Eastern Nile Water Resources Assessment: Situational Analysis

Theme II: Eastern Nile River Basin Ground Water Assessment

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Executive Summary

This study evaluates groundwater potential in the Eastern Nile Basin, focusing on the Baro-Akobo-Sobat (BAS), Blue Nile, Tekeze-Atbara, and Main Nile sub-basins. Given the increasing importance of groundwater due to unreliable surface water resources and climate change, this research employs multi-criteria decision analysis (MCDA) and GIS techniques to create detailed groundwater suitability maps. Seven thematic layers—geology, soil, slope, lineament density, drainage density, land use/land cover, and rainfall—were analyzed. Findings indicate that 44.93% of the BAS basin has moderate groundwater potential, while 31% exhibits high to very high potential. In the Blue Nile basin, the highest suitability is in the northeastern region, with significant areas in the central and southwestern parts. The groundwater potential map for the Main Nile area shows that approximately 50% of the region is moderate potential, and 33% is high potential. The study underscores the need for sustainable groundwater management practices and suggests further site-specific investigations and additional data layers. The methodologies developed provide a framework for future groundwater assessments in similar regions, aiding sustainable water resource management in the Eastern Nile Basin.

1. Introduction

Groundwater is becoming increasingly important as a global water source. It is crucial to understand how much groundwater is being used compared to the total volume available in order to assess future water availability (Richey et al. 2015). As rainfall and surface water resources become less dependable due to predicted climate change, assessing the spatial distribution and seasonal variation of stored water masses, especially the impacts on groundwater recharge, is becoming increasingly important (Bonsor et al. 2010). The Nile Basin's two most significant groundwater aquifers are the Nubian Sandstone Aquifer System (NSAS) in the Western Desert and the Nile Valley and Delta system, both located in the main Nile sub-basin (Sudan and Egypt) (MacAlister et al. 2013).

The Baro-Akobo-Sobat (BAS) basin is a critical sub-basin of the Eastern Nile, with vast potential for development. However, ensuring sustainable water use requires a thorough understanding of its groundwater resources. This assessment delves into the characteristics and potential of groundwater in the BAS basin, providing valuable insights for informed water management decisions.

The Blue Nile Basin is a crucial part of the Eastern Nile Basin, which encompasses the drainage system of the Blue Nile River. Located in northeastern Africa, the Blue Nile Basin covers a significant portion of the region, spanning across parts of Ethiopia, Sudan, and Eritrea (Kebede, S. 2013). The Blue Nile Basin is situated in the heart of the Horn of Africa, with the majority of its area located within the boundaries of Ethiopia. The basin extends from the Ethiopian Highlands in the east to the Sudan-Ethiopia border in the west, covering an area of approximately 324,500 square kilometers. The physiography of the Blue Nile Basin is characterized by its diverse and undulating terrain. The basin is predominantly defined by the Ethiopian Highlands, a vast mountainous region that serves as the primary source of the Blue Nile River (Melesse, A. M. 2011). Deep gorges, steep escarpments, and rugged peaks characterize these highlands, with elevations ranging from around 1,500 meters to over 4,000 meters above sea level. The central part of the basin is dominated by a series of plateaus, which gradually slope downward towards the west and merge with the lowlands of Sudan. Numerous rivers and tributaries, creating a complex network of valleys and drainage systems. Moving westward, the basin transitions into the lowlands of Sudan, where the Blue Nile River joins the White Nile to form the main stem of the

Nile River, dissect these plateaus. This region is characterized by relatively flat terrain, with occasional hills and isolated mountain ranges.

The groundwater in the Blue Nile basin is found in a variety of aquifer systems, ranging from shallow alluvial aquifers to deeper, confined bedrock aquifers (Kebede, S. 2013). These aquifers are recharged primarily through rainfall and the infiltration of surface water from the Blue Nile and its tributaries (Abtew & Melesse. 2014). The depth and characteristics of the aquifers can vary significantly across the basin, depending on factors such as geology, topography, and land use (Kebede, S. 2013).

The hydrological features of the Blue Nile Basin are equally diverse, with the Blue Nile River and its tributaries playing a crucial role in the region's water resources. The basin experiences a tropical climate, with distinct rainy and dry seasons, which have a significant impact on the river's flow and the overall water availability in the region. Overall, the Blue Nile Basin's unique topography and physiography have shaped the region's landscape, ecosystems, and socio-economic activities, making it a significant and complex component of the larger Eastern Nile Basin (Kebede, S. 2013), (Melesse, A. M. 2011), (Whittington, D., & Guariso.1983).

1.1.Objectives

The objective of this study is to assess and evaluate the groundwater Suitability in the eastern Nile Basin, specifically focusing on the Baro-Akobo-Sobat, Blue Nile, Tekeze-Atbara, and Main Nile Sub-basins. This will be achieved by analyzing groundwater potential zones using remote sensing data with Multi-Criteria Decision Analysis and GIS techniques.

2. Literature review

2.1. Geophysical characteristics

2.1.1. Geology of the Eastern Nile (EN)

The region of the Eastern Nile Basin is characterized by a diverse and complex geologic setting that gives the region different resources. Various tectonic events formed a number of basins and structures in the Eastern Nile region. The geology of Egypt consists of four main geological areas, Nile River valley and its delta, Western Desert, Eastern Desert, and Sinai Peninsula. The Nile Valley broadens gradually toward the north of Egypt and it is bounded by several sedimentary basins and desert sands that have been settled upon fluvial soils. It has three geomorphological units: the young alluvial plain, older alluvial plains, and the limestone plateau (Elbasiouny & Elbehiry, 2019). The Nile Delta is one of the earliest identified deltaic systems in the world and was formed by the sedimentary processes between the upper Miocene and present. The Eastern Desert is a part of the Arabian Nubian Shield (Shield is a collage of Neoproterozoic tectonostratigraphic terrains linked to ophiolite-decorated sutures. The Sinai Peninsula as part of the desert is characterized by very rough mountains formed by igneous and metamorphic rocks in the south, and limestone plateau in the middle and north (Elbasiouny & Elbehiry, 2019).

The geology of Ethiopia is underlain by Precambrian to Recent. These rocks are categorized into; Precambrian rocks, Paleozoic-Mesozoic sedimentary rocks, Cenozoic volcanic rocks and associated sediments. Precambrian metamorphic and associated intrusive igneous rocks make up 25% of the country's landmass. They are exposed in the northern, western, southern and eastern parts of the country and have a fundamentally important tectonic position in that they occupy the interface between the Mozambique Belt in the south and the Arabian-Nubian Shield to the north. They are dominantly north-trending linear belts of low-grade volcano-sedimentary rocks and mafic-ultramafic rocks, sandwiched between medium-to high-grade gneisses and migmatites (Alemu, 2019). A thick succession of Palaeo-Mesozoic sediments that covers 25% of the country's landmass are represented by three distinct sedimentary basins; the Ogaden Basin (350,000 km^2), the Abay (Blue Nile) Basin (63,000 Km^2), and the Mekele Basin (8,000 km^2). The sedimentary succession of the Mekele Basin comprises 2000 m thick sediments ranging from fluvio-lacustrine to shallow and deep marine types (Alemu, 2019). The other 50% landmass of the country is covered by Cenozoic volcanics and sediments which range in age from the late Eocene up to historical times. After several episodes of widespread flood basalts and subordinate silicic volcanism formed what is known as MER (Main Ethiopian Rift).

The geology of South Sudan constitutes part of the East African Orogenic Belt, comprising the Arabian-Nubian Shield in the north and the Mozambique Belt in the south, which resulted from the collision between east and west Gondwana (Stern, 1994). The Neoproterozoic Arabian-Nubian Shield crust is characterized by the occurrence of arc assemblages associated with ophiolites and granitoids, rejuvenated older crustal terranes, accumulation of sediments and volcanic rocks in aulacogens or tectonic basins, which subsequently were metamorphosed and deformed (Stern, 1994; Kujjo, 2019). The Arabian-Nubian Shield contains fragments of an intra-oceanic island arc/back arc basin and microcontinents welded together along suture zones. The regional structural setting indicates northeast-southwest lithospheric extension that formed the northwest-southeast-trending Mesozoic rift basins in the northeast region e.g., the Muglad and Melut Basins (Binks & Fairhead, 1992). These rift basins terminate abruptly against the Central African Shear Zone, which is a major dextral strike-slip shear fault related to the opening of the South Atlantic Ocean (Kujjo, 2019).

Another major geologic lineament is the northwest–southeast- trending Aswa Fault Zone that links the northern tip of the western branch of the East African Rift System with the southern end of the rift system. Generally, the geology of South Sudan is composed of; Precambrian Basement Complex, Mesozoic Nubian Supergroup and Quaternary Surficial Deposits. The geology of the Sudan is similar to South Sudan, it is largely underlain by Precambrian rocks, particularly in the southwest, center and northeast, which were almost exclusively reactivated during the Neoproterozoic Pan-African tectono-thermal event. Large parts in the north of the country are covered by continental clastic sequences of the predominantly Mesozoic Nubian cycle (previously Nubian Sandstone), and in the south by Tertiary to Quaternary unconsolidated superficial sediments. Some Tertiary and younger basalts occur in the border zone with Ethiopia (EBRAHIM & Alkhar, 1981).

2.1.2. Aquifer characteristics and formations

The Eastern Nile is densely populated region with limited water resources for drinking, energy, transport and irrigation purposes (Mohammed et al, 2022c). This include both surface and groundwater, with the present of groundwater being dictated by a number of factors including geology of the area, aquifer characteristics, and recharge mechanisms, etc. An aquifer is a geologic medium that can store and transmit water at rates fast enough to supply reasonable amounts of water to wells (Fetter, 1994). Generally, the upstream region of the Eastern Nile Basin comprises of basement complex formations, which are crystalline igneous and metamorphic rocks of the Precambrian age present across the region. In Africa generally, there are four types of hydrogeological environments; crystalline/metamorphic basement rocks, volcanic rock, unconsolidated sediments and consolidated sedimentary rocks (MacDonald & Calow, 2008).

The hydrogeological setting in the Ethiopian part of the Eastern Nile basin is extremely complex, with rock types ranging in age from Precambrian to Quaternary, with volcanic rocks most common in the highlands, complex metamorphic and intrusive rocks in peripheral lowlands and a few highland areas (Chernet, 1993). Sedimentary rocks cover incised river valleys and most recent sediments cover much of the lowlands of all the major river sub-basins. Groundwater flow systems, known from studies conducted in sub-basins such as Tekeze and Abay, suggest an intricate interaction of recharge and discharge, operating at local, intermediate and regional scales (Kebede et al, 2005). Springs are abundant at different topographic elevations, suggesting that the shallow groundwater operates under local flow systems controlled by static ground elevation. However, the thickness and lateral extent of the aquifers indicate that deeper, regional flow systems operate mainly in the volcanic and sedimentary rocks (MacAlister et al, 2013).

Most of the Precambrian rocks have shallow aquifers. The aquifer in a given geologic medium is largely a function of the degree of weathering, fracturing, and faulting, the nature of the geologic material, the sediment grain size, degree of sorting, and packing (Melesse & Bagyaraj, 2020). In these aquifers depth to groundwater level is not more than a few tens of meters. From a database of 1250 wells from across the country, showed that the yields of most shallow and intermediate aquifers do not exceed 5 l/s (MacAlister et al, 2013), whereas the highly permeable volcanoclastic deposits and fractured basalts of Addis Ababa and Debre Berehan areas can yield between 20 and 40 l/s, respectively (Ayenew & Wohnlich, 2008). Recent drilling in deep volcanic aquifers has located highly productive aquifers, yielding over 100 l/s. Depth to the static water level in the unconfined aquifers in alluvial plains and narrow zones close to river beds do not normally exceed 10m except in highland plains, where it is around 30 m. Seasonal water table fluctuations rarely exceed 2 m (MacAlister et al, 2013). Tectonic movements of the Rift System during the Paleogene and Neogene Periods (middle to upper Tertiary) led to the formation of large structural basins across South Sudan. The Melut Basin is the main rift basin in South Sudan, covering an area of approximately 160,000 km^2.

This basin, along with others in the rift systems, received thick fluvial and lacustral deposits during the Pliocene-Pleistocene (late Tertiary to early Quaternary Period), Volcanic activity during late Neogene and early Quaternary Periods produced the volcanic deposits that outcrop in the south-east of South Sudan (Dochartaigh & Bellwood-Howard, 2018; Kujjo, 2019). These deposits constitute the Umm Ruwaba Formation which is underlain by Nubian Sandstone to border with Sudan (Salih & Khadam, 1982). Umm Ruwaba Formation forms an unconsolidated aquifer is generally of low to moderate productivity. The properties of the aquifer vary depending largely on lithology, with lenticular sand and pebble horizons being the most productive. The aquifer can be unconfined, or locally semi-confined where permeable layers occur below clay strata at depth (UN. ECA, 1988; Dochartaigh & Bellwood-Howard, 2018). Southern part of South Sudan is covered by basement complex where groundwater is limited to tectonic fractures that formed aquifers. These aquifer zones are typically between 5 m and 20 m thick, but can be thicker.

The formation in the Sudanese part of the Eastern Nile Basin is a multi-structural system of rifts, which range in age from the Paleozoic through to the most recent Quaternary and have resulted from the accumulation and filling with consolidated and unconsolidated sediments (MacAlister et al, 2013). The major hydrogeological formations in Sudan include the Nubian Sandstone Aquifer System (NSAS), the Umm Ruwaba, Gezira sedimentary aquifer, the unconsolidated alluvium khors (seasonal streams) and wadis, and the Basement Complex aquifers (Salih & Khadam, 1982). The NSAS may attain a thickness of 500 m, and is found under water table (unconfined) conditions or semi-confined artesian conditions. The Umm Ruwaba sediments are characterized by thick deposits of clay and clayey sands under semi-confined to confined conditions. The Basement Complex, extending over half of Sudan, is a very important source of groundwater when subjected to extensive weathering, jointing and fracturing the parent rock is largely impervious (MacAlister et al, 2013). In the White and Blue Nile sub-basin sands and gravels in the Gezira and EI Atshan Formations constitute important aquifers. Quaternary and recent unconfined aquifers tend to comprise a few meters of sand, silt and clay as well as gravel. In Egypt, the major aquifers are generally formed of either unconsolidated or consolidated granular (sand and gravel) material or in fissured and karstified limestone. The hydrogeological provinces present in the Eastern Nile Basin parts of Egypt are the Nile Valley and Delta aquifers, Nubian sandstone aquifer, Moghra aquifer, tertiary aquifer, carbonate rock aquifers and fissured basement aquifers (MacAlister et al, 2013). The Nile Valley aquifer, confined to the floodplain of the Nile River system, consists of fluvial and reworked sand, silt and day under unconfined or semi-confined conditions (Hefily & Sahta, 2004). The saturated thickness varies from a few meters through to 300 m.

The Nile Delta consists of various regional and sub-regional aquifers with thicknesses of up to 1000 m. The delta aquifers are composed of sand and gravel with intercalated clay lenses and are highly productive with transmissivities of 25,000 m/day or more (El Tahlawi & and Farrag, 2008). The NSAS is an immense reservoir of non-renewable (fossil) fresh groundwater that ranks among the largest on a global scale, and consists of continental sandstones and interactions of shales and clays of shallow marine of deltaic origin (Manfred & Paul, 1989). The 200-600 m thick sandstone sequence is highly porous with an average bulk porosity of 20 per cent, in addition to fracture-induced secondary porosity. Aquifer transmissivities vary from 1000 to 4000 m^2/day. The Moghra aquifer is composed of sand and sandy shale (500-900 m thick) and covers a wide tract of the Western Desert between the Delta and Qattara Depression.

2.1.3. Groundwater flow dynamics and drivers

Groundwater flow is seen to be complicated due to intricate geologic setting of the complex siliciclastic, carbonate and volcanic framework in the Eastern Nile Basin upstream region. For example, in Ethiopia and South Sudan, most aquifers are formed as a result of volcanic activity or rifting. The main flow pattern is gravity-flow and poroelasticity, in the upper part intensive flow with complex geometry occurs (Toth, 2016). In the western and the downstream region of the Eastern Nile Basin where the formations are sedimentary in nature, the flow is governed by several mechanisms which includes; the evolving foreland basins, large scale compression and thrusting that develop high pore pressures in the foreland sag, regional groundwater flow and initiate transient groundwater flow (Toth, 2016).

Computations flow rates done by (Shemin & Garven, 1989) in similar environments like in Eastern Nile Basin suggest the order of 10^{-3} to 10^{-2} m/year are possible soon after compression of the foreland, and that the flow field dissipates in about 10^3 to 10^4 years, but longer diffusion times can exist in very low permeability strata. However, full understanding of the flow dynamics and drive mechanisms in basement complex and other formation is often difficult because; the rheological behavior of geologic media is complex and poorly understood and the architecture, mechanical properties and boundary conditions, and deformation history of most geologic systems are not well known. Much of what is known about hydromechanical processes in geologic systems is derived from simpler analyses that ignore certain aspects of solid-fluid coupling (Neuzil, 2003).

Generally, Gravity is the main driving force for groundwater flow, and both landscape topography and geology distribute the effects of gravity on groundwater flow (Toth, 2016). The groundwater table defines the distribution of the potential energy of the water. In humid regions where the bedrock permeability is relatively low and the soil depth is sufficiently shallow, the groundwater table closely follows the landscape topography and, thus, the topography controls the groundwater circulation in these regions.

2.1.4. Recharge mechanisms and zones

Groundwater recharge is a downward flow of water reaching the water table and forming an addition to the groundwater reservoir. Recharge may occur naturally from precipitation, rivers, canals, lakes, and as man induced phenomena (irrigation, urban recharge). Undertaking sustainable development of groundwater resources is strongly dependent on a quantitative and knowledge of the rates at which groundwater systems are being replenished. Using satellite data from the Gravity Recovery and Climate Experiment (GRACE), together with the recharge estimates derived from a distributed recharge model, the recharge values range from less than 50 mm/yr in the semi-arid lower as well as upper catchments, and a mean of 250 mm/yr in the subtropical upper catchments (Bekele & Smakhtin, 2012). The aquifers in the Eastern Nile Basin especially in the downstream region receive recharge from the base of those watercourses, and from seepage return flows in areas under irrigation. In the Ethiopian Highland sub-catchments, studies revealed that groundwater recharge varies considerably in space and time in relation to differences in the distribution and amount of rainfall, the permeability of rocks, geomorphology and the availability of surface water bodies close to major unconfined and semi-confined aquifers that feed the groundwater. Across the landscape, large differences are observed in recharge between the lowlands, escarpments and highlands (Chernet, 1993; Kebede et al, 2005). In South Sudan, it is reported that High rainfall and seasonal flooding are important for groundwater recharge, especially in the central Sudd Basin, which is the largest source of groundwater (USAID, 2021). Within the Nile Valley areas of Egypt, the Quaternary aquifer is recharged mainly from the dominant surface water, especially from the irrigation canals that play an essential role in the configuration of the water table. The aquifer is recharged by infiltration from the irrigation distribution system and excess applications of irrigation water, with some of this returned to the Nile River and Palaeo-groundwater is a vast resource in the more arid lower reaches of the basin (Bekele & Smakhtin, 2012; MacAlister et al, 2013). The Nubian Sandstone Aquifer System (NSAS) is fossil groundwater and non-renewable due to both limited modern-day recharge and the long travel time. It has been suggested that in Pleistocene times when more humid climatic conditions prevailed that the NSAS was recharged by meteoric waters (Isaar, Bein, & Michaeli, 1972). The replenishment of groundwater in arid regions is extremely poor or non-renewable and this require sustainable development concept to ensure continuous use of the groundwater (Abderrahman, 2003).

