large portion of the study area falls within intermediate temperature ranges (17.4°C to 26.2°C), represented by yellow, orange, and brown shades. These extensive zones form a clear transition between the hot western lowlands and the cooler central and eastern highlands, reflecting the mid-altitude plateaus that characterize much of the region.

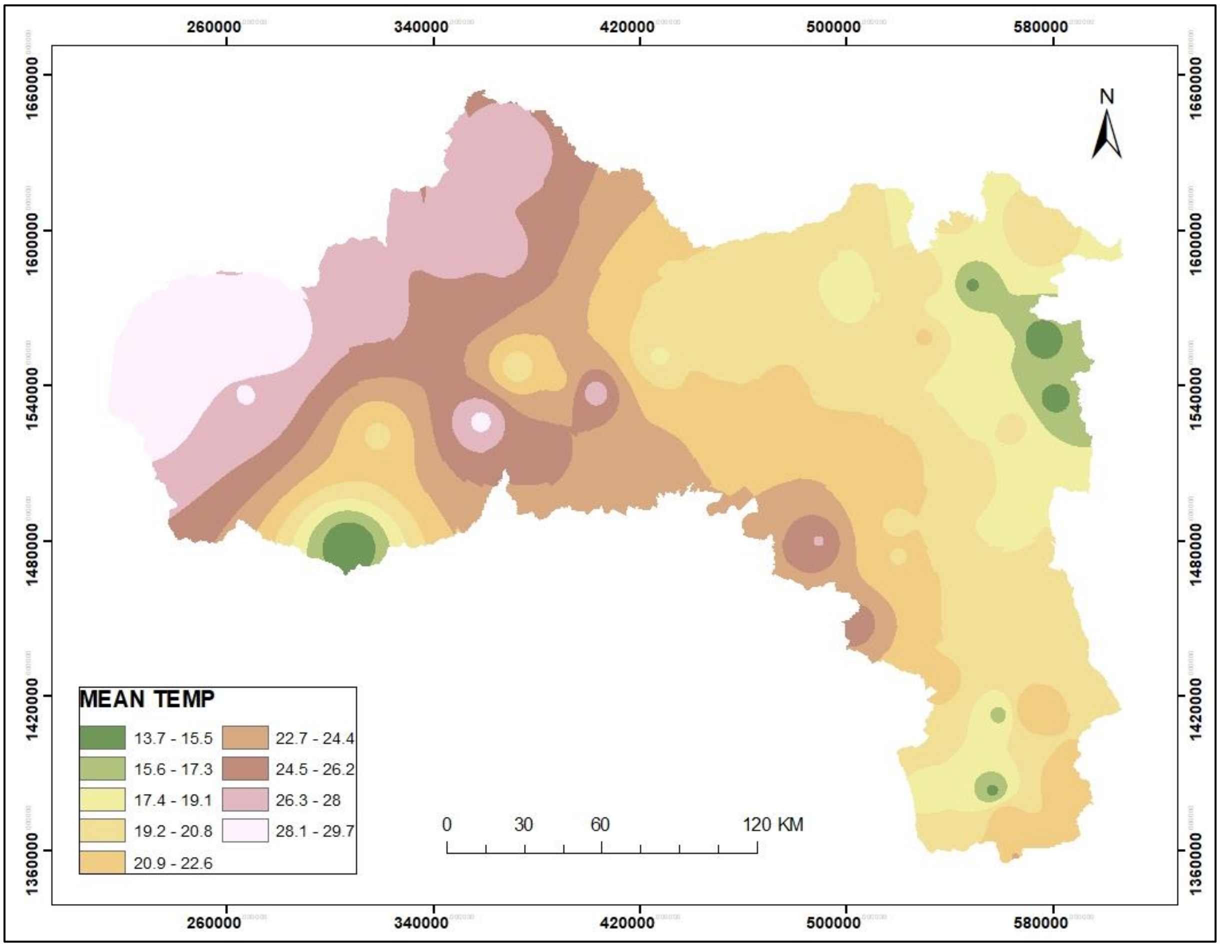


Figure 34. Spatial distribution of mean annual temperature (°C) across the study area based on NMA data from 1985-2024 G.C.

Topographic Control and Hydrological Implications

The spatial distribution of temperature shown in Figure 34. is a classic example of topographic control on climate. The inverse relationship between altitude and temperature, known as the environmental lapse rate, is the dominant factor shaping the thermal landscape of the study area. This strong altitudinal influence on local climate is a well-documented characteristic of Ethiopia's complex terrain (Conway, 2000; Gummadi et al., 2018).

Implications for Evapotranspiration and Water Balance: The high temperatures in the western lowlands have critical implications for the regional water balance. Temperature is a primary driver of potential evapotranspiration (PET), and as such, these warmer areas experience significantly higher rates of atmospheric water demand (Allen et al., 1998).

