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Eastern Nile River Basin Surface Water Resources Assessment

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Prepared by:

Aniley Tenaw Tesfaye

Esther Yeno David

Mohamed Yasir Mohamed

Workinesh Takele Tessema

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Executive Summary

Water resources play an irreplaceable role in supporting productive human activities such as agriculture, energy production, industry, transportation services, fishing, sanitation, and tourism. However, its availability, quantity, distribution, and quality have been reducing over time as a result of climate and land use/cover changes, emerging demand due to population growth, and economic development. The Eastern Nile basin is characterized by high variability in rainfall, and climate change is expected to increase the uncertainty, which will impact the water resources availability, especially with the increasing demand. This study was designed to assess the availability of surface water resources over the Eastern Nile basin, aiming to spatially and temporally analyze, considering the main sub-basins of the Eastern Nile basin; Blue Nile, Baro-Akobo-Sobat, Tekeze-Setit-Atbara, and the Main Nile.

To overcome the challenge of the data scarcity of the rainfall, actual evapotranspiration, interception, and soil moisture ground observations, all the data was acquired from satellite-based products; namely, CHIRPS, GRACE, FAO WaPOR, and the MODIS. Those products were selected according to their availability performance, coverage, and resolution. The assessment was conducted using a wide range of techniques, tools, and software depending on the type of data and the required outcome. In this study, the surface water resource (runoff) potentials of the EN four sub-basins were assessed based on the input parameters. The results in all four sub-basins are spatially different and most of the runoff is generated from the Blue Nile sub-basin. However, most parts of the Main Nile sub-basin are identified as a low runoff generating area. The Baro-Akobo-Sobat sub-basin is the second most runoff potential and generating sub-basin and the Tekeze-Setit-Atbara sub-basin is also the third highest runoff generating area from the EN sub-basins.

The results of this study provide crucial information for water resources management, which directly has impacts on human socio-economic life and environment. It can be also used by different stakeholders, researchers, and policymakers to inform the decision-making process.

1. Introduction

1.1 General Overview

Water is a critical and valuable natural resource for sustaining life, development, and the environment to achieve long-term economic and social growth. Water plays an irreplaceable role in supporting productive human activities such as agriculture, energy production, industry, transportation services, fishing, sanitation, and tourism. However, its availability, quantity, distribution, and quality have been reducing over time as a result of climate and land use/cover changes, emerging demand due to population growth, and economic development (IPCC, 2014; Kemal, 2021). As a result, a significant number of countries in the world are becoming water-stressed.

A major threat to the survival of living beings in developing nations like Africa in the 21st century is population growth, climate change, and land use change, which result in water scarcity (Abebe et al., 2022). With the potential threats of climate change, the basin's water-related problems are expected to increase shortly. Thereby, hydro-meteorological phenomena such as the uneven distribution of rainfall and soil water content (SW) that contributes on a large scale may result in water scarcity, which is resolved by an understanding of hydrological responses. To solve the scarcity problem, different countries in the world are implementing different policies to boost the management systems of the available water resource potentials (Coffel et al., 2019).

The assessment of the surface water resource potential of a river basin is essential for the current and future developments of any kind of water-related project in the Eastern Nile River basin in riparian countries like Ethiopia, Sudan, South Sudan, and Egypt. This, in turn, enhances the economic growth of the countries by paving the way for the utilization of the available potential of water for hydropower, irrigation, and water supply (Awulachew et al., 2009). The planning, designing, constructing, operating, and managing of the water resources project is essential for using the available water resources effectively in the basin (Leta et al., 2021). Additionally, assessing the surface water resource potential is crucial because it provides information to decision-makers about the river basin on how much water is available for different purposes (Megersa et al., 2017). Further, the water resource potential assessment needs detailed insights into the hydrological process and its components. Studying hydrological processes for sustainable basin management based on knowledge of rainfall characteristics and basin properties is very important (Abebe et al., 2022).

The Eastern Nile (EN) basin is described within the context of the entire Nile Basin, which constitutes over 60% of the area of the Nile River basin and contributes over 86% of the average annual flow of the main Nile River, which is about 84 Bm^3 at the Aswan High Dam in southern Egypt (NBI, 2012). The Eastern Nile basin (ENB) comprises four sub-basins: The Blue Nile, Baro-Akobo-Sobat, Tekeze-Setit-Atbara, and main Nile sub-basins and extends over four countries: Ethiopia, South Sudan, Sudan, and Egypt. According to the One System Inventory (OSI) socio-economic report the total population residing in the ENB is estimated at 154 million (Hassan, 2012). Among this population Egypt alone constitutes 51% although the area of Egypt in the ENB is the smallest. Ethiopia is the second largest contributor covering 33% of the total population of the ENB and the Sudan & South Sudan accounts for 16% of the ENB population (Hassan, 2012). The Eastern Nile Basin covers approximately 1.7 million km^2 and it is home to about 154 million people. The Eastern Nile supports an extraordinary range of ecosystems, from high mountain moorlands, afromontane forests, savanna woodlands, extensive wetlands, intensively cultivated catchments, groundwater, systems, and arid deserts. The basin is characterized by a low level of economic development, widespread poverty, water scarcity, low access to electricity, low efficiency of water use, rapid population growth, and increasing demand for water (Leta et al., 2021). This will produce higher uncertainties in surface water resource management and development, which is essential for water resource availability and distribution. On the other hand, water demand is increasing continuously in the Eastern Nile basin because of human life style, as well as changes in economic and social activities. This has a direct and indirect impact on water security, agriculture and food production, energy, and the environment. Therefore, there is a need to assess the general surface water resource potential and availability in the Eastern Nile basin, which is more vital and is of paramount importance for the sustainable management of water resources.

By stating the above problems, the objective of this study is to assess the surface water resources using water balance/budget and situation analysis approaches in the Eastern Nile River basin with its four sub-basins: the Blue Nile, Baro-Akobo-Sobat, White Nile, Tekeze-Atbara, and main Nile sub-basins.

1.2 Objectives

The overall objective of this study is to assess the availability of surface water resources of the Eastern Nile River sub-basins**.**

1.2.1 Specific objectives

- To assess the water balance components of the Eastern Nile sub-basins.
- To determine the EN River basin surface water availability and it’s potential.

2. Literature Review

2.1. Surface Water Availability and Its Characteristics

In the face of complex climate and land use/cover change, the world is facing huge water crises in balancing the demand and supply of water for the growing population. Globally, people in many parts of the world face severe water shortages and stress (Wu et al., 2019). The increasing pressure on this freshwater has been due to population growth, climate change, and economic development to improve the quality of life. As development increases, the water demand could increase for different sectors, under which the pressure would aggravate (Stephens & Couzens, 2016). Studies on surface water availability and, the potential and efficient use of water resources are vital to alleviate water scarcity problems and develop its sustainability.

2.2. The Eastern Nile Sub-basins

The Eastern Nile is one of the sub-basins of the Nile basins, which encompasses four sub-basins: the Abbay-Blue Nile, the Baro Akobo Sobat in the west, the Tekeze-Atbara in the east, and the Main Nile, which stretches from Khartoum to the Nile delta as revealed in Figure 1.

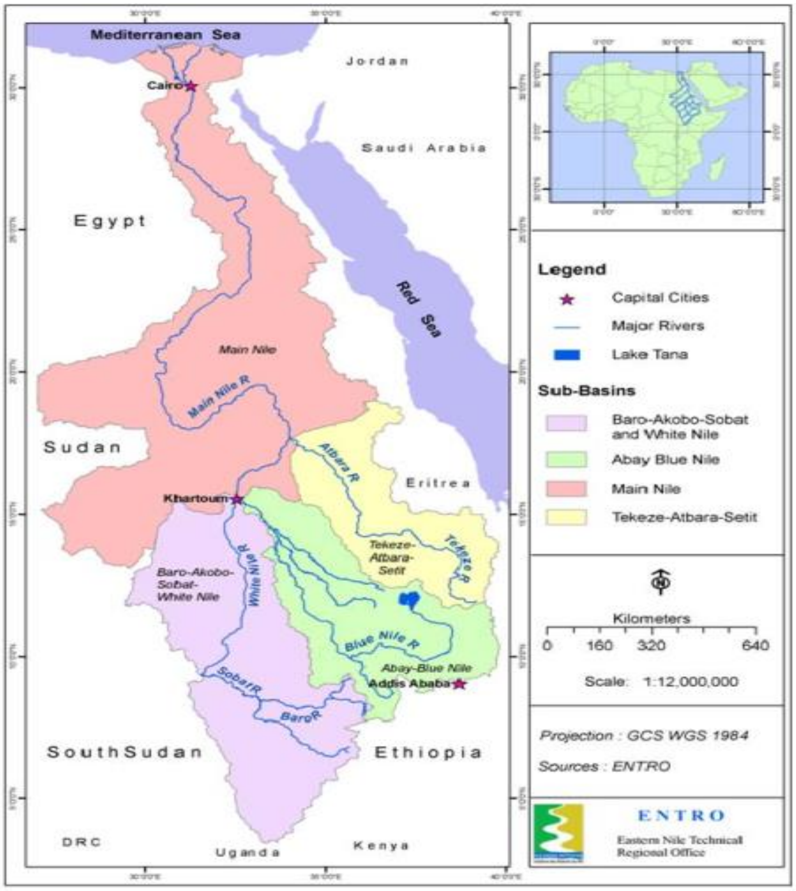

Figure 1: Location map of the Eastern Nile Basin

2.2.1. The Blue Nile river sub-basin

The Blue Nile sub-basin has a drainage area of approximately 311,548 km^2, and according to Dile et al. (2018) and Tesemma et al. (2010) studies, the Blue Nile sub-basin has an average discharge of 48.9km^3/year of water, based on long-term observations (1912–2003) until it joins White Nile at Khartoum. Relatively few analyses have been conducted on the Blue Nile River basin, largely due to the lack of hydrologic data (Ali et al., 2014). Flow volumes along the Blue Nile range from approximately 4 billion m^3 annually at the outlet of Lake Tana to 54 billion m^3 at the Sudan border (Johnson & Curtis, 1994; Dile et al., 2018; Gelete et al., 2020). The majority of this flow passes through the river during the rainy months of July, August, and September.

Due to its trans-boundary nature, the Blue Nile basin requires special attention to understand its inherent hydrology to implement sustainable water use in the region. Among the basin's natural, social, and political diversity and complexity (Coffel et al., 2019), it is necessary to quantify water budget components and their spatio-temporal variability’s for effective management, efficient water allocation, and sustainable planning and policymaking. Accurate estimation of flux terms such as runoff, evapotranspiration, and storage is essential to understanding basin water resources (Tong et al., 2020). In this regard, various attempts have been made to quantify the water budgets of the Blue Nile basin (Jung et al., 2017). However, basin-scale water budget estimations are limited due to the lack of hydro-meteorological data. Most studies focus on estimates at the catchment level, with relatively better information. Others concentrate on the estimation or characterization of only specific components such as precipitation (Abtew et al., 2009), évapotranspiration (Allam et al., 2016), and runoff (Tesemma et al., 2010).

2.2.1.1. Characteristics of the Blue Nile sun-basin

The Blue Nile River starts in Ethiopia as Little (Gilgile) Abbay, the largest tributary of Lake Tana, at an elevation of 2900 m above sea level (masl) (Ali et al., 2014) and ends in Khartoum, Sudan, where it joins the White Nile after having traveled for about 1600 km. The river and its tributaries drain a large proportion of the central, western, and south-western highlands of Ethiopia before dropping to the plains of Sudan. The basin is characterized by a highly rugged topography and considerable variation of altitude, ranging from about 350 meters at Khartoum to over 4,250 meters above sea level (masl) in the Ethiopian highlands (Keith et al., 2014). It is the largest of the 12 basins in Ethiopia and accounts for 55% of the annual renewable surface water resources of the country (King, 2013). It plays a vital role in the hydrology of the riparian countries. Although the Blue Nile basin covers only 10% of the entire Nile basin area (Roth et al., 2018).

Basin characteristics such as soil properties, geology, anthropogenic activities, relief, size, local climate, and vegetation cover influence the hydrological response to rainfall (Gebrehiwot et al., 2010; Leta et al., 2021). Some basic characteristics are more important in ways that are specific to different basins and scales. The characterization of the hydrological response of the basin is crucial in areas such as the Blue Nile basin where the well-being of the majority of the population depends on the ability to manage water scarcity. Although 62% of the Nile flow at Aswan comes from the Blue Nile, the local population can still suffer from water shortages during the dry season (Abebe, 2007; Gebrehiwot et al., 2010). Abebe (2007) found five generalized regional flood frequency curves for the basin. The Blue Nile Basin, which is part of the larger Nile River Basin, has several key characteristics that influence its hydrology, water resources, and ecosystem. Some of the main characteristics of the Blue Nile Basin include:

Topography from The Blue Nile basin covers a large area in East Africa, including parts of Ethiopia, Sudan, and South Sudan. It is characterized by diverse topography, ranging from highlands in the Ethiopian Plateau to lowlands in Sudan. There are three broad topographical divisions; the highland plateau, steep slopes, and the western lowlands, which are more flat (Easton et al., 2010). The topography of the basin is very complex, with elevation ranging from 500 m in the lowlands at the Sudan border to 4160 m in the upper parts of the basin. The primary tributaries of the Blue Nile basin are divided into 18 major sub-basins, namely, Lower Blue Nile, Upper Blue Nile, Dinder, Rahad, Tana, Beshelo, Beles, Dabus, Diddessa, Jemma, Muger, Guder, Fincha, Anger, Wenbera, South Gojam, North Gojam, and Welaka (Yilma & Awulachew, 2009).

Precipitation: Rainfall varies significantly with altitude and is considerably greater in the Ethiopian highlands than on the plains of Sudan. Rainfall ranges from nearly 2,000 mm/year in the Ethiopian highlands to less than 200 mm/year at the junction with the White Nile (Awulachew et al., 2009). Within Sudan, the average annual rainfall over much of the basin is less than 500mm (Ali et al., 2014). In Ethiopia, it increases from about 1,000 mm near the border of Sudan to between 1,400 and 1,800mm over parts of the upper basin, in particular, in the loop of the Blue Nile south of Lake Tana. Rainfall exceeds 2,000mm in parts of the Didessa and Beles watersheds. Both the temporal and spatial distribution of rainfall are largely influenced by the movement of air masses associated with the Inter-Tropical Convergence Zone (ITCZ). During the winter dry season (known in Ethiopia as Bega), the ITCZ lies south of Ethiopia, and the Blue Nile region is affected by a dry northeast continental air mass controlled by a large Egyptian zone of high pressure (Tesemma et al., 2010). This cool airstream from the desert produces the dry season. From March, the ITCZ returns, bringing rain, particularly to the southern and southwestern parts of the basin. This short period of rain is known in Ethiopia as the Belg, or (small rain). In May, the Egyptian high pressure strengthens and checks the northward movement of the ITCZ producing a short intermission before the main wet season (known in Ethiopia as the Kremt) (Awulachew et al., 2009). Around June, the ITCZ moves further north, and the southwest airstream extends over the entire Ethiopian highlands to produce the main rainy season. This is also the main rainy season in Sudan, though being further north and at a lower altitude, the period of rainfall is foreshortened and totals are considerably less than in Ethiopia. The summer months account for a large proportion of mean annual rainfall; roughly 70% occurs between June and September, and this proportion generally increases with latitude, ranging from 61% at Gore in the southwest to 73% at Debre Marcos, 78% at Gonder, 87% at Rosieres, and 93% at Khartoum (Leta et al., 2021).

Temperature: The highest temperature observed in the northwestern part of the basin, in parts of Rihad, Dinder, Beles, and Dabus, where the maximum temperature ranges from 28 C to 38 C and the minimum temperature ranges from 15 C to 20 C. Lower temperatures were observed in the highlands of Ethiopia, in the central and eastern parts of the basin. The maximum and minimum temperatures range from 12 oC to 20 oC and $^{-1}$ ^{o}C to 8 ^{o}C, respectively (Yilma & Awulachew, 2009).

Land use/cover: The land use/cover of the Blue Nile basin includes rain feed crops (sedentary), grassland, woodland, shrubland, cultivated land (semi-mechanized farms), cultivated land (irrigated crops), rock, high forest, water, cultivated land (rainfed crops), plantations, bare land, seasonal swamps, permanent swamps, urban (built-up), and afro-alpine forests. The type of rainfed crop (sedentary) covers around 26% of the area, mainly located in the Ethiopian highlands. Grassland covers 25% and woodlands and shrubland cover 28% of the sub-basin. The type semi-mechanized farms cover 10% and land under irrigated crops covers 2.6% (Awulachew et al., 2009). The land use/cover change has an impact on the water balance of the basin by changing the magnitude and pattern of runoff, peak flow, and groundwater levels.

Soil types: The dominant soil types of the Abay-Blue Nile basin are Vertisol, Nitisol, Leptosols, Luvisols, Cambisols, Regosols, Alisols, Phaeozems, Fluvisols, Swamp, and Water bodies (FAO, 1998). Nitisols (24%), dominate the western highlands whilst shallower and more infertile Leptosols (19%) occupy the eastern highlands. Vertisols (29%) dominate the unconsolidated sediments of the Sudan plains. Luvisols cover (13%); Water bodies (5%), Cambisols (4%), Regosols (3%), Alisols (3%), and Phaeozems cover (1%) etc.

Runoff: The runoff in the Blue Nile basin is mainly influenced by precipitation patterns, land use/land cover changes, soil characteristics, and topography. The Blue Nile basin receives significant rainfall, especially during the wet season, which leads to high runoff volumes. The steep slopes in the region also contribute to rapid runoff generation. To quantify the runoff volume, hydrological models can simulate the complex interactions between precipitation, land use, soil, and topography. Some of the commonly used methods to estimate runoff include: a) Hydrological modeling: Hydrological models simulate the processes that control the movement of water through the hydrological cycle (i.e. SWAT and HEC-HMS etc.), b) Water balance analysis: Water balance analysis involves quantifying the inputs (precipitation) and outputs (evapotranspiration, runoff) of water in the basin, and c) GIS-based analysis: Geographic Information System (GIS) tools can be used to analyze spatial data such as land use, soil types, slope, and precipitation distribution in the basin. GIS can help to map runoff patterns, identify critical areas for runoff generation, and assess the impact of land use changes on runoff.

2.2.2. Baro-Akobo-Sobat sub-basin

The Baro-Akobo-Sobat sub-basin (BAS) is one of the four major sub-basins located in the southern part of the Eastern Nile basin. Geographically, it extends from $15^0$47'40" to the north down to $3^0$25'52" in the south. It extends from $29^0$24'43" to the west up to $36^0$18'27". The elevation of the sub-basin ranges from 370 masl to 2,901 masl. Around 90% of the sub-basin falls from 370 masl to 1,000 masl and some 10% falls at an elevation that ranges from 1,000 masl to 2,901 masl. More than 88% of the sub-basin land is identified to have a land slope of less than 5% indicating its tremendous potential for agriculture irrigation. The BAS sub-basin possesses a total area of 468,216 km^2, which covers 28% of the total EN basin area. It is shared by Ethiopia, Sudan, and South Sudan with an estimated population of 12.4 million 60% living in Ethiopia and 40% in Sudan and South Sudan (Hassan, 2012). The basin is well endowed with water resources and is the second largest contributor of water to the Eastern Nile system. The main characteristics of the BAS include:

Temperature: The temperature in the highland plateaus of the sub-basin is identified as sub-tropical, with pleasant temperatures rarely exceeding 20. In the basin, the temperature ranges between 27.5 ^{0}C below at 500 meters elevation on the floodplain to about 17.5 ^{0}C at 2,500 meters in the highlands. The maximum temperatures in the highlands hardly exceed 25^{0}C while in the lowlands it could go beyond 36 ^{0}C during hot months (January to April) (Hassan, 2012).

Evaporation: The mean annual evaporation within the sub-basin is observed to vary from 1000 mm in the highland plateaus of Ethiopia to 6815 mm in Khartoum. For example, the evaporation loss at Jebel Aulia reservoir within the basin has a storage capacity loss of 3.5 Bm^3 per year due to evapotranspiration.

Precipitation: The rainfall patterns in the sub-basin show seasonal variability where high rainfall is often registered between June and September. Mean annual precipitation ranges between 600mm in the lowlands (less than 500 masl) and 3,000mm in the highlands (over 2,000 masl) showing the existence of significant spatial rainfall variability. Average rainfall greater than 100 mm occurs from May to October. The highest rainfall occurs from June to September.

Runoff patterns: The mean annual runoff of the Sobat River measured at Doleib hill (upstream of the Malakal gauging station) is 13.7 billion m^3 and combined with 16.8 billion m^3 inflows from Sudd swamp, on average it contributes 30.5 billion m^3 inflows to the White Nile system per year. The sub-basin contains important wetland areas such as the Machar and Sudd marshes. A large amount of spillage (3.03 billion m^3/year) from the lower course of the Baro River forms the Machar wetland where the return flow from the wetland to the Baro and White Nile rivers is estimated to be large. Sudd is another important wetland in the sub-basin and one of the largest in the world with an estimated average area coverage of 30,000 km^2 (ENTRO, 2014).

Soil characteristic: The basin is characterized by different types of soil, with the most dominant being the black-colored vertisols which cover 56% of the sub-basin. The low-lying area of Gambella, the entire watershed of the Sobat River, and the majority of the White Nile watershed d/s of Malakal are almost covered with vertisols of black and cracking in nature. This soil imposes considerable challenges in agricultural operations. Among other soil types, Arenosols cover 10%, Nitosols cover 9% and Luvisols cover nearly 7% of the sub-basin. The remaining part of the BAS White Nile sub-basin is covered by Fluvisols, Leptosols, Cambisols, Alisols, Solonetz, Lixisols, etc, with a few proportions for each soil unit (FAO, 1998).

Land use/land cover: The land cover units in the BASW sub-basin are grassland, open shrubland, and open woodland which cover 30%, 23%, and 17%, respectively. Agricultural land covers 5%, pasture land covers 3%, 2% is wetlands-mixed, 2% is wetlands-forest and 1% is under bare ground. The grassland predominantly covers the low-lying area of the sub-basin. In the low-lying area of the Gambella, there is a seasonally flooded area, and around the border, there is a savannah of considerably large size, which is maybe believed to be the largest food chain in Ethiopia. In this area, the grassland and the open woodland units are intermingled together forming the savannah land in the system.

2.2.3. Tekeze-Atbara Sub-Basin

The Tekeze-Atbara sub-basin stands out as the smallest among the four sub-basins of the Eastern Nile River basin. Its basin area spans parts of the Ethiopian highlands upstream of the river, the eastern region of Sudan downstream, and a small portion situated in Eritrea. Historically, the Tekeze-Atbara sub-basin has not received significant public and political focus compared to the blue and white Nile sub-basins. However, despite this lack of attention, it holds substantial environmental and economic importance. The sub-basin encompassing approximately 230,000 km^2, comprises the Tekeze River (known as the Setit in Sudan) and its tributaries, including the Goang (Atbara in Sudan) and Angereb. Originating in the north-central highland plateau of Ethiopia, these rivers embark on a 1325km journey, descending from an elevation of approximately 3000 meters above sea level (masl) near their source to around 500 masl upon joining the main Nile in Sudan, approximately 285 kilometers downstream of Khartoum (Abebe, Grum, Degu, & Goitom, 2022)

Water availability in the Tekeze-Setit-Atbara sub-basin is characterized by variability. Rainfall ranges from 1000 millimeters near the river's source to about 40 millimeters near its confluence with the main Nile. Flows exhibit significant variability, particularly during the crucial low-flow months, compared to other sub-basins such as the Blue Nile and Baro-Akobo-Sobat. This variability is particularly pronounced during the crucial low-flow months. An annual average inflow of 11.45 billion cubic meters (Bm³) at the El-Girba station on the sub-basin main stems (Deltares, 2017).

Rainfall: Historical rainfall records indicate that the annual precipitation in the Tekeze-Atbara Sub-basin ranges from approximately 300 millimeters to over 1000 millimeters. In some years, there are notable fluctuations, leading to periods of drought or excessive rainfall, which can impact water availability, agriculture, and ecosystems. The variability in rainfall within the sub-basin is influenced by several factors, including the Intertropical Convergence Zone (ITCZ), local topography, and climate oscillations such as the El Niño-Southern Oscillation (ENSO). These climatic phenomena can cause shifts in precipitation patterns, leading to periods of above-average or below-average rainfall. Furthermore, studies have shown that climate change is affecting rainfall patterns in the region. Increasing temperatures and altered weather systems may lead to more erratic rainfall, prolonged droughts, or intense rainfall events, posing challenges for water management and food security (ENTRO, 2014).

Land Use Land Cover: The Basin encompasses diverse forest and woodland ecosystems, particularly in the highland areas. Forests play a crucial role in regulating hydrological processes, soil erosion control, and biodiversity conservation. However, deforestation due to agricultural expansion, logging, and fuel wood collection poses a significant threat to forest cover in the basin (Haregeweyn, et al., 2014). Agriculture is a dominant land use in the Tekeze-Atbara River Basin, supporting livelihoods and food security for local communities. The basin's fertile soils and favorable climatic conditions make it suitable for a variety of crops, including cereals, pulses, oilseeds, fruits, and vegetables. Traditional farming practices, such as rainfed agriculture and small-scale irrigation, are prevalent in the basin. Rangelands and pasturelands are extensive in the basin, particularly in the lowland areas. These ecosystems support pastoralism, livestock grazing, and dairy production, contributing to the livelihoods of nomadic and semi-nomadic communities. However, overgrazing and land degradation are common challenges facing rangeland ecosystems. Urbanization is increasing in the Tekeze-Atbara River Basin, driven by population growth, rural-urban migration, and economic development. Urban areas, towns, and industrial zones are expanding, resulting in the conversion of agricultural land and natural habitats. Urbanization brings challenges such as land fragmentation, pollution, and habitat loss. The basin includes various water bodies, including rivers, streams, lakes, and wetlands. These aquatic ecosystems provide essential services such as water supply, fisheries, and habitat for wildlife. However, water pollution, habitat degradation, and over-extraction of water resources pose threats to the health and integrity of these ecosystems. Protected areas and conservation reserves are established within the Tekeze-Atbara River Basin to safeguard biodiversity and ecosystem services. These areas include national parks, wildlife reserves, and forest conservation zones. Conservation efforts aim to mitigate habitat loss, promote sustainable land management practices, and preserve critical habitats for endemic and endangered species. Infrastructure development, including roads, dams, irrigation schemes, and hydropower projects, is altering the landscape and land use patterns in the basin. While these developments contribute to economic growth and water resource management, they also pose environmental challenges such as habitat fragmentation, sedimentation, and hydrological changes.

Sedimentation: High sediment flow result from significant erosion originating from both grazing/settlement areas (over 70 million tons per year) and cultivated land (almost 30 million tons per year) (Bekele, 2019). Approximately 40% of the sediment is redeposited within the landscape. It has been estimated that around 80 million tons of sediment flow into the Khasham-el-Girba reservoir annually, leading to a reduction in its capacity to half of its original capacity (Areka, 2019). The sediment load at Humera is estimated at 68.61 million tons per year. Additionally, the upper Atbara region (Goang and Angereb) contributes an estimated 7.37 million tons per year, resulting in a mean annual sediment inflow of 76 million tons per year at the border. The Kerib land in Sudan contributes a mean annual sediment inflow of 3.22 million tons per year. The mean annual sediment load reaching the mouth of the sub-basin (Atbara) is estimated at 58.43 million tons per year. Notably, the Atbara River contributes 12.7% of the total discharge of the Main Nile. The average discharge at the Kashm el Girba station from 1986 to 2000 was recorded at 11.45 km^3. The total runoff is 52,834 m^3 of water per km^2 per annum, compared with 169,612 m^3/km^2/year for the Blue Nile and 28,833 m^3/km^2/year for the Baro-Akobo-Sobat (ENTRO, 2014).

Topography: The topography of the Tekeze-Atbara River Basin is characterized by diverse landforms, ranging from highland plateaus to lowland plains, shaped by geological processes and the flow of the river system. Here's an overview of the topography of the basin along with accompanying graphs illustrating elevation and slope distribution (Gebremicael, Mohamed, Zaag, & Hagos, 2017). The upstream areas of the Tekeze-Atbara River Basin are dominated by rugged highland plateaus and mountains, notably the Ethiopian Highlands. These highlands are marked by steep slopes, deep valleys, and towering peaks, with elevations exceeding 4,000 meters above sea level. The landscape is often characterized by dramatic cliffs, escarpments, and gorges carved by the erosive forces of rivers over millions of years. As the Tekeze and Atbara Rivers traverse through the basin, they carve deep river valleys and gorges into the landscape. These valleys exhibit a range of geological features, including narrow canyons, steep cliffs, and terraced slopes. The rivers' erosive power has created spectacular formations, providing habitats for diverse flora and fauna. The downstream regions of the basin consist of expansive lowland plains and floodplains that stretch along the riverbanks. These areas are characterized by gentle slopes, fertile soils, and seasonal flooding during the rainy season. The floodplains play a crucial role in agriculture, supporting the cultivation of crops and providing grazing land for livestock. The Tekeze-Atbara River Basin also features escarpments and rift valleys, which are prominent geological features in the landscape. Rift valleys, such as the Great Rift Valley, traverse the region, creating distinct topographic features and influencing the flow of water and drainage patterns within the basin.