2.1.5. Surface-groundwater interaction

The availability of sufficient water resources is critical for sustainable social and economic development globally. The arid environment and recurrent drought have been a precursor to inadequate water supply in some parts of EN. Groundwater is hydraulically connected to the surface waters in many regions and understanding this interaction is fundamental to effective and sustainable water resources management (Brodie, R. & Sundaram, B. , 2007; Owor, 2010). The interaction between groundwater and surface waters influences key characteristics of aquatic environments, including the stability of water levels and water quality (Winter et al, 1998). Interactions between groundwater and surface water are complex spatially, and are influenced by not only climate, landform, geology, and biotic factors but also human activities (Sophocleous, 2002). Interactions occur through a range of spatial scales which include local, intermediate and regional groundwater flow regimes (Tóth, 1963). Researchers observed that isotropic and homogenous porous interface media, fluxes between surface waters and groundwater decrease exponentially with distance from the stream or river bank. Repeated exchanges between surface waters and groundwater increase the contact times between the water and chemically reactive geologic materials (Owor, 2010). ENB is characterized by heterogenous geology and this variation complicated the quantification of the exchange mechanisms as some rivers are either gaining or losing depending on the elevation and hydraulic properties of the formation. The groundwater depth is also varying from few meters in sediments to more than 50 meters in volcanic and metamorphic rocks (Gobezie et al, 2023).

2.1.6. Groundwater Availability and distribution

The Nile Basin region is characterized by high climatic diversity and variability, a low percentage of rainfall reaching the main river and an uneven distribution of its groundwater water resources due to diverse geologic formations. Eastern Nile region supplies up to 90 per cent of annual Nile flows, but its contribution is highly seasonal. Extensive regional aquifer systems holding substantial quantities of groundwater underlie the Eastern Nile Region (NBI, 2021). Some aquifers hold fossil water, but others are recharged from precipitation over the basin, or from irrigation areas and the baseflow of the Nile. Groundwater is the dominant source of domestic water supply in rural communities across the basin (NBI, 2021). In upstream region of ENB, many parts have limited supplies of groundwater because of poor permeability of crystalline rocks and variable water-table depths, and locating them depends on water-bearing fractures. Permeability of ancient (Precambrian) rocks is generally poor and wells normally give poor yields as a result (UN, 2001).

Studies showed that groundwater potential for Egypt is estimated at 200 BCM in the Nile Valley and 400 BCM in the Delta region reservoir which are generally distributed in; the Nile Valley and Delta aquifer, coastal aquifer, Nubian Sandstone Aquifer, and Moghra aquifer. For Ethiopia, groundwater is estimated to about 40 BCM distributed in fractured crystalline basement rocks aquifers and used mainly for water supply in towns and dispersed rural communities across the country, where provision of reticulated surface-water schemes is often expensive because of initial project construction costs and poor water quality (Mengistu & Demlie, 2019). The sedimentary rocks of eastern, central and northern Ethiopia also have variable groundwater potential. A report from some studies indicates an estimated of 28 BCM of groundwater in the South Sudan eastern part of the Um Ruwaba and fractured crystalline basement rocks aquifers. This is the main source of water supply in small towns and vastly sparsed rural settlements (Lasagna & Bonetto, 2020). For Sudan it is estimated at 900 BCM distributed in the aquifers; the Nubian Sandstone Aquifer System, Um Ruwaba, Alluvial Deposits and the fractured crystalline basement aquifers of Gedarif region (UNEP, 2020).

2.1.7. Groundwater quality

The quality of groundwater in the Eastern Nile varies from one country to another and also from region to region due to diverse geologic formations. The groundwater environment differs significantly from surface water in ways that are important for the fate of natural and anthropogenic contaminants. It is dark and has no photosynthesis (but bioactivity exists), has a nearly constant temperature, has limited inputs from the surface (e.g. oxygen) and contains 102 to 106 times fewer bacterial organisms (Ghiorse & Wilson, 1988). The main source of natural groundwater recharge is precipitation and groundwater zone have long water residence times, this allows the groundwater time to react with rocks and minerals. Some reactions, depending on mineralogy, may lead to geogenic contamination (As, Fe, Mn, F, radionuclides, etc.) but in other cases may facilitate natural attenuation of contaminants from the surface.

The spatial scale of groundwater contamination largely depends on whether the contamination originates from point sources (e.g. factories) or diffuse sources of regional origin, e.g. agricultural or atmospheric origin (World Water Quality Alliance , 2021). Some researchers also attribute the deterioration of the groundwater quality in EN to increasing population growth, intensification of agriculture, and industrial development in some countries. Based on the available data, groundwater quality in the EN is known to be highly variable and influenced by the hydrogeological environment, type of water sources (tube wells, dug wells, springs) and level of anthropogenic influence. In BNB, it is reported that groundwater quality is good making it suitable for various uses in the region (MacAlister et al, 2013) and it fresh groundwater has a total dissolved salt of less than 200 mg/l (Ayenew et al,. 2008). Studies indicates that naturally high levels of hydrogen sulphide and ammonia can be present in deep anaerobic environments or shallow organic carbon-rich (swampy) areas and could cause problems of taste and odour. Fluoride is a major water-related health concern and is present at levels above drinking water standards in a number of localities, particularly in the western highlands, including waters emanating from hot springs and it is one of the major issues in Ethiopian volcanic rift terrain (Ayenew T. , 2008; MacAlister et al, 2013).

The Nitrate contamination of groundwater, derived mainly from anthropogenic sources including sewage systems and agriculture (animal breeding and fertilizers), is a problem in rural and urban center and another factor contaminating the groundwater in Ethiopia is reported to be microbiological (Ayenew T. , 2008). In Sudan, South and North, Nubian aquifers are considered to contain the best quality groundwater and are generally suitable for all purposes with the salinity varying from 80 to 1800 mg/l. More saline water is associated with down-gradient areas having enhanced residence times; shallow water table areas due to enrichment from evaporation and evapotranspiration, mineralization from claystones, mudstones, basalts, dissolution from salt-bearing; formations and mixing with overlying Tertiary and Quaternary aquifers. Nubian groundwater is mainly sodium bicarbonate type, with calcium or magnesium bicarbonate waters common near the recharge zones (Bekele & Smakhtin, 2012; MacAlister et al, 2013). In some areas around Khartoum State, groundwater quality is good but tend to change with elevation in major ions (Ahmed et al, 2000).

In the Nile Valley region of Egypt, groundwater quality is good with <1500 mg/l total dissolved solids, TDS, and mainly used for irrigation and domestic purposes but in the valley margins remote from surface water systems to the east and west, the groundwater salinity tends to be more elevated. The groundwater quality in the south is of higher quality <1000mg/l compare to the north close to the Mediterranean Sea coast where there is a marked increase in salinity due to seawater intrusion (El Tahlawi & and Farrag, 2008). There is also contamination of groundwater with nitrates in the Valley and Delta by industrial wastes around Cairo and other industrial cities and from sewer drain seepage poses a threat to public health, especially in areas where shallow hand pumps are used (MacAlister et al, 2013).

2.2. Groundwater potential assessment techniques

2.2.1. Data used for groundwater potential assessment

The study by Walker et al. (2019) entitled "Development of a Hydrogeological Conceptual Model for Shallow Aquifers in the Data Scarce Upper Blue Nile Basin" utilizes various types of data to develop a conceptual model for shallow aquifers in the Dangila district of Northwest Ethiopia. The data used in the study includes: Field investigations, Hydrochemistry data, Isotope analysis, well monitoring data Pumping test data, recharge assessments and Hydrometeorological analysis. These data sources and analyses were used to develop a hydrogeological conceptual model for the shallow aquifers in the study area, providing insights into the characteristics, behavior, and potential utilization of the groundwater resources.

(Duguma and Duguma 2022a) has conducted a study on "Assessment of Groundwater Potential Zones of Upper Blue Nile River Basin Using Multi-Influencing Factors under GIS and RS Environment: A Case Study on Guder Watersheds, Abay Basin, Oromia Region, Ethiopia". The study utilizes various types of data for assessing groundwater potential zones. The data sources include Geomorphology, Land use/cover, Lithology, Soil texture, Drainage density, Slope, Lineament, Rainfall, and Elevation. These influencing factors were used to delineate groundwater potential zones in the Guder watersheds of the Upper Blue Nile Basin.

Research by (Area and Zeinelabdein 2012) entitled "Assessment of Groundwater Potentiality of Northwest Butana Area, Central Sudan" focuses on evaluating the availability and quality of groundwater resources in the Butana plain, a significant area for livestock breeding in Sudan. The study addresses the acute water shortage in the region, particularly during dry seasons, caused by climatic degradation. The study employed remote sensing, geophysical survey, and well inventory methods to assess the groundwater potential. Digital image processing techniques were used to enhance the geological and structural details of the area using Landsat (ETM+7) images. Geo-electrical surveys were conducted using Vertical Electrical Sounding (VES) technique with Schlumberger array, measuring resistivity along profiles perpendicular to the main fracture systems.

(Mohammed, Szabó, and Szűcs 2023) Conducted a study on "Characterization of groundwater aquifers using hydrogeophysical and hydrogeochemical methods in the eastern Nile River area, Khartoum State, Sudan" utilizes data from various sources to assess the hydrogeological characteristics and groundwater quality in the study area. Here is a summary of the data used: Vertical Electrical Soundings (VES), Hydro chemical Parameters and Groundwater Quality Index (GWQI): The data collected and analyzed in this study helped characterize the spatial variation of hydrogeological properties, assess the protective capacity of the aquifer, and evaluate the groundwater quality in the eastern Nile River area of Khartoum State, Sudan.

(Megahed and Farrag 2019) conducted a study on “Groundwater potentiality and evaluation in the Egyptian Nile Valley: case study from Assiut Governorate using hadrochemical, bacteriological approach, and GIS techniques". The study analyzes the groundwater potential and quality in the Nile Valley Egypt. The study utilizes hadrochemical, bacteriological, and GIS methods to characterize the chemical and bacteriological compositions of the groundwater in the Quaternary and Eocene fractured limestone aquifers. The study also conducted a GIS-based water potentiality spatial model (WPSM) to identify groundwater potential in the area. They suggested that the developed scheme and GIS-based model could be valuable tools for evaluating water quality not only in the Egyptian Nile basin but also in similar settings worldwide. Overall, the study focused on assessing the groundwater potential and quality in Assiut Governorate, Egypt, using hadrochemical, bacteriological, and GIS techniques. The findings provide insights into the seasonal variability of groundwater composition and the suitability of groundwater for drinking and domestic purposes in the Nile Valley.

((NBI) and (ENSAP) 2019a) had conducted a study on “Groundwater Availability and Conjunctive Use Assessment in the Eastern Nile: Country Report - Ethiopia". The study utilized several tools and models to assess groundwater resources. In this study, a comprehensive methodology was employed to assess groundwater availability and conjunctive use in the Eastern Nile Basin of Ethiopia. The methodology involved gathering data from previous studies, including river master plans and geological surveys, as well as using satellite data for estimating the water balance. Aquifer dimensions were estimated using borehole data, geological maps, and digital elevation models. Groundwater potential was assessed using published and unpublished values such as storage and infiltration coefficients. Base flow recession analysis and borehole data were utilized to understand groundwater sensitivity to drought periods.

The study of the Abay basin master plan aims to integrated water resources management used data in the basin planning studies typically include a combination of primary and secondary data from various sources (ABDO 2020).

2.2.2. Variables and input parameters for GW potential assessment

Several input parameters must be considered during GW potential assessment. Regarding this (Çelik 2019) attempted to use eight input parameters for the "Evaluation of Groundwater Potential by GIS-Based Multicriteria Decision making as a Spatial Prediction Tool: Case Study in the Tigris River Batman-Hasankeyf Sub-Basin, Turkey". Eight hydrological and hydrogeological criteria, including geomorphology, geology, rainfall, drainage density, slope, lineament density, land use, and soil properties, were considered in the analysis. The study generated groundwater-potential index values and groundwater potential zone (GWPZ) maps for the sub-basin.

(Gebeyehu et al., 2023) studied on "Delineation of Groundwater Potential zones of the Transboundary Aquifers within the semiarid Bulal catchment, Southern Ethiopia", discusses the identification and delineation of groundwater potential zones in the Bulal catchment area of southern Ethiopia. The document mentions that ten input parameters were used to assess groundwater potential zones within the Bulal catchment. Some common parameters that are often considered in groundwater studies include geological features, Topography, Hydrogeological properties, Land use and land cover, Soil characteristics, drainage density, Precipitation, Vegetation cover, Hydrological data and Hydrochemical data.

(Mengistu et al. 2022a) employed eleven input parameters for the determination of potential aquifer recharge zones using geospatial techniques for proxy data of Gilgel Gibe catchment, Ethiopia. This study focuses on assessing potential aquifer recharge zones. GIS and Remote Sensing were employed to analyze ten factors influencing groundwater recharge. These factors include slope, lithology, topographic position index lineament density, rainfall, soil, elevation, land use/cover, topographic wetness index, and drainage density. Each factor was given a relative rank priority based on its predictive implication on groundwater potentiality. According to the study by (Satapathy & Syed, 2015) entitled “Characterization of groundwater potential and artificial recharge sites in Bokaro District, Jharkhand (India), using remote sensing and GIS-based techniques" focuses on assessing groundwater potential and identifying suitable sites for artificial recharge in the Bokaro District of Jharkhand, India. the input parameters used for assessing groundwater potential and identifying suitable sites for artificial recharge in the Bokaro District includes; land cover, land use, geology, geomorphology, Liniment density, rain fall, slope, drainage density, and soil type were used. (Abdalla 2012) attempted to use different input parameters for "Mapping of Groundwater Prospective Zones using Remote sensing and GIS techniques: a case study from the central eastern desert, Egypt". The study aimed to identify the contributing parameters indicating groundwater potential, such as slope, stream networks, lineaments, lithology, and topography. Thematic maps for each parameter were created using GIS and remote sensing data, and these layers were combined to produce the final groundwater prospective zones map. The results revealed different zones of groundwater potential, including very good, good, moderate, and low potential areas. On the other hand, a study titled "RS and GIS Analysis of the Groundwater Potential Zones in the Upper Blue Nile River Basin, Ethiopia" focuses on assessing and classifying groundwater potential zones using remote sensing (RS) and GIS techniques. The study examined various factors such as geomorphology, land use/cover, lithology, soil type, drainage density, rainfall, and elevation to determine the groundwater potential zones (Duguma 2023).

(Arnous 2016) studied on Groundwater Potentiality Mapping of Hard-Rock Terrain in Arid Regions Using Geospatial Modelling: Example from Wadi Feiran Basin, South Sinai, Egypt. The study focuses on identifying suitable areas for groundwater exploitation in hard-rock terrains. The study utilizes satellite data interpretation to delineate lithological units, weathered zones, and lineament density in the Wadi Feiran basin. Remote sensing data and a geographic information system (GIS) were used to create thematic maps of various factors such as slope, drainage density, lithology, landforms, structural lineaments, rainfall intensity, and plan curvature. These factors were assigned scores and weights to assess their influence on groundwater potential. Finally, the study generated a groundwater potential zone map and validated using well locations and previous geophysical investigations.

2.2.3. Methods and techniques for spatial analysis and mapping

The GIS based MCDA (multi-criteria decision analysis) technique is the best to map potential groundwater potential (GWP) zones and for groundwater recharge to encourage artificial groundwater potential suitability mapping activities (Mir et al. 2021a). Multi-Criteria Analysis employs a multi-criteria analysis technique to identify suitable sites for artificial recharge. This involves combining and overlaying different criteria, such as geology, geomorphology, and hydrological factors, to assess the suitability of specific areas for recharge (Satapathy and Syed 2015b). The various criteria are laid out in the planning process as criteria mentioned above affects our aim and are assigned attributes to different degrees of preferences or favors being seek from them (Saaty 1987a). By performing comparisons among the criteria on a similar scale of ranking, it normalizes the factors by ranking appropriate scores to multi-attributes represented by thematic information provided under each factor of impact designated as thematic layers over a GIS domain (Nyeko, 2012).

AHP method is a decision-making process to judge multilevel hierarchical classification system, which reveals the decision of each parameter (Anand, Karunanidhi, and Subramani 2021a), it is a widely used MCDA technique. To ensure a fair weight distribution among the various factors employed, AHP uses pair-wise comparison. Each factor will be assigned a weight based on the experts' opinions. A higher weighting assigned indicates greater relevance. The use of this technique also enables the integration of multiple expert opinions without bias (Sandoval and Tiburan 2019a).

According to Saaty (1987), the element of each layer class of each individual raster is generally retrieved for the AHP calculation and will later be utilized to perform the pairwise comparison within the matrix. The normalized weight for each thematic layer is then determined using the pairwise comparison matrix (PCM), and the consistency of the judgment matrix is then determined (Hussaini et al. 2022). RS, GIS, and AHP approaches are robust in identifying and mapping groundwater potential zones which can serves as a valuable tool for planning, managing, and developing groundwater resources (Gebeyehu, Ayenew, and Asrat 2023b).

To evaluate the consistency of expert opinions, the researchers employed the Analytical Hierarchy Process, which involved pair-wise comparisons. The final weights for each criterion were computed, and the method of spatial analysis and data re-classification was employed to generate suitability maps (Mohammed, Elnour, and Abdelgalil 2024).

2.2.4. Tools and models for groundwater potential assessment and modelling

(Khadim et al. 2020) conducted a study on "Groundwater Modeling in Data Scarce Aquifers: The case of Gilgel-Abay, Upper Blue Nile, Ethiopia". The study discusses the development of a groundwater model for the Gilgel-Abay catchment area in Ethiopia. The study aims to address the lack of in situ data and provide insights into groundwater resources in the region. This study utilized the MODFLOW-NWT modeling tool to develop a fine-resolution groundwater model with a grid resolution of 500 meters. The model incorporated daily distributed input forcing of recharge and streamflow, simulated by the Coupled Routing and Excess Storage (CREST) hydrological model. To calibrate the model, observed groundwater table data from 38 historical wells were used. The model was further validated using time series data collected from the Citizen Science Initiative (PIRE CSI) and the Innovation Lab for Small Scale Irrigation (ILSSI) project.

(El-hadidy and Morsy 2022) attempted to integrate modelling and GIS for the study entitled "Modelling groundwater deficit by integrating groundwater modeling, remote sensing, and GIS techniques". The study explored the spatio-temporal variation of groundwater deficit in the Nile Valley region. The study utilizes various data tools and methodologies to assess and manage groundwater resources. The study used Visual MODFLOW and GIS-based remote sensing parameters were incorporated into the analysis to monitor and assess groundwater resources. The research involved collecting and analyzing various field data, including static water level, discharge rate, and long duration and recovery tests from observation and production wells. These data were used to enhance the study's conceptual model and determine the hydrologic properties of the Quaternary aquifer. Overall, the integration of groundwater modeling, remote sensing, and GIS techniques provide a comprehensive understanding of the spatio-temporal variation of groundwater deficit in the study area and its potential impact on environmental management.