Consequently, a greater proportion of any rainfall received in these lowland zones is lost to the atmosphere through evapotranspiration. This process increases water stress on natural vegetation and crops and reduces the amount of "effective rainfall" available for recharging groundwater and contributing to streamflow (Hadgu et al., 2013).

Context for Climate Change Vulnerability: When considered alongside the rainfall and streamflow trend analyses, this temperature map provides crucial context for assessing climate change vulnerability. Global and regional climate models project continued warming, which is expected to exacerbate water scarcity, particularly in arid and semi-arid regions (IPCC, 2021). Any future warming trends would likely be felt most acutely in the already hot western lowlands, potentially pushing temperatures beyond critical thresholds for existing agricultural systems and intensifying water stress. Conversely, the cooler highlands may act as relative climatic refugia, although they are not immune to change. This differential vulnerability, where lowland areas are often more exposed to extreme heat and water stress than adjacent highlands, is a recognized pattern in climate impact assessments for the region (Mekonnen et al., 2018).

In summary, the temperature regime of the study area is fundamentally driven by its diverse topography. This spatial pattern not only dictates the distribution of agro-ecological zones but also plays a critical role in local and regional hydrology by influencing evapotranspiration rates and overall water availability (Nyssen et al., 2014).

6 CONCLUSION AND RECOMMANDATION

This chapter synthesizes the principal findings of the research and presents a set of formal conclusions based on the evaluation of the hydro-meteorological distribution in the Tigray Region. Following the conclusions, a series of strategic recommendations are proposed. These recommendations are designed to address the identified gaps and deficiencies, providing a clear, evidence-based roadmap for network optimization to support sustainable water resource management and enhance regional climate resilience.

6.1 Conclusion

The primary objective of this thesis was to conduct a systematic evaluation of the hydro-meteorological observation network in Tigray, analyze key climatic and hydrological trends, and propose a framework for network optimization. The research successfully achieved these objectives, and the analysis yields a clear, unequivocal conclusion: the hydro-meteorological monitoring distribution of the Tigray Region is in a state of critical deficiency, fundamentally inadequate in its spatial coverage, operational functionality, and structural balance to meet the scientific and planning needs of the region. This inadequacy severely constrains effective water resource management, climate change adaptation, and disaster risk reduction.

The principal conclusions drawn from the research are as follows:

1. **A Structurally Imbalanced and Numerically Deficient Conventional distribution:** The existing network of 108 conventional stations achieves only 51% of the total 210 stations required to meet the minimum density standards set by the World Meteorological Organization (WMO). This overall deficit masks severe internal imbalances. While the network nominally meets or exceeds the requirements for Class I (Principal) and Class III (Ordinary) stations, it suffers from a profound and critical deficit in Class IV (Precipitation) stations, with only 26 of the 154 required stations in place. This shortfall of 128 rain gauges represents the single greatest weakness of the network, rendering it incapable of accurately capturing the high spatial variability of rainfall, which is the most vital parameter for hydrology in this topographically complex region.

2. **A Systemic Collapse in Operational Functionality:** The numerical gap is catastrophically compounded by a collapse in operational capacity. Field verification and official data confirm that only 28 conventional stations (13% of the WMO requirement) are currently functional. The Fourth-Class network is virtually non-existent, with only 6 stations (3.9% of the requirement) operational. This systemic failure has created vast "data deserts," particularly in remote rural, highland, and peripheral areas, meaning the limited data being collected is spatially biased and unrepresentative of the region as a whole.
3. **An Underdeveloped Modern Network and Sub-Optimal Streamflow Monitoring:** The transition to modern technology is nascent, with only 27 functional Automatic Weather Stations (AWS) identified. While this represents a positive step, it falls short of the 38 stations needed to meet a benchmark equivalent to the Class III conventional network. Similarly, the streamflow gauging network, with 61 existing stations, meets the WMO minimum density requirement but is significantly below the optimum requirement of 134 stations needed for robust hydrological assessment, leaving numerous sub-basins unmonitored.
4. **Evidence of Pervasive Hydrological Stability:** This study finds compelling evidence of hydrological stability within the analyzed catchments. Trend analyses of both regional rainfall and river streamflow consistently revealed a lack of any statistically significant, long-term increasing or decreasing trends. This coherence between atmospheric inputs and river discharge suggests a resilient hydrological system at the regional scale. While this broad stability is a key finding, it hinges on the resolution of the current monitoring network, which may not capture localized stresses. Therefore, enhancing observational density is essential for a complete understanding of the catchment's water balance.

In summary, this study provides a comprehensive, data-driven diagnosis of a hydro-meteorological distribution that is failing to meet its purpose. The findings move beyond acknowledging general data scarcity to precisely quantifying the numerical, functional, and spatial gaps, thereby creating an undeniable, evidence-based case for urgent and strategic intervention.