Plateaus are also a notable feature of the Tekeze-Atbara River Basin, particularly in the higher elevations. These flat-topped elevated landforms are remnants of ancient geological processes and provide important habitats for biodiversity. Plateaus may vary in size and elevation, contributing to the overall topographic diversity of the basin (ENTRO, 2014).

Overall, the topography of the Tekeze-Atbara River Basin is characterized by a dynamic interplay of highland plateaus, river valleys, lowland plains, escarpments, and rift valleys. This diverse landscape influences the basin's hydrology, climate, and ecological systems, shaping the livelihoods and cultures of communities living within its boundaries. Understanding and conserving this unique topographic heritage are essential for sustainable development and environmental stewardship in the region.

Runoff Pattern: The runoff pattern in the Tekeze-Atbara River Basin exhibits pronounced seasonal variability. During the wet season, which typically occurs from June to September, the basin receives the majority of its annual precipitation. For example, in certain areas of the basin, the average monthly rainfall during the wet season can exceed 200 millimeters (mm), contributing significantly to surface runoff and river flow. The basin's topography significantly influences the runoff pattern. Highland areas with steep slopes experience rapid runoff during intense rainfall events. For instance, in areas with slopes exceeding 15 degrees, the runoff coefficient-the proportion of precipitation that becomes surface runoff-can reach up to 0.4 or higher, indicating substantial surface runoff generation. Land cover and land use practices play a crucial role in shaping the runoff pattern. Deforestation, agricultural expansion, and urbanization can alter the natural hydrological processes. Studies have shown that land cover changes, such as conversion of forested areas to agricultural land, can increase surface runoff by 20% to 30% in certain parts of the basin. Soil properties influence the runoff pattern by affecting infiltration rates and water storage capacity. In areas with sandy soils, characterized by low infiltration rates, surface runoff tends to be higher compared to areas with loamy or clayey soils. Soil moisture content also plays a significant role, with saturated soils contributing to increased surface runoff. Human activities, including dam construction, irrigation, and land drainage, have significant impacts on the runoff pattern. For example, the construction of dams and reservoirs can regulate river flow, altering downstream runoff dynamics. In the Tekeze-Atbara River Basin, the construction of large dams, such as the Tekeze Dam, has led to changes in downstream runoff patterns and water availability (Annys et al., 2020), before the construction of the dam, the Tekeze Atbara river used to be a seasonal river, but after the dam construction in 2009 the flow has been regulated throughout the year, this regulation of flow pattern has created more water availability for other water management purposes, such as water storage, irrigation expansion, and flood control. Climate change can influence the runoff pattern in the basin through changes in precipitation patterns and temperature. Studies project alterations in seasonal rainfall distribution and an increase in the frequency and intensity of extreme weather events, potentially affecting runoff dynamics. For instance, climate models suggest a 10% to 20% reduction in annual runoff in certain parts of the basin by mid-century due to climate change effects (Abebe, Grum, Degu, & Goitom, 2022).

Soil Characteristics: The Tekeze-Atbara sub-basin encompasses diverse soil types, contributing to its ecological richness and agricultural productivity. Here are some of the predominant soil types found in the Tekeze-Atbara River Basin:

Vertisols: These are clay-rich soils characterized by high shrink-swell potential. They are prevalent in the highland areas of the basin, particularly in regions with distinct wet and dry seasons. Vertisols are known for their ability to retain moisture, making them suitable for agriculture, especially for crops like sorghum and millet.

Acrisols: Acrisols are weathered soils found in upland areas with relatively high rainfall. They are acidic and rich in clay minerals, iron, and aluminum oxides. Acrisols support diverse vegetation and are commonly used for cultivation, especially for crops like maize, wheat, and barley.

Nitisols: These are deep, well-drained soils with a high content of clay and organic matter. Nitisols are prevalent in the highland regions of the basin, where they support extensive agriculture due to their fertility and good water retention capacity. They are suitable for a wide range of crops, including coffee, teff, and pulses.

Cambisols: Cambisols are moderately weathered soils commonly found in transitional areas between highlands and lowlands. They are characterized by a well-developed soil profile with distinct horizons. Cambisols support a variety of vegetation types and are suitable for mixed farming practices, including livestock rearing and crop cultivation.

Regosols: Regosols are shallow soils with limited development, often found in the lowland plains of the basin. They are characterized by rocky or sandy substrates and poor nutrient retention capacity. While not ideal for agriculture, regosols are used for grazing and support sparse vegetation cover.

Fluvisols: Fluvisols are soils formed from recent alluvial deposits along riverbanks and floodplains. They are characterized by their high fertility and good drainage properties. Fluvisols are extensively used for irrigated agriculture in the basin, particularly for crops like vegetables, fruits, and cash crops such as cotton.

These soil types play a crucial role in determining the agricultural potential and land use practices within the Tekeze-Atbara River Basin. Understanding their characteristics and distribution is essential for sustainable land management and agricultural development in the region.

Temperature: In general, the basin exhibits a semi-arid to arid climate with hot temperatures, especially in lowland areas, and cooler temperatures in higher elevations. During the dry season, which typically occurs from November to April, temperatures in the basin can be relatively high, with daytime temperatures often exceeding 30 degrees Celsius (86 degrees Fahrenheit) or more, particularly in lowland regions. In contrast, nighttime temperatures may drop significantly, especially in highland areas, resulting in a wide diurnal temperature range. In the wet season, from June to September, temperatures may be slightly cooler due to increased cloud cover and rainfall. However, daytime temperatures can still be warm to hot, especially during periods of clear weather between rain showers.

2.2.4. Main Nile sub-basin

The Main Nile sub-basin is one of the four sub-basins in the Eastern Nile basin, which extends across 656,398 km^2 from the point where the Blue and White Niles converge near Khartoum to the delta in northern Egypt, spanning more than 14^o of latitude. The Main Nile is the longest river, which measures 3006km, and is the largest sub-basin of the EN basin, and covers 44% of its entire area. It flows northward till it joins its tributary at the Tekeze-Atbara-Setite sub-basin, after that it flows northwest toward the Mediterranean Sea (ENTRO, 2006a). The river's course consists of a series of mildly sloped placid reaches, separated by steep-sloped turbulent rocky sections, called cataracts. From Khartoum onward the following cataracts are discerned: 1st cataract at Aswan, 2nd cataract, 3rd cataract at Kajbar, Dal cataract, 4th cataract near Merowe, 5th cataract between Atbara and Abu Hamed at Wadi Halfa and 6th cataract or Sabaluka cataract between Khartoum and Shendi. The entire region is included in the Main Nile sub-basin, which begins where the Nile River crosses the border between Egypt and Sudan and runs north toward Cairo until emptying into the Mediterranean Sea (NBI, 2012). The main characteristics of the sub-basin include:

Topography: The sub-basin is characterized by a mild land slope. About 69% of the Main Nile sub-basin topographical range is between 200 and 500m altitude, 22% of its area is between 500 to 1000 masl, and only about 1% of the basin has < 20masl while about 3%, 4.5%, and <0.1% of the sub-basin is having the altitudinal variation of 20 to 100, 100 to 200 and above 1000 meter above sea level altitude, respectively (ENTRO, 2006a).

Land Use/Cover: According to FAO and IHE Delft (2020) findings, the Main Nile sub-basin is classified as having bare ground and bare soil, 14% as loose sand, 13% as grass and shrub land, 4% as irrigated land, and 2% as woodland. The remaining area of the sub-basin is put to other uses.

Precipitation: The Main Nile sub-basin experiences mean annual rainfall of less than 50mm in more than 65% of the sub-basin area, while just 17% of the sub-basin experiences rainfall over

100 mm. The yearly rainfall in Sudan varies from less than 25 mm in the north to 400 mm in the south. In Egypt, the shoreline is where most rain falls, yet even the wettest region, the vicinity of Alexandria only gets 200 mm of precipitation annually (FAO and IHE Delft, 2020). Rainfall and surface water fluxes from the three upper sub-basins are all significantly higher than those found downstream in Sudan and Egypt. Rainfall provides very little of Egypt's water supply; surface water flows from Sudan account for the great majority.

Temperature: The Main Nile sub-basin has a hot and arid climate condition. The temperature of the Main Nile countries often exceeding 40°C during the summer seasons. Along the Mediterranean coast, temperatures are relatively mild compared to inland areas. Summers are warm to hot, with average highs ranging from 30°C to 35°C, while winters are cooler with average highs around 18°C to 20°C. Khartoum, located at the confluence of the Blue Nile and White Nile, experiences extremely hot summers, with average highs well above 40°C from May to September. Winters are relatively cooler but still warm, with average highs around 30°C during the day.

Hydrology: The seasonal variation in the Nile River flow is significant, about 80% of the total annual discharge of the River Nile occurs during the summer rainy season (July to October) mainly with the Blue Nile and the Atbara River. Throughout the year, the White Nile keeps the Nile flowing, while the Atbara River occasionally runs dry, around the event that the upper White Nile were to stop flowing, the Nile River would likely dry up around May. The highest water yield is generated from Blue Nile, Lake Victoria, and Bahr el Ghazal sub-watersheds at 82.9 km^3, 53.2 km^3, and 51.3 km^3, respectively.

Hydrologic inflows into the Main Nile are from three reaches including the Blue Nile, White Nile, and the Tekeze -Setit- Atbara sub-basins. At the Khartoum junction, the inflow into the main Nile system is estimated to reach 74 billion cubic meters. The Main Nile inflow at the Atbara confluence now exceeds 84 billion cubic meters as the Atbara-Setite-Tekeze sub-basin adds a mean annual inflow of 12 billion cubic meters to the Atbara confluence, approximately 300 kilometers downstream from the Khartoum junction. This raises the inflow of the main Nile d/s to around 84 billion cubic meters. According to NBI (2012), the average annual flow of the Main Nile at Tamaniat is approximately 72.691 km^3 for the estimated year of 1911-1995. Every year, around 94 billion cubic meters (BCM) enter Lake Aswan in Egypt; however, only 0.4 BCM are discharged into the Mediterranean through the main branches of Damietta, Rosetta, and other branches along its 40-kilometer-wide delta (Karyabwite, 2000).

2.3. Existing and Proposed Water Resource Infrastructures at EN Basin

The Eastern Nile basin countries utilize their rivers mainly for irrigation, hydropower, and domestic, and industrial water use, among which irrigation represents the largest portion of consumptive water demand (Mulat & Moges, 2014). The hydro system of the Eastern Nile consists of ten major hydraulic dams that are currently operational. In Ethiopia, the Tana-Beles Scheme on the Blue Nile consists of an artificial link between Lake Tana and the Beles River to generate hydroelectricity (460MW) and planned irrigation development of around 1,500 km^2. The upper Tekeze Dam (9.3×109m^3) on the Tekeze-Atbara river has an installed capacity of 300MW (Goor et al., 2010); there are no large irrigation projects yet in the Tekeze-Atbara river basin. A small-scale irrigation project18 km^2 is irrigated from a dam constructed in the Angereb River, a tributary of the Tekeze-Atbara basin. In Finchaa basin the Finchaa-Amerti dams with 134MW installed capacity producing hydropower and supplying irrigation water to 6,205 ha under the Finchaa Sugar. In addition, the Grand Ethiopian Renaissance Dam (GERD) close to the border with Sudan will have a large reservoir and generate up to 6,000MW of electricity.

In Sudan, there are two major dams in the Blue Nile basin: the Roseires (heightened by 10 m in 2012, to double its storage capacity) and Sennar dams. The dams were constructed to irrigate more than 10,000 km^2 of crops distributed over three irrigation schemes (Gezira, Rahad, and Suki). Their electricity production is relatively small, attributed to the limited available head, 280 and 16 MW at Roseires and Sennar dams, respectively. In the downstream Tekeze-Atbara River, Khashm Elgirba Dam has a relatively small hydropower capacity (10.6MW). All of the previously mentioned dams in Sudan face severe siltation problems. Jebel Aulia dam, located on the White Nile near the confluence with the Blue Nile, provides water for irrigation schemes around the reservoir estimated at 2,750km^2. At the main Nile, close to the fourth cataract, Merowe dam (12.5×109m^3) has an installed generation capacity of 1,250MW and can potentially irrigate 3,800km^2 (Digna et al., 2018).

In Egypt, there are five run-of-river dams and one major dam in the basin, the Aswan High Dam (AHD). The purpose of the AHD is to produce energy, supply irrigation water, regulate the flows to protect downstream against flooding and improve downstream navigation. The Old Aswan

Dam (OAD), located downstream of the AHD, is operated as a run-of-river hydropower plant. It is mainly used for hydropower production and regulation of the daily outflows from AHD (Goor et al., 2010). The Esna runoff-river plant located downstream from the OAD is operated for hydropower generation. The last three barrages, Assyut, Delta, and Naga Hammadi, divert Nile water to collectively irrigate 1.315 km^2. Generally, many new reservoirs and irrigation projects have been proposed in the Eastern Nile basin, particularly in the Ethiopian part of the basin. The potential hydropower of the Blue Nile is estimated at 13,000 MW (Mulat & Moges, 2014). Six potential dam sites have been identified along the main Nile in Sudan with a total potential energy generation capacity of 1,600 MW (Verhoeven, 2011). The potential of new irrigation in Sudan is estimated at 5,900 km^2 withdrawing water from the Blue Nile; 900 km^2 from the White Nile; and 2,850 km^2 from the Atbara (Digna, Castro-Gama, et al., 2018).

2.4. Climate Change Impacts on the Surface Water Resources

Climate change refers to long-term fluctuations of temperature, precipitation, wind, and other elements of the Earth's climate system. It's a climate change that is attributed directly or indirectly to human activity that alters the consumption of the global and/or regional atmosphere (Field, 2012; IPCC, 2014). The rainfall pattern in the tropics is strongly influenced by large-scale features including Hadley Circulation, the pattern of sea surface temperatures, the effects of planetary waves, and the influence of local winds, which also influences the position of the Inter-Tropical Convergence Zone (ITCZ) (Lau & Kim, 2015; Worqlul et al., 2018; Wheeler et al., 2020). The Eastern Nile Basin is strongly influenced by general circulation patterns in the Indian Ocean and El Nino in the Pacific. Drought and flood are two important shocks, due to climate changes, which affect water availability in the Eastern Nile basin. Historical incidents indicated that all countries of the basin are highly prone to drought and flood which are the manifestations of the extreme hydrological variability and seasonality in the basin (Zerga, 2016).

One of the most concerning aspects of climate change in the eastern Nile basin is the predicted shift in precipitation patterns. Rising global temperatures are expected to alter weather systems, leading to increased rainfall variability. This translates to periods of intense downpours interspersed with longer, more severe droughts. While flash floods can wreak havoc on infrastructure and ecosystems, prolonged droughts pose an even greater threat. Reduced precipitation directly translates to diminished river flows, leading to shrinking lakes and reservoirs, which are the lifeblood of agriculture, industry, and domestic water needs. The incidence of drought due to climate change will increase in several regions of Ethiopia and the overall EN basin due to evolutionary and anthropogenic climate change (ENTRO, 2006a; WB, 2006). The basin also has a prolonged history of flooding associated with the highly seasonal flow of the major tributaries of the Nile where in high rainfall seasons (July to September) the main rivers in the basin rise to an immense scale and cause flooding, especially in the floodplains of South Sudan, Sudan, and Ethiopia. Often, flooding results in a huge socioeconomic crisis largely associated with displacement of societies, interruption of social services, increased infestation with a waterborne disease as well as heavy loss of lives, livelihoods, infrastructures, and properties (McCartney & Menker Girma, 2012).

The EN basin's vulnerability to the impacts of climate change is enhanced due to the dependence of the basin's economy on rain-fed agriculture, coupled with poor land management and low adaptive capacity (Hasan et al., 2018). The limited water availability and the increasing demand for water from different sectors could also contribute to the vulnerability of the basin to water stress as the climate changes. Beyond agriculture, the impacts of climate change on surface water will ripple through various sectors. Hydropower generation, a vital source of clean energy, will be threatened by reduced river flows. This could force countries to turn to more polluting alternatives like fossil fuels, further exacerbating climate change. Additionally, shrinking water resources will put immense strain on sanitation and hygiene practices, potentially leading to outbreaks of waterborne diseases (Tedla et al., 2022).

The challenges posed by climate change to the eastern Nile basin are immense, but there is still hope. Collaborative efforts among the riparian states are essential for navigating this crisis. Investing in water conservation measures like improved irrigation techniques and rainwater harvesting will be crucial. Additionally, promoting sustainable land management practices can help reduce soil erosion and improve water retention capacity. Furthermore, exploring alternative water sources, such as desalination and wastewater treatment, can provide some degree of water security. Importantly, fostering regional cooperation on data sharing, infrastructure development, and joint management of the Nile River is essential. A unified approach, guided by scientific evidence and a commitment to sustainable water management, is the only way to ensure a future where the Nile continues to be a source of life for generations to come.

The eastern Nile basin stands at a crossroads. Climate change presents a formidable challenge, but through proactive adaptation strategies, responsible resource management, and unwavering regional cooperation, the countries can navigate these turbulent waters. By working together, they can ensure a future where the Nile remains a symbol of life, sustenance, and shared prosperity for all who depend on its bounty.

2.5. Water Use Governance and Policy in the EN Basin

Water is one of the most essential, shared, and scarce natural resources that cause conflict and politically contested processes about its use in international, national, and local settings. Today, the term "global water law" is used to describe both many treaties made to regulate the use or conservation of freshwater resources as well as the customary international law related to water resources. As an international river, the Eastern Nile Rivers are naturally governed by the rules of international customary law on the administration and the uses of the water of international river courses. According to Abebe (2014), treaties are the main tool used to define international rights and obligations for international water resources. The Eastern Nile River basin's management is divisive and fraught with political, economic, and social tensions. This is due to the unequal utilization of water resources by the upstream and downstream riparian countries. There must be a necessity to apply common agreement norms that are more arguing than the previous colonial agreements of 1929 and 1959 treaties to solve the pragmatic concerns in the EN basin. The upstream countries are completely opposed to the last two treaties. Because of all of the allocation regulations that solely consider Egyptian Hegemony of the Nile. The following Table 1 shows treaties in different years.

Table 1: The historical trans-boundary declaration of the Nile River.

Treaty	**Objective/Key points**	**Signed by**
Anglo-Italian Protocol (15 April 1891)	Mainly setting the colonial borders. Only Article 3 mentioned the subject of Nile water share, where it obliged Italy to not construct any project (irrigation or dam) that may disturb the natural flow of the Atbara River.	Great Britain and Italy

Anglo-Ethiopian Treaty (15 May 1902)	Restricting Ethiopia from constructing any works in the Blue Nile, Lake Tana, and Sobat rivers that may disturb the flow of the water.	Great Britain (representing Anglo-Egyptian Sudan) and Ethiopia
The London Treaty and The Tripartite Treaty (1906)	Both treaties focused on assuring that Britain and Egypt would get their shares of Nile water.	Britain and Belgium Britain, France and Italy
Roma Agreement (1925)	In the form of exchanging letters. Britain will gain Italy's support to convince Ethiopia to build a dam in Lake Tana. In return, Britain will assist Italy in constructing a railway from Eritrea to Somalia through Ethiopia. Confirming the importance and continuity flow of the Nile River.	Britain and Italy
The 1929 Anglo-Egyptian Nile Water Agreement	For the first time, Nile water was divided between Sudan and Egypt only, 4 to 48 billion m3 respectively. Agreed on two dams to be constructed in Sudan. Sennar dam in the Blue Nile for irrigating Gezira Scheme in Sudan. And Jebel Aulia Dam in White Nile for storing water for Egypt in the dry season. Egypt will monitor the flow of both rivers. Regulations were set for Sennar dam discharges with certain limits and periods	Britain representing Sudan (also Uganda, Kenya Tanzania) and Egypt
London Agreement (1934)	Set regulations on the uses of the Kajera River that flows into Lake Victoria. And declaration of any newly proposed projects before 6 months at least.	Britain (Tanzania) and Belgium (Rwanda and Burundi)
1938 Agreement	Italy confirmed its full acknowledgment of Britain's rights towards Lake Tana, and it has no intention of	Britain and Italy

	introducing any projects.	
1959 Nile Water Agreement	Recognition of the 1929 agreement under the new circumstances of implementing the new High Aswan Dam. A new share agreement has been made. Where Egypt's share is 55.5 and Sudan's 18.5 billion m^3 and 10 billion m^3 are set as evaporation loss at the reservoir of the High Aswan Dam. Any addition or subtraction in water is split evenly between the two countries. Any claim from other countries shall be reacted to as one body (Sudan and Egypt). Permanent joint technical cooperation was created between Sudan and Ethiopia.	Sudan and Egypt
1991 Agreement	It was concerned with Lake Victoria	Egypt and Uganda
1993 Cooperation Agreement	Obligation towards the Nile water conservation and safety. Cooperation between the two countries in implementing any new projects that may increase or decrease the flow. Respect the International law.	Egypt and Ethiopia
Entebbe Agreement (2010)	Also known as the Cooperative Framework Agreement (CFA). It concluded the equal usage for all countries, trans-boundary cooperation, exchange of trust, and the un-harming principle for other countries.	Ethiopia, Burundi, Kenya, Rwanda, Tanzania and Uganda.
Declaration of Principles-The GERD (2015)	Ten principles have been signed and agreed upon. The principles are simply a presentation of the 1997 convention on a specific scale which is the GERD.	Egypt, Sudan, and Ethiopia.

The key initiatives and institutes in the Eastern Nile basin are the following:

a) The Joint Permanent Technical Authority of Nile Water (1959): Established by a bilateral agreement between Egypt and Sudan, this body focused on implementing and monitoring water projects on the Nile. Notably, Ethiopia, a significant upstream riparian (riverside) nation, was absent. This reflected the unequal power dynamics embedded in the 1959 agreement, which granted Egypt a disproportionate share of the Nile's water.

b) The HYDROMET Project (1967): Sparked by rising water levels in Lake Victoria, this project aimed to study the weather and water patterns of tropical lakes. While initially involving Egypt, Kenya, Tanzania, Uganda, and Sudan, it later expanded to include Rwanda, Burundi, and the Democratic Republic of Congo. Ethiopia participated only as a supervisor, again highlighting its exclusion from key decision-making processes.

c) The UNDUNGO Group: Formed in the spirit of "brotherhood" (UNDUNGO in Swahili), this group aimed for broader regional development across Central and East Africa. However, its impact on Nile water cooperation remained limited.

d) The Technical Cooperation Committee for the Development of the Nile Basin (TECCONILE, 1992): A significant step forward, TECCONILE brought together Egypt, Sudan, Tanzania, Uganda, Rwanda, and the Democratic Republic of Congo. Notably, other Nile Basin countries were relegated to observer status. TECCONILE's ambitious goal was to establish a comprehensive framework for regional cooperation. Its central project, the D3, aimed to develop a legal and institutional framework. This involved revisiting previous agreements, including the controversial 1959 pact. TECCONILE proposed a new agreement emphasizing "equal utilization" for all Nile Basin countries. However, this was met with resistance from Egypt and Sudan, unwilling to relinquish their perceived water rights.

e) The Nile Basin Initiative (NBI, 1999): Marking a shift towards inclusivity, the NBI brought all Nile Basin countries, including the newly formed South Sudan, to the table. Its core objective: fostering cooperation for sustainable development and equitable water use across the entire basin. NBI represents a significant effort to move beyond historical power imbalances and work towards a shared future.

f) The Eastern Nile Technical Regional Office (ENTRO, 2001): Established by Egypt, Sudan, and Ethiopia, later South Sudan joins after getting independence from Sudan. ENTRO exemplifies a more focused approach on the development and management of water resources service as an investment arm to implement the Eastern Nile Subsidiary Action Program

(ENSAP). ENTRO, headquartered in Ethiopia, tackles shared water projects specific to these four countries. This historical overview reveals a gradual evolution towards more inclusive Nile water management. While earlier initiatives reflected unequal power dynamics, the NBI offers a promising framework for cooperation. Moving forward, collaborative efforts like ENTRO demonstrate the potential for specific project-based partnerships to address shared water resource challenges. However, the path towards equitable and sustainable Nile water management continues to be shaped by in more inclusive agreements, political realities, and the ever-present challenge of ensuring a secure water future for all Nile Basin countries.

2.5. Socio-economic

The Eastern Nile basin is generally characterized by high population growth where the average growth rate between 1950 and 2015 was estimated at 2.6%. The total population of the basin countries is estimated to be 245 million in 2015. The medium projection of the UN shows that the total population of the basin countries will reach 330 million by 2030 and 446 million by 2050. The majority of the population in South Sudan (81.2) and Ethiopia (80.5%) still lives in rural areas and to a lesser extent in Sudan (66.2%) and Egypt (56.9%) (NBI, 2012). Although rapid urbanization is expected in the future, the dominance of the rural population is projected to persist until 2030 in most of the basin countries. The Eastern Nile Basin countries are categorized as one of the least developed areas in the world except Egypt by the ranging of Human Development Index (HDI) (ENTRO, 2006a). Water resource in the Eastern Nile basin is used for various purposes including agriculture, hydropower generation, domestic water supply, industrial production, livestock, and fishery. Agriculture and hydropower production are the two most important water uses in the basin. Both rain-fed and irrigated agriculture are practiced in the basin. In Ethiopia and South Sudan, green water is largely used for agriculture since rain-fed agriculture is dominant in these countries. Sudan has a large area of both rain-fed and irrigated agriculture while in Egypt agriculture is almost entirely irrigated. Access to electricity is low in the region which holds back the economic growth despite the available potential of hydropower. Population growth, urbanization, and industrialization efforts in the countries of the ENB have variedly contributed to the exacerbation of the water problem in the ENB. In addition, historical, as well as, recent political factors both on the national and trans-boundary levels play a clear-cut role in water resources development in the basin (Hamouda, 2009; NBI, 2012).

2.6. Water stress at the EN Bain

The water resources of the EN basin have been severely strained by ongoing population expansion as well as new demands brought on by the developing economies of the upstream nations, such as Ethiopia, which has demonstrated a strong desire to increase its agricultural output. As studied by (Yitayew and Melese, 2011), the upstream riparian countries in the Nile Basin (Burundi, Rwanda, Egypt, Ethiopia, and Kenya) are expected to be deemed water "scarce," based on a threshold value of 1,000 m^3 per person annually by the end of 2025. The level of water stress in the Eastern Nile basin countries is the ratio of total freshwater withdrawal to total renewable freshwater resources varies. In 2017, Egypt had a 141% water stress level. With the overall amount of freshwater extracted far exceeding the total amount of renewable freshwater resources, this suggests that the nation suffered from acute water stress. A moderate level of stress was reached in Sudan in 2017 when the water stress level was 71%. With a water stress level of 33% in 2017, South Sudan was found to be under relatively modest stress. In 2017, Ethiopia had the lowest water stress level (8%), of all the countries in the Eastern Nile Basin.

It is important to note that these countries' degree of water stress has evolved. As an illustration, the water stress level in Egypt rose from 114% in 2002 to 141% in 2017. Water stress in Sudan has increased over time as well, rising from 48% in 2002 to 71% in 2017. On the other hand, the water stress level in South Sudan dropped from 57% in 2002 to 33% in 2017 (Simonin ea al., 2023). Ethiopia's water stress level, which was 10% in 2002 and 8% in 2017, has stayed largely constant over time. The information regarding the overall degree of water stress in the nations that make up the Eastern Nile basin emphasizes how critical it is to manage and conserve freshwater resources in the area in a sustainable manner.

2.7. Surface Water Sustainability

Water resource sustainability is a major concern in light of increased water demand for agricultural, industrial, and household applications (Singh & Panda, 2012), as the world requires nearly 60% more food in 2050 to feed the forecasted 9.7 billion population. Day by day water resources are dwindling in quality and quantity due to the growing population, changing lifestyles, climate change, rapid urbanization, and over-exploitation (Bhanja & Mukherjee, 2019). Such alarming situations require an intermediate intervention to conserve and optimize the use of water. Surface water sustainability refers to the ability to manage and maintain surface water resources in a way that ensures their availability and quality for current and future generations. This involves implementing practices and policies that promote the responsible use, conservation, and protection of surface water bodies such as rivers, lakes, and wetlands (Charlesworth & Booth, 2016; Boru et al., 2019).

The Eastern Nile basin is greatly affected by environmental pollution. The economies of the countries which the EN River flows through are relatively backward, and they are all in the stage of striving for economic development. As such, they have not had enough funds to improve the environment (Hamad & El-Battahani, 2005). The rapid industrialization and the abuse of chemical products, as well as the discharge of untreated domestic sewage, and the discharge of agricultural wastewater and agricultural residues, are the main reasons responsible for the pollution of the Eastern Nile River (El-Sheekh, 2009). Serious disasters from flooding occur during the season, but hydropower development is extremely low and loss of surface water resources is also very serious. Therefore, effective and efficient water resource allocation and management is needed in this basin (Li et al., 2022).