Another study by (Russo, Fisher, and Lockwood 2014) entitled "Assessment of Managed Aquifer Recharge Site Suitability Using a GIS and Modeling" presents a method for evaluating the suitability of sites for managed aquifer recharge (MAR) using a combination of geographic information system GIS analysis and numerical modeling. The paper focuses on the Pajaro Valley Groundwater Basin in California as a case study. The paper highlights the importance of using GIS analysis and modeling as tools for regional water supply planning and evaluating options for enhancing groundwater resources. It emphasizes the need for a comprehensive assessment of MAR suitability, considering both surface and subsurface conditions, and the potential benefits and drawbacks associated with different project locations and operating strategies.

(Nyende and TG 2013) conducted a study on "Conceptual and Numerical Model Development for Groundwater Resources Management in a Regolith-Fractured-Basement Aquifer System". The study discusses the management of groundwater resources in a specific geological setting. The study focuses on the Pallisa aquifer in eastern Uganda, which is located in a crystalline rock geologic setting. The article discusses the methodology employed, including the use of the Model Muse software for conceptual modeling and the MODFLOW model for groundwater flow simulation. The study also emphasizes the importance of understanding the groundwater flow system for protecting fractured aquifers from pollution.

Overall, the article presents a case study and modeling approach to assess and manage groundwater resources in a regolith-fractured-basement aquifer system. The findings contribute to the understanding of hydrogeological conditions and provide insights for water resource managers in the region.

(Naranjo-Fernández, Guardiola-Albert, and Montero-González 2018) conducted study on "Applying 3D Geostatistical Simulation to Improve the Groundwater Management Modeling of Sedimentary Aquifers: The Case of Doñana (Southwest Spain)". The study focused on enhancing the characterization of the Almonte-Marismas aquifer in order to improve groundwater management. The aquifer, located in Doñana National Park, is ecologically significant but is facing challenges due to groundwater extraction for agriculture and tourism. Six hydro-facies were identified and quantified using indicator variogram modeling, and a 3D geological model was constructed using Sequential Indicator Simulation. This detailed model was then integrated into the MODFLOW groundwater management model. The report concludes by discussing the integration of the 3D geological structure and hydrogeological properties into the existing numerical flow model of the Almonte-Marismas aquifer. The improvements in the groundwater model were evaluated based on modifications in piezometry and water balance, with a focus on the impacts on vital ecosystems within Doñana.

2.3.Groundwater Use and Application

2.3.1. Groundwater: A global perspective

Groundwater, containing the largest volume of unfrozen fresh water on Earth, is an indispensable natural resource. It has undergone a significant transformation globally, experiencing a notable surge in exploitation, particularly during the twentieth century, often dubbed as 'the silent revolution' (Gun 2012). MacDonald et al. (2012) demonstrate that groundwater storage exceeds annual renewable surface water flows by a factor of 100. Groundwater serves as the primary source of drinking water for nearly half of the world's population and plays a pivotal role in supporting half of the global food production (Nannawo, Lohani, and Eshete 2022). Worldwide, groundwater accounts for approximately one-third of all freshwater withdrawals, providing around 36% for domestic use, 42% for agricultural purposes, and 27% for industrial activities (Taylor et al. 2013). Despite its critical role in promoting socioeconomic development, groundwater has faced gradual declines in recent decades due to rapid population growth and economic expansion worldwide (Liu et al. 2020). Table 1, sourced from Gun (2012), offers a comprehensive overview of global groundwater abstraction across various sectors, accompanied by a comparison of the percentage of groundwater withdrawal from the total water withdrawal.

Table 1: Main assessments of worldwide groundwater withdrawal (Reference: Gun (2012)).

Continent	Groundwater abstraction					Compared to total water abstraction	
	Irrigation km3/yr	Domestic km3/yr	Industrial km3/yr	Total km3/yr	%	Total water abstraction km3/yr	Share of groundwater %
North America	99	26	18	143	15	524	27
Central America & Caribbean	5	7	2	14	1	149	9
South America	12	8	6	26	3	182	14
Europe (With Russian)	23	37	16	76	8	497	15
AFRICA	27	15	2	44	4	196	23
ASIA	497	116	63	676	68	2257	30
Oceania	4	2	1	7	1	26	25
WORLD	666	212	108	986	100	3831	26

2.3.2. Groundwater: A regional perspective:

Groundwater serves as the primary source of potable water throughout rural Africa due to the scarcity of accessible and cost-effective alternatives that are safe for consumption (Bonsor and Macdonald 2011). The arid regions of East Africa are among the most geographically challenged areas globally due to their limited overall availability of surface and groundwater resources (Kebede and Taye 2020). The urban population in Sub-Saharan Africa is experiencing rapid growth, typically ranging from 2% to 7% per year, accompanied by an increase in water demand of up to 10% annually. These trends are not confined to megacities but are also evident in numerous medium-sized towns across the region. Furthermore, these demographic shifts are expected to be exacerbated under certain climate-change scenarios (Foster, Hirata, et al. 2010). Groundwater serves as the essential foundation for human survival and economic progress in vast drought-prone regions across Sub-Saharan Africa (Foster, Tuinhof, and van Steenbergen 2012). In the Eastern Nile River Basin, the utilization of groundwater varies considerably. While groundwater is crucial for drinking and domestic water needs across much of the basin, its usage for irrigating agricultural lands is largely influenced by precipitation levels and the accessibility and availability of surface water sources (MaeAlister et al. 2012). In the Upper Blue Nile catchment in Ethiopia, where rainfall is typically abundant (though occasional droughts occur), the extraction of groundwater for agricultural purposes is relatively limited compared to regions like Egypt and Sudan, where groundwater resources are extensively exploited. In certain instances, such as in Gash, Sudan, the rate of groundwater abstraction exceeds the rate of recharge (MaeAlister et al. 2012). The efforts to enhance groundwater management across all Nile Basin countries are evident, involving critical activities like aquifer mapping, groundwater level monitoring, and analysis of extraction and recharge rates, alongside the implementation of robust data management practices (MaeAlister et al. 2012). These endeavors receive substantial backing from the research community, non-governmental organizations (NGOs), and donor groups. Figure 2 by Figueroa and Smilovic (2020) elucidates the geographical distribution of aquifers within the Nile Basin countries, offering valuable insights into their locations and potential. Furthermore, findings from the World Bank's Africa Infrastructure Diagnostic, based on a comprehensive 2007 database encompassing 63 large-scale surveys across 30 countries, underscore significant disparities in groundwater utilization between more and less urbanized nations (Foster, Hirata, et al. 2010). In addition, Tuinhof et al. (2011) highlight the pivotal role played by the Groundwater Management Advisory Team of the World Bank Water Partnership Program in providing technical support across Africa over the past decade, yielding positive outcomes.

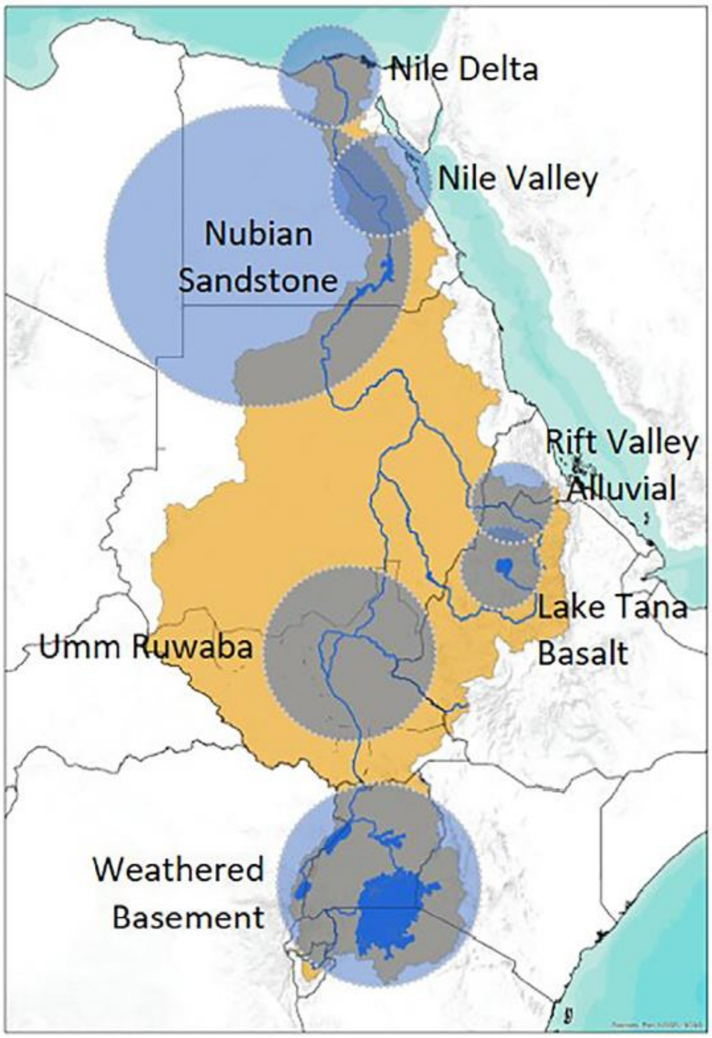


Figure 1: The general locations of aquifers within the Nile Basin countries, source: Figueroa and Smilovic (2020).

2.3.3. Groundwater: A transboundary perspective:

The interconnectedness of groundwater and surface water is undeniable, with aquifers either contributing to surface-water bodies or being replenished by them, contingent upon local conditions. Unlike river systems characterized by continuous flow, aquifers possess significant storage capacity and exhibit lower flow rates (Foster and Ait-Kadi 2012). Global attention has increasingly turned towards the exploitation of transboundary groundwater resources in recent years (Liu et al. 2020).

In the Ethiopian Blue Nile Basin, groundwater emerges as the primary source of domestic water, catering to at least 70 percent of the population's needs. Conversely, in Sudan, approximately 70 percent of groundwater extraction is channeled towards irrigation purposes. Groundwater constitutes around 50 percent of urban and 80 percent of rural domestic water supply in Sudan (MaeAlister et al. 2012). Egypt's reliance on surface water from the Nile is profound, with an annual allocation of 55.5 billion cubic meters per year under the 1959 agreement between Egypt and Sudan. With the total harvestable national runoff estimated at about 1.3 billion cubic meters per year, the balance of demand is met through groundwater utilization (MaeAlister et al. 2012).

Total groundwater usage, estimated at 5 million m^3 per year in 1984, likely exceeds 8 million m^3 per year currently. Apart from agricultural and domestic applications, industry in Egypt heavily depends on groundwater (MaeAlister et al. 2012). Egypt's primary groundwater aquifers include the Nubian Sandstone Aquifer System in the Western Desert and the Nile Valley and Delta system. The Nubian Sandstone Aquifer System, housing deep and non-renewable fossil water, sprawls across about 65 percent of Egypt's territory and extends into neighboring countries such as Libya, Sudan, and Chad (MaeAlister et al. 2012). Despite significant strides in aquifer mapping, as evidenced by initiatives like the BGR/IAH/UNESCO Africa Groundwater Resources Map (WHYMAP, 2008), substantial gaps persist in data related to aquifer attributes, groundwater recharge rates, flow patterns, quality monitoring, and utilization (Foster et al. 2012). Figure 3 by MacDonald et al. (2012) provides insights into aquifer productivity across Africa, depicting estimated groundwater depth.

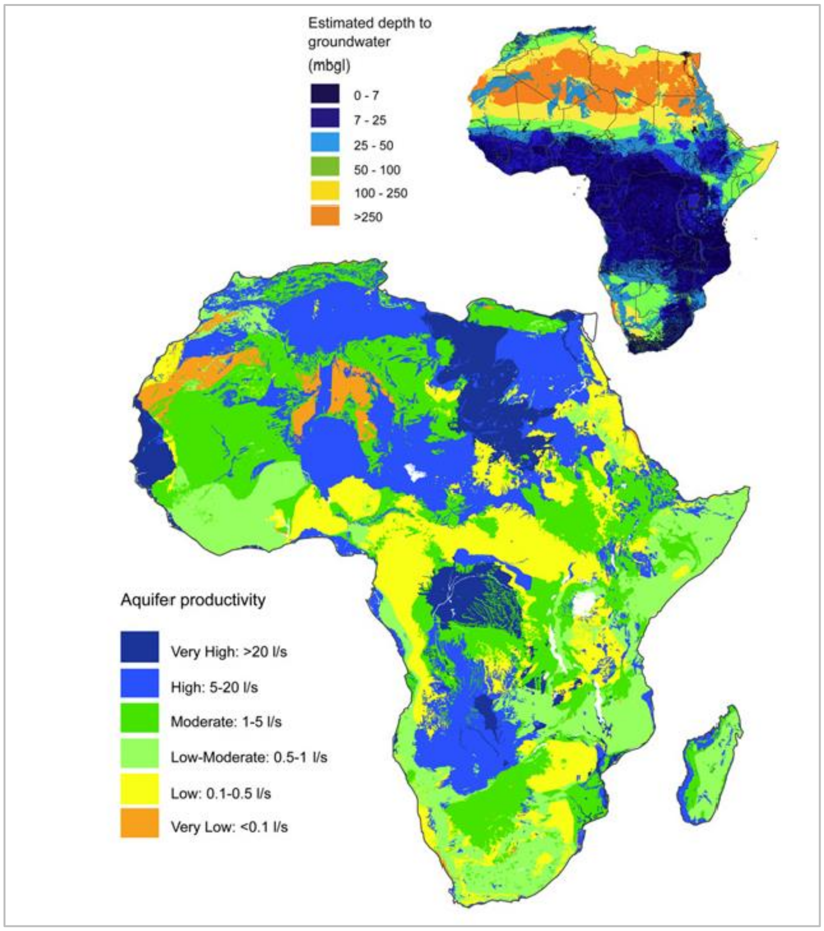


Figure 2: The aquifer productivity for Africa indicates the expected range for boreholes drilled and located using suitable methods and expertise. The inset displays an estimated depth to groundwater, source: (MacDonald et al. 2012).

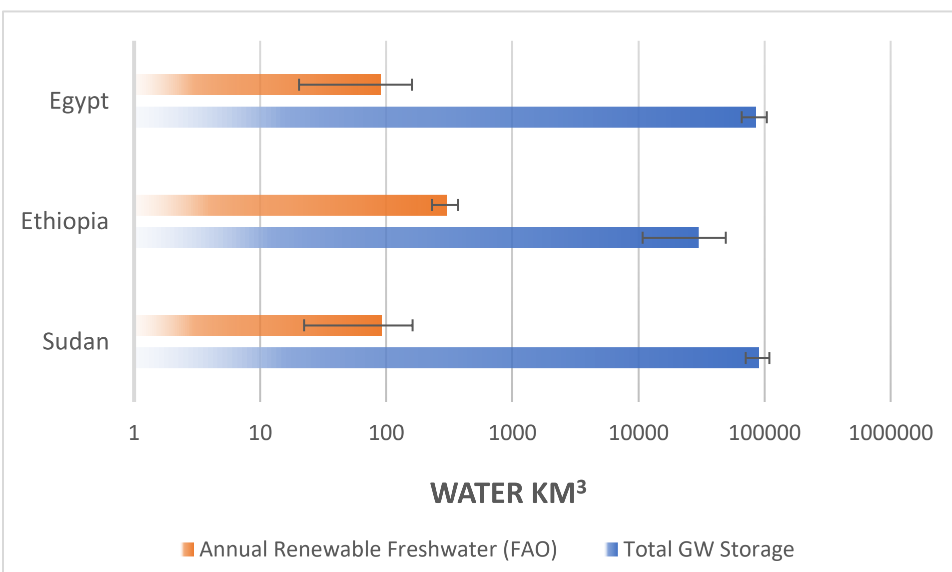


Figure 3: illustrates the volume of groundwater storage alongside the annual renewable freshwater availability for countries in the Eastern Nile region, Derived from: (MacDonald et al. 2012).

2.3.4. Groundwater for Irrigation:

Groundwater plays a crucial role in providing water for small-scale yet vital irrigation and ensuring stable water supplies during drought periods (Masiyandima and Giordano 2007). The significance of groundwater irrigation has grown significantly, with irrigated agriculture emerging as the primary user and predominant consumer of groundwater resources (Foster and Ait-Kadi 2012). Groundwater irrigation has expanded extensively across numerous irrigation canal networks, often arising spontaneously but occasionally facilitated by governmental financial incentives (Foster and van Steenbergen 2011). Globally, the total cultivated area under irrigation is estimated to be approximately 301 million hectares, with 38% equipped for groundwater irrigation (Foster 2012; Garduño and Foster 2010). India and China lead in areas equipped for groundwater irrigation, with 39 million hectares and 19 million hectares, respectively. However, in Africa, only 5 percent of cultivated land is irrigated, utilizing less than 10 percent of its potential (Siebert et al. 2010). Agricultural groundwater utilization in Sub-Saharan Africa remains limited, with only 0.4 million hectares estimated for irrigation, constituting a small fraction of all irrigated land and arable land (Siebert et al. 2010). Despite the potential, shallow groundwater remains underutilized for sustainable small-scale irrigation in Sub-Saharan Africa (Gowing et al. 2020). However, substantial increases in irrigated agriculture may face challenges due to various factors, including a lack of community tradition, high capital costs for drilling water wells, limited rural electrification, and insufficient access to financial credit for farmers (Foster et al. 2012). In regions where groundwater irrigation is more established, operational and economic challenges persist. These include restrictions on importing water-well equipment, high diesel energy expenses, logistical hurdles in crop management and transportation, and limited access to markets. Furthermore, the scarcity of data and inadequate appreciation of groundwater resources hinder investment in this area (Foster et al. 2012). Recent UN-FAO efforts have yielded valuable data on groundwater utilization for agricultural irrigation, as depicted in Table 1 by Siebert et al. (2010).

Table 2: presents data on the total area equipped for irrigation with groundwater (AEI_GW), the area actually irrigated with groundwater (AEI_GW), and the consumptive groundwater use for irrigation (ICWU_GW) in Africa, including regions and sub-regions. The data is sourced from Siebert et al. (2010).