6.2 Recommendations

Based on the conclusions of this research, the following recommendations are proposed to guide the strategic rebuilding and modernization of the Tigray Region's hydrometeorological distribution. These actions are prioritized to address the most critical deficiencies and to build a resilient, efficient, and scientifically robust monitoring infrastructure.

1: Prioritize a Phased and Strategic Expansion of the Core Observation distribution.

a. Immediate High-Priority Expansion of the Fourth-Class (Precipitation) Network: The most urgent priority is to rectify the critical 128-station deficit in the rain gauge network. A phased implementation plan for establishing these stations should be developed, prioritizing unmonitored highland water-source areas, key agricultural zones, and the identified "data deserts" in western and northern Tigray.

b. Filling the Synoptic Network Gap: The single missing Second-Class (Synoptic) station should be established in the underrepresented Plains/Midlands zone to complete the regional synoptic framework required for improved weather forecasting.

c. Expanding the Streamflow Network to Optimum Density: The streamflow gauging network should be expanded from 61 to the WMO optimum standard of 134 stations. A spatial optimization analysis should be conducted to site the 73 new gauges in unmonitored sub-basins and at critical hydrological control points.

2: Modernize the distribution through Accelerated Deployment of Automatic Weather Stations (AWS).

a. Adopt AWS as the Standard for Future Expansion: Future network expansion should prioritize the deployment of AWS over conventional stations due to their higher data resolution, real-time transmission capabilities, and operational reliability. This study's proposal to establish 49 new AWS should be adopted as a strategic goal to create a state-of-the-art network.

b. Strategic Placement of AWS: New AWS should be strategically deployed in remote and inaccessible areas where maintenance of conventional stations is challenging, and in locations critical for hydrometeorological services and flash flood early warning systems.

3: Optimize Existing Assets and Enhance Operational Integrity.

Implement a Robust Maintenance and Rehabilitation Program: A dedicated budget and technical team must be established for the systematic repair and continuous maintenance of all non-functional stations. This is a prerequisite for ensuring the long-term sustainability of any investment in new infrastructure.

4: Strengthen Data Management and Institutional Capacity.

a. Establish a Centralized, Quality-Controlled Regional Database: All hydro-meteorological data from conventional, automatic, and streamflow stations should be integrated into a single, centralized, and publicly accessible database. Rigorous quality control and data-filling protocols, such as those used in this study, should be standardized and applied.

b. Invest in Human Capacity: Provide continuous training and capacity-building programs for technicians and data managers on station maintenance, data collection, quality control, and analysis to ensure the network is managed effectively.

5: Directions for Future Research.

Conduct a Cost-Benefit and Spatial Optimization Analysis: Future research should focus on detailed spatial optimization modeling to determine the most cost-effective locations for the proposed new stations, maximizing the value of the information gained from each new installation.

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APPENDIX

Appendix 1: Mean annual Rainfall Data

No	Tabya	Altitued	Latitued	Longuited	Database period	RF
1	Abi-Adi	1829	13.64	39.17	1995-2018	1082
2	Adie Dero	1772	14.31	38.17	1997-2018	735.2
3	Adie Gudom	2107	13.25	39.51	1992-2018	496
4	Adikilette	1657	14.31	38.15	2011-2017	392.1
5	Adi mehameday	2062	14.14	38.78	2010-2018	956.3
6	Adishihu	2466	12.89	39.52	1998-2018	632
7	Aditsetser	1063	14.36	37.61	2010-2017	597.9
8	Adiremets	2028	13.75	37.32	2006-2017	1160
9	AdiGebru	1650	13.8	38.21	2007-2018	1070.7
10	AdigOshu	1117	14.17	37.31	2006-2017	615.1
11	Agbe	1497	13.54	39.04	1998-2018	599.8
12	Agule	2013	13.41	39.35	2008-2017	491.1
13	Alamata	1560	12.42	39.56	1978-2018	714
14	Asgede	1512	14.07	38.05	1999-208	844.5
15	Axsum	2110	14.11	38.73	1992-2018	713.8296
16	Aynalem	2189	13.46	39.49	1992-2018	546
17	Badme	1072	14.72	37.8	2008-2017	510
18	BA-EKER	770	13.88	36.85	2009-2017	719.3927
19	Banat	488	13.78	36.36	2011-2017	656.2857
20	Bizet	2037	14.29	39.29	2008-2017	649.3273
21	BORRA/Chelena	1954	12.89	39.34	2009-2017	639.3813
22	Chila	1664	14.28	38.6	2006-2018	686.5
23	Dansha	782	13.34	36.87	2006-2018	1005.1
24	Debub	2536	13.08	39.64	2007-2018	557.4
25	Dengolat	2371	14.32	39.32	2016-2017	696.2
26	Dera	2791	13.99	39.73	2010-2015	674.6
27	DaeroHafash	1953	13.95	38.77	2009-2017	652.8
28	Dewhen	1926	14.3	39.33	2005-2017	320.7