The conjunctive use of water is a significant tool to overcome water scarcity, drought conditions, and waterlogging problems and a powerful tool to achieve sustainable development goals. One way to promote surface water sustainability is through integrated water resources management, which involves considering the interconnected nature of surface water sources, groundwater, and ecosystems when making decisions about water use and allocation (Sabale et al., 2023).

2.8. Upstream and Downstream Transect Water Use

The Eastern Nile basin comprises four countries mainly Egypt, Ethiopia, South Sudan, and Sudan. Ethiopia and South Sudan are the upstream countries whereas Egypt and Sudan are downstream countries. In the case of upstream and downstream transect in water use, the downstream countries use water for both irrigation and hydropower with noticeable dams like HAD in Egypt, Merowe, Jebel Aulia, and Kashim al Girba recognition among others in Sudan. The upstream countries use the basin water for small-scale irrigation. Upstream countries have a high potential for hydropower dams and if constructed, it will have the benefit of reducing evaporative losses, reducing soil erosion and sediment accumulation, and minimizing flood in downstream areas. (NBI, 2012).

2.9. Surface and Groundwater Interaction and Dynamics in the EN Basin

Groundwater is hydraulically connected to surface waters in many regions of the world and an understanding of this interaction is fundamental for effective water resource management in the EN basin (Owor et al., 2011). Interactions between groundwater and surface water are complex both in time and space and are influenced by not only climate, landform, geology, and biotic factors but also human activities (Wu et al., 2014). Interactions can occur through a range of spatial scales which include local, intermediate, and regional groundwater flow regimes. Worldwide, there are several examples where interactions between groundwater and surface water bodies have played a critical role in influencing surface water levels and, by extension, lake water balances. Within tropical Africa, this connection between groundwater and surface water has had the most considerable influence on the availability of water resources (Owor et al., 2011). Understanding the interaction between groundwater and surface water is imperative to address the conjunctive use of water, mitigate contamination of aquifer and surface water bodies, manage water rights and reservoirs, and integrate groundwater flow into watershed management and planning (Tigabu et al., 2020).

Assessments of the interactions between surface water and groundwater commonly employ a wide range of methods (Owor et al., 2011). These include hydrographic analysis, hydrogeological mapping, modeling, ecological indicators, field indicators, artificial tracers, geophysics and remote sensing, hydrochemistry and environmental tracers, hydrometrics, seepage measurements, temperature monitoring, and water budgets (Lin et al., 2018). Since the number of field measurements is limited for a complete understanding of the connectivity between groundwater and surface water, modeling, both conceptual and numerical, provides a valuable tool for integrating information obtained from other methods (Gobezie et al., 2023). More recently, the SWAT-MODFLOW became an important modeling tool for many researchers worldwide to (1) investigate regional and catchment scale groundwater and surface water interactions; 2) to study water management strategies, climate change impact, and abstraction scenarios; (3) to determine hydrologic system responses such as stream flow, groundwater level, and groundwater discharge to streams; and (4) to simulate the spatio-temporal variability of water resources (Guevara-Ochoa et al., 2020). By studying the dynamics of surface and groundwater interaction and considering these key points (recharge and discharge**,** flow paths, seasonal variability, ecological connections, climate change, and human impacts), water managers and policymakers can make informed decisions to sustainably manage water resources, protect ecosystems, and ensure water security for communities in a changing environment.

2.10. Runoff Generation Mechanisms and Seasonality in the EN Basin

The EN basin is characterized by extreme hydro-climatic variability over space and time, complicated hydro-politics governed by numerous agreements and pacts, and rapid population and environmental changes. The soil moisture content in the surface soil layer before a rainfall event strongly affects infiltration, and will thus affect the occurrence of runoff (Merz & Plate, 1997). For a rainfall event of high intensity or where soils are less permeable, runoff generation might not depend on the antecedent soil moisture content of the surface soil layer. In this case, infiltration excess overland flow will be predominant (Guzmán et al., 2013; Yimam et al., 2019). In this case, more runoff is generated on the landscape and groundwater recharge is likely by infiltration of the surface runoff (Tilahun et al., 2016).

However, when rain storms are less intense and fall on soils with high permeability, runoff is strongly controlled by the antecedent soil moisture of the surface soil layer. In this case, saturation excess overland flow will be the dominant runoff-generating mechanism. On shallow-depth soils located on hill slopes, rainwater infiltrates and drains laterally following the deep or short path to valley bottoms and raising the water level of shallow groundwater located on deep soils (Steenhuis et al., 2009). Both, soil types and land use change determine the physical properties and infiltration characteristics of runoff generation mechanisms of the watershed (Tilahun et al., 2013). The slope is also a major topographical factor that influences soil infiltration, runoff velocity, and soil stability. According to Abd-Elbaky & Jin's (2018) study, there is a significant positive relationship between runoff and precipitation with a correlation coefficient of 0.69 and a P-value < 0.001 in the Eastern Nile basin. Therefore, the runoff variations are mainly dominated by the precipitation in the Nile River Basin.

Numerous methods have been developed by different researchers to simulate the rainfall-runoff process. Although a variety of rainfall-runoff models are available, the selection of a suitable rainfall-runoff model for a given watershed is essential to ensure efficient planning and management of the watershed. To estimate runoff from rainfall events, loss rate or infiltration parameters have to be calculated (Tilahun et al., 2013; Choudhari et al., 2014). The dominant runoff process (DRP) is defined as the runoff process that mostly contributes to runoff generation during a rainfall event. The research methods used to study the DRP in the basin in recent years can be divided into two: (1) manual field investigation and (2) automatic recognition based on geographic information system (GIS), also called GIS- dominant runoff process (Tilahun et al., 2016). The Soil Conservation Service Curve Number method is often used to predict runoff. The methods applied to estimate surface runoff are based on different assumptions and data requirements. The choice of method depends on the data availability, scale of analysis, and the level of detail required for the runoff estimation.

2.11. Water Accounting Concepts and Applications:

Global water challenges are escalating, yet access to critical information for water sector decision-makers is dwindling. Effective solutions require a multi-disciplinary approach with a strong foundation in physical data on water sources and uses. This data needs to be consistent and unified to create a comprehensive picture for problem assessment. The current fragmented data landscape hinders clear communication with water consumers and ultimately impedes the development of responsible water management practices.

Water accounting integrates hydrological processes with land use. It also considers managed water flows and the services that result from water consumption in river basins. This approach aims to achieve equitable and transparent water governance for all users and a sustainable water balance. Users can contribute valuable data, like process assessments and more accurate datasets, which can improve water accounting models. At the International Water Management Institute (IWMI), Water Accounting Plus (WA+) is a methodology specifically applied to river basins. It utilizes open-source remote sensing datasets. Notably, WA+ is a multi-institutional effort led by international knowledge centers (IWMI, IHE Delft, and FAO) that are independent of any specific political or geographical region. This approach allows WA+ to provide independent estimates of water fluxes, water resource availability, consumption, derived services, and stocks, all generated near real-time. While WA+ leverages open-source remote sensing data, user-provided information helps refine these estimates for improved accuracy.

This framework goes beyond just remote sensing data. It incorporates other readily available global datasets and ground measurements to create standardized WA+ sheets. These sheets are comprehensive, containing graphs, maps, and tables that effectively communicate water resource information.

2.11.1. Application of water accounting:

Water Resource Management: Water accounting provides critical information for effective water resource management, enabling policymakers, water managers, and stakeholders to make informed decisions about water allocation, usage, and conservation. By tracking water inflows, outflows, and stocks, water accounting helps optimize water resource allocation and planning, ensuring sustainable use and availability of water for various sectors such as agriculture, industry, and urban areas.

Drought Monitoring and Early Warning: Water accounting can be used as a tool for monitoring drought conditions and providing early warning systems to mitigate the impacts of drought. By assessing changes in water availability, soil moisture, and hydrological indicators, water accounting helps identify regions at risk of drought and enables proactive measures such as water conservation, drought-resistant crop cultivation, and emergency water supply interventions.

Water Quality Management: Water accounting complements water quality management efforts by tracking the sources and pathways of water pollution, identifying pollutant loads, and assessing the impacts of land use activities on water quality. By integrating water quantity and quality data, water accounting supports pollution control strategies, watershed management initiatives, and efforts to safeguard water ecosystems and human health.

Climate Change Adaptation: Water accounting contributes to climate change adaptation by assessing the vulnerability of water resources to climate variability and change. By analyzing historical water data and climate projections, water accounting helps identify potential shifts in water availability, hydrological patterns, and extreme weather events, allowing for the development of adaptation strategies such as water storage, rainwater harvesting, and water-efficient technologies.

Ecosystem Conservation and Restoration: Water accounting plays a crucial role in ecosystem conservation and restoration by evaluating the water needs of natural habitats, assessing ecological flow requirements, and monitoring changes in aquatic ecosystems. By accounting for water allocations to ecosystems, water accounting supports habitat restoration efforts, river basin management plans, and the protection of biodiversity and ecosystem services.

Integrated Water Resources Management (IWRM): Water accounting is a key component of Integrated Water Resources Management (IWRM), which promotes holistic and participatory approaches to water governance. By providing a comprehensive understanding of water dynamics, stakeholders can collaboratively develop and implement IWRM plans that balance competing water demands, promote equity and social justice, and enhance water security and resilience in the face of global water challenges.

Water Accounting Sheets:

Water accounting sheets are essential tools used to systematically record, analyze, and report water-related data for a specific region, basin, or water management unit. These sheets serve as a structured framework for quantifying water inflows, outflows, stocks, and uses, providing valuable insights into water availability, distribution, and management.

Components of Water Accounting Sheets: Water accounting sheets typically comprise several key components, including:

Water Inputs: These include sources of water inflows such as precipitation, surface water inflows, and groundwater recharge.

Water Outputs: These represent water outflows from the system, including evapotranspiration, surface water outflows, and groundwater abstraction.

Water Stocks: These refer to changes in water storage within the system, including changes in groundwater levels, surface water storage (e.g., reservoirs), and soil moisture content.

Water Uses: These encompass various sectors or purposes of water usage, such as agriculture, industry, domestic supply, and environmental flows.

Water Balances: These summarize the overall water budget, accounting for the balance between inputs, outputs, stocks, and uses within the accounting period. Water accounting sheets rely on data collected from various sources, including meteorological stations, hydrological monitoring networks, water utilities, and government agencies. These data are systematically organized, analyzed, and entered into the accounting sheets to quantify water fluxes and stocks. Advanced techniques such as remote sensing, geographic information systems (GIS), and hydrological models may also be used to enhance data accuracy and completeness. Water accounting sheets can be developed at different temporal (e.g., daily, monthly, annual) and spatial (e.g., basin-wide, sub-basin, watershed) resolutions, depending on the specific needs and objectives of the water management context. Higher temporal and spatial resolutions provide more detailed insights into water dynamics but may require more data and computational resources.

Water accounting sheets have numerous applications across water resource management such as assessing water availability and demand, evaluating water use efficiency and productivity, monitoring water quality and pollution loads, supporting water allocation and planning decisions, facilitating drought monitoring and early warning systems, informing climate change adaptation strategies, enhancing ecosystem conservation and restoration efforts, promoting integrated water resources management (IWRM) initiatives.

Despite their utility, water accounting sheets may face challenges related to data availability, quality, and reliability, particularly in data-scarce regions or underdeveloped monitoring networks. Additionally, uncertainties associated with hydrological processes, climate variability, and human activities can affect the accuracy of water accounting results.

2.12. Data Sources for Surface Water Resources Assessment

The datasets used for surface water resources assessment are meteorological data, hydrological (stream flow) data, remote sensing, and spatial data (digital elevation model, land use land cover and soil data) (Abebe, 2007; Kushwaha et al., 2022). The sources and applications of each data are presented as follows:

a) Metrological data: This includes information on precipitation, temperature, evapotranspiration, relative humidity, sunshine hours, and wind speed which can be accessed from the remotely sensed Water Productivity Open-access portal (WaPOR v2.0) database of the Food and Agricultural Organization (FAO) (https://wapor.apps.fao.org/catalog/WAPOR_2/1). The WaPOR version 2.0 levels 1 with 5km resolution data for precipitation and level 2 with 100m resolution data for actual evapotranspiration, reference evapotranspiration, interception, and land cover classification layers (FAO and IHE Delft, 2020).

b) Hydrological data: The stream flow data from gagging stations is collected from the Ethiopian Ministry of Water and Irrigation and various literatures.

c) Spatial data: The spatial data include the digital elevation model (DEM), land use land cover, and soil data. The DEM data is collected from the U.S. Geological Survey (USGS) and accessed through the USGS Earth Explorer platform (https://earthexplorer.usgs.gov/). The DEM data is used to describe topographic characteristics such as contour, slope, elevation difference, aspect, hill shed, and others. The land use land cover data was accessed through Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type Product (MCD12Q1) data for 2001 and 2010. The MCD12Q1 product is developed using a supervised classification of MODIS reflectance data (Sulla-Menashe et al., 2011). It has a resolution of 500m and is accessed via https://lpdaac.usgs.gov/products/mcd12q1v006/. The Harmonized World Soil Database (HWSD), developed by FAO and IIASA, is used to extract soil information (https://www.fao.org/soils-portal/soil-survey/soil-mapsand-databases/harmonized-world-soil database-v12/ru/) for the EN basin. HWSD contains over 15,000 different soil mapping units distributed all over the world. Soil information such as soil texture, available water capacity, and root zone depth has extracted.

d) Remote sensing data**:** Satellite imagery and remote sensing data can help monitor changes in surface water bodies and vegetation cover over time.

The rainfall data is accessed from different satellite-based rainfall products. The selection of each product was made based on the spatial coverage, data record length, temporal and spatial resolution of the datasets, the type of data input (calibrated with gauge data or not), as well as the performance of products observed in previous studies for Eastern Nile basin region and countries. Therefore, the Climate Hazards Group Infrared Precipitation with Station (CHIRPS) dataset was used for this surface water resource analysis, which has a high-resolution rainfall dataset that combines satellite observations blended with ground station data, covering a wide area (50°S-50°N), with long record starting from 1981 until now. By integrating multiple data sources, CHIRPS enhances the accuracy and reliability of its rainfall data, to provide reliable precipitation estimates, so it is widely used in climate research, hydrology, agriculture, and disaster management. CHIRPS provide high-resolution rainfall estimates at a spatial resolution of approximately 0.05 degrees (about 5 km) globally.

2.12.1. Data acquisition and preprocessing

Daily rainfall data of CHIRPS products were acquired from the Climate Data Tool (CDT) platform that is based on the R programming language. Q/ArcGIS, Climate Data Tool (CDT), as well as R and Python codes, were used for the initial presentation and reprocessing of the data; i.e. visualization, clipping to sub-basins level, combining of separate daily data into one file for each year, and the conversion to GeoTiff (.tiff) or Comma-separated values (.csv) formats and vice versa.

2.13. Water Balance Components and Assessment Methods

The water balance concept is useful to evaluate the change in River basin conditions, which can alter the partitioning of rainfall into different components. The water balance works on the principle of the equilibrium between water inputs and outputs within a system of natural or disturbed ecosystems (Zhang et al., 2001). Precipitation is the primary input of water into a system, including rain, snow, sleet, and hail. It's the water that falls from the atmosphere to the Earth's surface. The rest components like evapotranspiration, runoff, infiltration, percolation, surface storage, and groundwater flow are the output of the water balance system. The evapotranspiration is the process by which water changes from a liquid to a gas or vapor and enters the atmosphere. It mainly occurs from water bodies like oceans, lakes, and rivers but also from soil and vegetation. Runoff is the portion of precipitation that flows over the land surface and eventually into streams, rivers, lakes, and oceans. The water seeps deeper into the earth through the soil layers and eventually contributes to groundwater storage or percolation process is also one of the output systems. The flow of water through subterranean aquifers is known as groundwater flow, and it is impacted by geological formations and gravity. Water that collects on the ground's surface, such as in puddles, ponds, and reservoirs, is referred to as surface storage all are water losses or outputs.

$$R = P - ET - In - \Delta S$$

Where; P = is precipitation, In = is infiltration, R = is the runoff, ET = is evapotranspiration, ΔS = is the change in storage.

To compute the water balance in the Eastern Nile basin, different researchers employed various methods. FAO and IHE Delft (2020) used open access of remotely sensed derived data of

(WaPOR v2.0) for the period 2009 to 2018**.** The result revealed that at the basin level, between 2009 and 2019, more than 90% of the evapotranspiration (ETa) was greater than the precipitation (P). The NBI (2014) also produced the estimation methods of ETa over the whole of the Nile Basin at a resolution of 1 km^2 in an 8-day time step. This dataset covers from January 2000 to 2014 using an improved algorithm from the global MOD16ET al algorithm which uses daily meteorological data and MODIS land surface dynamic datasets as inputs for daily ET calculations. The NBI ETa estimates are 17 to 66 % higher than that of WaPOR where the biggest difference is for Lake Kyoga followed by Lakes George and Alberta. Further, Belete et al. (2018) studied the Nile Basin hydrology using Integrated Valuation of Environmental Services and Tradeoffs (InVEST). To assess how much of the difference between P and ETa due to groundwater outflow and change in storage (FAO and IHE Delft, 2020) the Gravity Recovery and Climate Experiment (GRACE), a dual-satellite mission continuously monitoring and mapping Earth's changing gravity field to estimate the total water storage anomalies (TWSA). The longer-term trend in storage change (ΔS) as observed by GRACE is positive. The trend of water storage for several GRACE pixels that cover the Nile River Basin from 2009 to 2016 is 0.95 mm/year, which is translated into 2.8 km^3/year. The increase in the trend in change in storage may be a result of the construction of several reservoirs.

2.14. Tools and Models Used for Surface Water Potential Assessment

There are different hydrological models used as tools for decision-makers to forecast and predict the quantity and quality of water resources in the watershed (Chow et al., 1988). Some of these models could also predict the impacts of natural and manmade changes on water resources and also to quantify the spatial and temporal availability of the resources. These models vary in complexity, data requirements, and computational demands. The choice of model depends on factors such as the scale of analysis, data availability, modeling objectives, and user expertise. Of this model, the Soil Water Assessment Tool (SWAT) is a widely used physically-based, continuous-time hydrological model developed by the United States Department of Agriculture (USDA). The Soil Conservation Service Curve Number (SCS-CN) method **is** also widely used for estimating runoff from rainfall events. It considers factors such as soil type, land use, antecedent soil moisture, and rainfall intensity to calculate runoff**.** The Hydrological Simulation Program-FORTRAN (HSPF) is also used as a comprehensive watershed model developed by the

U.S. Environmental Protection Agency (EPA). It simulates water quantity and quality processes, including surface runoff, infiltration, evapotranspiration, groundwater flow, and pollutant transport. Further, the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model is developed by the U.S. Army Corps of Engineers to simulate rainfall-runoff processes using a variety of methods, including unit hydrographs, linear reservoirs, and distributed models. Furthermore, the Precipitation Runoff Modeling System (PRMS) is a modular, distributed-parameter hydrological model developed by the U.S. Geological Survey (USGS). It simulates hydrological processes at the watershed scale, including precipitation, snow accumulation and melt, infiltration, evapotranspiration, and stream flow routing.

2.15. Situation Analysis

Situation analysis is a critical process in various fields, including water resources management, business, marketing, and public policy. It involves assessing the current conditions, trends, challenges, and opportunities within a specific context. In the context of water resources management, several types of situation analysis can be conducted:

Hydrological Analysis: This type of analysis focuses on understanding the quantity, distribution, and movement of water within a watershed or water basin. It involves studying factors such as precipitation patterns, river flow rates, groundwater levels, and water quality. Hydrological analysis helps assess water availability, identify sources of water stress or scarcity, and predict potential impacts of climate change on water resources.

Water Quality Analysis: Water quality analysis involves evaluating the chemical, physical, and biological characteristics of water bodies such as rivers, lakes, and groundwater sources. This analysis assesses parameters such as pH, dissolved oxygen, nutrient levels, pollutants, and microbial contaminants. Understanding water quality is crucial for safeguarding human health, protecting ecosystems, and ensuring the sustainability of water resources.

Demand-Supply Analysis: This analysis examines the balance between water demand and supply within a given region or water system. It involves quantifying current and projected water demands from various sectors such as agriculture, industry, households, and the environment, and comparing these with available water supplies. Demand-supply analysis helps identify potential water shortages, prioritize water allocation, and develop strategies for sustainable water management.

Stakeholder Analysis: Stakeholder analysis involves identifying and understanding the interests, roles, and relationships of individuals, organizations, and communities involved in water resources management. This analysis helps identify key stakeholders, assess their influence and priorities, and understand potential conflicts or synergies among different stakeholders. Effective stakeholder engagement is essential for developing inclusive and participatory water management policies and projects.

Policy and Institutional Analysis: This analysis examines the legal, regulatory, and institutional frameworks governing water resources management at local, national, and international levels. It involves assessing existing policies, laws, and institutional arrangements, as well as their implementation and enforcement mechanisms. Policy and institutional analysis help identify gaps, inefficiencies, and barriers to effective water governance and suggest reforms or improvements.

Economic Analysis: Economic analysis evaluates the economic value of water resources and the costs and benefits associated with different water management interventions. It involves assessing water pricing mechanisms, cost-recovery strategies, investment priorities, and the economic implications of water-related decisions. Economic analysis helps policymakers and water managers make informed choices about resource allocation, infrastructure investments, and policy interventions.

Risk and Vulnerability Assessment: This analysis examines the potential risks and vulnerabilities associated with water resources management, including natural hazards, climate change impacts, water-related conflicts, and socio-economic factors. It involves identifying vulnerable populations, critical infrastructure, and areas prone to water-related disasters. Risk and vulnerability assessment inform the development of adaptation strategies, emergency response plans, and resilience-building measures.

Composite multi-criteria analysis: is one of the decision-making tools that combine multiple criteria to evaluate and rank different alternative scenarios. In the context of water resources management and planning, a situation analysis uses composite multi-criteria analysis, which can help in assessing the performance of various water management strategies on a set of criteria. The steps involved in computing composite multi-criteria analysis include: i) Identification of criteria, that are relevant to the water resources management; ii) Weighting of criteria, which assigns weights to each criterion based on their importance in the decision-making process. This reflects the relative significance of each criterion in achieving the objectives of water resources management; iii) Aggregation of criteria, such as weighted sum, weighted product, or analytical hierarchy process (AHP); and iv) Ranking of alternatives to identify the most suitable option for water resources management. The ranking provides a structured way to compare and prioritize different solutions. By using composite multi-criteria analysis for situation analysis in water resources management, decision-makers can make informed choices that consider multiple dimensions of performance and trade-offs between different criteria. This approach enhances transparency, rigor, and objectivity in the decision-making process, leading to more effective and sustainable water management strategies.

2.16. Hydrological Drought Trends in EN Basin

Drought is a worldwide natural disaster that has harmful effects on the economy, society, and environment. Extreme hydrological events, the two most concerning global crises are drought (low flow) and flood (high flow). Drought, in particular, is a common natural disaster that significantly impacts water resources and agricultural activities in the EN basin (Kalura et al., 2021). Hydrological drought is marked by reduced reservoir and lake water levels and a lack of stream flow water (Kalura et al., 2021). Research on drought has become increasingly significant in recent years due to climate change.

Most African countries, with their rain-fed agriculture, are especially vulnerable to the effects of climate change, such as droughts and floods (Gemeda & Sima, 2015). In regions of Ethiopia, Kenya, and Somalia where droughts are currently posing an immediate threat of starvation, for instance, forecasts show that the October–December 2022 rainy season would underperform, making it the fifth consecutive failed season. Ethiopia has long suffered from seasonal droughts brought on by erratic rainfall and climate change (Amognehegn et al., 2023). Ethiopia is highly susceptible to drought in several Amhara regions, such as North-Wollo, South-Wollo, South Gondar, and Afar; it is also a challenge in the entire Somalia Region, Eastern parts of Oromia Region, and the Upper Blue Nile basin in northeastern Ethiopia, which encompasses the Northern Tigray region (Melaku, 2020). Examining the temperature and precipitation patterns in the EN basin under projected future conditions is crucial in real-world applications. In the EN basin, hydrological drought is the least studied drought type compared to meteorological drought which is conducted almost in every station in the basin, especially in Ethiopia and Sudan.

The severe hydrological drought in the Blue Nile basin was in the years 1973, 1979, 1986, 1987, and 2011 (Abera & Gebeyehy, 2022). In Sudan, a period of drought has occurred throughout history. In most cases, these have been followed by famine and outbreaks of disease. Drought is one of the most important natural disasters in Sudan not only for its substantial impacts on agricultural production, food security, and livestock but also it causing significant disturbances to the forest ecosystems.

Sudan has suffered several long and devastating droughts in the past decades. All regions have been affected with one of the worst regions being the White Nile state and others. A major drought was experienced in the 20th century. The most devastating ones were in 1913, 1940, and 1954. In 1913 and 1940, about 1.5 million people were affected and in 1984, 4.5 million people went hungry.

2.16.1. Methods for Assessing Hydrological Drought

Extensive recent research on drought analysis at the continental or global scale, focusing on both present and future climate change, has been conducted. The drought index remains a useful technological tool for quantitatively assessing and defining drought conditions. Thus, various researchers around the world have utilized drought index methods to assess droughts in various regions. Choosing a drought indicator requires a thorough evaluation of the drought type and the suitable indicator considering data availability, ease of communication, implications of results, strengths and weaknesses of the indices, and the objective of the study. Some of the methods utilized for drought assessments have been the index-based approaches, namely Standardized Precipitation Index (SPI) (Liu et al., 2021), Standardized Precipitation Evapotranspiration Index (SPEI) (Waseem et al., 2022), Reconnaissance Drought Index (RDI) (Amognehegn et al., 2023), Hydrological drought (Stream flow Drought Index: SDI) (Nazarenko et al., 2023), Agricultural Drought (Agricultural Standardized Precipitation Index: aSPI) (Tigkas et al., 2022), Effective Drought Index (EDI), and Percent Normal Precipitation Index (PNPI) (Swain et al., 2022). These indices were developed to evaluate the impacts of droughts and to determine various drought characteristics, including regional scope, severity, size, and length.

SPI is a widely recognized metric for monitoring metrological drought conditions. It operates on the premise that insufficient precipitation across different timeframes impacts groundwater, reservoir levels, soil moisture, snowfall, and stream flow, with precipitation being its key determinant (Elkollaly et al., 2018). However, a hydrological drought is characterized by fluctuations in the time series of water supply and demand. River flow represents the supply time series, while the demand time series is dictated by the requirements of a particular user (such as irrigation) or by the overall demand for all users (Nazarenko et al., 2023). The hydrological drought indices (HDIs) are derived from hydrological monitoring and forecasting objectives, such as irrigation, hydroelectric generation, reservoir operation, and water supply for domestic or industrial purposes. Stream flows form the foundation for most hydrological drought indexes, but assessing stream flow deficits against standard conditions may not always be precise, particularly in river systems with altered flow patterns. There is a significant lack of data for stream flow studies of floods and droughts in the countries around the eastern Nile basin. Research on hydrological drought faces difficulties in using more data-intensive drought indicators due to the absence of gauge staff in most reservoirs and the lack of knowledge about groundwater levels in all basins. Because of this, the stream flow drought index (SDI), which requires less input and is easier to analyze and comprehend, is the best substitute for hydrological drought analysis in such situations (Kalura et al., 2021). Geospatial analysis of the drought also demonstrates the temporal and regional variability of the drought threat and its impact on vegetation systems, water resources, and society.

2.16.1.1. Drought index

Drought characterization (hydrological, meteorological, and agricultural) based on indices was addressed by the development of the Drought Indices Calculator (DrinC) software (Amognehegn et al., 2023). It provides tools for drought analysis using indices for operational and research purposes. DrinC is standalone software available for free download from https://drought-software.com/. It is currently used in more than 145 countries for different research and applications related to drought (Waseem et al., 2022).

a) A recent indicator of drought analysis, the Reconnaissance Drought Index (RDI) considers temperature in addition to precipitation when monitoring droughts (Amognehegn et al., 2023). Unlike the Standard Precipitation Index (SPI) which relies solely on precipitation data, RDI incorporates both temperature and precipitation to better understand the impact of temperature on water balance. The ratio of total precipitation to potential evapotranspiration is the basis for calculating RDI.

b) For the monitoring stations, the Stream Flow Drought Index (SDI) is calculated for both the past and the projected future. The historical SDI was calculated using data from observed stream flows and future forecasts produced by the hydrological model. A hydrological drought is indicated by negative SDI values, whereas positive values suggest wet circumstances. The SDI defines states of hydrological drought in the same manner as the RDI and other meteorological drought indices. The ratio of drought events to the entire time series is known as the drought frequency and the length of time that drought events continue to occur is known as the drought duration. As stated in Table 3 above, drought indices values are used to identify drought episodes. The classification of drought conditions based on the reconnaissance drought index is similar to SPI, ranging from -2 to 2, representing extreme drought to extreme wet as shown in Table 2.

Table 2:Drought index classification using SPI, SDI, and RDI values (Amognehegn et al., 2023).