Sub-region	**AEI_GW** (ha)	**AEI_GW** (%)	**AAI_GW** (ha)	**ICWU_GW** (Mm3 yr−1)
Africa	2 505 954	18.5	2 157 978	17 863
Northern Africa	2 092 196	32.8	1 817 844	15 685
Sub-Saharan Africa	413 758	5.7	340 134	2178
Central Africa	17 000	12.8	8000	50
Eastern Africa	21 285	3.4	21 190	117
Gulf of Guinea	86 545	14.6	82 829	426
Indian Ocean Islands	7 711	0.7	6822	21
Southern Africa	157 991	7.7	151 369	908
Sudano-Sahelian	123 226	4.6	69 923	655

2.3.5. Groundwater for water supply:

The reliance on groundwater for rural water supply is evident today, with successful water wells supporting essential facilities such as villages, clinics, schools, markets, and livestock posts across vast regions (Foster et al. 2012). Groundwater presents several advantages for water supply development. Aquifers, often covering expansive areas, can be accessed relatively close to points of demand, reducing the need for extensive distribution networks, especially for smaller supplies. Moreover, with proper aquifer protection, groundwater typically maintains excellent microbiological and organic quality, often requiring minimal treatment (Foster 1984). Access to safe drinking water is crucial for human and animal health as well as livelihoods, yet only 58 percent of Africans have access to it (Foster and Briceño-Garmendia 2010). The rapid expansion of urban populations, coupled with increasing water demand, is a prevalent trend in Sub-Saharan Africa, where groundwater is expected to play an increasingly vital role in providing reliable water supplies (Macdonald and Calow 2009). This reliance on groundwater is anticipated to intensify due to rural-to-urban migration and rising temperatures driven by certain climate-change scenarios (Foster et al. 2012). Although there is currently no comprehensive inventory of urban groundwater dependence, significant public and/or private use of groundwater is observed in cities such as Lusaka, Ndola, Maputo, Kampala, Dakar, Abidjan, Nairobi, Dar-es-Salaam, and Addis Ababa. Provisional estimates for the latter three cities all exceed 100 million liters per day (Mℓ/d), including substantial private use (Foster et al. 2012). The evidence suggests a growing reliance on groundwater for urban water supply in developing cities, driven by factors such as population growth, rapid urbanization, higher individual water consumption, rising temperatures, and concerns about the reliability of surface water sources due to climate change. However, there is a lack of systematic and comprehensive data to accurately quantify this trend. Rough estimates suggest that over 1.5 billion urban residents worldwide currently depend on groundwater for their water supply (Foster, Hirata, et al. 2010). Access to piped water and standposts remains limited, showing minimal increase over the past 15 years. Notably, countries with higher levels of urbanization have significantly better access to piped water and standposts in rural areas (Foster and Briceño-Garmendia 2010). Various reports underscore the significant role of groundwater in meeting rural domestic water needs (Masiyandima and Giordano 2007). While reliance on surface water remains common in rural areas, there has been a stable trend in the percentage of the population depending on surface water since the 1990s (see Table 4) by Foster and Briceño-Garmendia (2010). Boreholes serve as the primary source of improved water, meeting the needs of about 40 percent of the population (Foster and Briceño-Garmendia 2010).

Table 3: The Progress of Water Supply Coverage in Africa

	Piped supply		Standposts		Well and boreholes[a]		Surface water	
Period	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural
1990–95	50	4	29	9	20	41	6	50
1995–2000	43	4	25	9	21	41	5	41
2001–05	39	4	24	11	24	43	7	42

Source: (Foster and Briceño-Garmendia 2010)

2.3.6. Groundwater as option for climate change adaptation

Climate change presents significant risks to water resources, economic stability, and political harmony, potentially leading to adverse consequences (Foster and Ait-Kadi 2012). One of the primary issues exacerbated by global warming is the disruption of the water cycle due to climatic variations. Indeed, available data indicate that the hydrological cycle is already experiencing effects in numerous instances (Labat et al. 2004). Groundwater, serving as Earth's life support system, becomes increasingly vital amid climate change, offering a buffer against floods and droughts (Nannawo et al. 2022). Although climate change will impact groundwater, its buffer capacity makes it more resilient to climate change effects compared to surface water (Gun 2012). For example, fluctuations in precipitation patterns, along with changes in temperature and evapotranspiration rates, influence groundwater replenishment (Dragoni and Sukhija 2008). The lack of research on the connection between climate and groundwater in previous Intergovernmental Panel on Climate Change (IPCC) assessment reports limited understanding of their interactions. However, recent studies employing various modeling techniques and monitoring methods have significantly enhanced our comprehension of these relationships (Taylor et al. 2013).

Climate variability and change directly impact groundwater systems by affecting replenishment through recharge, and indirectly through alterations in groundwater utilization (Taylor et al. 2013). Irrigation systems fueled by groundwater serve as a vital buffer against climate extremes, playing an indispensable role in ensuring global food security (Taylor et al. 2013). Climate and land cover play crucial roles in determining precipitation levels and evapotranspiration rates, while the composition of the soil and underlying geology determine whether excess water can be effectively transmitted and stored underground (Taylor et al. 2013). The strategic significance of groundwater for global water and food security is likely to escalate under climate change, particularly with the heightened occurrence of intense climate extremes such as droughts and floods, leading to increased variability in precipitation, soil moisture, and surface water (Taylor et al. 2013).

Water stored in aquifers is largely shielded from evaporation by natural means, and the amount of water that can be drained from them is often significant, sometimes reaching enormous volumes. This provides a reliable water supply in areas vulnerable to prolonged droughts (Foster 1984). Research on groundwater in Sub-Saharan Africa indicates its potential as a fundamental resource to bolster irrigated agriculture, as well as urban and rural water security, and to enhance resilience to drought throughout the region (Kebede and Taye 2020). However, a recent study by IFPRI on farmer responses to climatic challenges indicates significant adoption of small-scale irrigation in regions where governments actively promote such practices, such as Kenya and Nigeria (Foster et al. 2012). Cuthbert et al. (2019) concludes that forthcoming climate trends indicating increased aridity may impact surface water availability but are not necessarily expected to diminish groundwater resources. Substantial portions of the Nile River Basin countries experience significant fluctuations in rainfall patterns and recurrent droughts, a situation expected to exacerbate with climate change. It is widely acknowledged that groundwater can serve as a vital buffer against these challenges by complementing surface water sources, mitigating risks, enhancing resilience, and alleviating water scarcity vulnerabilities among impoverished communities (MaeAlister et al. 2012).

2.3.7. Surface and Groundwater Conjunctive Use

Conjunctive use involves optimizing the interaction between surface and groundwater to meet specific objectives within defined limitations (Rao et al. 2004). It aims to enhance water yield, reliability, and overall efficiency by diverting water from streams or surface reservoirs to groundwater basins during scarcity. This coordinated management ensures the overall yield surpasses that of individual components managed independently. Advantages include reduced evaporation loss, enhanced well water levels, decreased salinity, and balanced groundwater tables (Sabale, Venkatesh, and Jose 2023). Conjunctive use projects typically involve stream diversions, reservoir-only projects, or total system integration, often leading to increased yields at lower costs compared to separate operations (Coe 1990).

The utilization of conjunctive water resources is crucial for addressing water scarcity, drought conditions, and waterlogging, supporting sustainable development goals (Sabale et al. 2023). Additionally, conjunctive water management can prevent seasonal river depletion and is effective in groundwater-stressed areas, saving up to 22% in revenue through efficient deficit irrigation (Safavi and Falsafioun 2017). In Odisha, India, integrated planning incorporates groundwater and surface water resources using borewells, dug wells, and water harvesting structures (Sethi-R.B.Singandhupe and Kumar 2014). Similarly, Tehran utilizes contaminated surface water alongside groundwater for irrigation (Karamouz, Kerachian, and Zahraie 2004). Understanding water quality is vital for successful conjunctive use practices (Gupta 2020). Effluent from wastewater treatment plants is a significant source of groundwater contamination, as highlighted by Jurado et al. (2012). Groundwater, crucial for supporting ecosystems and human adaptation, is increasingly recognized for its economic and developmental importance globally (Taylor et al. 2013). Its management, often fragmented among various stakeholders, is pivotal for ensuring water security, aligning with Integrated Water Resources Management principles (Foster and Ait-Kadi 2012). The diverse array of potential benefits stemming from the integration of groundwater and surface water resources is highlighted in Figure 5 (Foster, Van Steenbergen, et al. 2010).

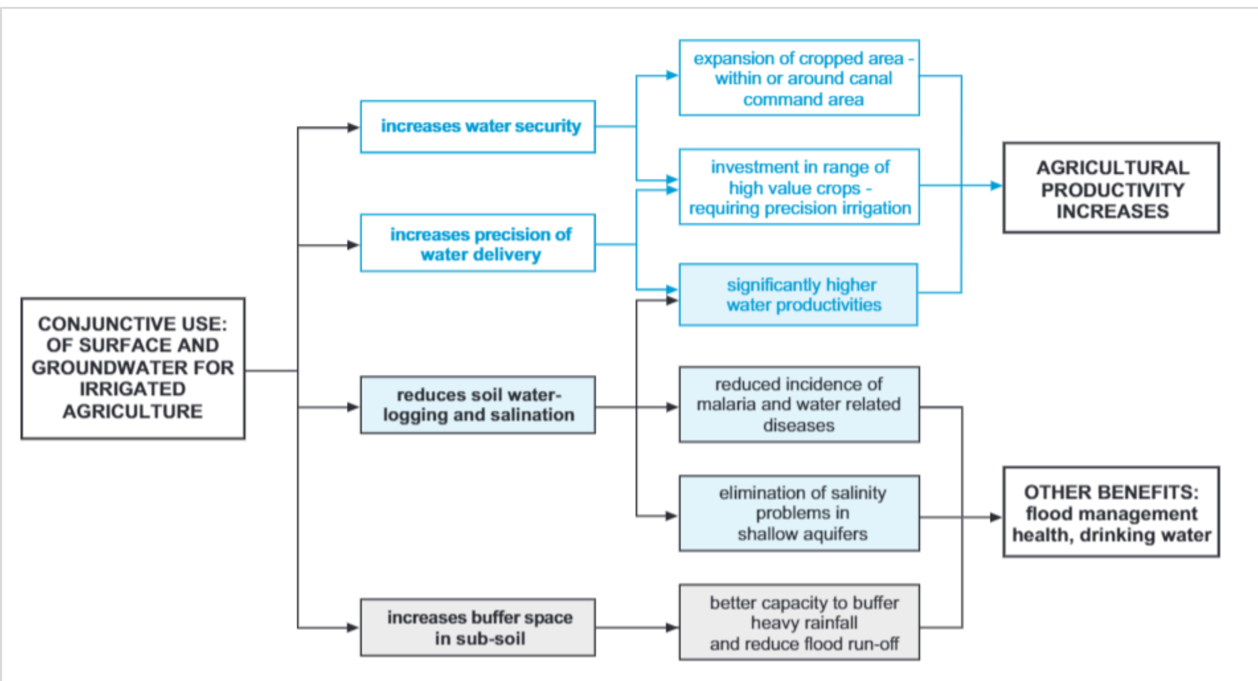


Figure 4: Various potential advantages of combining the utilization of groundwater and surface water resources Source: (Foster, Van Steenbergen, et al. 2010).

2.3.8. Groundwater Sustainability

The adoption of conjunctive use strategies integrating groundwater and surface water, along with initiatives such as farmer training, public awareness campaigns for water conservation, supportive government policies, addressing institutional challenges, and fostering international cooperation, are essential best practices for achieving sustainable water management (Sabale et al. 2023). Ensuring the sustainability of groundwater resources globally entails addressing two primary issues: the depletion of stored groundwater, evidenced by declining water levels, and groundwater pollution (Gun 2012). Sustainable management of groundwater is crucial for both societal welfare and environmental integrity. However, achieving sustainable groundwater exploitation is challenging in scenarios involving the tapping of non-renewable groundwater resources (Gun 2012). It's essential to underscore the significant nexus between groundwater and agricultural policy, urban infrastructure, and energy consumption. Without a coordinated approach and action at these intersections, addressing the critical issue of groundwater resource sustainability remains inadequate (Foster, Hirata, et al. 2010; Garduño and Foster 2010). Irrigated agriculture has emerged as the primary user and dominant consumer of groundwater, raising concerns about resource sustainability and irreversible degradation. Similarly, urbanization is closely intertwined with groundwater, with land-use interactions and sanitation playing pivotal roles. Without integrated metropolitan and municipal planning, these issues may persist and result in significant costs (Foster and Ait-Kadi 2012). Groundwater recharge, the replenishment of groundwater, is a critical determinant of sustainable groundwater utilization. It represents the maximum volume of groundwater that can be extracted from an aquifer without causing irreversible depletion, considering existing climatic conditions (Döll and Fiedler 2008). Augmenting the water stored in this reservoir during periods of heavy rainfall by actively directing surface water to recharge groundwater can promote sustainable groundwater utilization (MaeAlister et al. 2012). The sustainable management of groundwater resources in the Nile Basin countries presents numerous challenges. Apart from Egypt, most of the nine countries are still in the early stages of industrial and commercial agricultural development, with groundwater primarily serving domestic needs. However, as these nations progress, the demand for groundwater in various sectors is expected to rise (MaeAlister et al. 2012), necessitating sustainable water management practices for their water resources.

3. Methodology

3.1. Study area

3.1.1. Baro-Akobo-Sobat (BAS) Sub-basin

The Baro-Akobo-Sobat (BAS) sub-basin, spanning 481,000 km² in the Eastern Nile Basin, is a region of significant hydrological interest (Sileet et al., 2013). Originating near Gambella within the Ethiopian equatorial forest zone at elevations of 2,000 to 3,000 meters above sea level, the BAS sub-basin features a complex network of rivers and extensive wetlands. Major river systems include the Baro, Gilo, and Akobo Rivers, which originate from the Ethiopian Plateau, and the Pibor River, which originates from South Sudan. These rivers converge at Malakal to form the Sobat River. The Sobat River is notable for its large seasonal marshes along the Ethiopia-South Sudan border, created by overflows from the Akobo, Baro, Sobat, and other minor rivers. Eventually, the Sobat River joins the White Nile at Malakal. This highlights the BAS sub-basin's geographical extent, riverine network, and wetland formations, underscoring its importance as a major tributary to the Nile Basin.

3.1.2. Blue Nile Sub-basin

The Blue Nile Basin is situated in the northeastern part of the African continent, primarily within the borders of Ethiopia, South Sudan, and Sudan. Geographically, the basin is located between the following UTM coordinates: Northern Boundary: E: 450,000 m, N: 2,000,000 m; Southern Boundary: E: 400,000 m, N: 900,000 m; Eastern Boundary: E: 500,000 m, N: 1,300,000 m; Western Boundary: E: 350,000 m, N: 1,100,000 m. It is bordered by the Tekeze-Atbara sub-basin to the north, the Main Nile sub-basin to the west, and the Baro-Akobo-Sobat sub-basin to the south. The basin's eastern boundary is defined by the crest of the Ethiopian Highlands, a prominent topographic feature that plays a crucial role in the basin's hydrology and climate (Kebede, 2013).

3.1.3. Tekeze-Atbara Sub-basin

The Tekeze-Atbara sub-basin covers an area of 227,128 km², including the Mereb-Gash basin. This sub-basin extends from northwestern Ethiopia to the lowlands of Sudan, meeting the Main Nile approximately 285 km downstream of Khartoum. In Ethiopia, the Tekeze River travels more than 750 km from its source near Lake Ashange to the border with Sudan. In Sudan, the river extends another 575 km in a northwesterly direction.

3.1.4. Main Nile Sub-basin

The Main Nile area is located in the northern part of the Eastern Nile Basin, extending from the confluence of the Blue Nile and White Nile at Khartoum to the Mediterranean Sea. This area covers 899,496 km², accounting for about 47% of the total area of the Eastern Nile Basin.