No	Tabya	Altitued	Latitued	Longuited	Database period	RF
29	Dima	1622	13.68	38.32	2007-2017	784
30	Edaga Arbie	1800	14.04	39.07	2006-2018	853.6
31	Edaga Hamuse	2707	14.11	39.33	1973-2018	631.7
32	Edagarebue	2936	14.09	39.69	2005-2016	487.4
33	Endabaguna	1755	13.56	38.1	1997-2018	1030.4
34	ENDIRIS	807	14.11	36.95	2009-2017	912.4
35	Enticho	1972	14.28	39.15	2002-2017	707.4
36	Fatsie	2519	14.48	39.37	2002-2018	484.9
37	Finarwa	1492	13.1	39.03	2007-2017	839.3
38	Gelebeda	1713	13.5	39.09	2011-2018	268.4
39	Gerhu Senrnay	2028	14.49	39.17	2006-2018	744.8
40	Gjiet	1921	13.33	39.18	2008-2018	424.5
41	Guroro	1860	13.69	39.81	2010-2018	866.4
42	Hagere selam	2618	13.64	39.17	1994-2018	708.7
43	Hashenge	2481	12.6	39.52	2003-2018	914.1
44	Hawzen	2243	13.97	39.43	2002-2017	535.4
45	Hiwane	1813	13.11	39.5	2006-2017	462
46	Ketema Nguse	2840	13.39	37.4	2006-2017	1214.1
47	Korem	2435	12.51	39.52	1993-2017	1011.2
48	May Gaba	920	13.8	37.69	2014-2016	520
49	Maihanse	1115	14.07	37.52	2007-2017	949.7
50	Maytsebrie	1351	13.35	38.08	2006-2018	1236.6
51	MEHONI	1763	12.79	39.65	2008-2018	603.5
52	Mugulat	2720	14.22	39.35	2006-2018	683.9
53	Rama	1386	14.41	38.79	2002-2018	674.4
54	Samre	2066	13.18	39.2	2000-2018	532.9
55	Selekleka	2002	14.11	38.48	1996-2018	1018.153
56	Tsigereda	1977	13.77	39.35	2007-2018	523.9
57	Waja	1411	12.28	39.6	1994-2018	832.3
58	Wedi Semero	2275	12.76	39.34	1999-2018	673.7
59	Werka Emba	1872	13.73	39	2009-2018	744.8
60	Yechilla	1593	13.28	39.99	2005-2018	562.4
61	Yiha	1984	14.28	39.02	2009-2017	773.6
62	ZALANBSA				2011-2016	467.4
63	Feresmay	1836	13.6	39	2000-2018	602
64	Adigrat	2509	14.28	39.45	1997-2018	528.47
65	Adwa	1927	14.17	38.88	1992-2018	800
66	Atsbi	2511	13.88	39.74	2006-2018	638.44
67	Axum AP	1114	13.99	37.82	2006-2018	735.87

No	Tabya	Altitued	Latitued	Longuited	Database period	RF
68	Chercher	1717	12.54	39.77	2006-2017	579.28
69	Maichew	2402	12.28	39.53	1992-2018	785.84
70	Mekelle AP	2221	13.47	39.53	1995-2018	613.74
71	Mekelle (obs)	2001	13.52	39.47	2004-2018	568.16
72	Nebelet	1988	14.1	39.28	2009-2017	685.57
73	Senkata	2269	14.07	39.57	2003-2018	569.27
74	Sheraro	998	14.39	37.76	2006-2014	706.39
75	Shira	1732	14.1	38.3	1992-2018	1026.8
77	Humera	796	14.18	38.6	2007-2011	603.1
76	Maitsebrie	1351	1489992	37407523	2005-2018	1236