RDI, SDI, and aSPI	Drought level
>2.00	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately we
-0.99 to 0.99	Near Normal
-1.00 to -1.49	Moderate Drought
-1.50 to -1.99	Severe Drought
< - 2	Extreme drought

2.16.1.2. Hydrological Drought Characterization

To determine several aspects of the drought, including its duration (D), severity (S), magnitude (M), and relative frequency (RF), and to assess the effects of the drought, the drought index is really important (Liu et al., 2021). The amount of time between consecutive dry spells (the beginning and the end of the drought) is known as the drought duration. The duration is the amount of time it takes for an SDI value to go from negative to positive. The total summation of negative SDI values from the start to the end of a drought event determines the severity of the drought. The ratio of drought duration to severity is known as the drought magnitude (Elkollaly et al., 2018). The relative drought frequency is the ratio between the number of droughts with negative SDI in drought duration and the total number of drought years in of assessment.

3. Material and Methods

3.1. Description of the Eastern Nile Basin

The Nile River, with an estimated length of over 6,800 km, is the longest river flowing from south to north over 35 degrees of latitude. The Nile Basin viewed southward from the delta in Alexandria, Egypt, is one large basin. The Nile Basin includes two main sub-basins: the Eastern Nile sub-basin (Egypt, Ethiopia, Eritrea, the Sudan, and South Sudan) and the Equatorial Lake sub-basin (Burundi, the Democratic Republic of Congo, Egypt, Kenya, Rwanda, the Sudan, South Sudan, Tanzania, and Uganda). The total area of the Nile basin represents 10.3% of the area of the continent and spreads over ten countries.

The Eastern Nile basin is one of the main sub-basins of the Nile River basin as shown in Figure 3. It lies between latitudes 7ºN and 31ºN. The countries of the Eastern Nile Region are Egypt, Sudan, South Sudan and Ethiopia. The Eastern Nile River basin covers an area of 1,800,569 km^2 of which Egypt contributes 4%, Ethiopia 22%, Sudan 13%, and South Sudan contributes 62%. A very small part of Eritrea is also included in the Nile River basin system. The area coverage of the EN basin riparian countries are revealed in Figure 2.

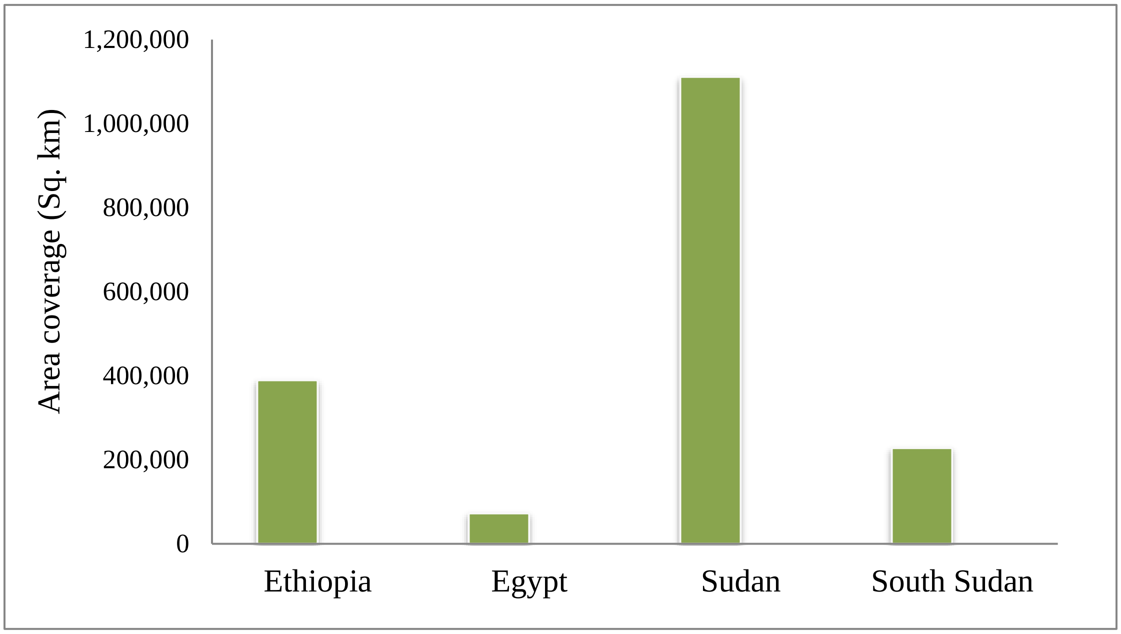

Figure 2: Total land area coverage of the ENB countries.

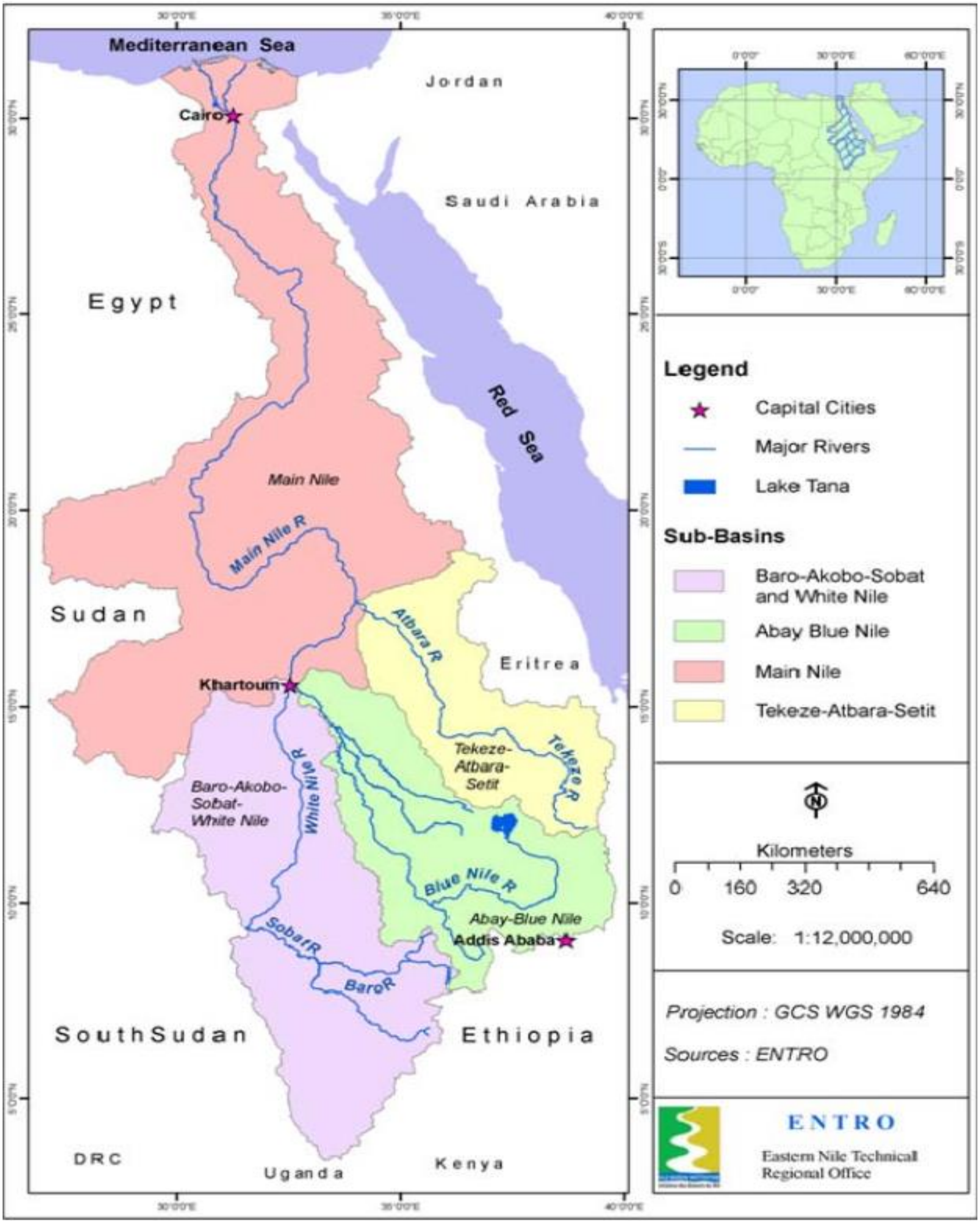

Figure 3: Location map of the Eastern Nile Basin.

Most of the EN basin is a water scarce region, with most of the Nile water generating from the Ethiopian highlands. The main Nile has a total yearly runoff of about 83.8 BCM, with contributions of about 64% (53 BCM per year) and 28% (23.6 BCM per year) by the Abbay-Blue Nile and Tekeze-Atbara sub-basin, respectively, which both show clear wet and dry spells as a direct response to the seasonal rain patterns.

3.1.1. Sub-basins of Eastern Nile basin

The EN basin is divided into four sub-basins that include the Abay-Blue Nile, the Tekeze-Atbara-Setite, the Main Nile, and the Baro-Akobo-Sobat. The sub-basin area coverage percentage in respect of the total EN basin area is revealed in Figure 4. The Figure 4 showed that the Main Nile is the largest sub-basin of the EN basins covering 44% of its total area while the Tekeze-Atbara-Setite is the smallest sub-basin covering 13% of the area.

Among the sub-basins the Abay-Blue Nile and the Main Nile are the most heavily populated accounting for 82% of the EN basin population. The Baro-Akobo-Sobat sub-basin and the Tekeze-Atbara-Setite have 8% and 10% of the EN basin population, respectively (ENTRO, 2006a). Each of these sub-basins offers distinctive natural resource potentials and constraints that entail the need for context-specific short- and long-term development interventions.

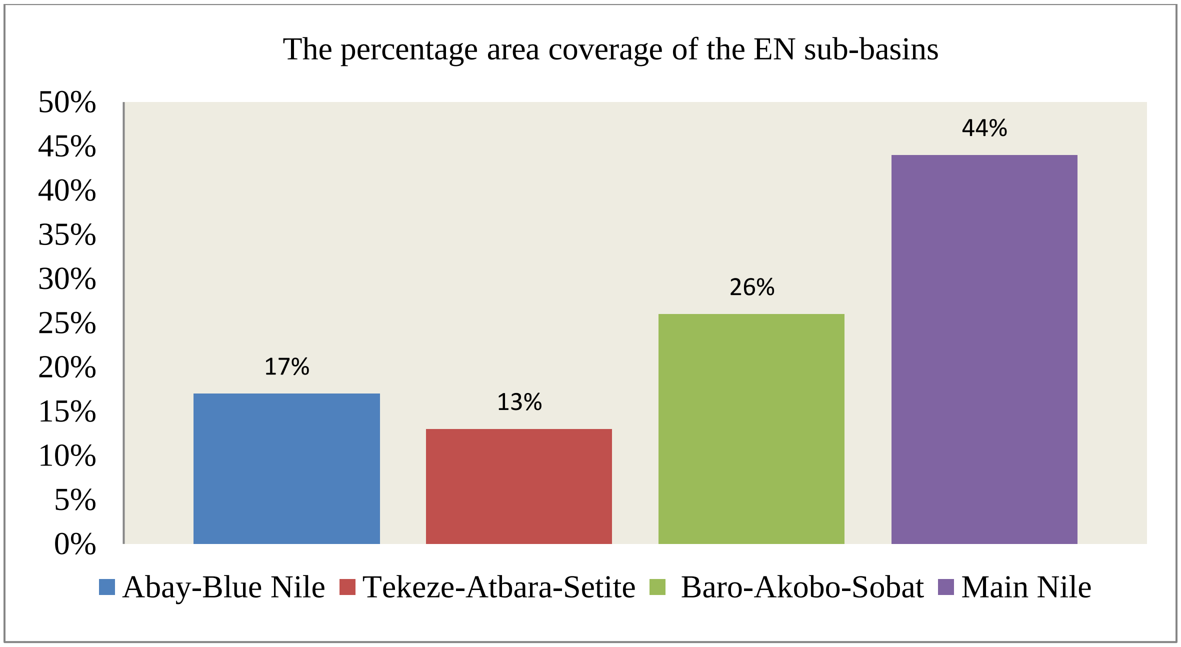

Figure 4: Sub-basin percentage area coverage in the EN basin system.

3.1.2. Topography

Elevation of the ENB ranges from 0 masl to around 4,300 masl. The area elevation curve of the EN basin is generated from digital elevation model (DEM) data, shown in Figure 5. About 5% area of the basin is very low lying areas, most of the area (around 70%) falls in the ranges of 300-600masl (NBI, 2012). The other 20% is between 600-2000 masl and the remaining 5% is with very steep slope (around 2000-4300 masl). Ethiopia has a general elevation ranging from 1,500 to 3,000masl and the mountainous part of the Ethiopia has elevation above 4000masl. A key geographical feature in Ethiopia is Lake Tana, created by past volcanic activity, at a mean elevation of 1785 masl. Most of the population lives on the elevated cooler plateaus above the steep river valleys where the soils are more fertile. In the Sudan, minimum elevation starts from 170 masl and extends up to 1,475 masl with a mean elevation of 450masl whereas in South Sudan, elevation ranges from 380-2,885 masl. In Egypt, the highest lands are in the south and the land slopes gently toward the Mediterranean Sea. In the south, elevation raises up to 1520masl and the land at the Mediterranean is at sea level.

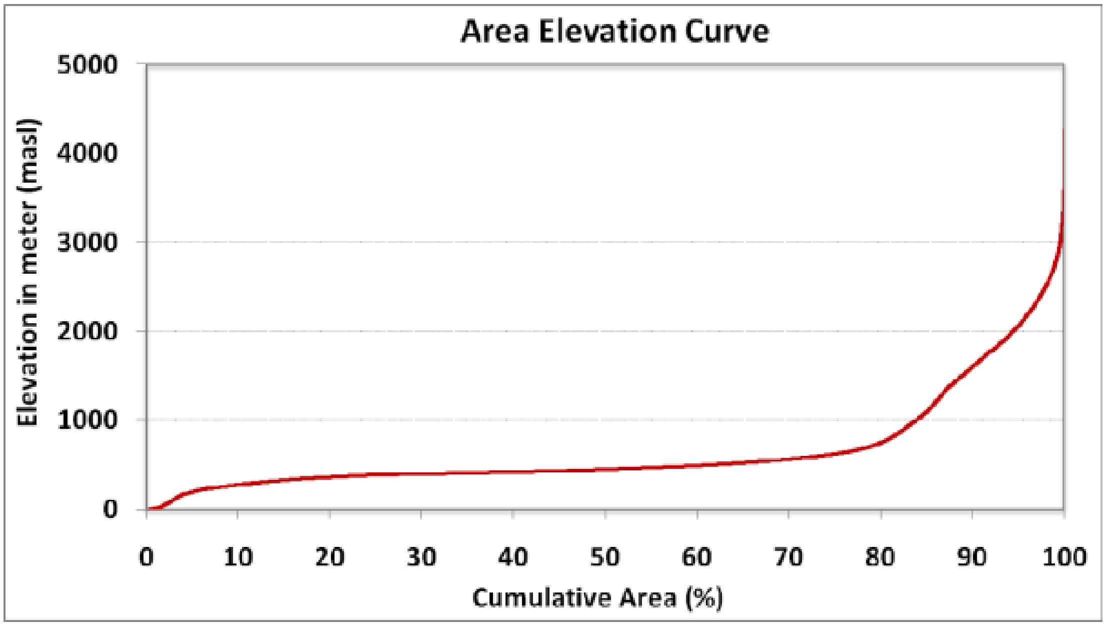

Figure 5: The area elevation curve of Eastern Nile basin.

3.1.3. Climate condition

The EN basin has different climates as it extends through large latitudes, with wide range of elevations. It is host of extremities, ranging from the rugged highlands of Ethiopia in the east, to the wetland areas of South Sudan and Southern Ethiopia, to the deserts of Sudan and Egypt in the north. Ethiopia and the Sudan experience tropical or sub-tropical climates, with seasonal rainfall that mostly occur in the summer months (June to August). Temperatures and annual rainfall depths vary widely, depending on elevation. The elevated plateaus in Ethiopia experience cool to mild temperatures year round, whereas in the central and northern Sudan the climate is hot year-round and very hot in the late spring and early summer (May to July). The far northern part of the Eastern Nile river basin in Lower Egypt experiences a Mediterranean climate, with mild winters and hot summers.

Parts of the Ethiopian highlands receive over 2000mm of rain yearly, while the far northern Sudan and Upper Egypt experience minimal rainfall. Sudan and South Sudan can be categorized into three rainfall zones: the southern region with 1,200 to 1,500mm of rain annually; the fertile clay-plains receiving 400 to 800mm of rain yearly; and the desert in the northern third of the country where rainfall averages just 20mm annually. Egypt sees consistently low rainfall, peaking in winter months (December to February), with some northern areas receiving less than 20mm of rain yearly.

3.1.3.1. Rainfall

The mean annual rainfall spatial map of the EN basin has ranges from 2195 mm per year at the highlands of Ethiopia to about 0.19 mm per year near its confluence with the main Nile (Figure 6a). Rainfall over the Blue Nile (BN) sub-basin varies with altitude. The BN sub-basin climate ranges from temperate cool at the Ethiopian highlands to semiarid at Khartoum. The wet season (June to September) has the most rainfall, with smaller amounts occurring in the dry (October to January) and mild seasons (February to May). Rainfall in the BN basin ranges from 500 mm/year to 2100 mm/year. The Baro-Akobo-Sobat sub-basin is characterized by a humid climate, and intense rainfall with spatial variation because of the elevation differences. Wet season is from May to October with the highest rainfall from June to October. The mean annual precipitation isomer than between 2180 mm per year at the highlands of Ethiopia and to 112 mm per year near its confluence with the main Nile at Sudan. Climate of the Tekeze-Atbara sub-basin varies with altitude, with rainfall ranging between 1800 mm per year near the source at the Ethiopian highlands, to about 50 mm per year at the dry climate region near Atbara, Sudan.

Lastly, the main Nile sub-basin has a mild land slope, and a hot and arid climate with mean annual rainfall less than 300mm per year in Khartoum, reducing to the north direction until reaching about 0 mm/year at Cairo crossing the Saharan desert, and increasing again to 200 mm/year at the coastal line with the Mediterranean Sea.

3.1.3.2. Actual evapotranspiration

Evapotranspiration (E) is defined as actual evapotranspiration (ETa), which is the actual rate at which water vapor is returned to the atmosphere from the ground and by plants and potential evapotranspiration of which the water vapor flux under ideal conditions of complete ground cover by plants, uniform plant height and leaf. Generally actual evapotranspiration (ETa) is the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration if the total amount of water is limited. The actual evapotranspiration of the EN basin depends on the altitude. The mean annual actual evapotranspiration of the EN basin ranges from 411 mm/year near the Khartoum and some parts of the river's source of Ethiopia to about 0 mm/year near the center of the main Nile (Figure 6b).

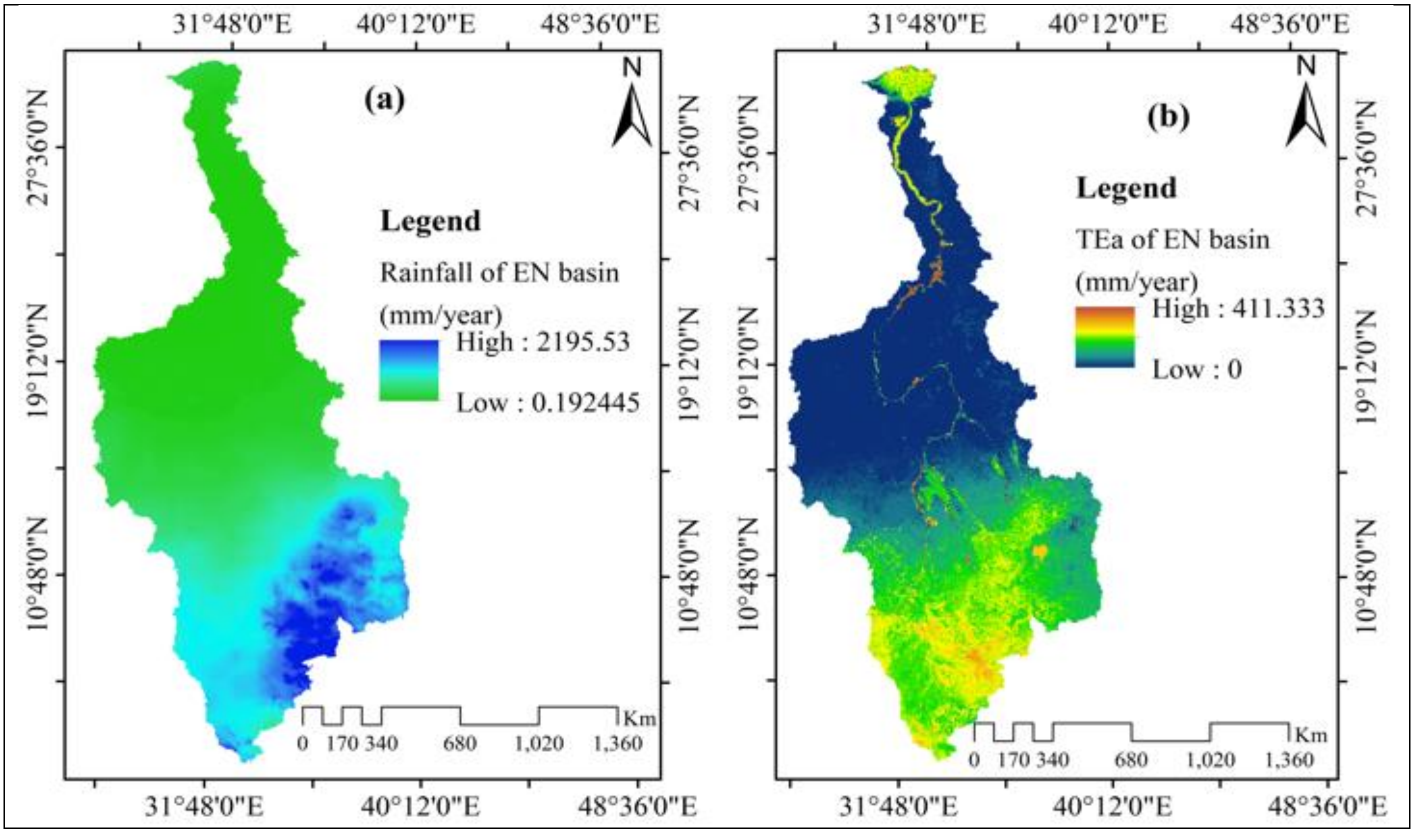

Figure 6: (a) the mean annual rainfall spatial map and (b) the actual evapotranspiration (ETa) spatial map distribution.

3.1.3.3. Interception

Interception is the act of disrupting the flow of water in the sequence of transportation events that lead to streams. This disruption can occur through vegetation cover or storage in depressions like puddles, rills, and furrows. When the surface reaches maximum capacity, water forms droplets around edges. Eventually, drops fall due to weight surpassing surface tension. Wind and raindrops can release water from organic material. Water droplets at edges and on surfaces can also evaporate. The interception loss of the hydrological cycle in the EN basin is dependent on the land use land cover changes of the area. The mean annual interception loss of the EN basin ranges from 153 mm near the river's source (Ethiopia) to about to 0 mm near its confluence with the main Nile. As revealed in Figure 7c, most of the main Nile sub-basin has the minimum interception losses because the sub-basin is covered by bare land; but, the Blue Nile sub-basin has somehow more interception losses.

3.1.3.4. Soil moisture

Soil moisture storage has a physically important role in the hydrological cycle, and it has a vital influence on the amount of rainfall which becomes runoff and groundwater recharge, etc.; thus, it has a role in global climate. The water held in the spaces between soil particles is commonly known as soil moisture. While soil type and plant cover influence how quickly water moves through the soil and surface runoff, evaporation and precipitation rates are the main factors determining soil moisture. The role of soil moisture storage in maintaining vegetation or crop growth during dry periods is important and it plays a key part in controlling runoff in a monsoon climate; soil moisture investigations played an important part in an investigation of basin water balance and groundwater recharge.

Soil moisture storage is a key factor in the water balance of a basin, as it provides a short-term reservoir maintaining the continuous outputs to basin evaporation and transpiration from the discontinuous rainfall inputs. The volume, or equivalent depth, of soil moisture storage between the ground surface and the lower limit of the rooting zone is an important indicator of the state of the basin at any given time. Remote sensing is definitely the most appropriate technique to obtain large scale soil moisture measurements. Different methods were developed in the last 40 years for the retrieval of soil moisture from microwave, optical and thermal satellite sensors. Several review papers on this topic were published recently (Brocca et al., 2017) that well describe the algorithms developed for the retrieval of soil moisture from the different bands of the electromagnetic spectrum. The soil moisture spatial map of the EN basin ranges from 12.33 mm near the river's source (Ethiopia) to about to 0.69 mm near its confluence with the main Nile (Figure 7d). As revealed in Figure 7c, most of the main Nile sub-basin has the minimum soil moisture status because the sub-basin is observed by low rainfall; but, the basin near the Ethiopian highlands is observed by a high soil moisture contents.

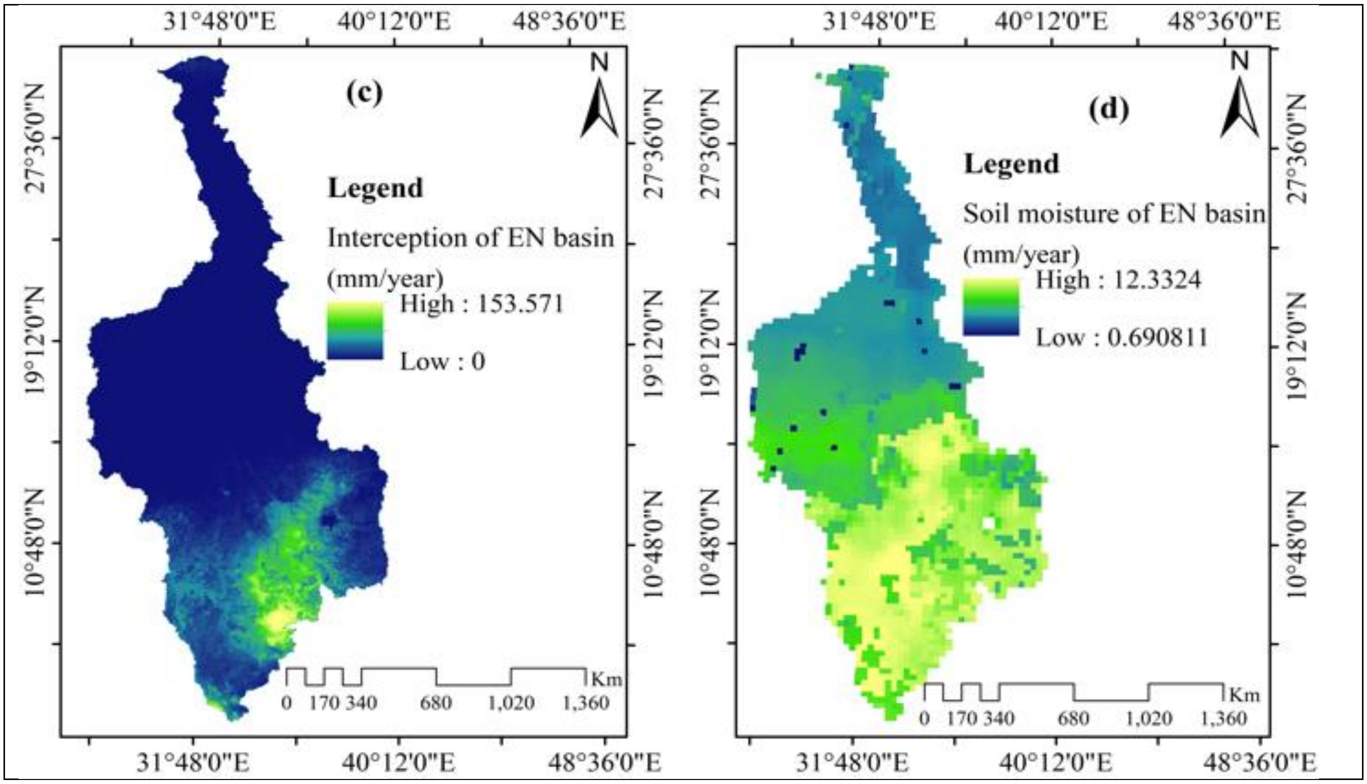

Figure 7: (c) the mean annual interception loss spatial map and (d) the mean annual soil moisture spatial map distribution of the EN basin.

3.1.4. Water and land use

Increasing population, urbanization, and agricultural practices are exerting pressure on land and water resources globally. Urban areas witness a rise in water withdrawal to meet domestic and industrial needs, while rural regions extract water for agricultural purposes. Moreover, agricultural land is being transformed into urban settlements, and wetlands and forests are converted into agricultural land. Consequently, there is immense stress on land and water resources, potentially leading to unsustainable development of human resources and the climate.