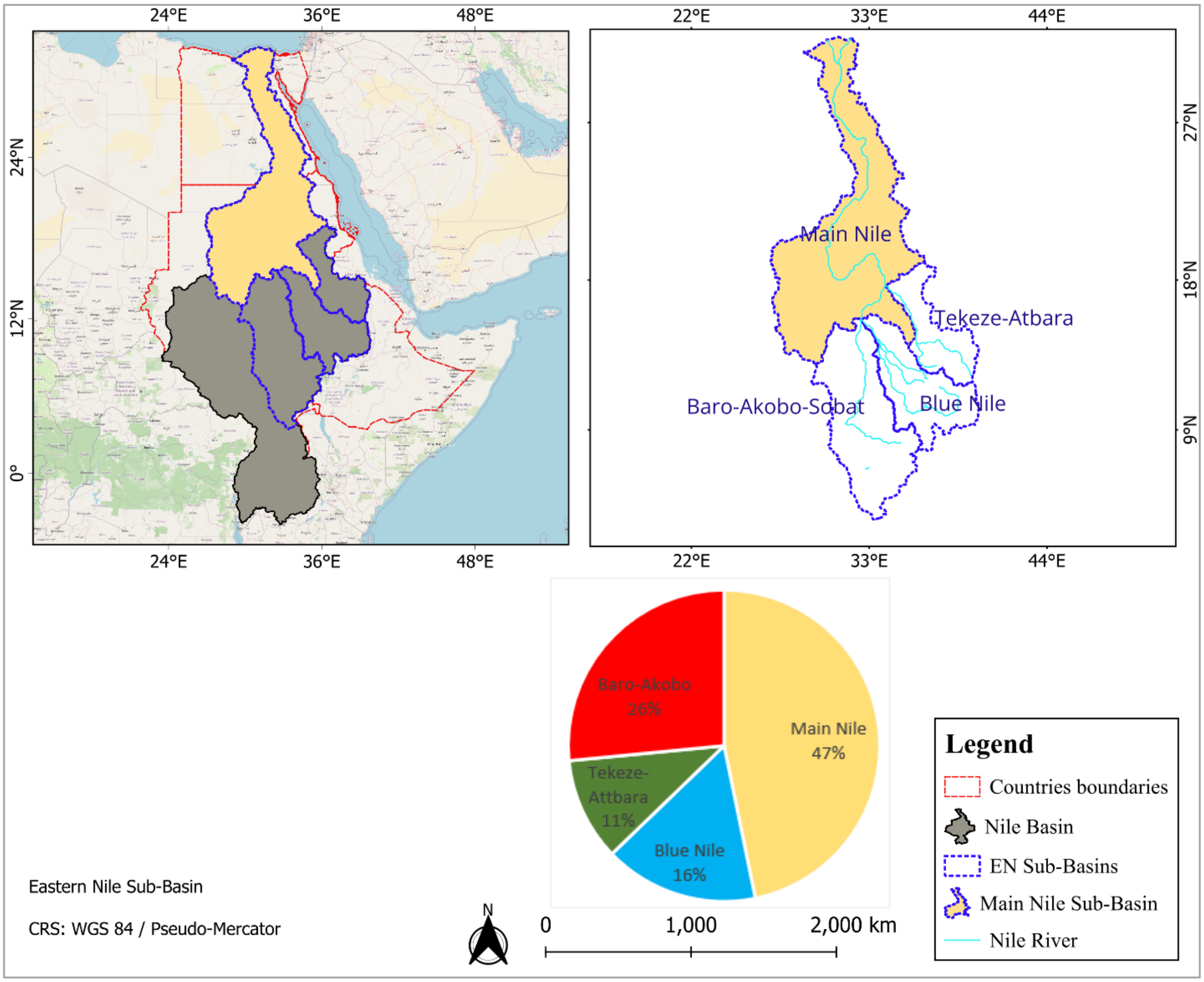


Figure 5: Eastern Nile Basin Study Area

3.2. Methodology flowchart

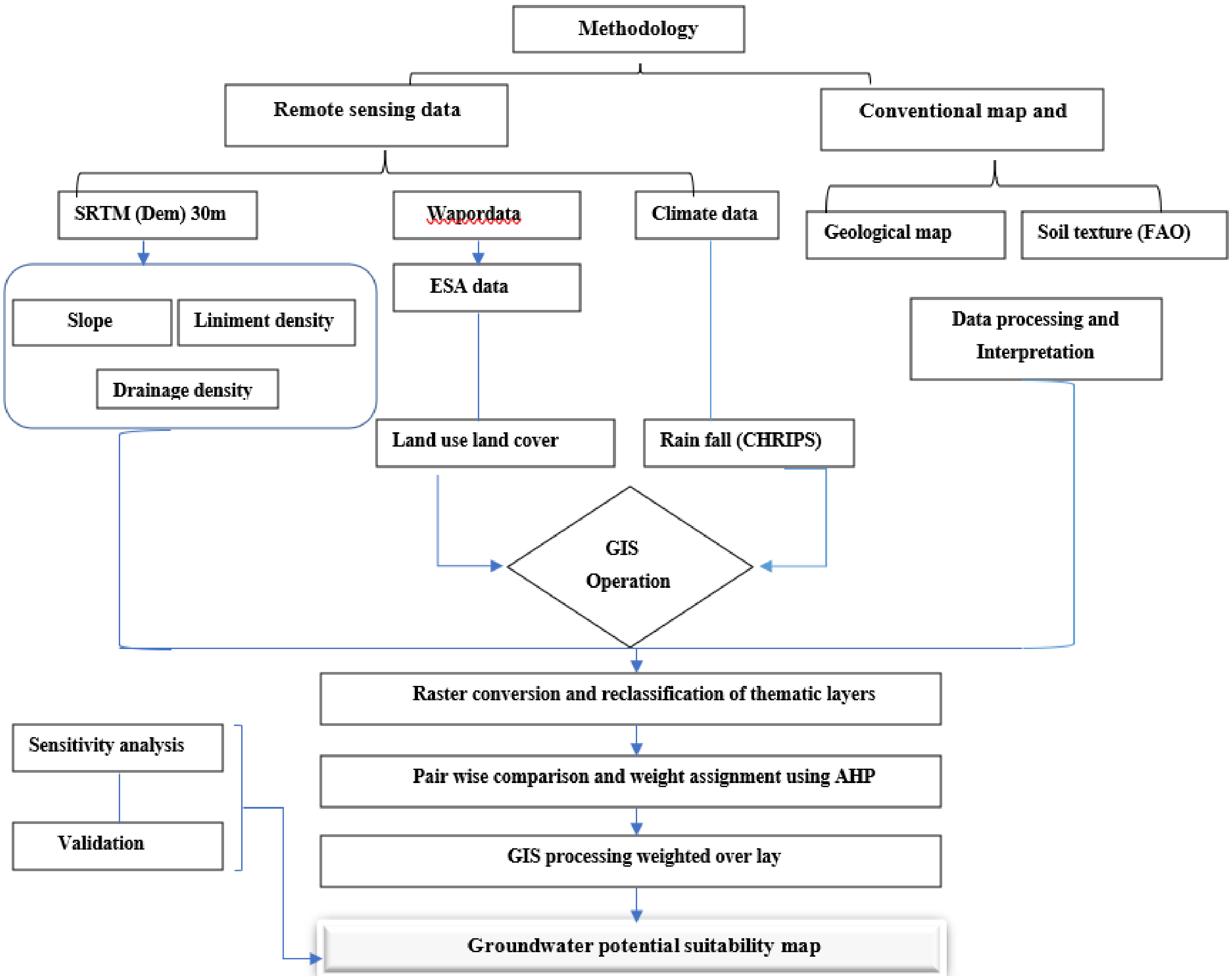


Figure 6: Flow chart of the methodology

3.3. Data acquisition and pre-processing

To produce the groundwater potential zone map, seven thematic layers were utilized, incorporating remote sensing data and GIS software for data pre-processing. These layers include Geology, Soil Texture, Slope, Lineament Density, Drainage Density, Land Use and Land Cover (LULC), and Rainfall. The following sections will provide detailed discussions on each of these layers, focusing on their data sources and resolutions for the four sub-basins: BAS, Blue Nile, Tekeze-Atbara, and Main Nile.

3.3.1. BAS sub-basin

3.3.1.1. Lithology

Groundwater availability in any region is heavily influenced by its geological composition. This study explores the impact of diverse geological formations on groundwater potential within the Eastern Nile Basin. Geological layers play a critical role in both the presence and movement of groundwater. Porous and permeable formations, characterized by interconnected spaces, facilitate water storage and allow for its easy movement. Conversely, less permeable formations like clay or dense rock impede water infiltration and movement. To assess the geological influence on groundwater in the Eastern Nile Basin, geological data was obtained from the Nile Basin Initiative's ENTRO. This data was then compared with a geological map from the United States Geological Survey (USGS) to ensure consistency and completeness. The analysis revealed a wide range of geological formations within the basin, that include Cambrian sedimentary rock, massive sandstone, Cenozoic volcanic rock (multiple occurrences), Cretaceous-Carboniferous sandstone, Recent alluvial deposits, Pleistocene undifferentiated deposits, Precambrian basement rock, Quaternary alluvial deposits, Quaternary volcanic rock, Tertiary Nubian Deposits and Tertiary Ashenege Formation (igneous) as shown in the figure 6 below. Given the diverse nature of these formations and their varying impact on groundwater, a reclassification scheme was implemented. The geological layers were grouped into five categories based on their ability of the rock to allow water to percolate through its pores and fractures and the likelihood of infiltrated water reaching the groundwater table. Each reclassified category was assigned a specific score or weight, reflecting its relative influence on groundwater occurrence. Formations with high infiltration capacity and recharge potential received higher weights, while those with limited capacity were assigned lower weights.

3.3.1.2. Soil Texture

Soil is a natural resource that is an influential factor in delineating groundwater potential zones Soil characteristics play a significant role in delineating zones with varying groundwater potential within the Eastern Nile Sub-basin. The study identifies five primary soil types in the sub-basin: sand, sandy loam, clay, loam, and clay loam. These soil types have varying infiltration rates, which directly affect groundwater recharge. Sand: Due to its large grain size and pore spaces, sand exhibits a very high infiltration rate. This allows for rapid infiltration of rainwater, promoting significant groundwater recharge and leading to areas with high groundwater potential. Sandy Loam: A mixture of sand and finer particles, sandy loam offers a good balance between infiltration and water holding capacity. This translates to moderate to high groundwater potential, Loam: Loam is a balanced mixture of sand, silt, and clay, offering moderate infiltration rates. Depending on the specific composition, loam can have moderate groundwater potential, Clay: Clay particles are very small and tightly packed, resulting in a low infiltration rate. This limits rainwater infiltration and reduces groundwater recharge, leading to areas with low groundwater potential and Clay Loam: A combination of clay and loam, clay loam exhibits infiltration rates that fall between clay and loam see figure 6 below. Depending on the clay content, clay loam can have low to moderate groundwater potential. The ArcGIS tool was used to reclassify soil texture into five classes representing different groundwater potential zones. This classification ranges from very high potential, high potential, moderate potential, low potential and very low potential.

3.3.1.3. Slope

Slope, or the steepness of the land, is a crucial factor influencing groundwater availability. It affects how much rainwater infiltrates the ground and replenishes aquifers. Gentle slopes allow for gradual surface runoff. Rainwater has more time to soak into the ground, promoting greater infiltration and potentially higher groundwater recharge. Steeper slopes, on the other hand, encourage faster and stronger surface runoff. Rainwater has less time to infiltrate, leading to less infiltration and potentially lower groundwater recharge. A Digital Elevation Model (DEM) from the USGS, essentially a detailed map of the land's surface elevation, was used to create a slope map of the area. This DEM has a high resolution of 30 meters, meaning it captures even small changes in elevation. The slope map was then classified into five categories using ArcGIS software: very steep slope, steep slope, moderate slope, gentle slope, and flat slope see figure 6 below. Finally, weights were assigned to each slope category in an ArcGIS table based on their impact on potential groundwater occurrence. Steeper slopes received lower weights due to less infiltration, while gentler slopes received higher weights for promoting infiltration.

3.3.1.4. Lineament Density

Lineaments are elongated, linear features visible on satellite imagery or aerial photographs. These features often have a geological origin, meaning they reflect underlying structures in the Earth's crust. Lineaments can form in various ways, including: Structural zones: These are zones of weakness in the rock caused by major geological events, Fracture zones: Areas where the rock has been broken and cracked, Fault-aligned features: Linear features associated with faults, which are zones of movement between rock masses and Zones of increased permeability and porosity: Lineaments can sometimes indicate areas where the rock is more fractured or weathered, allowing water to flow more easily. High lineament density can indicate zones of increased fracturing and permeability in the underlying rock. These fractured and permeable zones can act as pathways for groundwater flow and storage, potentially leading to higher groundwater potential. ArcGIS tools were used to reclassify the lineaments density into five categories: very low, low, moderate, high, and very high density see the figure 6. This classification helps identify areas with varying degrees of potential for groundwater occurrence based on the presence and concentration of lineaments.

3.3.1.5. Drainage Density

Drainage density refers to the concentration of streams within a specific area. It essentially describes how closely spaced streams are in a watershed. This factor is inversely related to permeability, a measure of how easily water can flow through rock or soil. In areas with low permeability (water has difficulty infiltrating), streams tend to be closely spaced (high drainage density) as surface runoff dominates. Conversely, areas with high permeability (water infiltrates easily) often have fewer streams (low drainage density) because more water infiltrates the ground. This analysis used ArcGIS's "spatial analysis hydrology tools" to extract the stream network from a Digital Elevation Model (DEM). A DEM is a digital representation of the Earth's surface topography. By analyzing the extracted stream network, drainage density was calculated and classified into five categories based on their impact on groundwater occurrence**.** This classification helps identify zones with varying groundwater potential see the figure 6 hereunder.

3.3.1.6. Land Use/Land Cover

Land use and land cover significantly impact the hydrological processes within a watershed or sub-basin. Areas with low permeability, like settlements or barren land, generate more surface runoff as water struggles to infiltrate the soil as shown in the figure 6 below. Conversely, areas with high permeability, like cropland with vegetation, allow for greater water infiltration, replenishing groundwater. Land cover directly influences groundwater recharge. Areas with high infiltration promote groundwater recharge, while areas with high runoff limit it. Land use and land cover datasets were obtained from the ESA World Cover. The land use/land cover map was reclassified into five classes/ranks. Wetland received a high score, whereas barren land and settlements with low permeability received a lower score. Land use/land cover was clipped, projected, and weighted in ArcGIS' attribute table.

3.3.1.7. Rainfall

Rainfall is a critical factor influencing groundwater potential because it represents the primary source of water that replenishes aquifers see fig 6. During periods of high rainfall, a greater volume of water infiltrates the ground, replenishing aquifers and increasing groundwater storage. Conversely, low rainfall periods lead to less infiltration and potentially a decrease in groundwater levels. The rainfall map was projected after being cropped to the Baro-Akobo-Sobat sub-basin extent and was collected in millimeters and reclassified into five classes according to natural breaks.

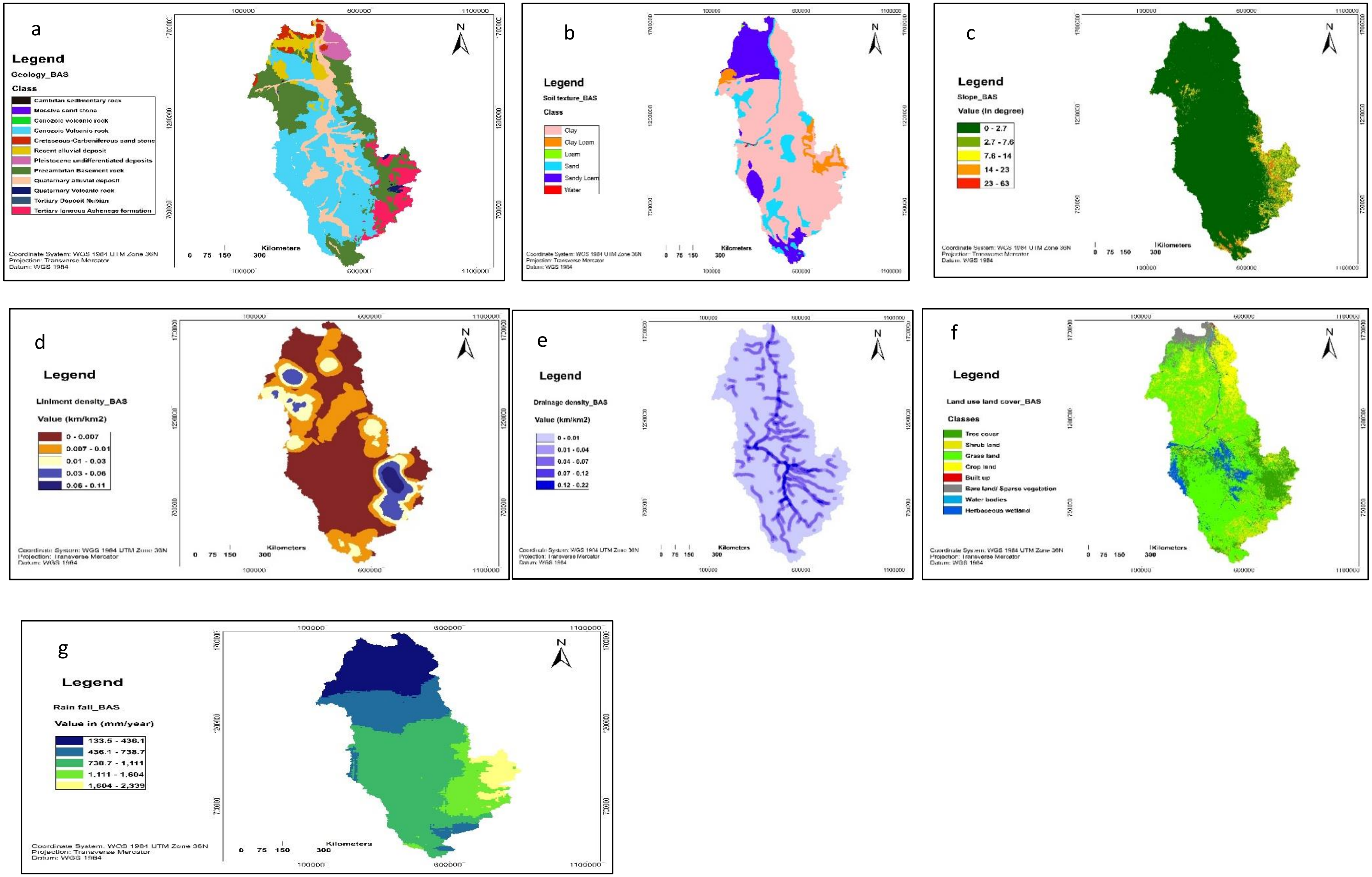


Figure 7: a) geology b) soil texture c) slope d) liniment density e) drainage density f) LULC g) rainfall.

Table 4: Reclassification (Suitability Levels of Class for Groundwater Occurrence)

Criteria	**Reclassification values and suitability level of sub-factors for groundwater occurrence**					**Weight in %**
	1	**2**	**3**	**4**	**5**	
Geology	Precambrian Basement rock	Csed, MS, Pl und deposit	Cretaceous-carboniferous Sandstone, CVR	QAD, TIAF, RAD, QV	Nubian Tertiary Deposit	30.2
Soil	Clay	Clay loam	Loam	Sandy loam	Sand, water body	26.1
Slope	Very steep slope (62.7)	Steep slope (47.1)	Moderate slope (31.4)	Gentle slope (17.7)	Flat slope (0)	18.3
LD	Very low density (0.0)	Low density (0.028)	Moderate density (0.056)	High density (0.084)	Very high density (0.11)	10.7
DD	Very low drainage (0.0)	Low drainage (0.06)	Moderate drainage (0.11)	High drainage (0.17)	Very high drainage (0.23)	6.1
LULC	B, B/SV	Grassland	Cropland	Sh, TC	PWB, HWe	5.3
Rainfall	Very low rainfall (133.5)	Low rainfall (684.8)	Moderate rainfall (1236.0)	High rainfall (1787.3)	Very high rainfall (2338.5)	3.3

LD: Lineament Density, DD: Drainage Density, LULC: Land Use/Land Cover, C Sed: Cambrian sedimentary rock, B: Built-up, Bare/Spare Vegetation, Sh: Shrubland, TC: Tree Cover, PWB: Permanent Water Bodies, HWe: Herbaceous Wetland, CVR: Cenozoic Volcanic Rock, MS: Massive sandstone, PL: Pleistocene undifferentiated deposit, QAD: Quaternary Alluvial Deposit, TIAF: Tertiary Igneous Ashenege Formation, RCD: Recent Alluvial Deposit, Quaternary Volcanic

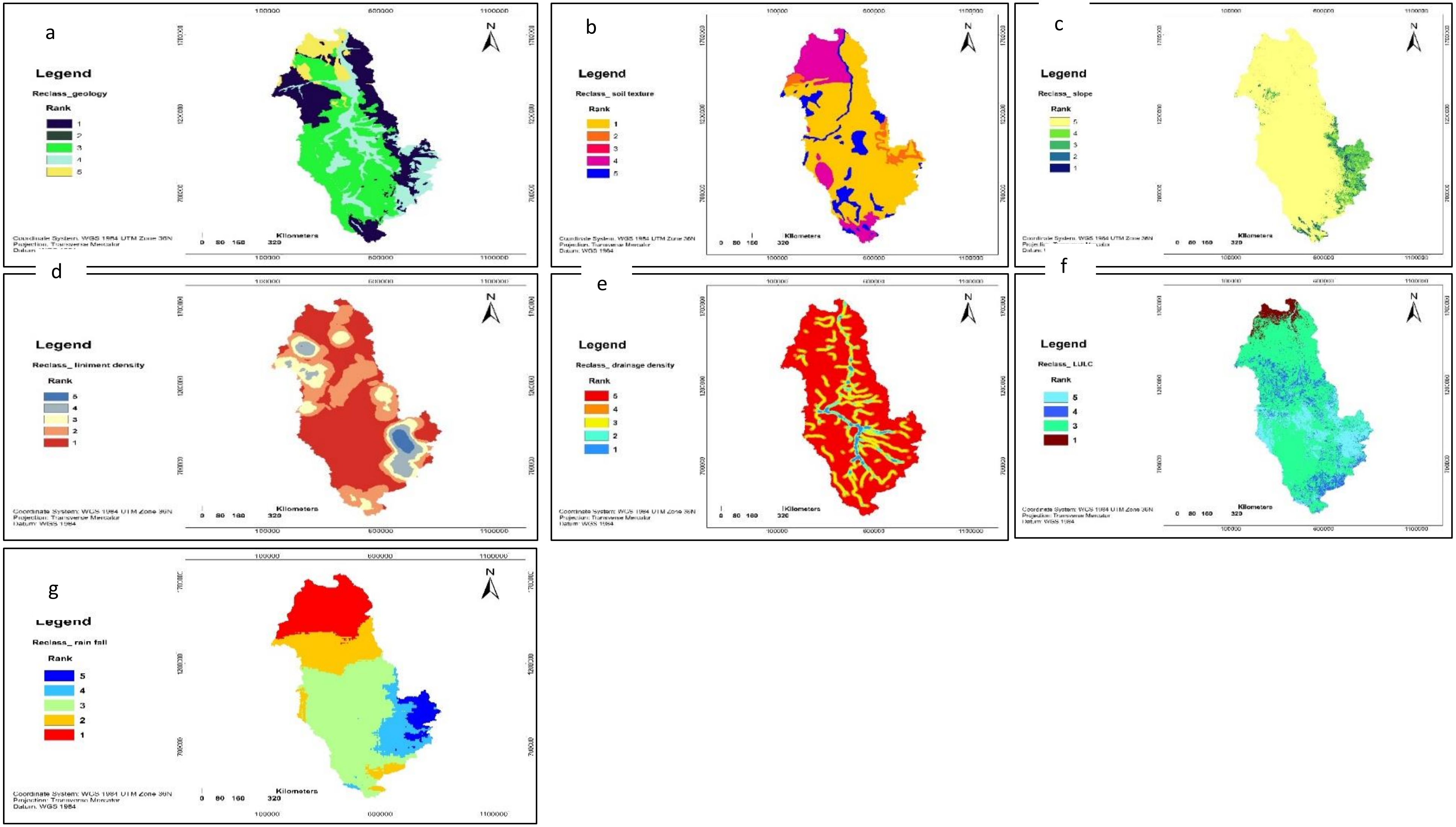


Figure 8: a) reclassified geology b) reclassified soil c) reclassified slope d) liniment density e) drainage density f) LULC g) rain fall.