Appendix 2: Maximum and Minimum Temperature of the study area

No	Station Name	Altitued	Latitued	Longuited	Database period	Max T	Min Tem
1	Abi-Adi	1829	13.64	39.17	1995-2018	29.4	13.7
2	Adie Hageray	1480	14.27	37.27	2011-2017	33.2	17.6
3	Adi mehameday	2062	14.14	38.78	2010-2018	34.7	19.6
4	Aditsetser	1063	14.36	37.61	2010-2017	35.9	17.7
5	Adiremets	2028	13.75	37.32	2006-2017	27.5	13.5
6	AdigOshu	1117	14.17	37.31	2006-2017	34.7	18.9
7	Alamata	1560	12.42	39.56	1978-2018	29.8	14.8
8	Axsum	2110	14.11	38.73	1992-2018	27.6	11.4
9	Badme	1072	14.72	37.8	2008-2017	36.9	17.4
10	BA-EKER	770	13.88	36.85	2009-2017	36.8	19.2
11	Banat	488	13.78	36.36	2011-2017	38.1	19.8
12	Bizet	2037	14.29	39.29	2008-2017	29.3	11.8
13	BORRA/Chelena	1954	12.89	39.34	2009-2017	28.2	14.8
14	Debre Kerbie	1929	13.95	38.45	2009-2017	28.5	13.3
15	DaeroHafash	1953	13.95	38.77	2009-2017	29.5	13
16	Dewhen	1926	14.3	39.33	2005-2017	26.5	14.8
17	Dima	1622	13.68	38.32	2007-2017	30.6	16.1
18	Edagarebue	2936	14.09	39.69	2005-2016	19.6	8.5
19	Endabaguna	1755	13.56	38.1	1997-2018	28.9	15.7
20	ENDIRIS	807	14.11	36.95	2009-2017	38.5	20.9
21	Finarwa	1492	13.1	39.03	2007-2017	32.4	18.6
22	Gelebeda	1713	13.5	39.09	2011-2018	30.2	14.9
23	Gjiet	1921	13.33	39.18	2008-2018	28.6	12.9

No	Station Name	Altitued	Latitued	Longuited	Database period	Max T	Min Tem
24	Guroro	1860	13.69	39.81	2010-2018	27.8	12.7
25	Hagere selam	2618	13.64	39.17	1994-2018	22.3	11.1
26	Hawzen	2243	13.97	39.43	2002-2017	27.4	10.2
27	Hiwane	1813	13.11	39.5	2006-2017	27.6	11.6
28	Ketema Nguse	2840	13.39	37.4	2006-2017	20.1	7.3
29	Korem	2435	12.51	39.52	1993-2017	22.3	7.8
30	May Gaba	920	13.8	37.69	2014-2016	36.1	20.8
31	Maihanse	1115	14.07	37.52	2007-2017	35.5	35.5
32	Maytsebrie	1351	13.35	38.08	2006-2018	32.4	18.3
33	MEHONI	1763	12.79	39.65	2008-2018	29.6	15.6
34	Mugulat	2720	14.22	39.35	2006-2018	23.1	12.5
35	Semema	1856	14.2	38.34	2008-2018	28.4	13
36	Selekleka	2002	14.11	38.48	1996-2018	26	10.6
37	Waja	1411	12.28	39.6	1994-2018	31	14.3
38	Wukro	1783	13.79	39.6	1992-2018	27.9	11.2
39	Yechilla	1593	13.28	39.99	2005-2018	34.2	18.4
40	Yiha	1984	14.28	39.02	2009-2017	26.1	10
41	ZALANBSA				2011-2016	25.6	13.1
42	ZATTA	2334	12.51	39.28	2009-2018	25.4	12
44	Adigrat	2509	14.28	39.45	1997-2018	23.8	6.52
45	Adwa	1927	14.17	38.88	1992-2018	27.88	12.54
46	Atsbi	2511	13.88	39.74	2006-2018	20.1	9.55
47	Axum	1114	13.99	37.82	2006-2018	26.1	12.84
48	Cherche	1717	12.54	39.77	2006-2017	27.55	16.14
49	Maichew	2402	12.28	39.53	1992-2018	23.28	10.22
50	Mekelle AP	2221	13.47	39.53	1995-2018	24.43	11.2
51	Mekelle Obs	2001	13.52	39.47	2004-2018	27.35	12.2
52	Nebelet	1988	14.1	39.28	2009-2017	28.18	14.2
53	Senkata	2269	14.07	39.57	2003-2018	24.04	11.2
54	Sheraro	998	14.39	37.76	2006-2014	34.92	19.2
55	Shire	1732	14.1	38.3	1992-2018	27.58	14.09
56	Humera	429	14.18	38.6	2007-2011	37.8	21.7
57	Maytsibrie	796	1580748	37242116	2005-2018	32.4	18.3

Appendix 3: First class station

No	Tabya	Wereda	Altitued	Latitued	Longuited	class of station
1	Adigrat	Gant Afeshum	2509	14.28	39.45	1st
2	Adwa	Adwa	1927	14.17	38.88	1st
3	Maychew	Endamkonie	2402	12.28	39.53	1st
4	Maytsebrie	Tselemetie	1351	13.35	38.08	1st
5	Sinkata	Sesie Tsedaemba	2269	14.07	39.57	1st
6	Shire	EndaSlasie	1732	14.1	38.3	1st
7	Sheraro	Tahtay Adyabo	998	14.39	37.76	1st
8	Atsbie	Atsbie Wenberta	2511	13.88	39.74	1st
9	Chercher	Raya Azebo	1717	12.54	39.77	1st
10	Mekelle Obs	Mekelle Obs	2001	13.52	39.47	1st
11	Neblet	Werie Leke	1988	14.1	39.28	1st
12	Mekelle AP	Mekelle AP	2221	13.47	39.53	2nd
13	Axsum AP	Axsum AP	1114	13.99	37.82	1st
14	May Gaba	Welkayet	920	13.8	37.69	1st
15	Humera AP	Kafta Humera	796	13.84	36.88	1st
16	Samre	Sahrtie Samre	1743	13.23	39.17	1st
17	Ketema Nguse	Tsegeda	2840	13.39	37.4	1st