Egypt, Ethiopia, the Sudan, and South Sudan in the ENB are grappling with similar challenges related to land and water stresses. According to World's Water (2009), freshwater has been withdrawing for domestic, agricultural, and industrial purposes in these four countries. The data reveals that agriculture dominates water usage, accounting for nearly 90% of total water consumption in all four nations. In contrast, domestic and industrial water usage is relatively minimal.

3.1.5. Surface water resources

The availability of hydrologic components data is an important step for surface water resources availability and management in the world, e.g., Surface runoff. The water resources appear to be sufficient in terms of quantity and quality looking at the great potential opportunities of water, however, the Eastern Nile basin faces many water availability and accessibility challenges, and climate change is imposing additional burden. In Ethiopia and Sudan, people suffer from the high variability of rainfall spatially and temporally, which cause drought and floods in different parts. Water accessibility is also a major problem (Arsano & Tamrat, 2005). Moreover, Egypt also faces challenges and limitations regarding fresh water availability with the increasing water demand, land use changes, and environmental requirements (Abd Ellah, 2020). Similarly, water insecurity is an existential threat in South Sudan, with a core concern of lack of access to safe drinking water supply.

3.2. Sources of the datasets

The datasets used for surface water resources assessment were precipitation, actual evapotranspiration, interception, and soil moisture. The water stress index and population data were also collected, which is used for the situation analysis. The sources and the type of data used were revealed in Table 3. The rainfall data for the analysis was collected from CHIRPS websites and has an average temporal coverage of over 40 years. The actual evapotranspiration data was sourced from the Moderate Resolution Imaging Spectroradiometer (MODIS). The interception data was collected from FAO WaPOR sources and soil moisture data was also collected from Gravity Recovery, Climate Experiment (GRACE) to estimate the surface runoff of the EN basin. All the above datasets were resampled to a spatial resolution of 5km by 5km.

Table 3: The types of datasets and its sources.

Datasets collected	**Its sources**	**Remarks**
Precipitation data	https://earlywarning.usgs.gov/fews/datadownloads/Global/CHIRPS%202.0.	40 years
Actual evapotranspiration	https://modis.gsfc.nasa.gov/data/dataprod/mod16.php	20 years
Soil moisture data	https://grace.jpl.nasa.gov/data/get-data/	4 layers
Interception data	https://data.apps.fao.org/catalog/iso/3141c4ea-647b-4028-a90b-c1a9219db9fd.	20 years
Water stress index	https://data.apps.fao.org/aquamaps/?lang=en	-
Population data	https://cmr.earthdata.nasa.gov/search/concepts/C1597159135-SEDAC.html.	-

3.3. Method of data analysis

In this study, the water balance approach was used to compute the surface runoff in the Eastern Nile River basin. The method assumes that surface drainage divides coincide with groundwater flow divides so that inputs and outputs of groundwater can be neglected. The perimeter to area ratio is small over a large basin, and also considering the slow movement of groundwater relative to surface water, the error associated with this assumption should be small, respectively (Rodell et al., 2011).

The law of water balance states that the inflows to any water system or area are equal to its outflows plus change in storage during a time interval. The water balance is also referred to as a water budget. Developing water budgets is a fundamental activity in the science of hydrology. According to the US Geological Survey, an understanding of water budgets and underlying hydrologic processes provides a foundation for effective water-resource and environmental planning and management. Observed changes in water budgets of an area over time can be used to assess the effects of climate variability and human activities on water resources. Comparison of water budgets from different areas allows the effects of factors such as geology, soils, vegetation, and land use on the hydrologic cycle that can be quantified.

A water balance used to estimate the surface water volume, which is generated as surface runoff and to properly size the system. A water balance consists of estimating the amount of water that can be captured and the amount of water that is used. In this project a key parameters such as precipitation, actual evapotranspiration, interception, and soil moisture were considered to estimate the surface water resource potential of the four EN sub-basins. The surface water potential of the EN sub-basins were estimated by subtracting the raster value of each parameter (cell by cell) method (i.e., the simple method). The raster map of each of the four parameters raster maps were pre-and post-processed using QGIS and ArcGIS software. The raster map of each parameter was resampled to bring all the parameters to the same resolution, which is 5km by 5km.

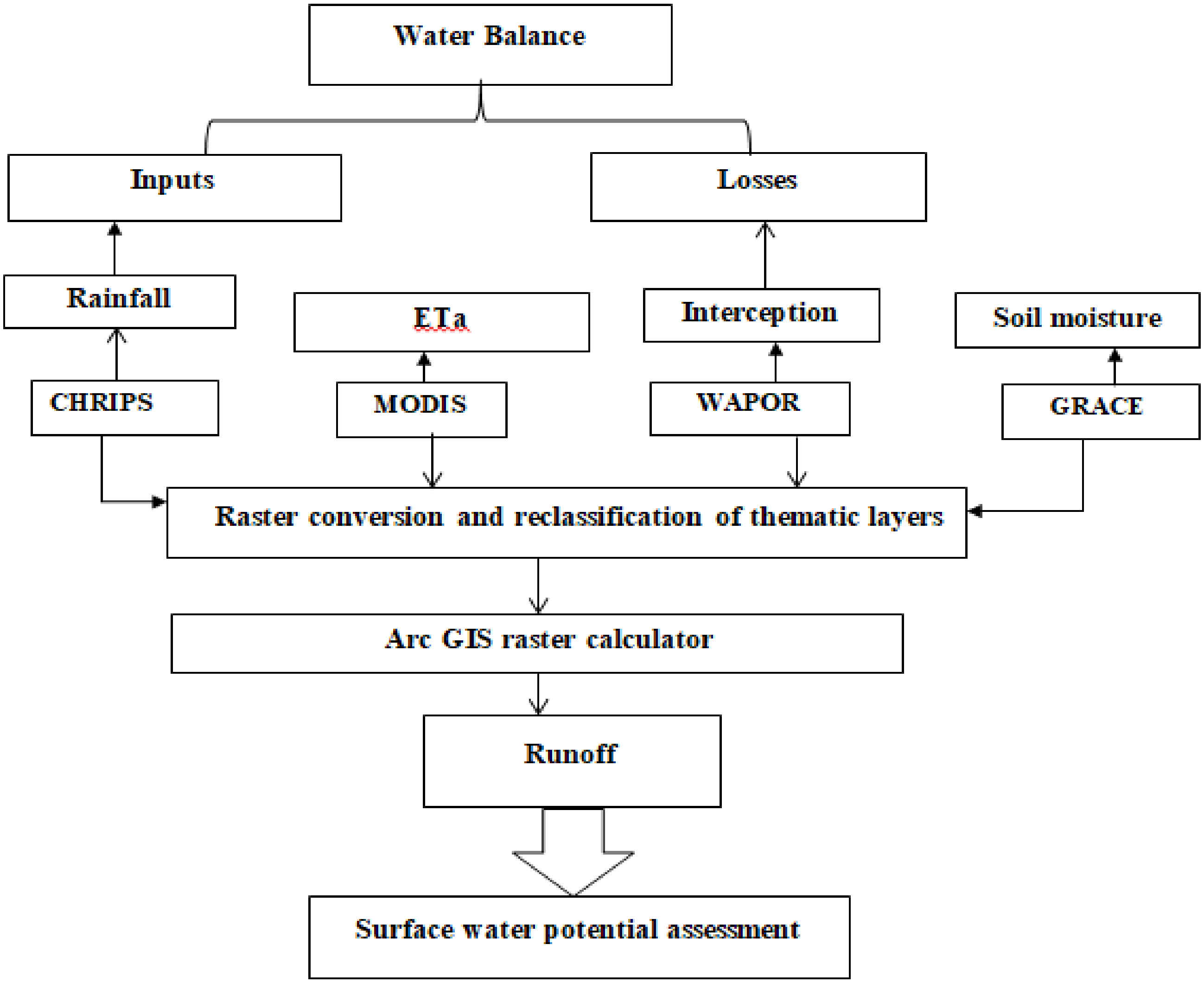

Figure 8: The general frameworks of the study.

The runoff (R) potential was estimated using the water balance methods, equation (1):

$$R = P - AET - In - SM - \Delta S \qquad 1$$

Where, P is total precipitation, AET is actual evapotranspiration, In is interception, SM is soil moisture, and ΔS is the terrestrial water storage change for a specific time period. Therefore, there are four components, which are needed to use the water balance approach, the interception (In), the soil moisture (SM), precipitation (P), and actual evapotranspiration (AET). The terrestrial water storage change (ΔS) was taken as zero for this study. Generally, the working frameworks of this study were revealed above in Figure 8.

4. Results and Discussion

4.1. Water Resources Assessment over the BN sub-basin

4.1.2. Rainfall of BN sub-basin

The average annual rainfall of the BN sub-basin ranges from 500 to 2196 mm/year. Areas with less rainfall is within Sudan which has an average annual rainfall of less than 500 mm/year (Figure 9 and 10), ranging from an average of about 948 mm/year near the Ethiopia-Sudan border to 1364 mm/year in the upper central parts of the basin. The Ethiopia highland is a region with a very greater and high annual rainfall during rainy season with an average annual rainfall value exceeding from 2000 mm/year.

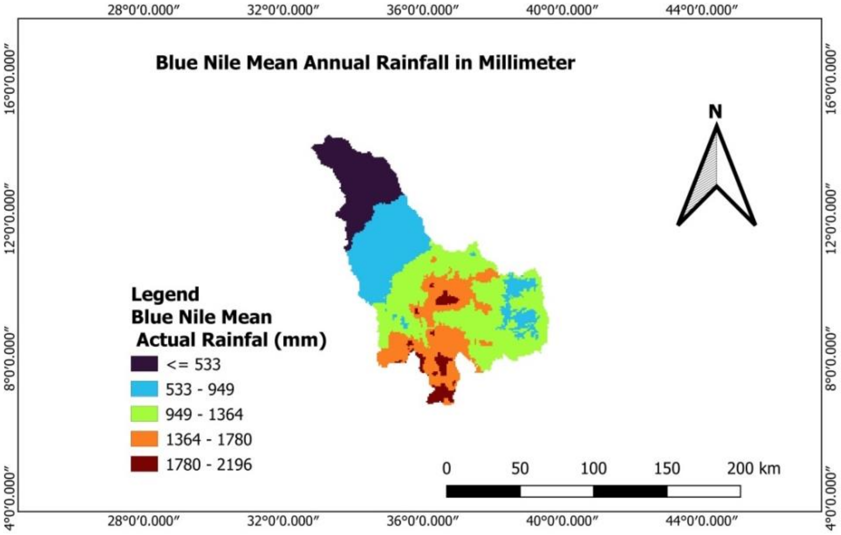

Figure 9: The mean annual rainfall spatial map of the Blue Nile sub-basin.

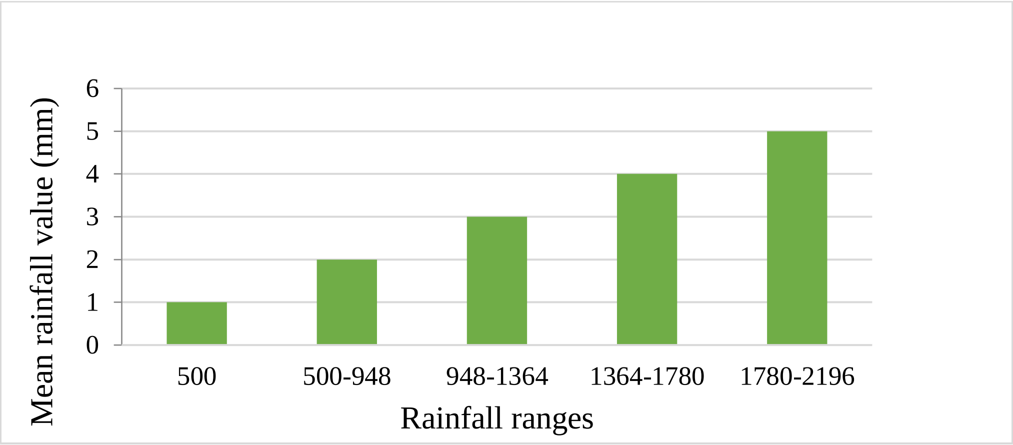

Figure 10: Mean annual rainfall ranges and its amount in the Blue Nile sub-basin.

4.1.3. Actual evapotranspiration of BN sub-basin

The spatial variability of actual evapotranspiration is strongly related to rainfall variability and vegetation cover. The actual evapotranspiration in Blue Nile sub-basin ranges from 72 to 350 mm per year (Figure 11 and 12). Actual evapotranspiration is high in Sudan part of the basin around the reservoir with an average annual range between 280-353 mm per year, 142–213 mm per year in the upper basin and also in Dedessa basin, respectively. The actual evapotranspiration is low in Sudan regions of Al Gadarif way up to Khartoum and also in the Beshilo region of Ethiopia with an average value of less than 70 mm per year.

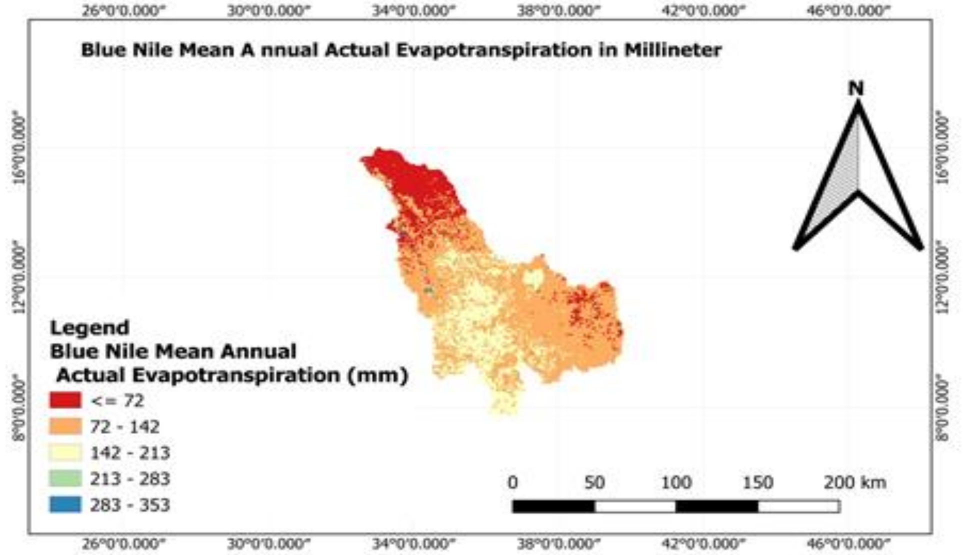

Figure 11: The mean actual evapotranspiration spatial map of the Blue Nile sub-basin.

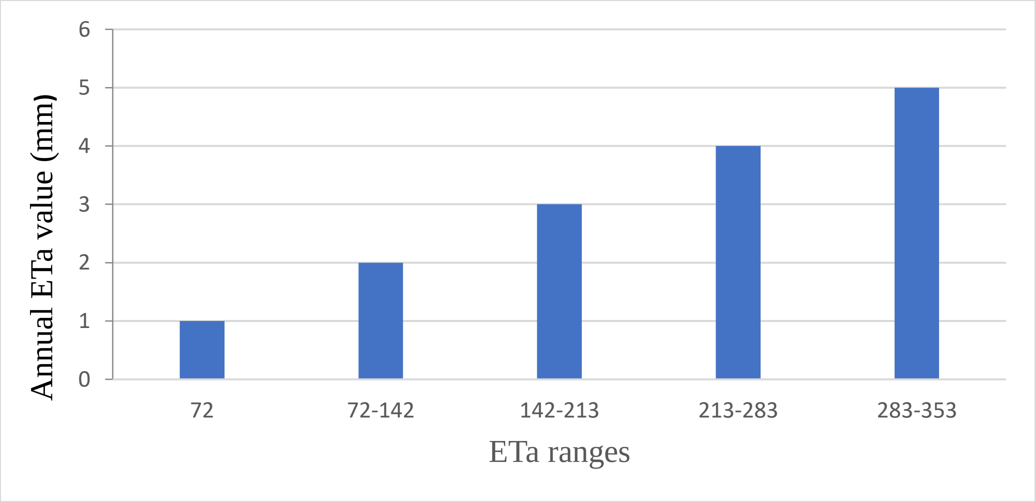

Figure 12: Annual actual evapotranspiration in Blue Nile basin.

4.1.4. Interception of BN sub-basin

The interception over the BN basin mostly occurs during the rainy season when all-natural vegetation and crops flourish in Ethiopia highland. The average annual interception ranges from 26-131 mm per year. The average annual interception in Sudan is relatively low with only 26 mm per year and that is because of the hot dry climate zone of Sudan. At the border between Ethiopia-Sudan the range increases from 79 mm per year to 105 mm per year in the upper basin and the value reaches up to 131 mm per year in the Ethiopia highland (Figure 13 and 14).

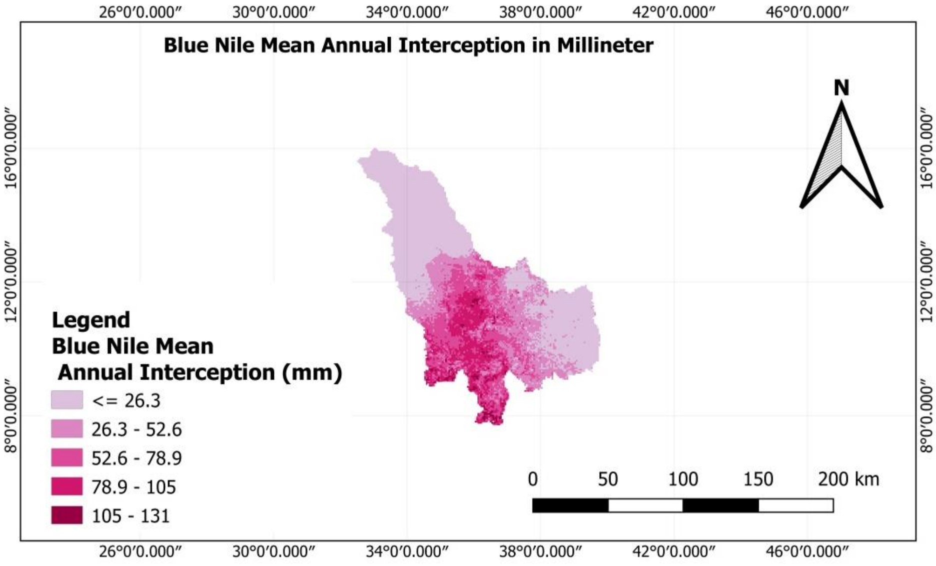

Figure 13 Annual interception raster map of the Blue Nile basin.

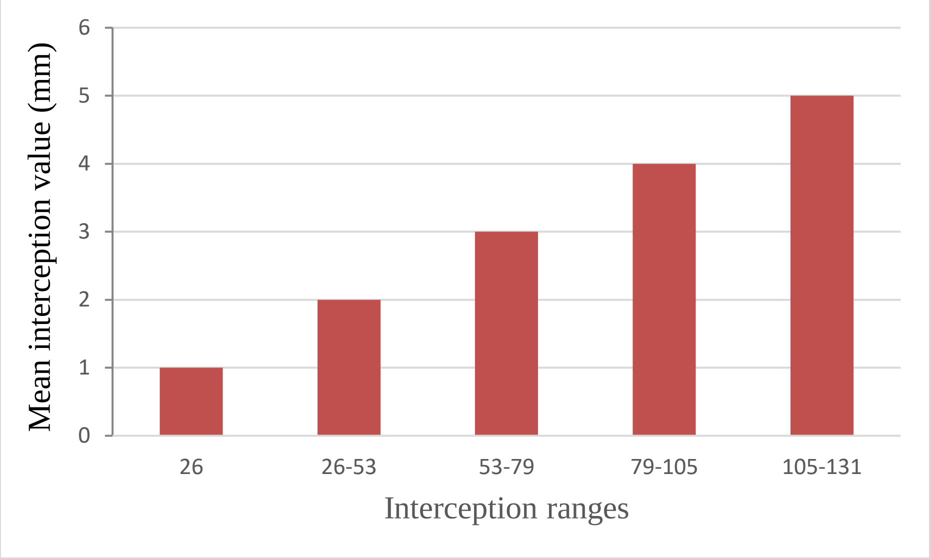

Figure 11: Interception ranges and its value in Blue Nile basin.

4.1.5. Soil moisture of BN sub-basin

The soil moisture can be affected by precipitation, temperature and soil characteristic. Over the Blue Nile sub basin, the amount of soil moisture varies depending on the location, soil type and depth. The average annual soil moisture ranges from 7-12 mm per year as shown in (Figure 15 and 16). The analysis result showed the spatial distribution of soil moisture is much higher in Sudan with an average of 12 mm per year, an average of about 7–8.5 mm per year is at Khartoum as well as at the Ethiopia-Sudan border and also in Fincha and East Gojam to mentioned few of many regions.

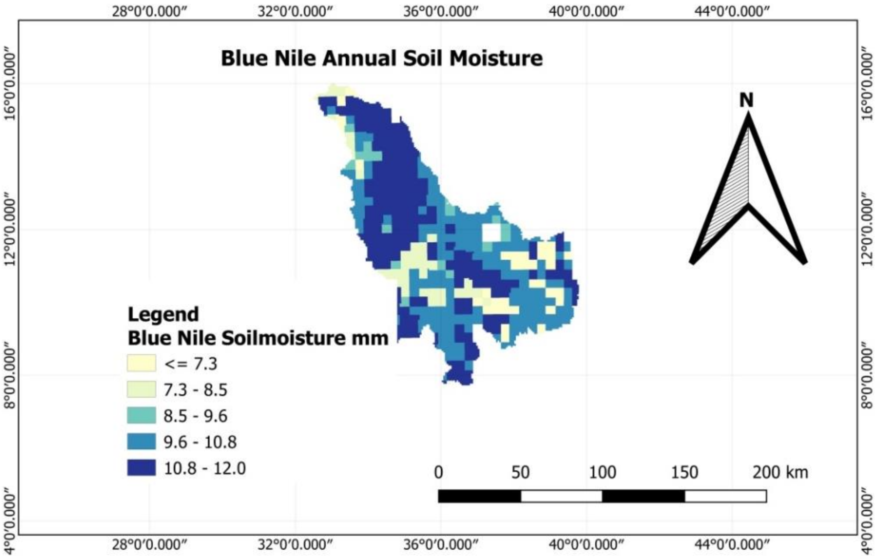

Figure 12: The mean annual soil moisture raster map of Blue Nile sub-basin.

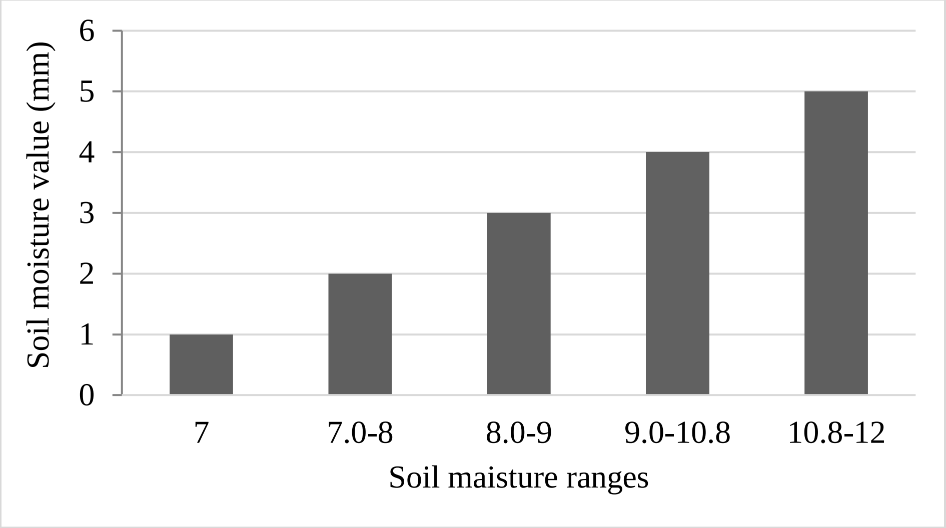

Figure 13: Interception ranges and its value in Blue Nile basin.

4.2. Water Resources Assessment over the TSA sub-basin

4.2.1. Rainfall of TSA sub-basin

Rainfall significantly contributes to the formation of surface runoffs in the basin. The rainfall of the TSA sub-basin is the tropical type with the wettest season limited to around three months (June/July to August/September). Hydrological variability is significant and highly seasonal. Seasonal distribution is more erratic and variable affecting agricultural production significantly. The upper course of the Tekeze Atbara-Setite sub-basin is identified as one of the most drought prone areas in Ethiopia (ENTRO, 2006d). The historical average annual rainfall records from (1983-2023) indicated that the mean annual precipitation in the Tekeze-Atbara Sub-basin ranges from 1800 mm/year near the river's source (Ethiopia) to about 50 mm/year near its confluence with the main Nile. The spatial distribution of mean annual rainfall values are strongly related to altitude. The average monthly rainfall spatiotemporal map of the sub-basin is revealed in Figure 17. The spatial distribution of rainfall was reclassified into five ranges in mm and the first value ranges from 50.9-330.2 mm/year, which covers an area of (36.68%). The range of values and its area coverage are also 330.2-665.3 mm/year (20.24%), 665.3-923.7 mm/year (22.98%), 923.7-1,175.0 mm/year (12.56%), and 1,175.0-1,831.3 mm/year (7.54%), respectively (Figure. 18).

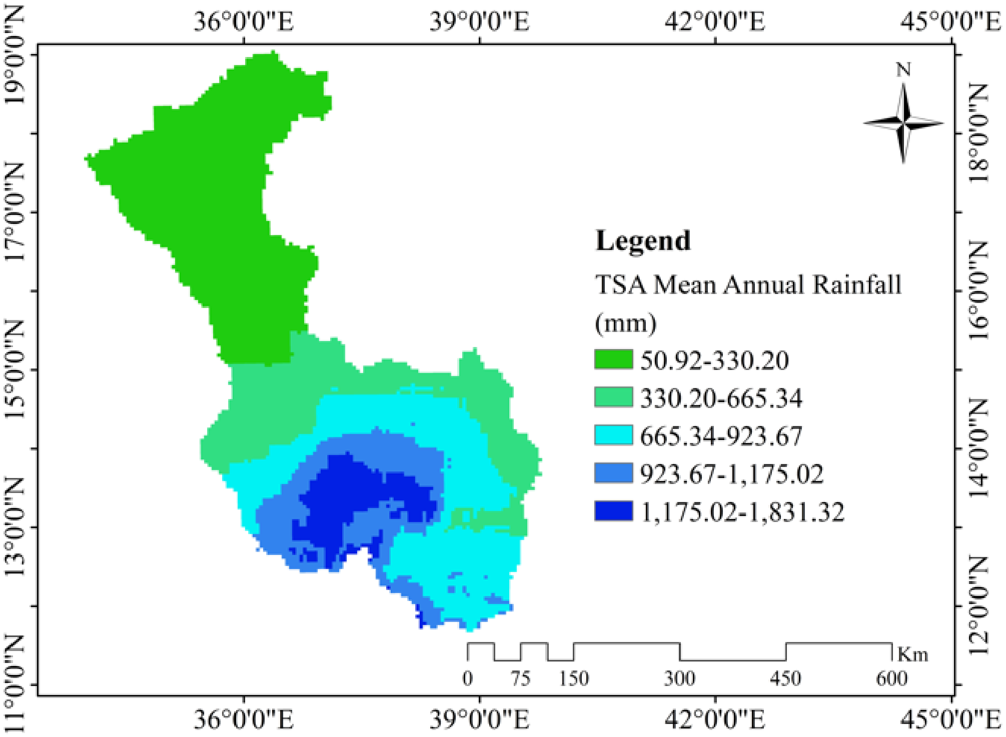

Figure 14: The mean annual rainfall spatial map of the Tekeze-Atbara-Setite sub-basin.

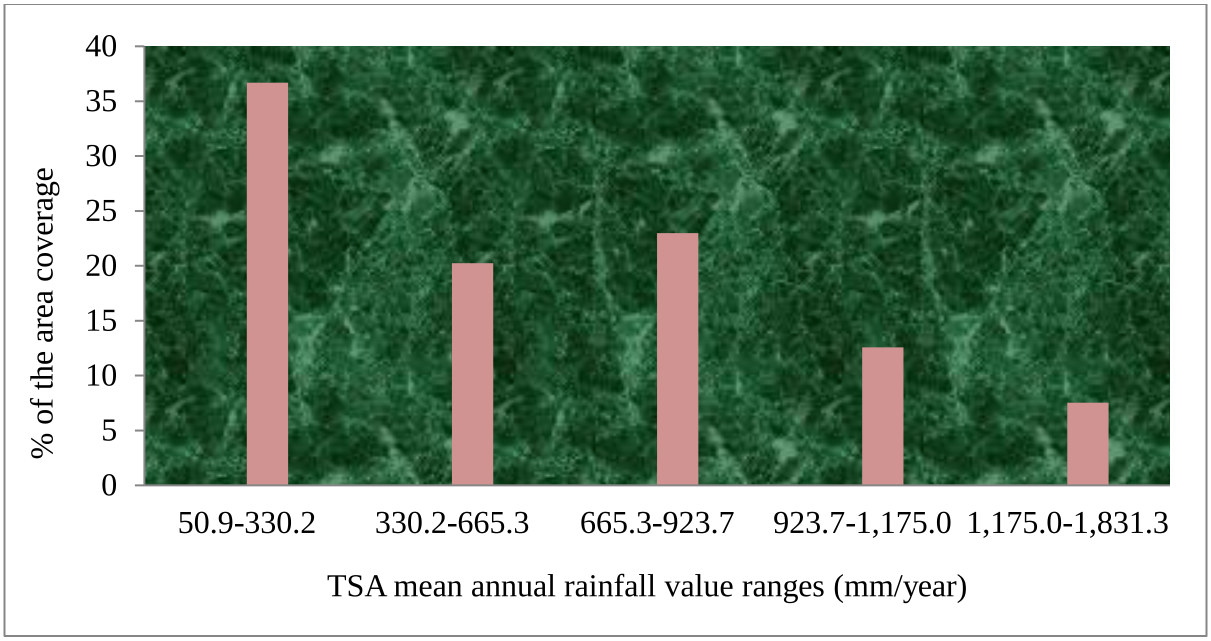

Figure 15: Mean annual rainfall value ranges and its % area coverage of the sub-basin.