3.3.2. Blue Nile sub-basin

The geospatial database is prepared for each thematic map: drainage density, slope, LULC, soil texture, geology, and rain fall. All sets of information were generated from multiple data sources and contain satellite images, topographical, geology maps, borehole data, and other ancillary information (Table 5). Administration and basin boundary, and rivers are adopted from the Eastern Nile Technical Regional Office (ENTRO). The LULC features were demarcated using the Wapor (30 m resolution) satellite. The topography and characteristics of the basin are delineated in the map format using the SRTM DEM data (30m) in ArcGIS (version 10.8) software. Furthermore, the soil characteristics of the catchment were taken from the FAO. The borehole pumping test data for validation is collected from Ministry of Water, Energy, and Gondar University.

Table 5: Details on the data sources used

S. No	Input data	Resolution	Data sources
1	Geology	100 × 100 m	USGS, ENTRO
2	Soil	100 × 100 m	FAO
3	Slope	100 × 100 m	SRTM (Dem 30m)
4	Liniment	100 × 100 m	SRTM (Dem 30m)
5	Drainage density	100 × 100 m	SRTM (Dem 30m)
6	LULC	100 × 100 m	Wapor, ESG
7	Rainfall	100 × 100 m	CHRIPS

3.3.2.1. Lithology

Lithology is one of the governing factors of groundwater that is included in groundwater investigations and substantially affects the extent and occurrence of groundwater (Tamesgen, Atlabachew, and Jothimani 2023a). Lithological control reveals several classifications of landforms, geomorphic features, and the subsequent hydrogeological settings which aid in the interpretation of the structures, as well as lithological composition governing groundwater distribution (Mir et al. 2021). Geological characteristics are important in terms of reflecting aquifer status, which shows groundwater storage (Duguma and Duguma 2022b). The lithological units in the catchment are further classified into four major groups based on their hydraulic properties, which affect their relative hydrogeological importance and productivity (Fig. 8 a): (i) pre-Cambrian basement (ii) Tertiary volcanic sequence and quaternary volcanic rocks (iii) Mesozoic formations; and (iv) Quaternary alluvial deposit.

The basement complex of metamorphic rocks consists of high- low-grade rocks like biotite gneiss and hornblende-biotite gneiss (pre-cambrian basement), low-grade meta sedimentary and meta volcanic rocks on the western part of the catchment and it covers 32.2% of the total area and distributed in the western and southern part of the catchment (Fig. 8 a). Tertiary volcanic sequence and quaternary volcanic rocks covers most Part of the study area. The tertiary volcanic episode was characterized by the extrusion of flood tholeiitic to alkaline lava flow, with highly variable magmatic characteristics. Due to the occurrence of distinct volcanic events and their large extent, variations on composition, structure and degree of weathering are observed throughout the study area. The tertiary Igneous Ashenege formation covers the north- eastern part of the study area with a 32.4% total coverage. Cenozoic volcanic rock covers 7.3% of the area located on the western part of the study area and transitional basalt covers 2% of the study area located in the eastern and central part of the catchment. Quaternary volcanic rock covers 4% of the catchment distributed in the northern part around Lake Tana and some part of the east. The quaternary alluvial formation s and mesozoic formations covers the rest part of the catchment covering 20.8% of the total area and it is distributed in the western and eastern part of the catchment. The geological structure of the catchment is affected by normal faults in the Early–Late Oligocene basalts are dominantly N- to NE-trending and less often NW-trending. These faults have throws ranging from a few cm to 50 m, and rarely 400m, with fault zones ranging between a few cm and 50m wide. The dominant fractures are dilatational and are NNE and E-trending with subordinate NW-trending set ((NBI) and (ENSAP) 2019).

3.3.2.2. Slope

The slope is a crucial component that regulates groundwater infiltration into subsurface formations and serves as an indicator for delineating the MAR potential zone (Vishwakarma, Goswami, and Pradhan 2020). The slope directly affects the process of runoff and infiltration (Arya, Subramani, and Karunanidhi 2020). Steep slopes facilitate higher runoff rates; because of this, water runs off on soil rather than penetrates it. Gentle slopes enable water to have more time to infiltrate the soil ((Sandoval and Tiburan 2019). The slope is function of geomorphology of area, it regulates groundwater infiltration into the subsurface and recharge processes (Ababulgu 2022a). The slope ranges from (0 – 73.8.3º) in which the flat to gentle slope covers (78.5 %) of catchment and the very steep to steep slopes cover (10 %) of the catchment area. The moderate slope area covers

11% of the total study area. In the catchment, the slope gradually decreases from the east to the west (Fig. 8 b).

3.3.2.3. Soil texture

The soil zone manages the entry of surface water into the subsurface aquifer system and also governs the rate of percolation and hydraulic conductivity (Arya, Subramani, and Karunanidhi 2020b). Soil texture gives indications of the amount of water that can infiltrate through the unsaturated zone to reach the aquifer and different soil texture is important factor that determines potential or rate for groundwater recharge process (Ababulgu 2022b). The optimal soil for GWP will have a high infiltration rate, whereas soils with poor infiltration are not regarded as suited for GWP (Kumari et al. 2021). For this criterion, the parameters are taken from the FAO soil texture classification (Schad 2016), and the associated infiltration rate is used to standardize the soil texture criterion. The catchment area comprises soil textures such as clay 64%, which covers most part of the catchment, clay loam 16.4%, loam 9.4%, sandy loam 8%, and the rest group 1.6% (Fig. 8 d). The coarse texture soil is permeable whereas fine texture soil has less permeability. The highly permeable soil allows the surface water to infiltrate into the subsurface at a rapid speed (Rajapaksha et al. 2016).

3.3.2.4. Rainfall

The rainfall factor, has been established as the main driver of the entire hydrology process as well as the major source of recharge and the amount of water that would be percolating into the groundwater system as the major source of recharge is largely a function of the amount of precipitation/rainfall (Mogaji et al. 2016). Variations in rainfall have an impact on stream discharge, which affects the potential water supply for GWP (Varouchakis et al. 2023a). The normal yearly rainfall in the high slopping regions is generally more than the zone with lower slopping regions(Ababulgu 2022b). The study area rainfall is divided into five zones as very low, low, moderate, high and very high from highest to lowest. It clearly shows that most parts at middle and upstream area classified as extremely high and high potential while less parts towards the downstream area (Fig. 8 g). The annual catchment rainfall ranges from (141.8–2412.8 mm/year). The areal rainfall distribution is classified into five as (141.8 - 551.5), (551.5 - 925.6), (925.6 - 1,246.2), (1,246.2 - 1,629), and (1,629 - 2,412.8) mm/year as very low, low, moderate, high, and very high, respectively. Low rainfall shows low recharge indicating low groundwater potential zones, while the excessive rainfall quantities suggest the chance of high recharge, the potentiality of high groundwater zones. The catchment zones that obtained high rainfall have a chance of getting more percolated water than with low rainfall. In contrast, the high rainfall class is given high ranks as of its significance for groundwater recharge potentiality of the aquifer system. Rainfall infiltrates if the soil has sufficient permeability or goes away as overland flow based on the aquifer's nature and slope of the area (Mengistu et al. 2022b) . Therefore, it is reasonable to account for precipitation to determine its influence on groundwater recharge. Similar studies confirmed that rainfall is a critical parameter governing the groundwater potential recharge (Mengistu et al. 2022b).

3.3.2.5. Land use and land cover (LULC)

An important component in determining the potential for groundwater recharge is the permeability of the top surface, which is altered by LULC changes brought on by anthropogenic activities (Kariyawasam et al. 2022). Land use and land cover are also the key factors that need to be considered for GWP potential selection (Thilagavathi, Subramani, and Suresh 2015). It is an important parameter for groundwater recharge because it controls the groundwater infiltration in the area (Sandoval and Tiburan 2019). The effect of various LULC categories, for example, farmland, grassland, bare soil, water bodies, and built-up areas, on runoff depth generation differs greatly (AL-Shammari et al. 2021). The LULC map was further classified based on suitability for GWP. The final LULC map (Fig. 8 c) is prepared which contains eight representative major classes in the Blue Nile catchment (Tree cover, shrub land, grass land, crop land, built up, bare land/ Sparse vegetation, Water bodies and Herbaceaus wet land). Cropland covers most of the catchment area (41.1%), followed by grass land (25.2 %), shrub land (15 %), tree cover (13.4 %), bare land (3.1%), water bodies, wet land (1.6%), and built up (0.2 %). The distribution of the LULC is expected to enhance the groundwater recharge depending on the underlying soil and geologic conditions (Mengistu et al. 2022b). Agricultural land (crop land) has high groundwater potential with more porosity increasing soil water percolation (Mengistu et al. 2022b). An intense agricultural activity changes the hydrologic cycle by causing soil moisture conditions and recharge. Waterbodies are the most fundamental and permanent source of groundwater recharge. Forest-mixed sites have lower groundwater recharge rates than grassland increases groundwater recharge and reduce the runoff process by increasing infiltration rates, thereby augmenting groundwater recharge. On the other hand, built areas generate runoff having poor groundwater recharging potential. Other studies have agreed that land use covers are essential in delineating potential groundwater zones (Mengistu et al. 2022b).

3.3.2.6. Drainage density

The total length of all the streams in a given area (stream network) can be considered the drainage density (Sardar et al. 2022). It can serve as a surface runoff and infiltration indicator. An area with a very high drainage density represents more closeness of drainage channels and high runoff, while a lower DD indicates lower run-off and a higher probability of recharge and groundwater potential (Gebeyehu et al. 2023b). Permeability is associated with high drainage density, which reduces infiltration and increases runoff, Permeability has an inverse relationship with drainage density. As pointed out by (Hussaini et al. 2022), high drainage densities imply favorable conditions for runoff and, therefore, low recharge for GWP implementation. As stated by (Anand et al. 2021), zones with low drainage density have higher importance for GWP siting, whereas zones with high drainage density received lower importance value. Utilizing the line density, the drainage density was created from the SRTM-DEM. The drainage density (km/km^2) was calculated using Eq. (1):

$$\text{Drainage Density} = \frac{\sum L_i}{A} \qquad (1)$$

Where Li, denotes the length of drainage of all streams in kilometers, and A denotes the area of the catchment in square kilometers (Hussaini et al. 2022). Accordingly, the drainage density of the catchment ranging from (0 – 0.20 km/km^2). Indicating, the lowest drainage density covers 74.4% of the catchment area and ranging from (0 – 0.01 km/km^2) and the highest drainage density covers (13.5%) of the catchment area ranging from (0.07 – 0.20 km/km^2 (Fig. 8 e).

3.3.2.7. Lineament density

Lineaments are the essential structural features observed for the process of groundwater movement, and they mainly depend upon the permeability and porosity of the rock material, resulting from the geological phenomena of the fold, fault, fractures etc. Lineaments and fractures are the influencing factors for the groundwater recharge and movement (Anand, Karunanidhi, and Subramani 2021b). Lineaments are linear, rectilinear, and curvilinear features of tectonic origin, which can easily observe in the satellite imagery, and it may characterize master joints, fractures, faults, topographic linearity and formation, vegetation cover, infrastructures like road and bridges, valleys and straight course of streams, and boundaries between the different lithological units (Duguma and Duguma 2022b). Lineament density (LD) is directly relational to the groundwater perspective (Mengistu et al. 2022b). The lineament density of the catchment was defined as the sum of all the measured lineaments divided by the catchment area (Tamesgen, Atlabachew, and Jothimani 2023b). These fissures aid the subsurface penetration of surface runoff and are crucial for groundwater flow and storage. Most geological linear features are located in areas where the bedrock is fractured and in states where it is porous and permeable, which can lead to the increased well output (Tamesgen et al. 2023b). The line density function of the ArcGIS spatial analysis tool created a lineament density map of the blue nile area. The equal-interval method was used to redistribute the lineament density map. Generating lineaments must be used to establish the direction of the groundwater circulation within the catchment. Those with a low lineament density are less favorable for groundwater recharge and discharge, whereas areas with a high lineament density are acceptable for both—jointed and sheared zones with good groundwater conduction. The lineament density map was reclassified into five categories, (Fig. 8 d). Accordingly, the liniment density of the catchment ranging from (0 – 0.09 km/km^2). Indicating, the lowest liniment density covers 75.3% of the total basin area and ranging from (0 – 0.01 km/km^2) and the highest liniment density covers (10%) of the basin area ranging from (0.03 – 0.09 km/km^2).

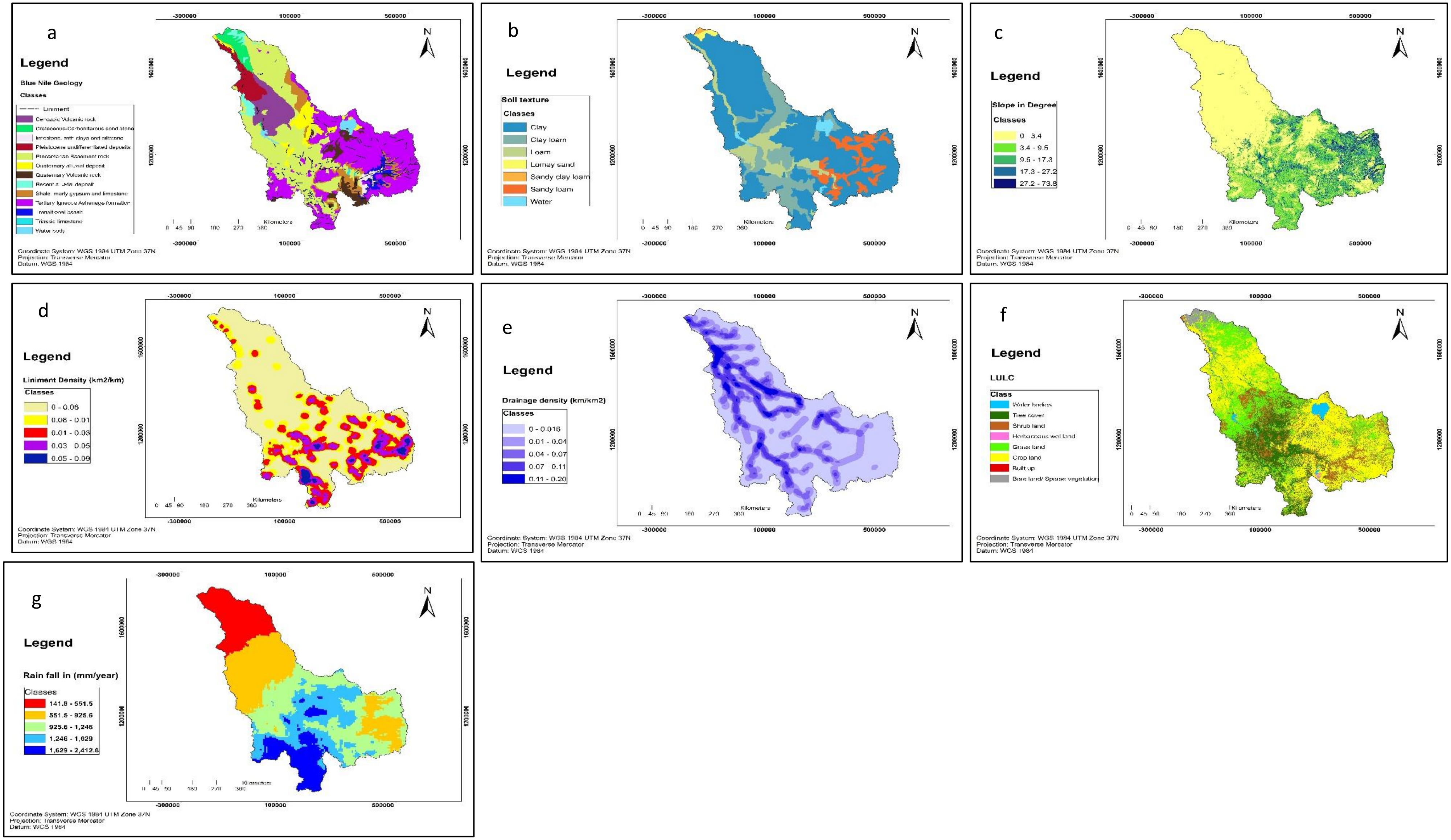


Figure 9: a) Geology b) Soil texture c) Slope d) Liniment density e) Drainage density f) LULC g) Rainfall

Table 6: Weight and ranks given for the thematic map classes using AHP

Thematic maps	Assigned weight (%)	Class	Potential for GWP	Assigned rank	Thematic maps	Assigned weight (%)	Classes	Potential for GWP	Assigned rank
Geology	30.2	Recent alluvial deposit	Very High	5	Slope	18.3	0 - 3.4^0	Very high	5
		Quaternary alluvial deposit, Quaternary, Volcanic rock and Tertiary Igneous Ashenege formation	High	4			3.6 - 9.5^0	High	3
		Cenozoic Volcanic rock, Cretaceous-Carboniferous sand stone, Transitional basalt and Triassic-limestone	Medium	3			9.5 - 17.3^0	Moderate	2
		Shale, marly gypsum and limestone, limestone, with clays and siltstone and Pleistocene undifferentiated deposits	Low	2			17.3 - 27.2^0	Low	1
							27.2 - 73.8^0	Very low	
		Precambrian Basement rock	Very Low	1	Liniment density	10.7	0.05 - 0.09 km/km^2	Very High	5
Soil texture	26.1	Sandy loam and Loamy sand	High	4			0.03 - 0.05 km/km^2	High	4
							0.018 - 0.03 km/km^2	Medium	3
		Loam and Sandy clay loam	Medium	3			0.006 -0.018 km/km^2	Low	2
		Clay loam	Low	2			0 - 0.006 km/km^2	Very Low	1
		Clay	Very Low	1	Rain fall	3.3	1,629.1 - 2,413 mm/year	Very High	5
Drainage density	6.1	0 - 0.016 km/km^2	Very High	5			1,246 - 1,629 mm/year	High	4
		0.016 - 0.04 km/km^2	High	4			925.6 - 1,246 mm/year	Medium	3
		0.04 - 0.074 km/km^2	Medium	3			551.5 - 925.6 mm/year	Low	2

		0.074 - 0.11 km/km^2	Low	2			141.8 - 551.5 mm/year	Very Low	1
		0.11 - 0.20 km/km^2	Very Low	1					
LULC	5.3	Water bodies, herbaceous wet, and tree cover land	Very high	5					
		Shrub land	High	4					
		Grass land and Crop land	Medium	3					
		Built up and Bare land/ Sparse vegetation	Very Low	1					

Each parameter was reclassified based on its relative influence on GWP. For lithology, the type and composition of rock significantly affect the infiltration rate and groundwater recharge. In the Blue Nile basin recent alluvial deposit, Quaternary alluvial deposit, Quaternary, Volcanic rock and Tertiary Igneous Ashenege formation therefore, most areas lie in the very high-to-high suitability zone for GWP. The Cenozoic Volcanic rock, Cretaceous-Carboniferous sand stone, Transitional basalt and Triassic-limestone have a moderate potential. The shale, marly gypsum and limestone, limestone, with clays and siltstone and Pleistocene undifferentiated deposits have a low potential and Precambrian basement rock have very low permeability, and limit groundwater percolation; therefore, these areas are less suitable for GWP. The lithology classes are reclassified based on their influence on GWP suitability in which the highest rank is given for more suitable lithological classes and a lesser rank for the unsuitable classes (Fig 9 a).