Appendix 4: Third Class station (2025)

No	Tabya	Wereda	Altitued	Latitued	Longuited	class of station
18	Zban gedena	Tahtay Adyabo	1124	14.33	37.89	3dr
19	Megue	Welkayet	868	14.03	37.49	3dr
20	Degena	Welkayet	2159	13.68	37.36	3dr
21	Abeyadie	Abeyie Adie	1829	13.64	39.17	3dr
22	Adieremetse	Welkayet	2028	13.75	37.32	3dr
23	Alamata	Alamata	1560	12.42	39.56	3dr
24	Axsum	Axsum	2110	14.11	38.73	3dr
25	Dewhen	Erop	1926	14.3	39.33	3dr
26	Edaga Robue	Sesie Tsedaemba	2936	14.09	39.69	3dr
27	Endabaguna	Asgeda Tsimbla	1755	13.56	38.1	3dr

No	Tabya	Wereda	Altitued	Latitued	Longuited	class of station
28	Hagere selam	Degua Tembien	2618	13.64	39.17	3dr
29	Hawzen	Hawzen	2243	13.97	39.43	3dr
30	Korem	Ofla	2435	12.51	39.52	3dr
31	Slekleka	Tahtay Koraro	2002	14.11	38.48	3dr
32	Waja	Alamata	1411	12.28	39.6	3dr
33	Wedi Semero	Endamokenie	2275	12.76	39.34	3dr
34	Wukro	Wukro	1783	13.79	39.6	3dr
35	Yechele	Tanqua Abergele	1593	13.28	39.99	3dr
36	Hiwane	Hintalo Wejerat	1813	13.11	39.5	3dr
37	Mugulat	Ganta Afashum	2720	14.22	39.35	3dr
38	Adigeshu	Kafta Humera	1117	14.17	37.31	3dr
39	Dima	Tselemetie	1622	13.68	38.32	3dr
40	Ketma Nguse	Tsegeda	2876	13.4	37.41	3dr
41	Semema	Tahtay Koraro	1856	14.2	38.34	3dr
42	Finarwa	Sahrtie Samre	1492	13.1	39.03	3dr
43	Adie Hageray	Tahtay Adiabo	1480	14.27	37.27	3dr
44	May Hanse	Asgede Tsembela	1115	14.07	37.52	3dr
45	Bizet	Ganta Afashum	2037	14.29	39.29	3dr
46	Badme	Tahtay Adyabo	1072	14.72	37.8	3dr
47	Gjiet	Sahrtie Samre	1921	13.33	39.18	3dr
48	Baker	Kafta Humera	770	13.88	36.85	3dr
49	Bora/Chelena	Emba Aleje	1954	12.89	39.34	3dr
50	Mokenie	Enda Mokenie	1763	12.79	39.65	3dr
51	Zata	Ofla	2334	12.51	39.28	3dr
52	DeroHafesh	Nader Adet	1953	13.95	38.77	3dr
53	Debre Kerbie	Medebay Zena	1929	13.95	38.45	3dr
54	Yiha	Adwa	1984	14.28	39.02	3dr
55	Adie Mehameday	Asgede Tsembla	2062	14.14	38.78	3dr
56	Adie Tsetser	Tahtay Adiabo	1063	14.36	37.61	3dr
57	Endries	Kafta Humera	807	14.11	36.95	3dr
58	Kafta	Kafta Humera	1697	13.91	37.14	3dr
59	Maykadra	Kafta Humera	635	14.07	36.56	3dr
60	Guroro	KolaTenben	1860	13.69	39.81	3dr

No	Tabya	Wereda	Altitued	Latitued	Longuited	class of station
61	Dera	Atsbie Wenberta	2791	13.99	39.73	3dr
62	Banat	Kafta Humera	488	13.78	36.36	3dr
63	Edaga Hibret	Asgede Tsembla	1309	14.04	38.03	3dr
64	Gelebeda	Kola Temben	1713	13.5	39.09	3dr
65	Zalambesa	Gulomekeda				3dr
66	Adie Kleta	Lelay Adyabo	1657	14.31	38.15	3dr
67	Adie Dero	Lelay Adyabo	1772	14.31	38.17	3dr
68	Adie Gudom	Hintalo Wejerat	2107	13.25	39.51	3dr
69	Rama	Mereb Leke	1386	14.41	38.79	3dr
70	Dengolat	Hintalo Wejerat	2371	14.32	39.32	3dr
71	Fatsie	Gulomekeda	2519	14.48	39.37	3dr
72	Enticho	Ahferom	1972	14.28	39.15	3dr