4.2.2. Actual evapotranspiration of TSA sub-basin

As shown in Figure 19, mean annual actual evapotranspiration spatial map of the Tekeze-Atbara-Setite sub-basin ranges from 312.00 mm/year near the river's source (Ethiopia) to about 0.67 mm/year near its confluence with the main Nile. The actual evapotranspiration in the northwestern parts of TSA sub-basin is characterized by higher actual evapotranspiration and near the confluence with the main Nile; the actual evapotranspiration is relatively high. The

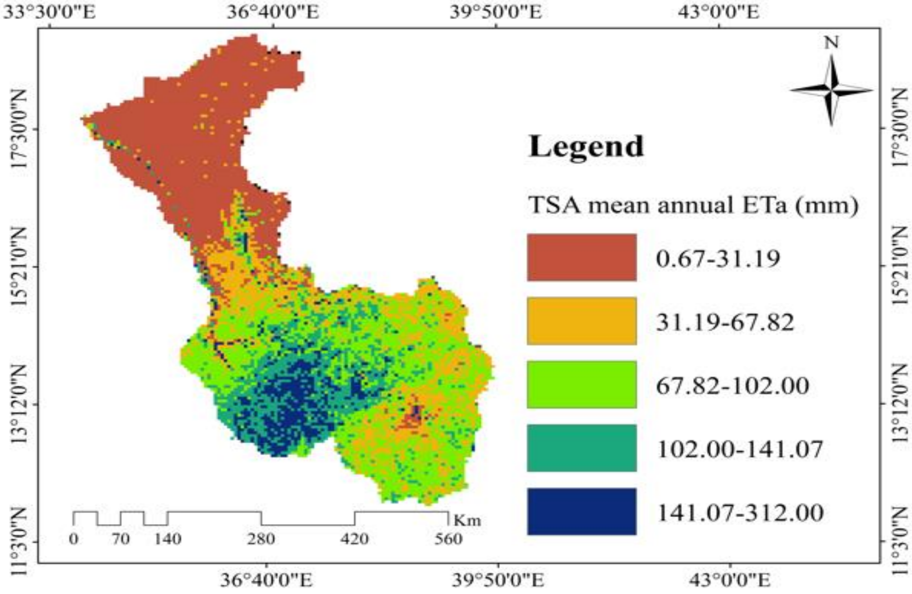

Figure 16: The mean actual evapotranspiration spatial map of the TSA sub-basin.

spatial distribution of mean annual actual evapotranspiration was reclassified into five ranges in millimeter. The mean annual ETa value ranges and its area coverage of the TSA sub-basin are 0.67-31.19mm/year (33.42%), 31.19-67.82 mm/year (19.54%), 67.82-102.00 mm/year (25.02%), 102.00-141.07 mm/year (14.46%), and 141.07-312.00 mm/year (7.56%), respectively (Figure 4.12).

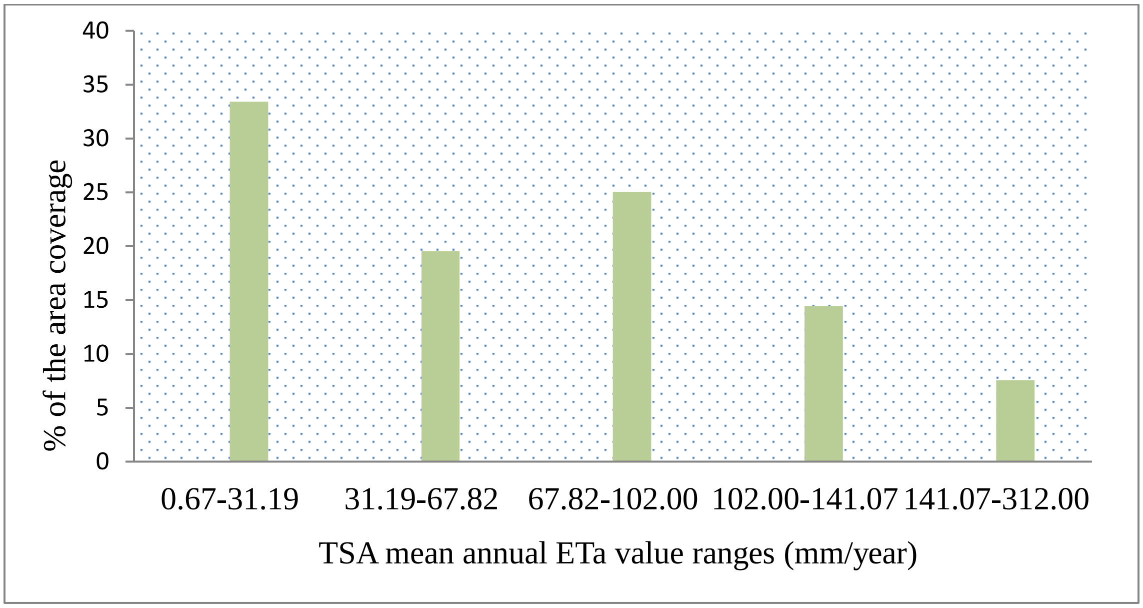

Figure 17: The mean actual evapotranspiration value ranges and its % of area coverage.

4.2.3. Interception of TSA sub-basin

Most of the southwestern parts of the Tekeze-Atbara-Setite sub-basin have maximum interception losses. The Tekeze-Atbara-Setite sub-basin in Sudan experiences low interception loss due to it has a relatively lower rainfall value compared to the Ethiopian highlands (Figure 21). In this study, the spatial distribution of mean annual interception values and its area coverage of the TSA sub-basin are 0.00-5.42 mm/year (48.13%), 5.42-16.27 mm/year (28.7%), 16.27-31.52 mm/year (11.45%), 31.52-50.84 mm/year (7.69%), and 50.84-86.43 mm/year (4.03%), respectively (Figure 22).

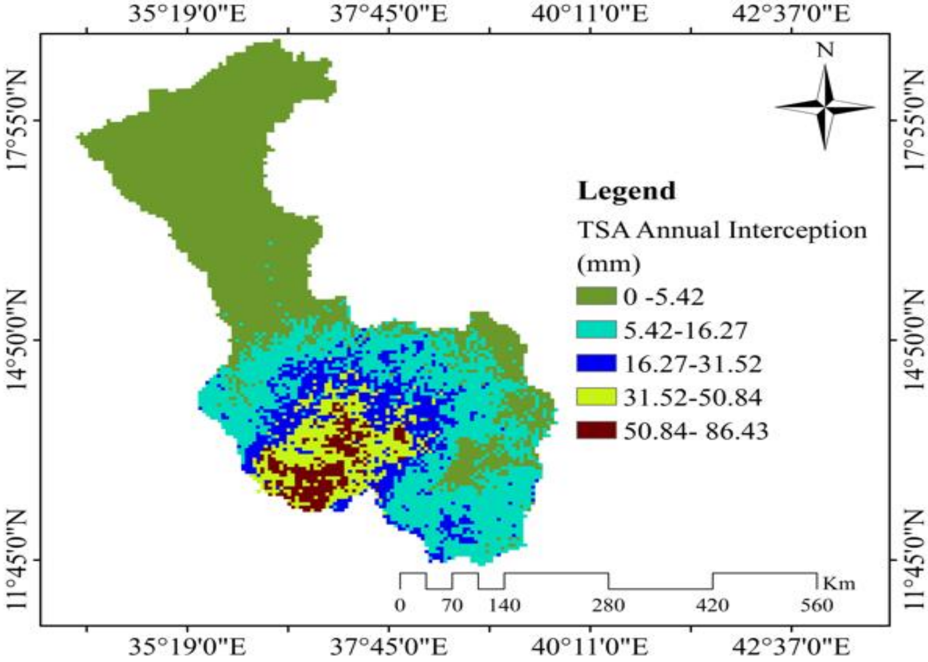

Figure 18: The mean annual interception spatial map of the TSA sub-basin.

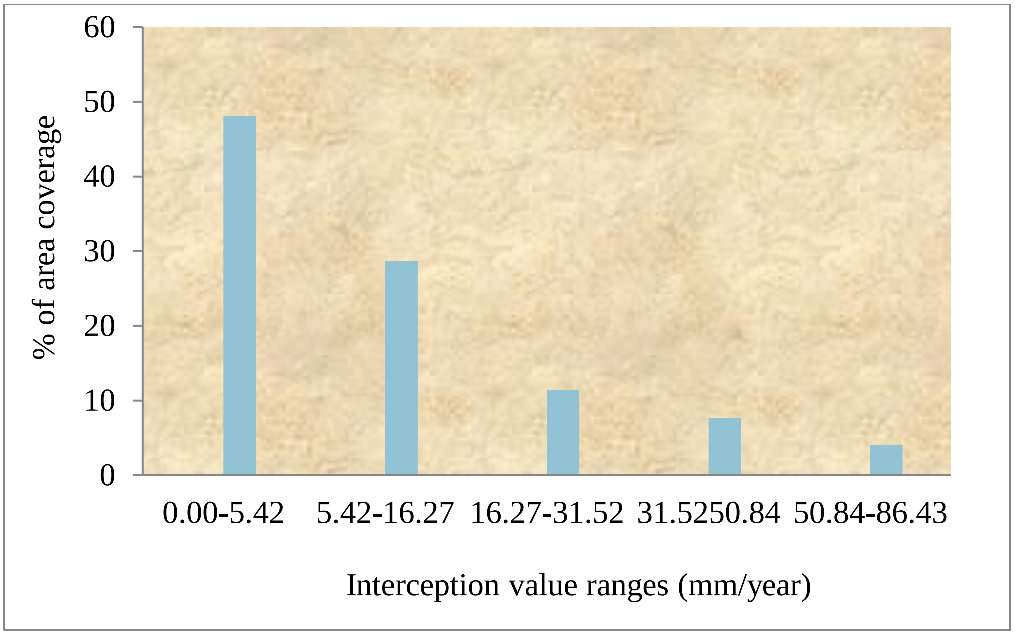

Figure 19: The mean annual interception value ranges and its % of area coverage.

4.2.4. Soil moisture of TSA sub-basin

The soil moisture data was downloaded in layers such as, layer 1 (0-10cm), layer 2 (10-40cm), layer 3 (40-100cm), and the last layer 4 (100-200cm). Those four layers were averaged to calculate the net soil moisture status of the Tekeze-Atbara-Setite sub-basin. The spatial map of the soil moisture of the Tekeze-Atbara-Setite sub-basin ranges from 12.04 mm near the river's source (Ethiopia) to about 1.74 mm near its confluence with the main Nile and some part of the south eastern area of the sub-basin. The average soil moisture spatial map of the Tekeze-Atbara-Setite sub-basin is revealed in Figure 23. In this study, the spatial distribution of mean soil

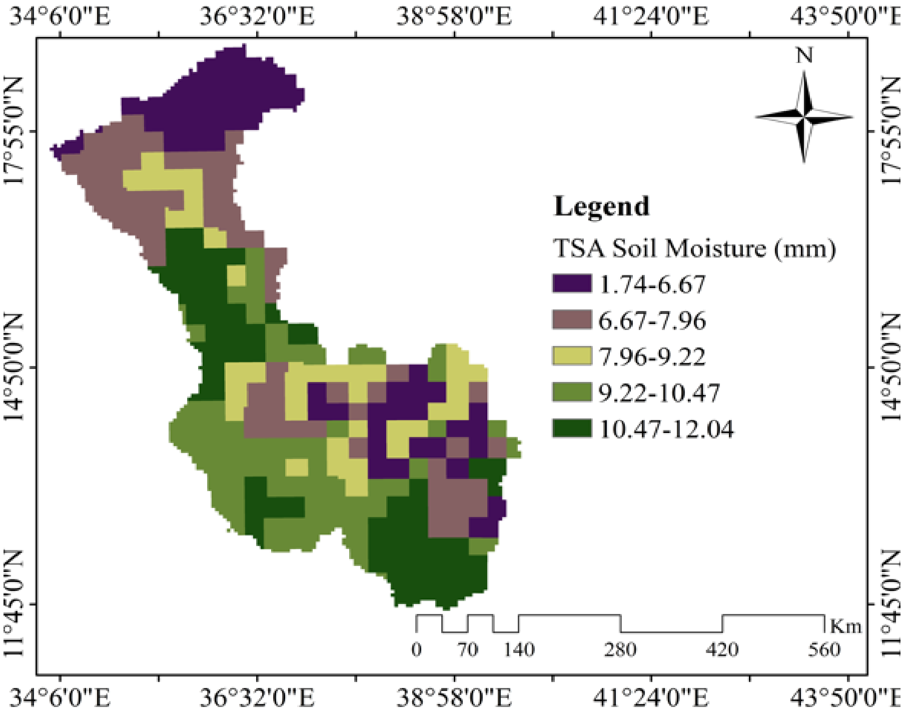

Figure 20: The soil moisture spatial map of the Tekeze-Atbara-Setite sub-basin.

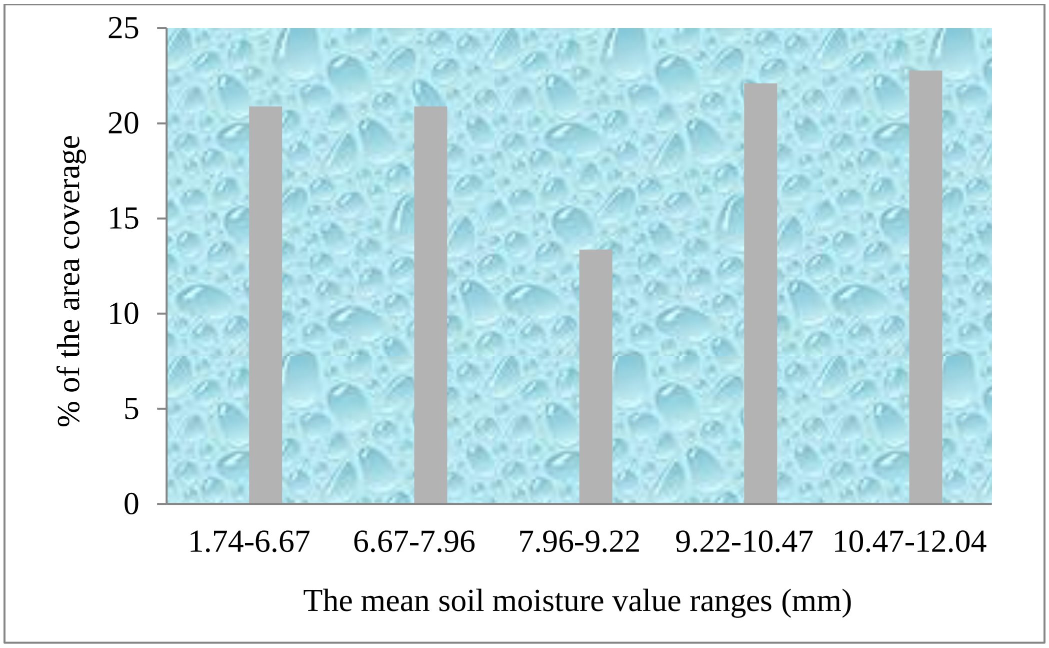

Figure 21: The soil moisture spatial map ranges and its % of area coverage.

moisture status/values and its area coverage are 1.74-6.67mm (20.89%), 6.67-7.96mm (20.88%), 7.96-9.22mm (13.37%), 9.22-10.47mm (22.1%), and 10.47-12.04mm (22.76%), respectively (Figure 24).

4.3. Water Resources Assessment over the BAS sub-basin

4.3.1. Rainfall of BAS sub-basin

The mean annual rainfall in the Baro-Akobo-Sobat (BAS) sub-basin ranges between 112.8 to 2184.3 mm per year from northern to southern part of the sub-basin. As shown in Figure 25, the spatial variability of the average annual precipitation in the BAS basin for the periods of the last 40 years. Significant spatial rainfall variability is evident in the BAS sub-basin where, 45.5% of the basin area received rainfall between 722.1 and 1038.9 mm per year. Less than 429.6 mm per year of rain fall covers 20.7% of the sub-basin's area (Figure 26). The BAS sub-basin receives 1038.9 to 1477.5 mm per year and greater than 1477.5 mm per year. As it is seen clearly in the map, most of the rainfall falls in the southern parts of the basin in the Ethiopian highlands and the central and north-eastern part of the basin produces medium to little amount of rainfall.

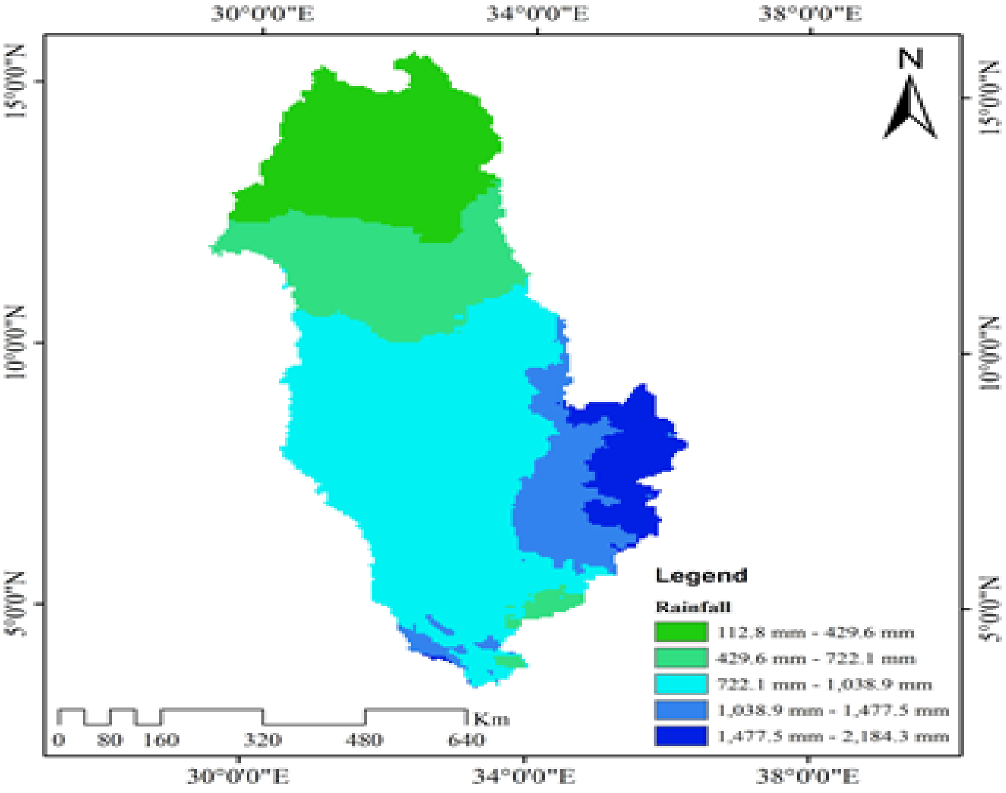

Figure 22: The mean annual rainfall spatial map of the Baro-Akobo-Sobat sub-basin.

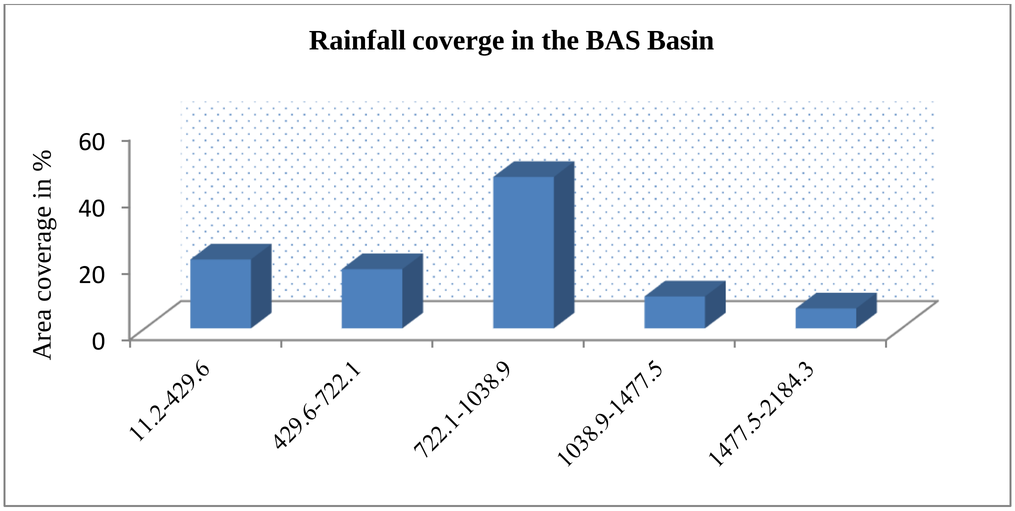

Figure 23: Mean annual rainfall value ranges and its % area coverage of the BAS.

4.3.2. Actual evapotranspiration of BAS sub-basin

The mean actual evapotranspiration (ETa) over the BAS sub-basin ranges from 0.67 mm to 362.6 mm per annum. The basin have the actual evapotranspiration value ranges and area coverage's of 0.67 to 60.3 mm/year (16%), 60.3 to 107.1 mm/year (15.1%), 107.1 to145.5 mm/year (31%), 145.5 to 184 mm/year (28.2%) and 184 to 362.6 mm/year (9.7%), respectively (Figure 27 and 28).

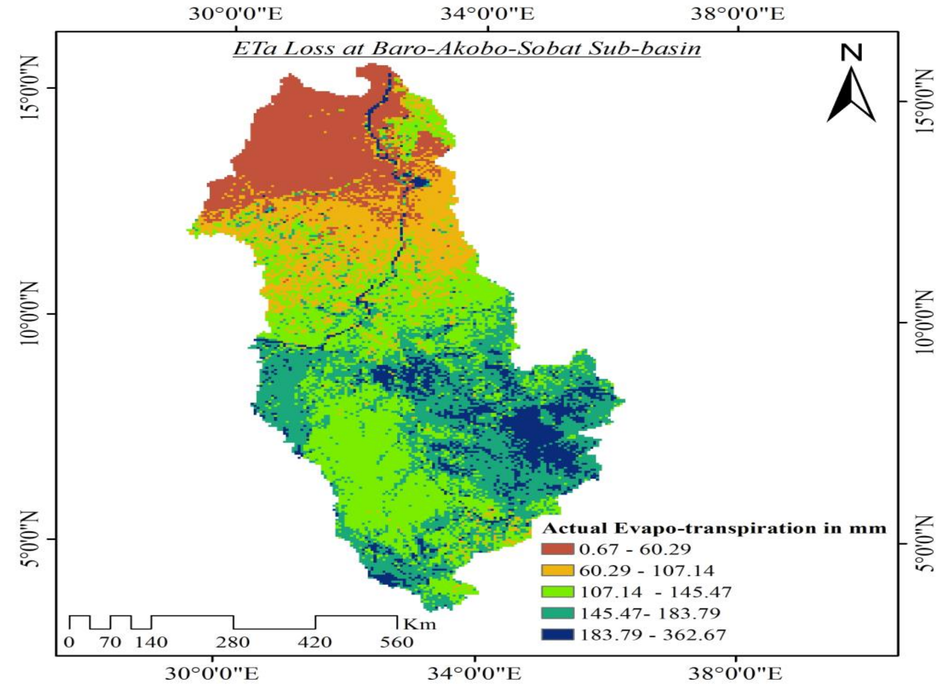

Figure 24: The mean actual evapotranspiration spatial map of the BAS sub-basin.

The basin ETa have spatial distribution similar to the rainfall, ETa in the southern part of the basin is significantly higher than the dryer northern part. The value of the ETa is higher in the upper basin part and reduced to downstream area except the water bodies where water bodies the ETa far exceeds the rainfall value. The Evapotranspiration loss is high in the upstream due high water availability for evaporation and presence of vegetation.

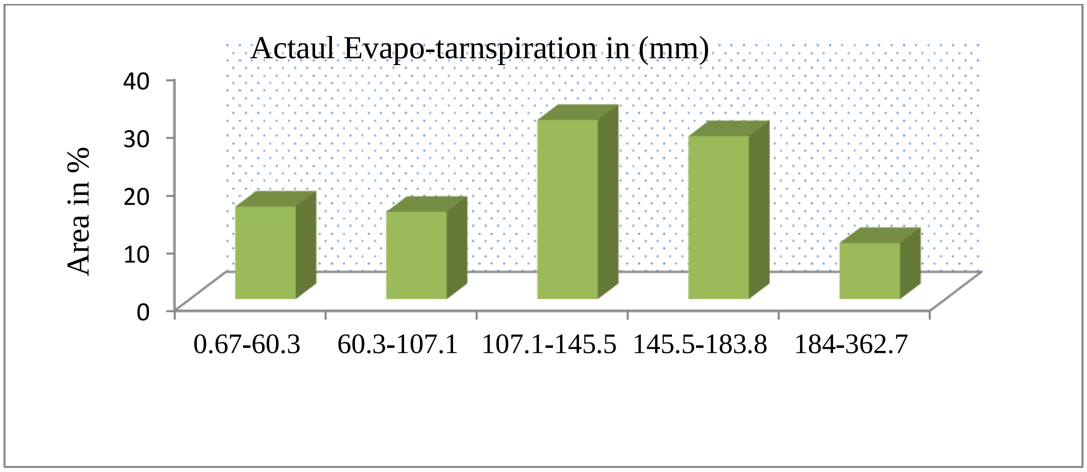

Figure 25: The mean evapotranspiration value ranges and its % of area coverage.

4.3.3. Interception of BAS sub-basin

The distribution of interception loss roughly corresponds to that of evapotranspiration; more interception loss occurs upstream in Ethiopia's highlands and less in the sub-basin's downstream

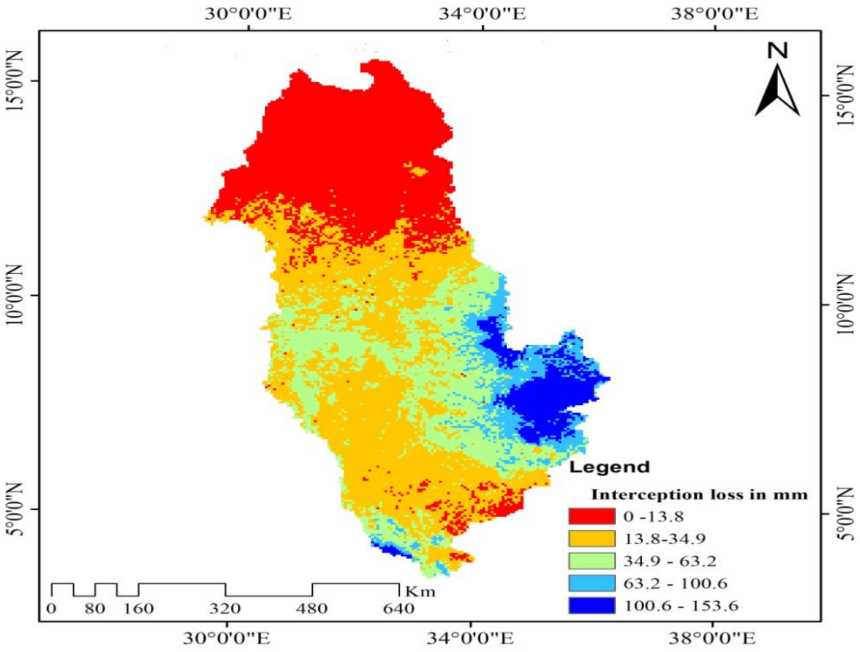

Figure 26: The mean annual interception spatial raster map of the BAS sub-basin.

region. Over the sub-basin, the interception loss varies from 0.0 to 153.6 mm per year (Figure 29). In the result, the spatial distribution of mean annual interception loss value was reclassified into five ranges in mm depth such as 0.0-13.8 mm, 13.8-34.9 mm, 34.9-63.2 mm, 63.2-100.6 mm, 100.6-153.6 mm (Figure 29).

4.3.4. Soil moisture of BAS sub-basin

The soil moisture of the BAS sub-basin ranges from 12.3 mm per year in the upper (Ethiopian highland) and middle part of the basin and to about 1.8 mm per year near its confluence in Sudan. The average soil moisture spatial map of the BAS sub-basin is revealed below in Figure 30.