Areas with relatively gentle slopes were given higher weights than those on steep slopes (Fig 9 b). The areas on gentle slopes facilitate longer water retention, thus, increasing the amount of water infiltrated. The slope of (0 - 3.4^0) was given a very good suitability rank since at this condition, the land surface is relatively gentle (covers an area of 177,136 km^2). Whereas starting from (27.2 - 73.80), the slope is considered unsuitable since the land surface is highly steep (covers an area of 8334.6 km^2). When evaluating the texture of soil, one of the factors taken is the suitability to GWP. Accordingly, each class are ranked based on their influence on GWP (Fig. 9 d). Sandy loam and loamy sand has great infiltration capabilities and is given the highest rank, it covers (25830.85 km^2) whereas clay soil is given the lowest rank (covers an area of 196829.12 km^2).

The catchment was reclassified based on its infiltration capacity of the different land use land cover types (Fig. 9 c). The land cover influences surface runoff and infiltration and gives information relative to the availability of land for the implementation of GWP zonation. The water bodies (18164.1 km^2), herbaceous wet land (322949.8 km^2), and tree cover (698401.6 km^2) and shrub land covering an area of (658172.64 km^2) were ranked as the most suitable sites for GWP zonation. The built-up (5007.38 km^2) and bare land (248080.3 km^2) areas are unsuitable sites because these areas have impervious surfaces, which restrict water infiltration and generate runoff.

The drainage density is also one of the controlling factors for GWP suitability (Fig. 9 e). Low-density areas were preferable sites with the highest rank (covering an area of 172996 km^2) and the high drainage density (covering an area of 9717.8 km^2) was assigned the lowest rank indicating high runoff and low infiltration, and are considered least suitable for GWP. Contrarily, a high score was assigned to low drainage density areas, indicating high suitability for GWP. For rainfall, higher values indicate higher groundwater recharge. The highest rank is given for the highest rainfall value covering an area of (35643.4 km^2) and vice versa for the lowest rainfall, value covering an area of (45133 km^2) (Fig. 9 f). For liniment density, high-density areas are considered highly suitable for GWP (Fig. 9 g). Based on this, the liniment density is ranked with the highest rank given for high dense area, which covers an area of (5907.6 km^2). Whereas, the lowest rank is given for low dense liniment and covers an area of (176438.4 km^2).

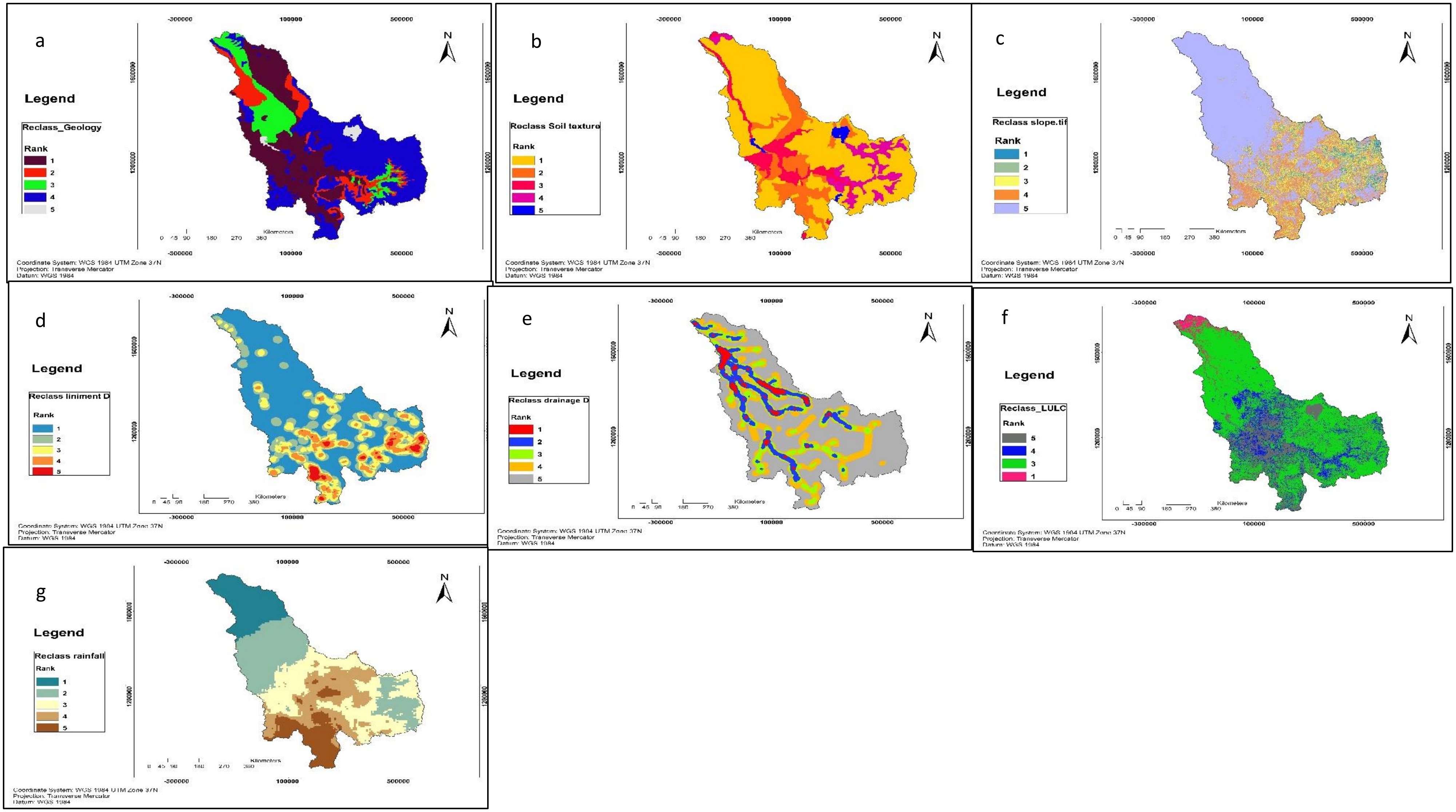


Figure 10: Reclassified Thematic layers; (a) Lithology, (b) Soil texture, (c) Slope, (d) Lineament, (e) Drainage, (f) LULC, and (g) Rainfall

3.3.3. Tekeze-Attbara

3.3.3.1. Lithology

The study area's lithology (Figure 11) is considered as one of the controlling factors influencing the groundwater flow and its existence. The serial arrangement of different rocks or lithological units and their interaction determines the area's total infiltration capacity. Porous and permeability of the litho units refer to the storage and transmitting capacity, which supports the groundwater occurrence and occurrence of an area. Delineated rock units in the study area were further classified into Eleven classes, Shale, marly gypsum and limestone, Recent alluvial deposit, Transitional basalt , Limestone-with clays and siltstone, Ordovician Limestone , Paleozoic Igneous rock, Precambrian Basement Rock , Quaternary alluvial deposit, Tertiary Igneous Ashenege formation, Triassic -limestone.The group of Quaternary alluvial deposit, Tertiary Igneous Ashenege formation it high for groundwater potential and the Precambrian Basement Rock lowest of groundwater potential, as for the rest of calcification are the moderate.

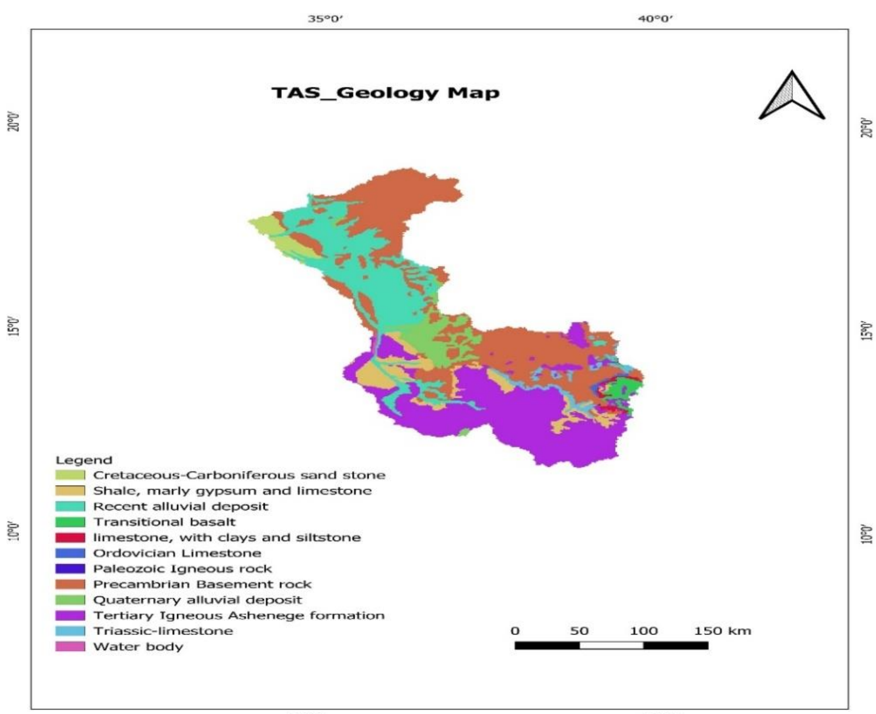


Figure 12: Geology Map of TAS

3.3.3.2. Land use land cover (LULC)

Consumption of land for different processes also affects the pattern of infiltration within that area. LULC of the study area was captured and monitored by satellite image using visual interpolation techniques in QGIS software. The LULC was categorized into eight extensive classes, namely, Tree cover, shrubland, grassland, cropland, built-up, Bare/sparse vegetation, permanent water bodies and herbaceous wetland that has been identified and demarcated, as shown in (Figure 11).

Each subclass in the land uses land cover class assigned with different weights according to their participation in groundwater infiltration. Within the subclasses, the permanent water bodies and herbaceous wetland high weighted due to less runoff, and built-up, Bare/sparse the low weight due to high runoff, and moderate to good groundwater potential can be found in the areas that cover Tree cover, shrubland, grassland, cropland.

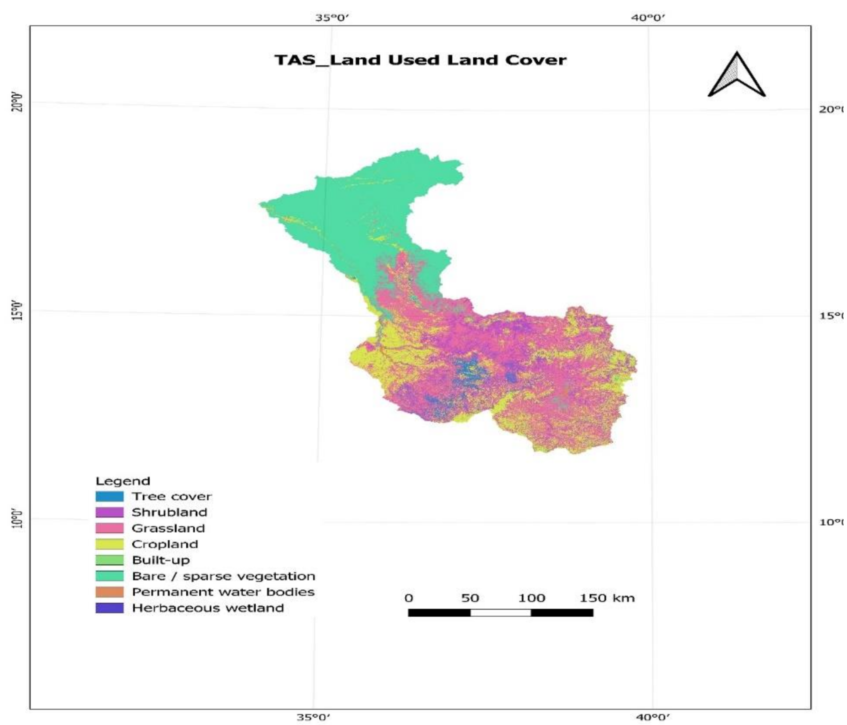


Figure 13: Land used Land Cover Map of TAS

3.3.3.3. Soil texture

Soil types of the area are playing a significant role in groundwater recharge and water holding capacity of the area. Consequently, it could be considered as one of the important factors for the delineation of groundwater potential zones. The study area consists of eight types of soil, namely clay, clay-loam, loam, sandy clay loam, sandy loam, silt loam, UWB and water, as shown in (Figure 12). Sandy group soil has a low runoff rate and high groundwater potential, whereas the clay soil group has a high runoff rate and very low groundwater.

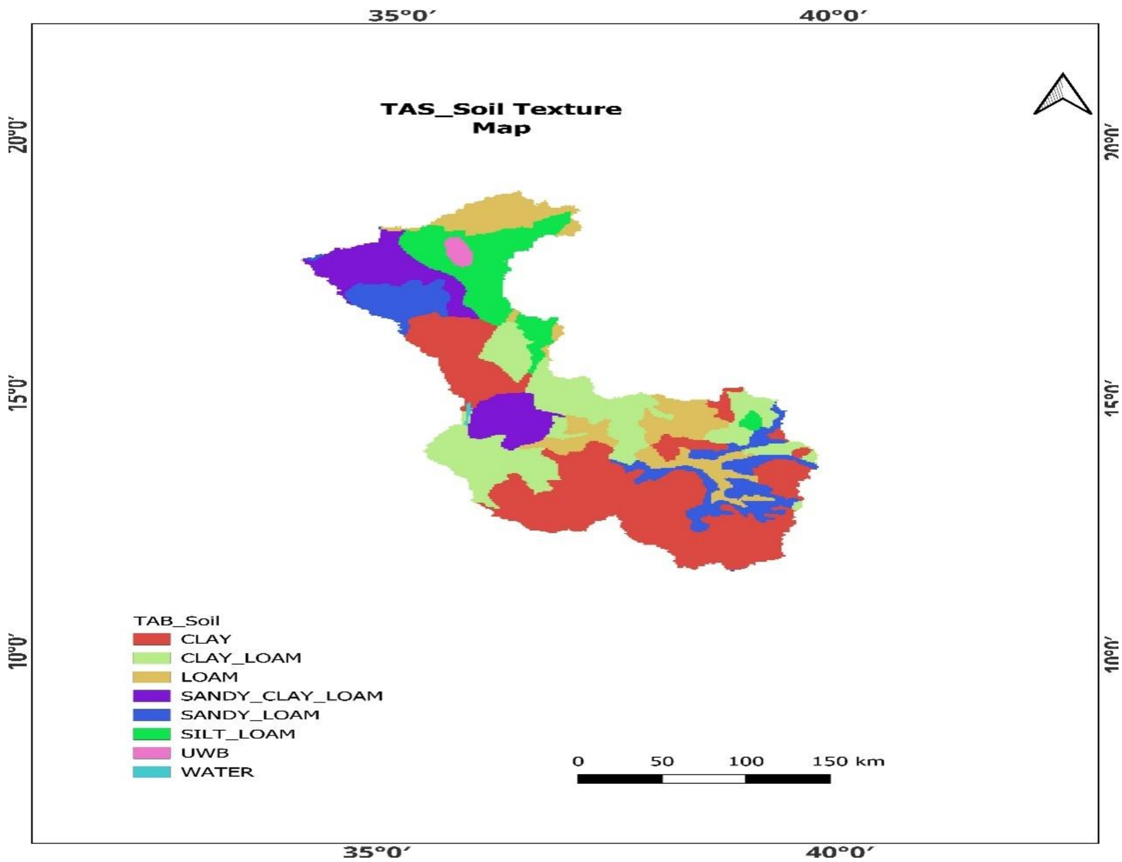


Figure 14: Soil Texture Map of TAS

3.3.3.4. Rainfall

Rainfall plays a crucial role in delineating groundwater potential and hydrological sources. the data indicates a variation in rainfall across the area, with higher amounts in the southern regions and decreasing amounts towards the northern part. This variation has been classified into five categories, with maximum and minimum rainfall values of 1914mm and 54mm, respectively, as shown in (Figure 13). In terms of analysis, the southern areas, receiving the highest rainfall, are likely to have been assigned the highest rating, reflecting their greater potential for groundwater storage and hydrological significance. Conversely, as rainfall decreases towards the northern escarpment of the basin, the assigned ratings would also decrease in correlation with this trend, indicating diminishing groundwater potential and hydrological significance in those areas.

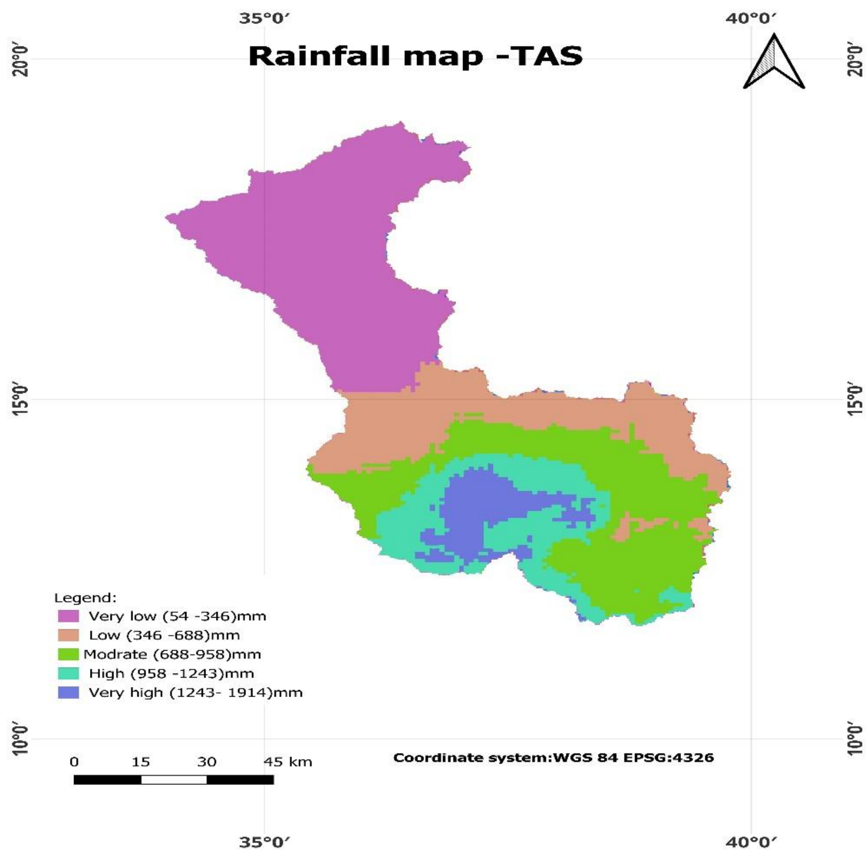


Figure 15: Rainfall Map of TAS

3.3.3.5. Drainage Density

The length of the stream to a unit area of the region is defined as the drainage density (Horton 1945; Strahler 1952). It is a suitable tool for analysis of the landform in terms of groundwater potential. The ordering of the tributary streams has been done according to Strahler's stream ordering method (Strahler 1957). The drainage network development within an area is controlled by the rock formation, which it drains, and gives some indirect information about the percolation rate. Drainage density has been divided into five, ranging from very low to very high.