Appendix 5: Forth Class station (2025)

No	Tabya	Wereda	Altitued	Latitued	Longuited	class of station
73	Adie Sheho	EmbaAlaje	2466	12.89	39.52	4th
74	Agbe	Tanqua Abergle	1497	13.54	39.04	4th
75	Asgede	Asgede Tsimbla	1512	14.07	38.05	4th
76	Aynalem	Mekelle	2189	13.46	39.49	4th
77	Chila	Tahtay Maychew	1664	14.28	38.6	4th
78	Dansha	Tsegeda	782	13.34	36.87	4th
79	Edaga Arbie	Werie Leke	1800	14.04	39.07	4th
80	Edaga Hamuse	Sasie Tsedaemba	2707	14.11	39.33	4th
81	Gerhu Senrnay	Ahferom	2028	14.49	39.17	4th
82	Hashenge	Ofla	2481	12.6	39.52	4th
83	Maykenetal	Werie Leke	1799	13.94	39.91	4th
84	Samre	Sahrtie Samre	2066	13.18	39.2	4th
85	Mechera	Raya Azebo	1351	12.77	39.81	4th
86	AdiGebru	Asged Tsimbla	1650	13.8	38.21	4th
87	Tsigereda	Wukro	1977	13.77	39.35	4th
88	Debub	Hintelo Wejerat	2536	13.08	39.64	4th

No	Tabya	Wereda	Altitued	Latitued	Longuited	class of station
89	Werka Emba	Kola Tembien	1872	13.73	39	4th
90	Agule	Wukro	2013	13.41	39.35	4th
91	Haykie Meskel	Atsbie Wenberta	2121	13.75	39.7	4th
92	Wrhat	Ganta Afashum	3028	14.14	39.26	4th
93	Hitsatse	Asgede Tsimbla	1092	14.03	37.57	4th
94	Dgume	Wukero Kilte Awlelo	2003	13.79	39.598	4th
95	May Keyh	Ahferom	2320	13.19	39.31	4th
96	Wukero Maray	Tahatay Maychew	2208	14.06	38.36	4th
97	Siero	Ahferom	2051	14.19	39.13	4th

Appendix 6: Stream/River flow stations in the Study area

FID	Site__Name	Nr__Area	Latitude	Longitude	Altitued	Basin
0	Giba -Mekele	Mekele	13.6001	39.3818	1739.939	Tekeze
1	Giba -Addikumsi	Aber gele	13.4635	39.028	1358.825	Tekeze
2	Gerb-Segen Dam	Mekele	13.3852	39.4204	1904.938	Tekeze
3	Weri-1	Temben	13.8466	39.0031	1360.572	Tekeze
4	Eilala -1	Mekele	13.5572	39.4508	1912.097	Tekeze
5	Astela	Adishihu	12.9328	39.5203	2431.498	Tekeze
6	Astella-1	E/Alage	12.5784	39.5198	2458.028	Tekeze
7	Midimar	Adwa	14.1163	38.8755	1802.117	Tekeze
8	Ariqa ku -1	yechila	13.333	38.8792	1283.623	Tekeze
9	Tekeze Emba Mider	Embamider	13.7373	38.1982	835.1969	Tekeze
10	Tekeze shiraro	shiraro	13.9129	37.6719	757.791	Tekeze
11	Hawzen suluh Dam	Hawzen	14.0139	39.4908	2230.284	Tekeze
12	Genfel	Wiqro	13.7984	39.6011	1994.445	Tekeze
13	Tekeze Dam	Creast of Dam	13.34828	38.74103	1011.226	Tekeze
14	Ariqa ku- 2	UPPER ARIQA	13.318407	39.00229	1425.172	Tekeze
15	Werie ku -2	Upper temben	14.039552	39.12843	1667.724	Tekeze
16	Belles shire	Akusum	14.1214	38.75833	2090.334	Tekeze
17	Gando	korem	12.489	39.515	2469.248	Denakille
18	Alamta (Gw)	Alamat	12.386	39.584	1482.613	Denakille
19	meswaet	meswat	12.689	39.546	2381.806	Denakille
20	Babur	Maichew	12.782	39.539	2424.971	Denakille
21	Qeit Gereb	maichew	12.798	39.552	2360.65	Denakille