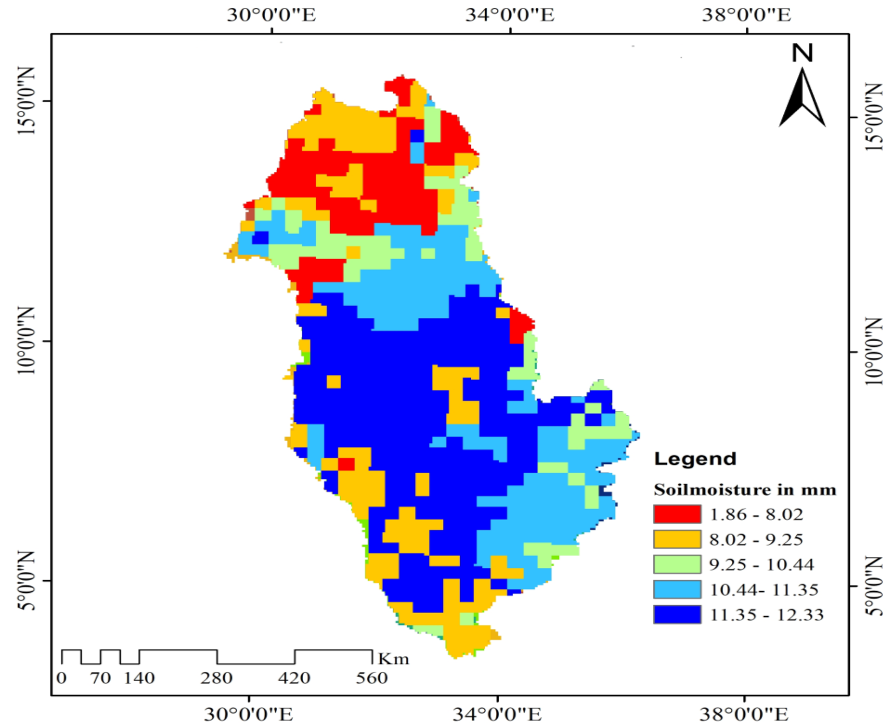

Figure 27: The soil moisture spatial raster map of the BAS sub-basin.

4.4. Water Resources Assessment over the main Nile sub-basin

4.4.1. Rainfall of the main Nile sub-basin

As mentioned earlier the Main Nile sub-basin is considered to be the least sub-basin in terms of the rainfall component with an average of only 60 mm per year when calculating the rainfall average over the total area. When compared to the Blue Nile annual mean of more than 1000 it is considered very low. Although it covers more than 44% of the total area of the Eastern Nile

Basin, but its rainfall representation is less than 6% of the total rainfall that falls into the Eastern Nile basin. The upstream of the sub-basin has higher records of rainfall of 375 - 415 mm per year in Gedaref and Al Obeyed regions respectively, while in Khartoum it is about 120 mm per year (Figure 31). The region between the Nile Confluence and the Delta is mostly semi-arid and arid region, where the Sahara desert covers most of the area with almost no rainfall throughout the year. On the contrary, The Nile Delta region is considered to be identified with the Mediterranean climate which is mild, wet winters, and warm to hot, dry summers, hence the rainfall tends to record between 80-140 mm per year along the Nile Delta.

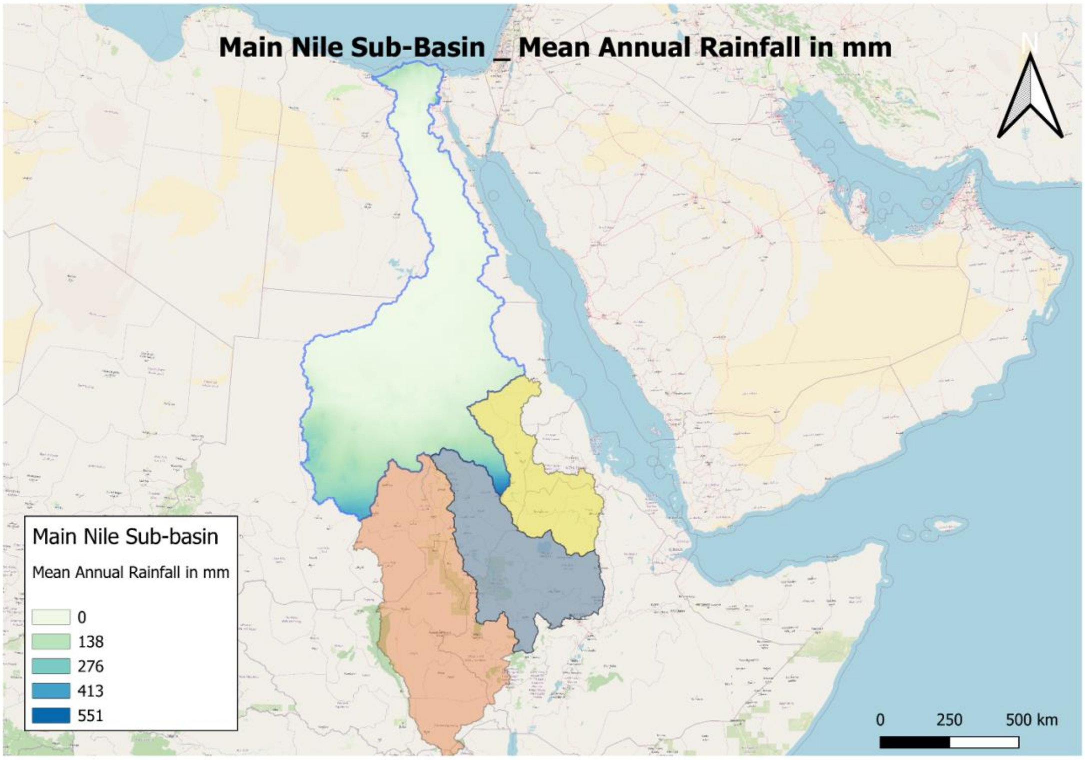

Figure 28: Main Nile Sub-basin mean annual rainfall in mm (1983-2023).

4.4.2. Actual evapotranspiration of the Main Nile sub-basin

As can be seen from the map below (Figure 32), the Main Nile Sub-basin records the highest evapotranspiration record among the other three sub-basins, although the average may be low, but the highest record is obtained from the Main Nile sub-basin. The highest value is 411 mm per year, while the lowest is 0. It can been seen the evapotranspiration map is closely linked with the water bodies in the Main Nile Sub-basin, in addition to the large irrigation schemes in Sudan. For example, the highest record of evapotranspiration (above 400 mm per year) is recorded in the high Aswan dam reservoir and the Merwoe Dam. Considering the actual evapotranspiration equation into account, the we can understand the increase of the evapotranspiration values along the main Nile until reaching the Delta where water is spread out before reaching the Mediterranean Sea. Where the evaporation ranges between 100-200 mm per year. Also the few lakes in the western bank of the main Nile near the Delta, Lake Qarun and Wadi Alrayan show high values of evapotranspiration of nearly 300 mm per year. The evapotranspiration map of the Main Nile Sub-basin illustrates location where water source is being evaporated and not benefited from, hence can act as a guidance to better water management intervention to minimize this loss.

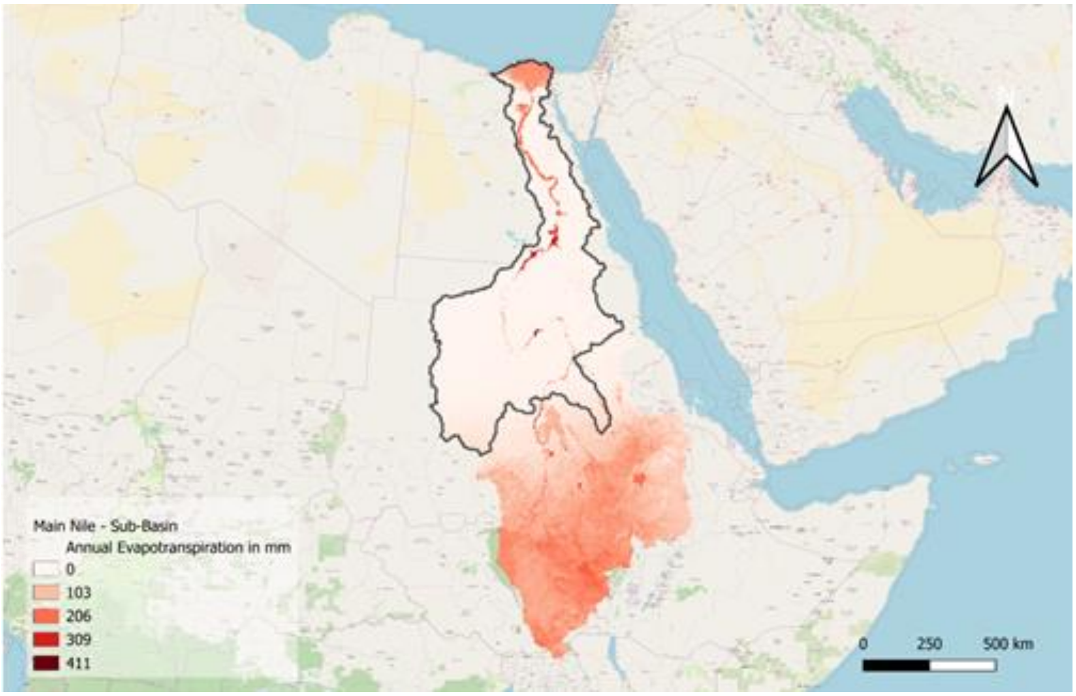

Figure 29: Main Nile annual evapotranspiration in mm/year.

4.4.3. Main Nile Sub-basin interception:

The Main Nile sub-basin is considered to have low records of interception due to its climatic area. As stated in the earlier sections that Main Nile sub-basin mainly consists of semi-arid and arid region, leading to low vegetation coverage area. The two locations that show significant increment in interception are the Delta region and the most upstream point of the Sub-basin near Gedaref city; while the rest of the sub-basin is almost zero (Figure 33).

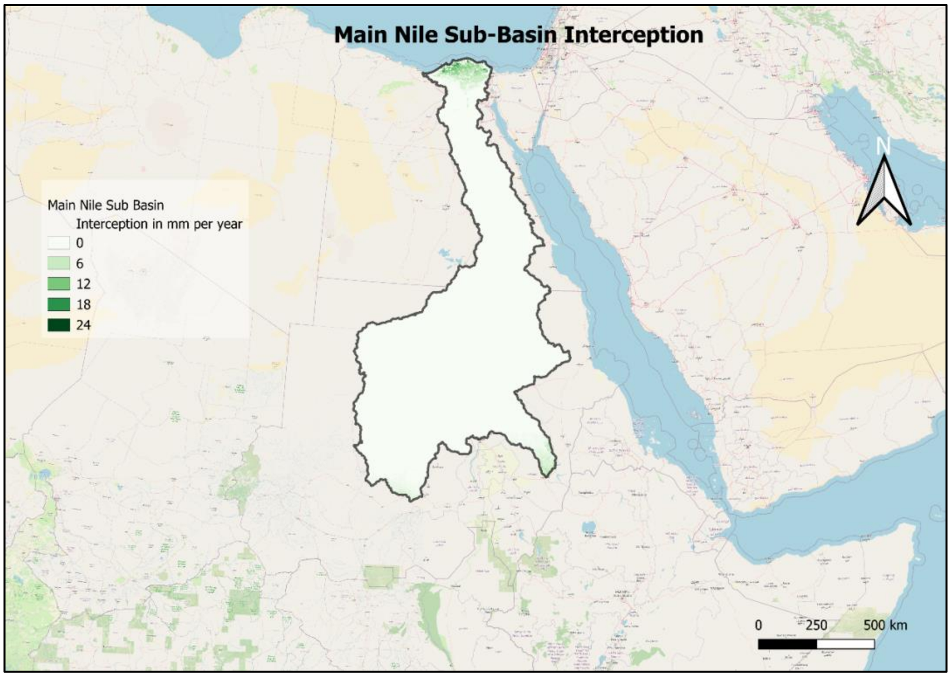

Figure 30: Main Nile sub-basin interception in mm per year.

The second map below on Figure 34 shows clearly the contribution of the Main Nile sub-basin within the entire Eastern Nile basin is almost negligible.

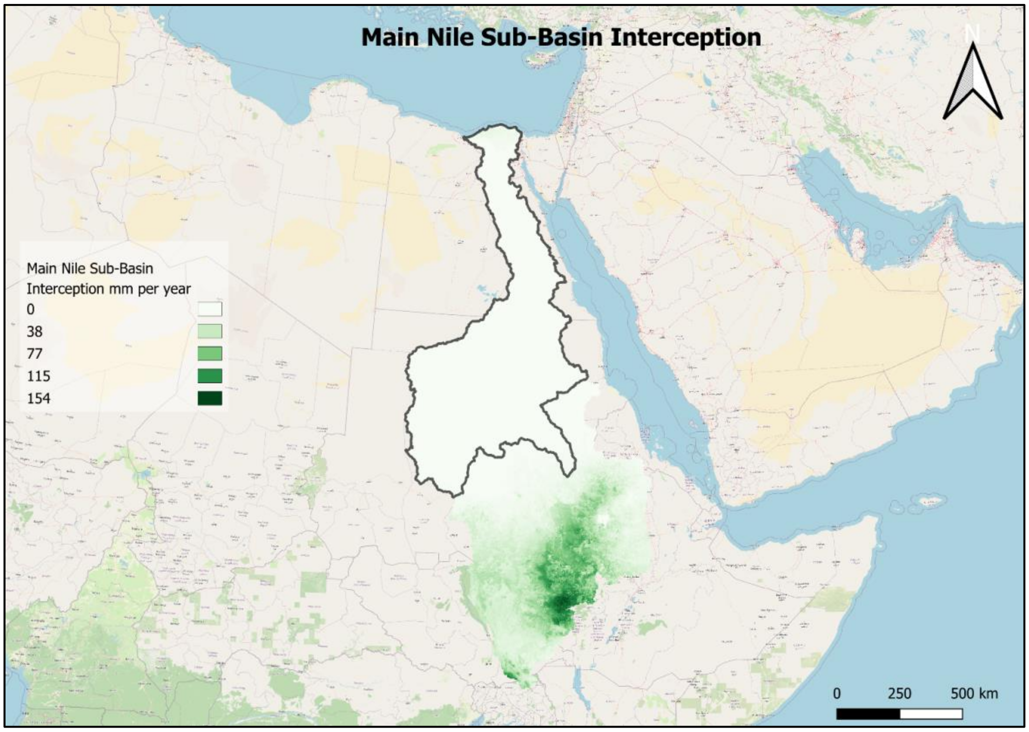

Figure 31: Eastern Nile basin Interception map in mm per year.

4.4.4. Main Nile sub-basin soil moisture

The soil moisture map of the Main Nile follows a similar pattern like the interception map, which scientifically can be adhered to soil moisture availability, is correlated to vegetation presence. Most of the soil moisture content is present in the upstream part of the sub-basin, while in the middle towards the end it is less (Figure 35). The region between Gedaref and Kassala cities, present the highest value of soil moisture content, ranging between 10-12 mm.

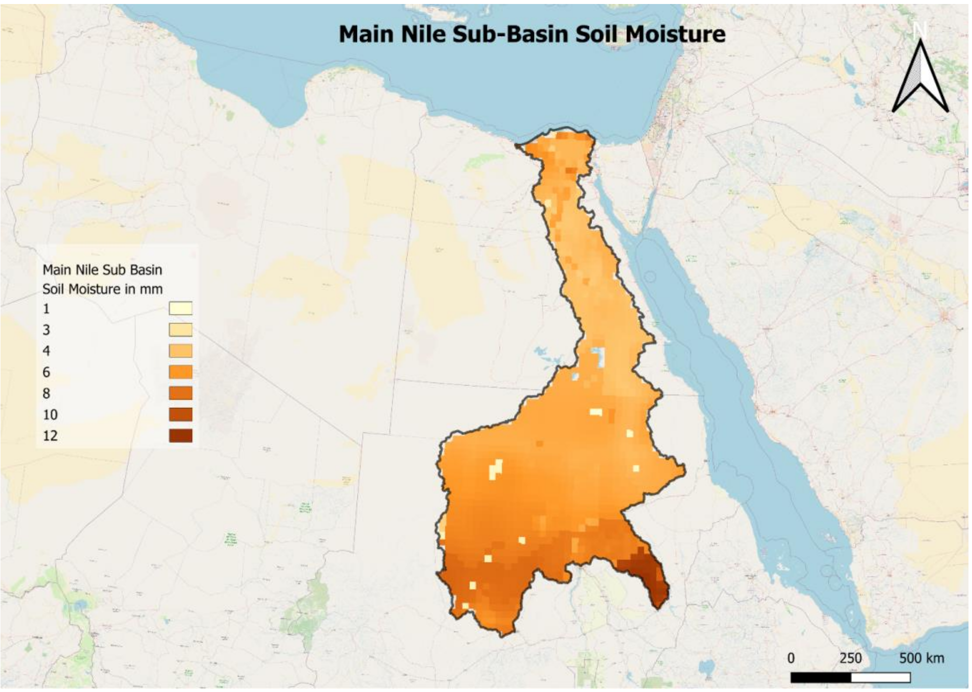

Figure 32 Main Nile sub-basin soil moisture map.

4.5. Surface water resource of the Eastern Nile sub-basins

Runoff can be defined as water from rain and outdoor water use that drains from the surface that doesn’t absorb into the ground. As discussed in the methodology part, the surface water resource potential of the EN sub-basins were estimated following the water balance methods or principles using the ArcGIS spatial analysis tool (raster calculator). As indicated in equation (1) above the surface water potential of the EN sub-basins were estimated by subtracting the raster value of each parameter (Rainfall, actual evapotranspiration, interception, and soil moisture). The surface water resources potential of the EN sub-basins were discussed in detailed below.

i) Runoff coefficient

The runoff coefficient (C) is a dimensionless coefficient relating the amount of runoff to the amount of precipitation received. It is a larger value for areas with low infiltration and high runoff (pavement, steep gradient), and lower for permeable, well vegetated areas (forest, flat land). The runoff coefficient (C) represents the integrated effect of the catchment losses and hence depends upon the nature of the surface, surface slope and rainfall intensity.

$$\mathrm{C} = \text{coefficient of runoff} = \frac{\text{Runoff}}{\text{Rainfall}} \qquad 2$$

4.5.1. Surface runoff of the BN sub-basin

The runoff in the Blue Nile sub-basin was quantified using GIS with the statistical analysis of water balance such as rainfall, actual evapotranspiration, interception, and soil moisture. The BN sub-basin received a huge annual rainfall during a long rainy season and with the impact of high rainfall, the annual runoff generation is also high. The range of runoff is from 10.2–50.8 million cubic meters per year (Mm^3 per year). The Ethiopia highland is the region with high runoff of 50.8 Mm^3 per year. The mean annual runoff the BN sub-basin is ranging from 30.6 Mm^3 per year at the Ethiopia-Sudan border and 40.7 Mm^3 per year in upper basin part. The annual runoff at Khartoum decreases to 10.2 Mm^3 per year due to obstruction for different uses and also the land/use land cover nature of the area. The surface water resource (runoff) spatial map of the BN sub-basin was revealed in Figure 36 and 37.

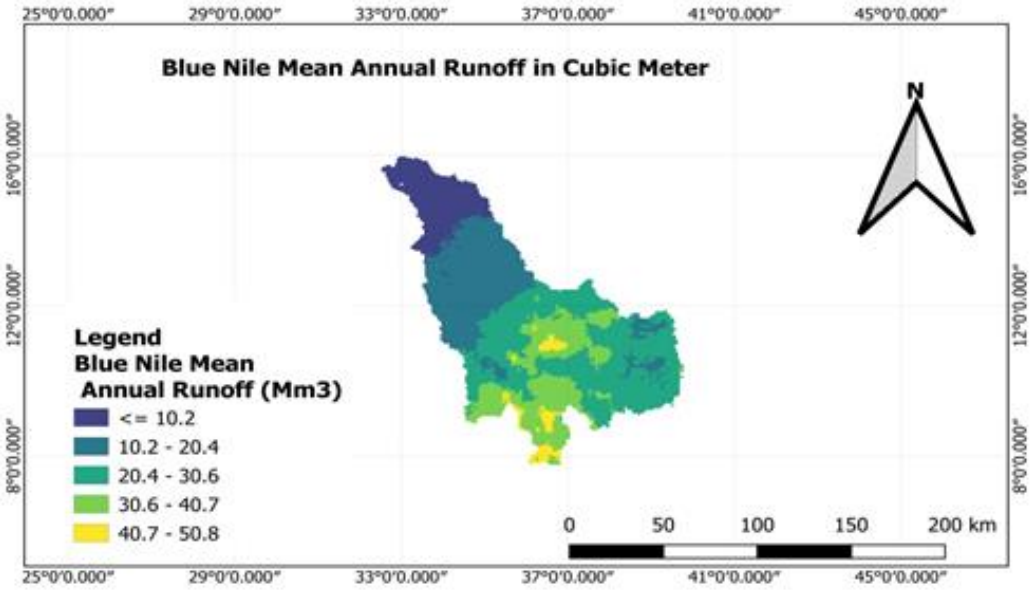

Figure 33: The mean annual runoff (Mm^3) spatial raster map of the BN sub-basin.

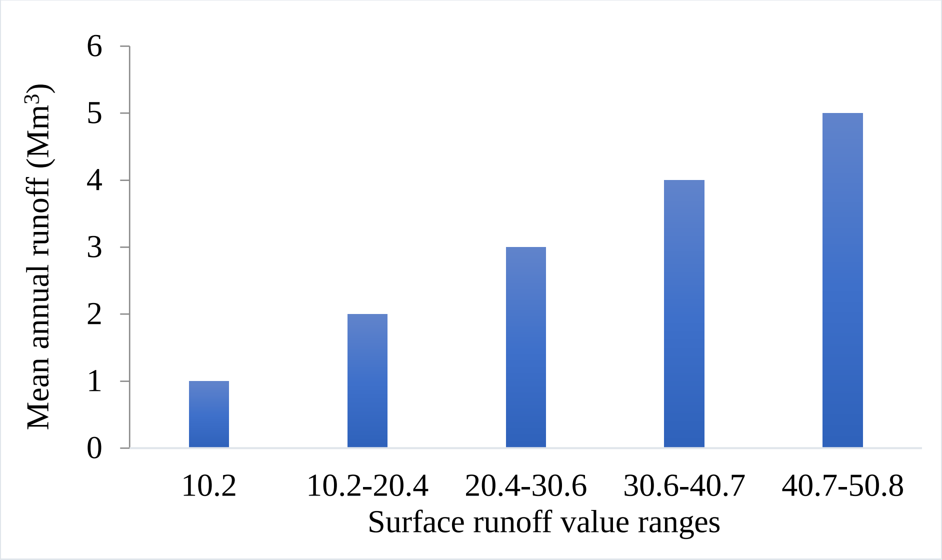

Figure 34: The mean annual runoff ranges and its value in Mm^3.

4.5.1.1. Runoff coefficient of the BN sub-basin

The runoff coefficient value always is considered to be constant from 0 to 1, although the values may vary according to intensity, temporal and spatial distribution of precipitation events, humidity conditions, soil and land use. As shown in Figure 37 and 38 the spatial map ranges of the BN sub-basin varies from 0.00 to 0.99. Its high in regions around the Lake Tana with an average range between 0.89–0.99, an average of about 0.29 is near the Gezira scheme in Sudan, the value is low in Gezira due to the land use/ cover of the area.

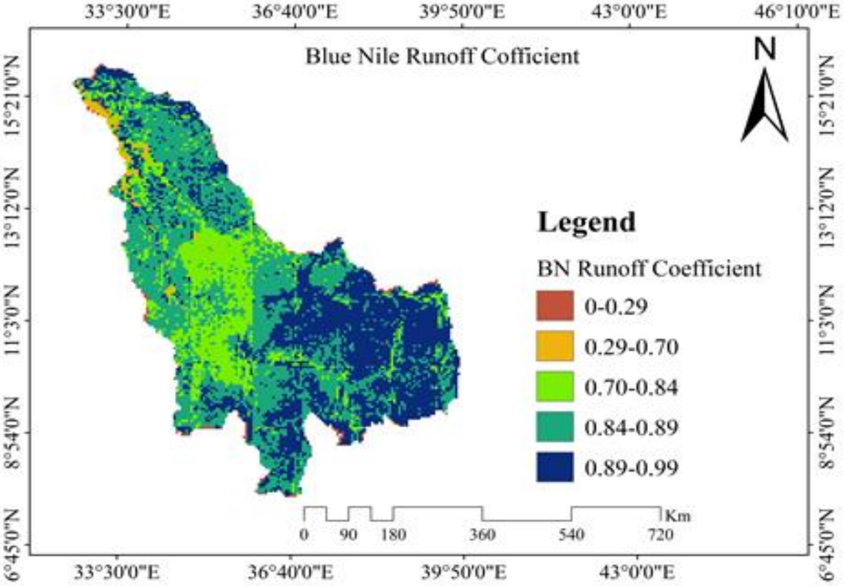

Figure 35: The runoff coefficient spatial raster map of the Blue Nile sub-basin.

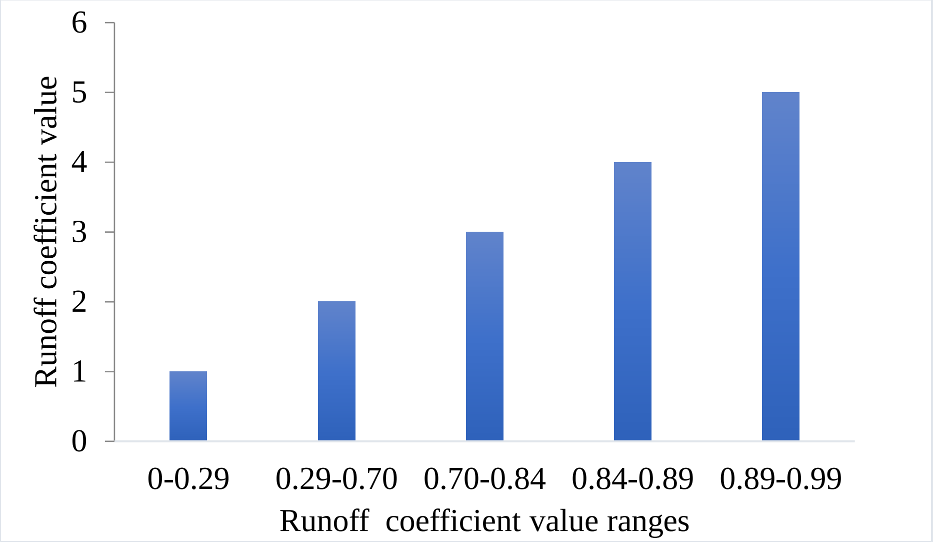

Figure 36: The runoff coefficient of Blue Nile sub-basin value and ranges.

4.5.2. Surface runoff of the TSA sub-basin

The mean annual surface runoff value of the Tekeze-Atbara-Setite sub-basin spatial map ranges from 0.04 (million cubic meters Mm^3) near the river's source (Ethiopia) to about 44 Mm^3 near its confluence with the main Nile. Most of the Ethiopian highlands have higher surface runoff potential areas (specifically southwester parts of the TSA sub-basins). The northern parts of the

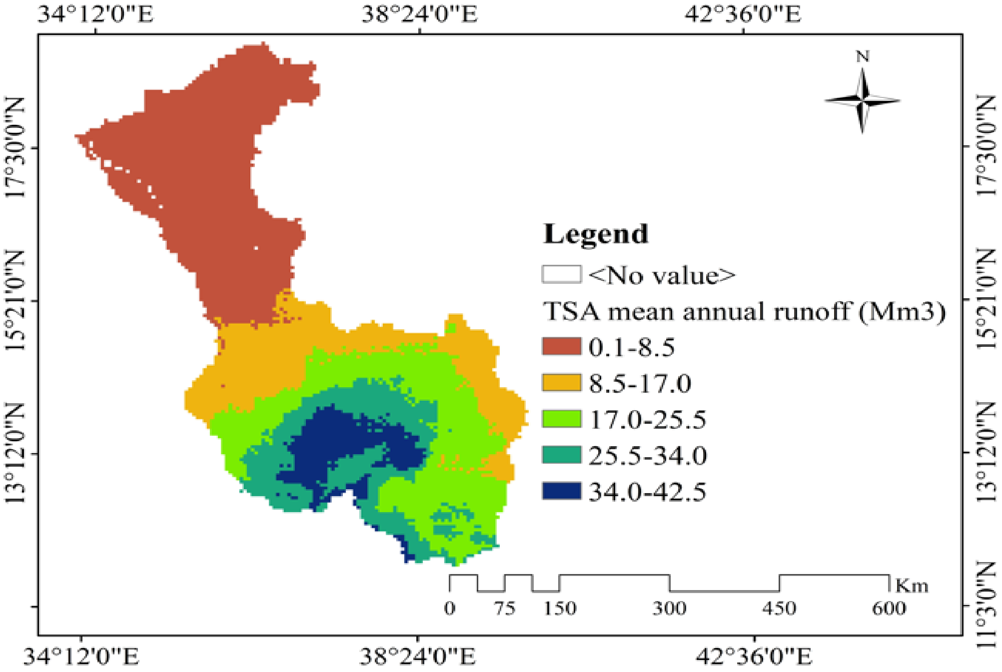

Figure 37: The mean annual runoff (Mm^3) spatial map of the TSA sub-basin.

sub-basin have a lower runoff potential area. This is due to the fact that most of the TSA sub-basin in Sudan has a low rainfall value, and the only source of water is from the Tekeze Atbara River as a base flow. The mean annual surface runoff potential spatial map of the TSA sub-basin is revealed in Figure 39. In this study, the mean annual spatial value of surface runoff and its percentage area coverage are described as 0.1-8.5Mm^3/year (36.67%), 8.5-17.0 Mm^3/year (18.41%), 17.0-25.5Mm^3/year (21.48%), 25.5-34.0Mm^3/year (14.86%), and 34.0-42.5Mm^3/year (8.58%), respectively (Table 4 and Figure 40). Therefore, the mean annual surface runoff potential of each pixel of TSA sub-basin is ranges from 0.1 to 42.5Mm^3/year.