22	Gereb ano	mokoni	12.897	39.722	1666.939	Denakille
23	Samre	samre	13.182	39.224	1835.521	Tekeze
24	Dello	Mekelle	13.496	39.558	2130.662	Tekeze
25	Aynalem	mekelle	13.468	39.511	2238.225	Tekeze
26	mihqan	Adi 4 Rama	14.451	38.792	1325.797	Mereb
27	Rama mereb E/ asa	Rama	14.473	38.744	1242.011	Mereb
28	Suluh	hawzen	14.334	38.965	1916.441	Tekeze
29	E/maryam entcho	entchu	14.303	39.171	1962.406	Mereb
30	Dirimrmo	bizet	14.397	39.278	1915.037	Mereb
31	Molgi	shiraro	14.449	37.769	1007.352	Tekeze
32	staeidat	Golagul naeder adet	14.117	38.108	1506.688	Tekeze
33	Sibta shire	shire	14.184	38.157	1478.304	Tekeze
34	Adigudem	adigudem	13.223	39.516	2082.587	Tekeze
35	Ariqa 1	yechila	13.261	38.993	1579.562	Tekeze
36	Eilala 1	Upper mekelle	13.524	39.501	2006.267	Tekeze
37	Werie 2	Lower werei	13.674	36.678	612.1961	Tekeze
38	Stedeya	Edaga Arbi	13.849	39.042	1418.863	Tekeze
39	mY dingur	Adwa	14.202	38.894	1908.657	Tekeze
40	Tekeze dam site	Tekeze dam	13.35	38.744	1241.3	Tekeze
41	Dur ambesa	Samre	13.182	39.224	1835.521	Tekeze
42	Felege weyni	frewayni	13.722	39.683	2141.426	Tekeze
43	Hiwane	Hiwan, adigudem	13.101	39.508	2031.847	Tekeze
44	maynebri	hiwane	13.064	39.498	2205.06	Tekeze
45	Hashenge	korem	12.561	39.502	2440	Denakille
46	Dur ambesa	Samre	13.24252	39.45994	2011.556	Tekeze
47	Aynalem	Aynalem irrigation	13.4673	39.4654	2160.059	Tekeze
48	May stebri	flood	13.60132	38.14569	1295.14	Tekeze
49	Freweyni	Fre.touwn	13.72238	39.68386	2120.267	Tekeze
50	Feleg weyni	Agulae	13.91603	39.73573	2718.241	Tekeze
51	TEkeze TDedebit	t. dedebit	13.912955	37.6716	758.2071	Tekeze
52	Tekeze shiraro	Nr. shiraro	13.9129	37.6719	757.791	Tekeze
53	Giyits	Nr. adi geshu	14.187	37.323	1086.433	Tekeze
54	Digagum	Nr. adi geshu	14.097	37.467	976	Tekeze
55	Tekeze humera	Humera	14.292	36.611	580.8463	Tekeze
56	Tekeze dima	Dima ,sudan border	14.265	36.565	538.1915	Tekeze
57	rawian	Humera	14.204	36.614	616.5586	Tekeze
58	mokozo	Mokozo angreb	13.561	36.981	771	Tekeze
59	Kalema	My geba	13.831	37.649	813.4834	Tekeze

60	Zarema dam site	My geba	13.686	37.777	834.501	Tekeze

Appendix 7: Inventory of Existing Automatic Weather Stations (AWS) in the Tigray Region (as of 2025).

NO	Station name	Latitude	Longitude	Altitude (masl)
1	Meseret	13.34	39.569	2307
2	Mosobo	13.574	39.557	2250
3	Abyadi	13.61	39.002	1828
4	Chercher	12.542	39.76	1779
5	Wuqro	13.79	39.598	2003
6	Mehoni	12.795	39.647	1759
7	Mugulat	14.23	39.35	2729
8	Tekeze H/power	13.36	39	1425
9	Mekelle	13.32	39.32	2257
10	Humera	14.17	36.4	760
11	Endabaguna	13.94	38.0	1761
12	Shire E/slasy	14.1	38.0	1897
13	Maichew	12.78	40..00	2432
14	Adigrat	14.28	39.45	2509
15	Axum Air port	13.99	37.82	1114
16	Dansha	13.34	36.58	782
17	Atsbi	13.88	39.74	2511
18	Alaje (FTC)	13.08	39.64	2536
19	Adigudom(FTC)	13.26	39.47	2056
20	Samre(FTC)	13.23	39.17	1743
21	Hawzen(FTC)	13.97	39.43	2243
22	Fatsi(FTC)	14.48	39.37	2519

23	Enticho(FTC)	14.28	39.15	1972
24	Adidaero(FTC)	14.31	38.17	1559
25	Baeker(FTC)	13.97	36.85	795
26	Adiremets(FTC)	13.74	37.31	2055
27	ketemangus(FTC)	13.42	37.38	2522