Table 4: The mean annual runoff spatial value and its % of area coverage**.**

Mean annual runoff (Mm^3) spatial ranges	Area (km^2)	% of the area coverage
0.1-8.5	74600	36.67
8.5-17.0	37450	18.41
17.0-25.5	43700	21.48
25.5-34.0	30225	14.86
34.0-42.5	17450	8.58
Total	203,425	100

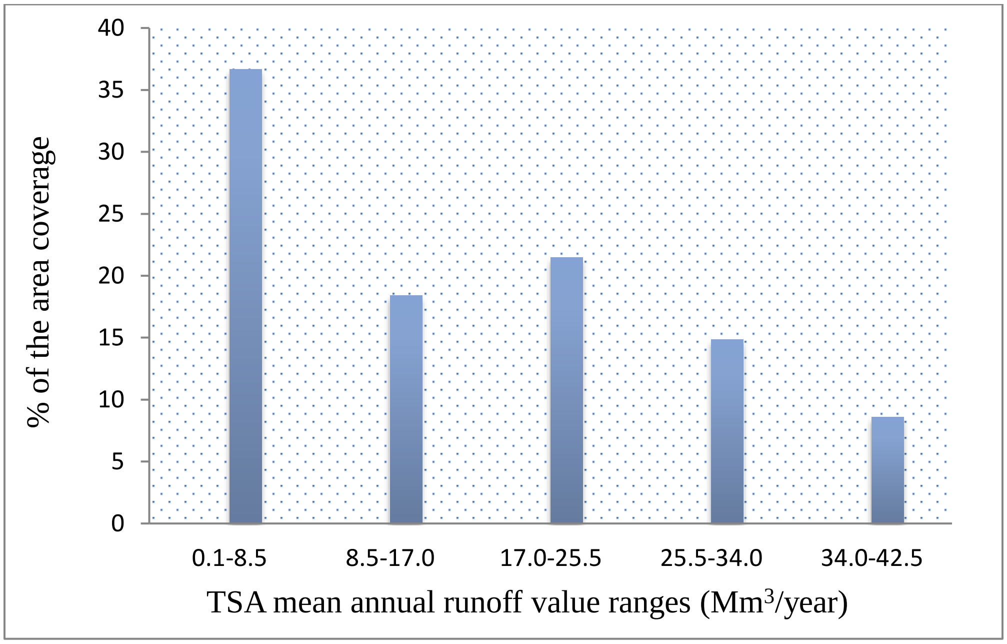

Figure 38: The mean annual runoff value ranges and its % of area coverage.

4.5.2.1. Runoff coefficient of the TSA sub-basin

The runoff of coefficient of the Tekeze-Atbara-Setite sub-basin ranges from 0.03 to 0.99. The runoff coefficient near the river's source (Ethiopia) and within the main Nile is relatively higher. The south western parts of the TSA sub-basin at Ethiopia have a lower runoff coefficient because the area has a sandy loam soil textural class and the area land use land coverage is much vegetated. But, the southeastern parts of the TSA sub-basin at Ethiopia have relatively higher runoff coefficient because the area has steep slopes and covered by bare land. The northwestern parts of the TSA sub-basin at Sudan have a relatively a higher runoff coefficient because of the area is covered by bare land and has sandy loam soil textural classes. The central parts of the sub-basin at Sudan has relatively lower runoff coefficient, this is due to the area is covered by vegetated land and the area has a gentle slope.

The runoff coefficient value ranges of the Tekeze-Atbara-Setite sub-basin are revealed in Figure 41. In this study, the spatial distribution of runoff coefficient value ranges and its percentage of area coverage indicated as 0.03-0.43 (0.99%), 0.43-0.70 (1.7%), 0.70-0.84 (6.62%), 0.84-0.90 (40.4%), and 0.90-0.99 (50.32%), respectively (Figure 42).

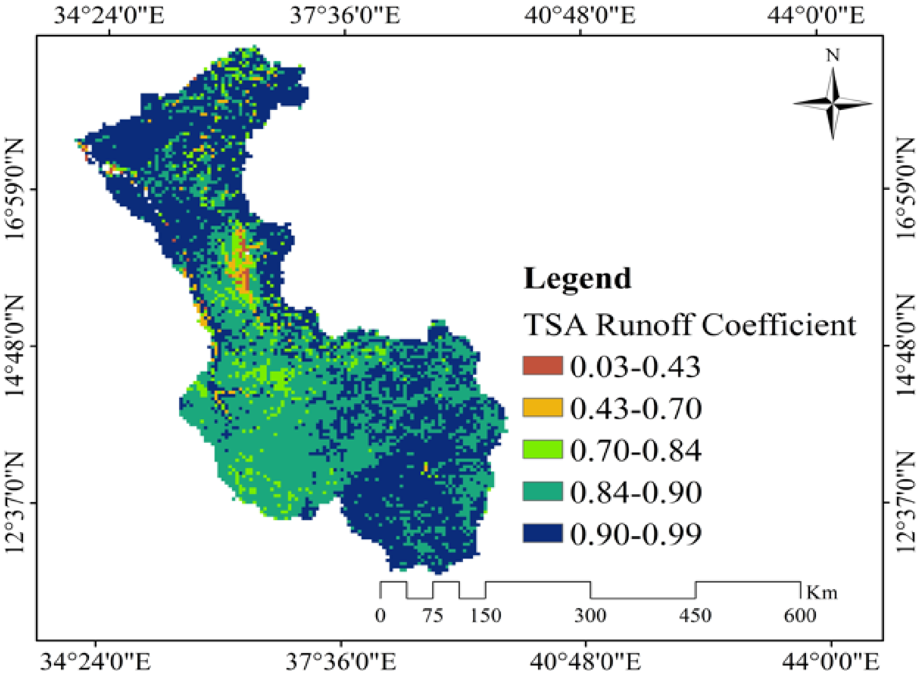

Figure 39: The runoff coefficient spatial value map of the TSA sub-basin.

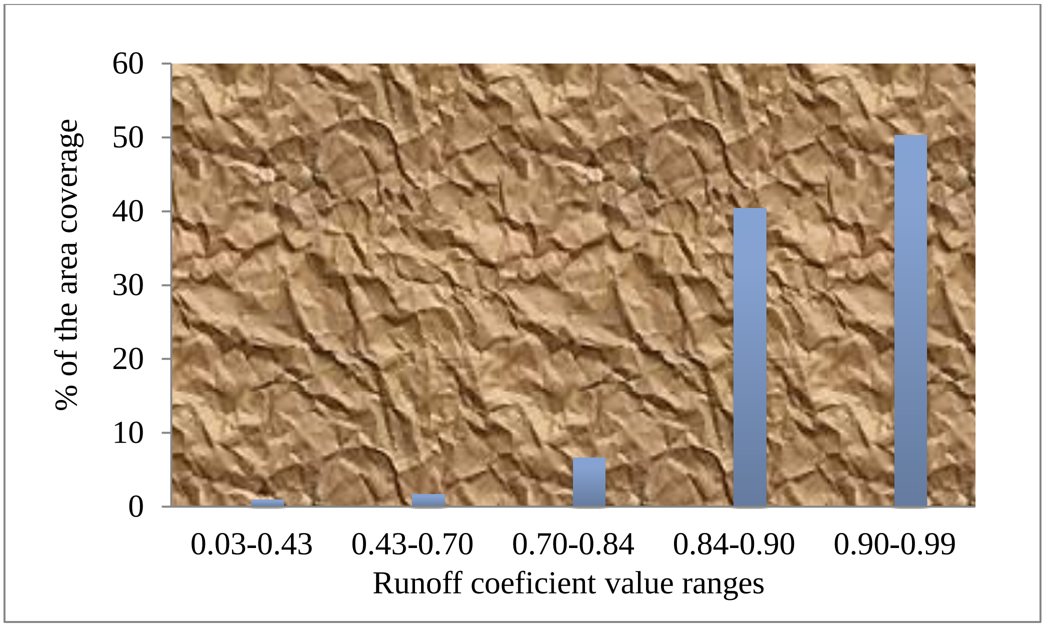

Figure 40: The runoff coefficient value ranges and its % of area coverage.

4.5.3. Surface runoff of the BAS sub-basin

The part of precipitation (rainfall, snowmelt, or irrigation) that flows over the surface of the land without being absorbed by the earth is referred to as runoff. This flow finally makes its way into rivers, lakes, and oceans. Runoff is a crucial part of the water cycle and has significant implications for both natural ecosystems and human activities. As shown in Figure 43, the surface runoff spatial map of the BAS sub-basin is ranging from 0.015 Mm^3/year to 49.4

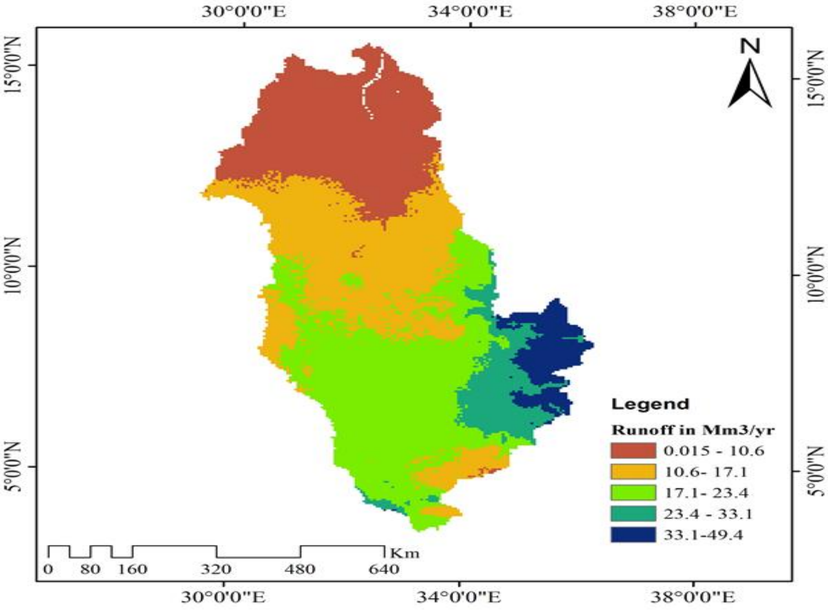

Figure 41: The mean annual runoff (Mm^3/year) spatial value map of the BAS.

Mm^3/year. The northern parts of the BAS sub-basin have a low runoff potential and the southern parts of the sub-basin has relatively high runoff potentials. The runoff value and its area coverage map are shown below in Figure 44.

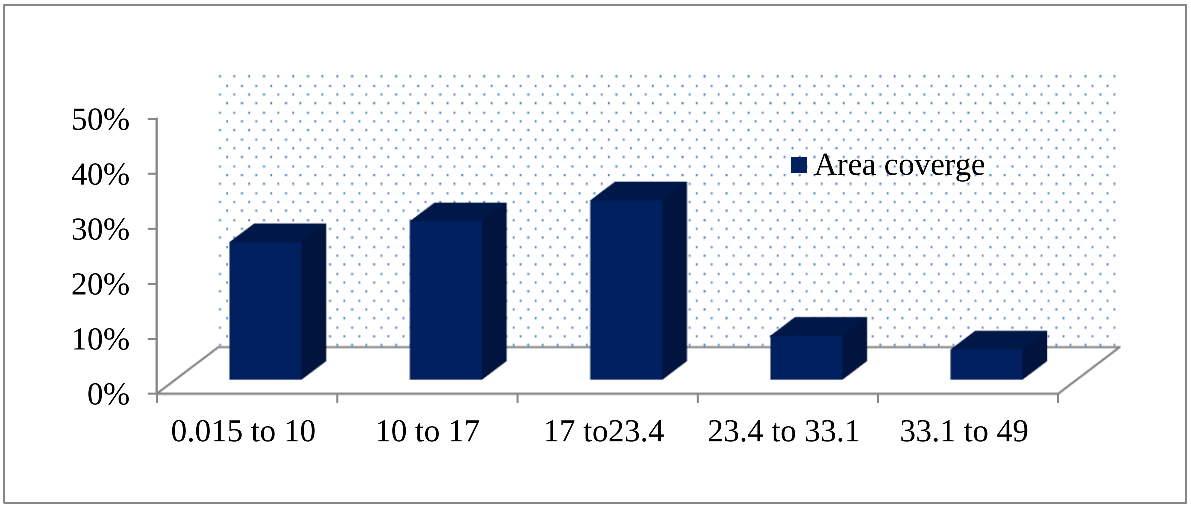

Figure 42: The mean annual runoff spatial coverage of area.

4.5.3.1. Runoff coefficient of the BAS sub-basin

Higher runoff coefficients indicate higher surface runoff generation in the region. The runoff of coefficient of the BAS sub-basin ranges from 0.0 to 0.9 (Figure 45). The runoff coefficient is larger than 0.8 in more than half of the sub-basin area. Less than 1% of the sub-basin area has a runoff coefficient of less than 0.5. According to the spatial map of the coefficient, both the northern and southern tip of the basin generates the most runoff. The middle part of the sub-basin have lower coefficient of runoff as the area is highly cover with vegetation. The Northern parts of the BAS sub-basin at confluence area relatively have a higher runoff coefficient because the area is bare land, land use type. Similarly, the south parts of the BAS sub-basin also have relatively higher runoff coefficient because the area has steep slopes and higher rainfall amount. The outlet parts of the BSA sub-basin at Sudan have a relatively a lower runoff coefficient because of the area has a gentle slope and covered by shrub. The runoff coefficient spatial map ranges of the BAS sub-basin were revealed in (Figure 45).

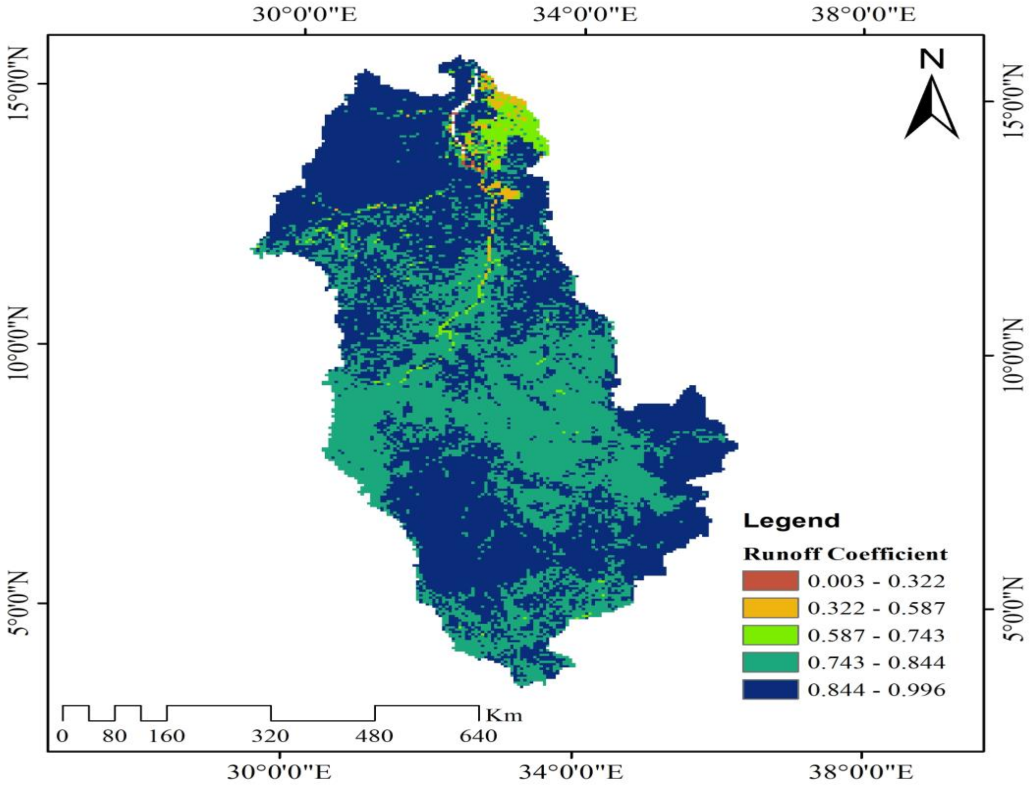

Figure 43: The runoff coefficient spatial map value of the BAS sub-basin.

4.5.4. Surface runoff of the Main Nile sub-basin

When mentioning the water balance concept we recall the general equation of input – output – change in storage = zero, which has been reflected in equation 1 stated earlier. This equation does not necessarily give the result in a positive runoff, which is the case of the Main Nile sub-basin. Since there is limited amount of rainfall in the Main Nile sub-basin with high record of evapotranspiration, in which these two represent that largest influential components in the water balance equation, this will result in negative result (Figure 46). We have also neglected the change of storage component in our computation due to unavailable data, but we can also state that, the water cycle of dam or reservoir is closed annually meaning in a yearly computation the change in storage would be zero. Therefore, looking at the map below for the Main Nile sub-basin we understand that more water is going out the sub-basin in terms of evapotranspiration rather than going in. One point to have into consideration is that, these are (spatial) satellite data, but if we include a hydrological model to route the runoff being generated from the upstream part of the Eastern Nile basin, these results would be give us a more accurate value in terms of runoff computation.

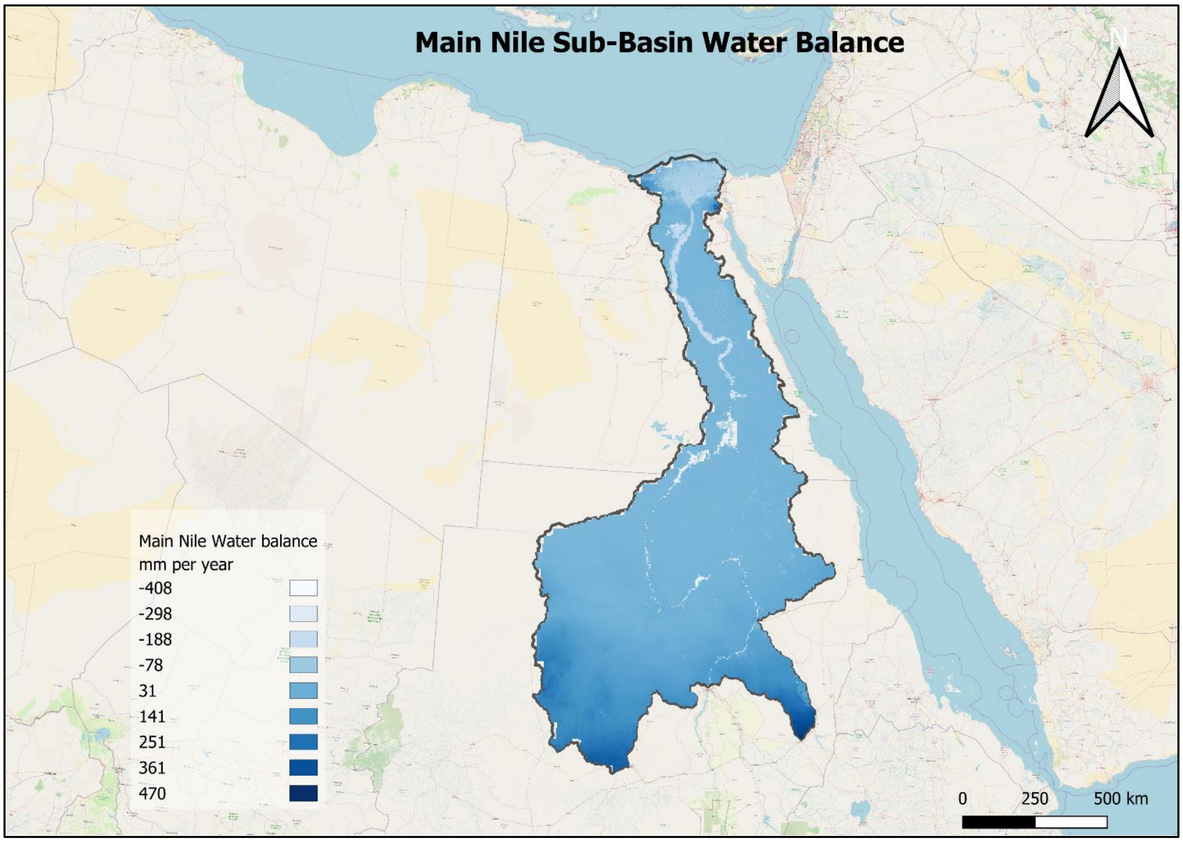

Figure 44: The Main Nile sub-basin water balance.

4.6. Surface water resource of the EN basin

The surface runoff potential spatial map of the eastern Nile basin is generated based on the four parameters (rainfall, actual evapotranspiration, interception, and soil moisture) raster data. The delineated map of the EN basin revealed that its value ranges from 0.7 Mm^3 per year to 50.4 Mm^3 per year (Figure 47). The northern parts of the EN basin have a runoff value of negative this is because the rainfall value in the main Nile sub-basin is very low and the actual evapotranspiration value is very high compared to the southern parts of the basin (especially in Ethiopian highlands). The surface runoff value of the EN basin in the Ethiopian highlands is very high compared to the northern parts, near Sudan. In this project, the negative value of the runoff in the main Nile changed to ‘‘no value’’ to use it for further analysis.

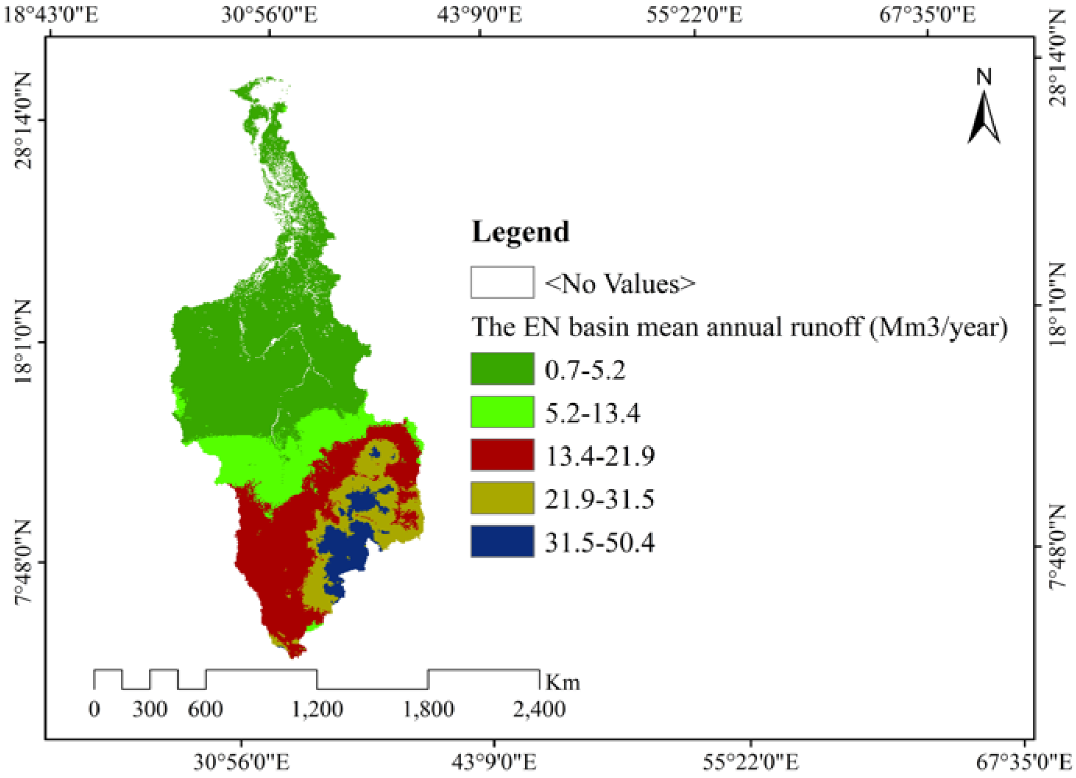

Figure 45: The surface runoff value spatial map value of the EN basin.

5. Limitations

While this study employs a comprehensive geospatial analysis, there are certain limitations to be acknowledged. Firstly, the availability of good data in the EN basin is limited, which presents a challenge in the results and in performing extensive validation. This lack of data could potentially impact the accuracy of the spatial surface runoff map generated. Secondly, as the water balance method (using Arc GIS) is essentially a decision-making method, it only provides an estimated average value and may not guarantee an extremely high level of accuracy. The results of the runoff map (value) should therefore be interpreted with caution, taking into account its inherent limitations.

Lastly, the surface runoff map generated in this study simplifies the characteristics of the area. Although this simplification makes it easier to identify potential surface runoff zones, it might overlook local variations. Consequently, while these results can provide valuable information at a broader scale, they may not be as reliable when assessing runoff potential at a more localized level. Thus, future research should seek to address these limitations by incorporating more detailed spatial and temporal resolution data. The time given for this study was not enough due to much lot of work in the resource process including the need for simultaneous data collection activities with a limited time frame. Furthermore, for this study, only one method was used which was the water balance method, so for future studies, we suggest multiple methods such as ArcSWAT and HEC-HMS for more and clear accuracy of results.

6. Conclusions

The surface runoff of the EN basin and sub-basins has been effectively achieved through the integration of remote sensing, water balance, and GIS methodologies, all implemented remotely without the need for direct physical interaction. The assessment of runoff potential areas involved the consideration of crucial factors including rainfall, actual evapotranspiration, interception, and soil moisture raster maps. The main objective of this study is to assess the surface water availability of the Eastern Nile River basin. The methodology used for this assessment was the water balance (water budget) method. These four components were downloaded from four different data sources, which are CHIRPS, GRACE, FAO WAPOR, and MODIS. The data were downloaded with different spatial and temporal resolutions and the data were resampled into 5km by 5km to get the same resolution using the Q GIS/Arc GIS software.

The spatial map value of each EN sub-basins were generated after the total EN basin map was determined. The generated mean annual runoff value of the BN sub-basin ranges from 10.2 to 50.8 Mm^3/year. The mean annual spatial runoff value of the Tekeze-Atbara-Setite sub-basin ranges from 0.1 Mm^3/year near its confluence with the main Nile to about 44.5 Mm^3/year near the river sources (Ethiopia). The mean annual surface runoff spatial value of the BAS sub-basin ranges from 0.015 Mm^3/year to 49.4 Mm^3/year. The spatial map of each EN sub-basin revealed that most of the northern parts (Sudan, S. Sudan, and Egypt) of the sub-basin have relatively low runoff values compared to the southern parts (Ethiopia) of the sub-basin. Since there is limited amount of rainfall in the Main Nile sub-basin with high record of evapotranspiration, in which these two represent that largest influential components in the water balance equation, this will result in negative result. The mean annual surface runoff spatial value of the main Nile sub-basin ranges from 0.0 Mm^3/year to 12 Mm^3/year. The mean annual surface runoff of the EN basin revealed that its value ranges from 0.7 Mm^3/year to 50.4 Mm^3/year. Most of the northern parts of the EN basin have a runoff value of negative this is because the rainfall value in the main Nile sub-basin is very low and the actual evapotranspiration value is very high compared to the southern parts of the basin (especially the Ethiopian highlands).

The results of this study provide important inputs for all water resources management-related sectors and can be used by the different stakeholders, and policymakers for research, as well as for informing the decision-making process.

7. Recommendations

The following points are recommended as continuation for this study:

- The ENTRO should have data archives to use that data for analysis and to get a fruitful result.
- To enhance the predictive accuracy of future surface water resource assessments, it is recommended that other relevant hydrological factors, not covered in the current study, be included.
- Expand the analysis to focus on smaller regions to understand the localized variations in rainfall patterns and trends, considering factors such as topography, land use, and climate variability.
- Conduct further research to assess the impacts of changing rainfall and evapotranspiration patterns on various sectors, such as agriculture, water resources, environment, and socio-economic conditions, to inform adaptation strategies.
- Encourage collaboration and data sharing among researchers, meteorological agencies, and policymakers within the EN basin to enhance the availability and accessibility of rainfall, actual evapotranspiration, interception, and soil moisture data for research and decision-making purposes.

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