Conversely, regions with high drainage density usually experience higher rates of surface runoff and lower rates of infiltration, which are less conducive to groundwater recharge. Therefore, these areas would be assigned a lower weight in the analysis because they contribute less to groundwater recharge compared to areas with lower drainage density as shown in (Figure 14).

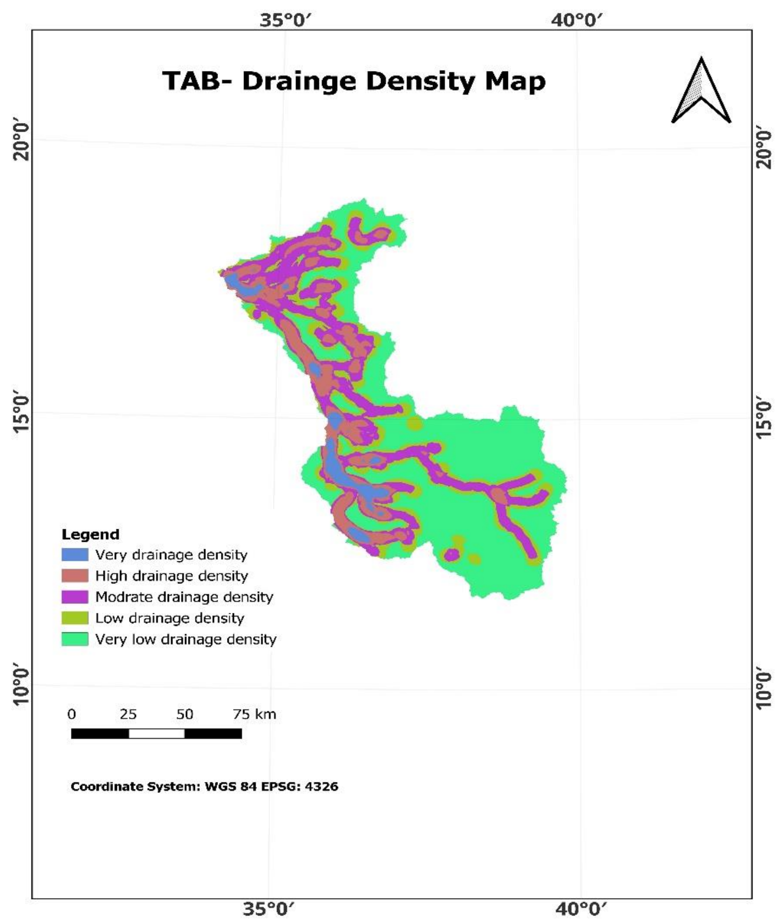


Figure 16: Drainage Density Map

3.3.3.6. Slope

The slope is an important criterion that helps to delineate the groundwater potential zone. It directly affects infiltration and surface runoff. Low/nearly level slope has high infiltration and low runoff, resulting in good groundwater recharge, while moderate to steep slope enhances surface runoff. A slope map was prepared from the SRTM elevation data with the help of ArcGIS software, the slope map is categorized into five classes, very steep slope, steep slope, Moderate slope, gentle slope and flat slope as showing in (Figure 15). Flat slope it is very low of runoff and very high infiltration of groundwater and very steep slope high runoff that mean low infiltration of the groundwater.

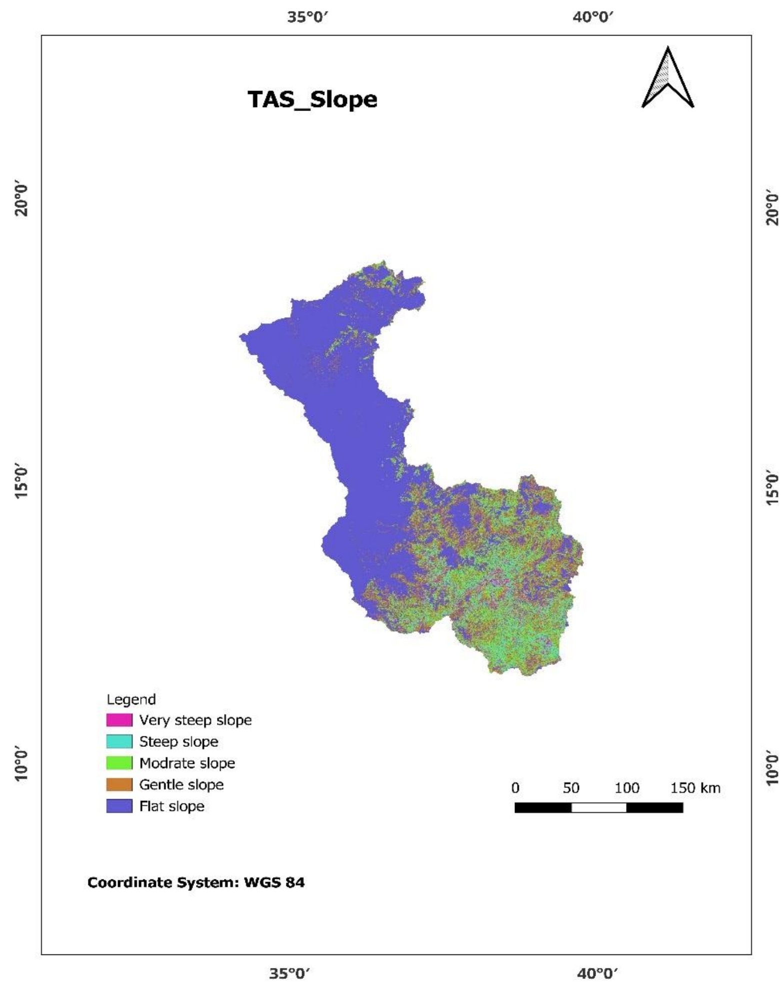


Figure 17: Slope Map of TAS

3.3.3.7. Lineament

Largely extended faults and joint systems are responsible for the occurrence of groundwater and very important for local (perched) aquifer system recharge. Lineaments are structurally controlled linear or curvilinear geological features that represent faulting and fracturing zone developed when the geologic formation is subjected for external pressure and in increased secondary porosity and permeability. The lineament density of the present study area was classified into 5 classes as showing in (Figure 16). very low, low, moderate, high and very high, very low that mean less effective and very high is more effective of the groundwater.

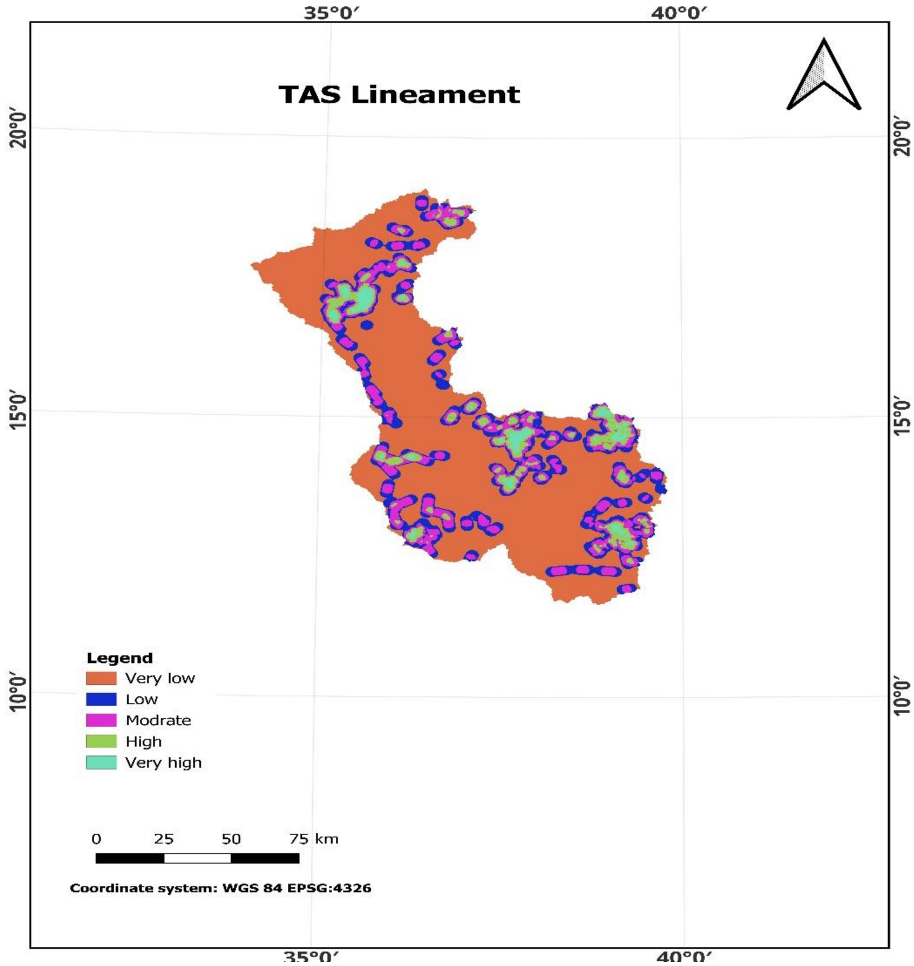


Figure 18: Lineament Map of TAS

3.3.4. Main Nile Sub-basin

3.3.4.1. Lithology data

The presence of groundwater largely depends on the underlying rock formations, as the porosity and permeability characteristics vary between different rock types. According to Deepa et al. (2016), the type of rock exposed at the surface plays a significant role in influencing groundwater recharge. The geology was obtained from ENTRO and it was compared with geology data from USGS website, see figure 17.

3.3.4.2. Soil data

The availability of groundwater is significantly affected by the infiltration capacity of the topsoil in any region (Maity et al. 2022). Therefore, soil characteristics are an essential factor in delineating groundwater potential zones (Maity et al. 2022; Melese and Belay 2022). Main Nile Catchment comprises seven major soil textural groups, including loam, sandy loam, and sandy clay loam. The predominant soil texture is sandy loam, covering approximately 49% of the total area, followed by loam at 28% and sandy clay loam at 13%, as shown in Figure 17 below. Due to variations in infiltration and porosity, soil textures are ranked based on their infiltration rates (Abrar et al. 2023).

3.3.4.3. DEM

Elevation serves as a topographic factor and is regarded as a surface indicator for assessing groundwater potential (Melese and Belay 2022). It is anticipated that topographic elevation will impact groundwater prospects, with regulation by various hydrogeological and geomorphological processes (Maity et al. 2022). The topographical elevation of the main Nile region was derived from a Digital Elevation Model (DEM) (see fig. 17), obtained from ASTER DEM USGS through the Google Earth Engine platform. Higher elevations are observed in the southern region, while lower elevations are predominant in the northern area around the Mediterranean Sea. Additionally, certain areas in Egypt are noted to have elevations below sea level.

3.3.4.4. Slope

Precipitation serves as the primary driver of groundwater recharge in tropical and subtropical areas. The slope gradient directly impacts rainfall infiltration. Gentle slopes result in reduced recharge, as water quickly runs off the surface during rainfall, limiting the opportunity for infiltration and subsequent saturation of the groundwater zone (Yeh et al. 2009a). The slope was derived from DEM data (Fig. 17). In the Main Nile region, the slope has been reclassified into five classes based on slope values, represented as percentage values. The <15º slope class, which indicates gentle slopes favorable for the highest rate of infiltration, covers almost the entire area. The remaining parts of the study area are categorized into 15–30º, 30–45º, 45–60º, and greater than 60º slope classes.

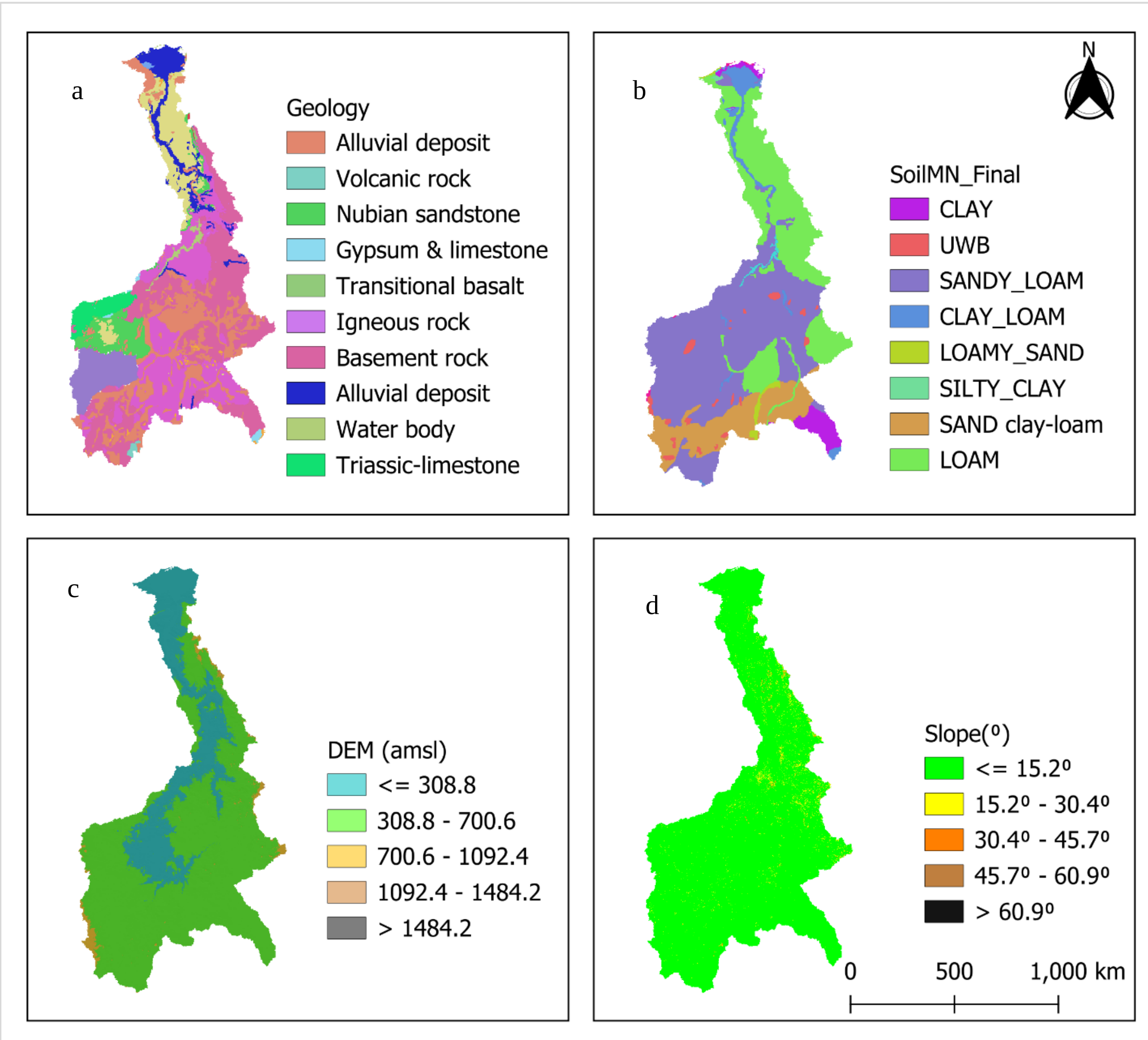


Figure 19: Thematic layers for the Main Nile sub-basin: (a) Lithology, (b) Soil, (c) DEM (Digital Elevation Model), and (d) Slope.

3.3.4.5. Lineament density

Lineament density plays a significant role in the planning and development of groundwater resources (Rajesh et al. 2021). Areas with higher lineament density are considered favorable for groundwater development (Pinto et al. 2017). The lineament map was generated from DEM data using ArcGIS software, the lineament density analysis in the study area, as depicted in Fig. 18, indicates that the majority of the region, particularly the eastern side, exhibits a low lineament density of less than 1.2 km/km^2. The areas with medium lineament density (1.2–2.4 km/km^2) and high lineament density (2.4–3.6 km/km^2) cover 123.27 km^2 and 94.30 km^2, respectively. Additionally, regions with very high lineament density, exceeding 3.6 km/km^2, encompass 17.24 km^2. Lineaments, which signify potential obstructions to groundwater movement, suggest that zones with very high and high lineament densities are more favorable for Groundwater Recharge Potential Zones (GWRPZ).

3.3.4.6. Drainage density

Drainage density refers to the total length of streams within a drainage basin divided by the total area of that basin (Maity et al. 2022). Many researchers have merged only the lineament map with drainage maps to identify the potential areas for groundwater recharge (Shaban, Khawlie, and Abdallah 2006; Yeh et al. 2009b). The drainage density map (Fig. 18) is generated by extracting data from the DEM using ArcMap. Areas with higher drainage density are assigned greater weight, and vice versa.

3.3.4.7. Land Use and Land Cover (LULC)

Land use and land cover (LULC) significantly influence groundwater recharge, occurrence, and availability (Melese and Belay 2022). Based on the research conducted by Sener, Davraz, and Ozcelik (2005), Suja Rose and Krishnan (2009), and Fenta et al. (2015), the ranking of these land use/cover classes for groundwater potential aligns with the following hierarchy: water bodies > forests > shrub lands > cultivated lands > grasslands > bare lands. The land use land cover (LULC) map data for the study area was obtained from the ESA WorldCover dataset for the year 2021, with a spatial resolution of 10 meters. The study area encompasses seven distinct types of LULC, as depicted in Figure 18: cultivated land, shrubland, grassland, forest, bare land, and wetland. Among these, cultivated land emerges as the predominant LULC class, comprising 47% of the total area, followed by grassland, which covers 35% of the area.

3.3.4.8. Rainfall data

Rainfall is the primary source of recharge, dictating the amount of water that can infiltrate and replenish the groundwater system (Agarwal et al. 2013). The greater the rainfall intensity, the higher the groundwater recharge will be, and conversely, lower rainfall intensity results in reduced groundwater recharge (Abrar et al. 2023). The rainfall map was classified into five categories: <129, 129-258, 258-387, 387-516, and >500 mm/year, representing very low, low, moderate, high, and very high rainfall, respectively. It is observed that the upstream areas of the main Nile, specifically in the southern region near Khartoum, receive the highest amount of rainfall, while the northern part receives the lowest amount, as illustrated in Figure 18.

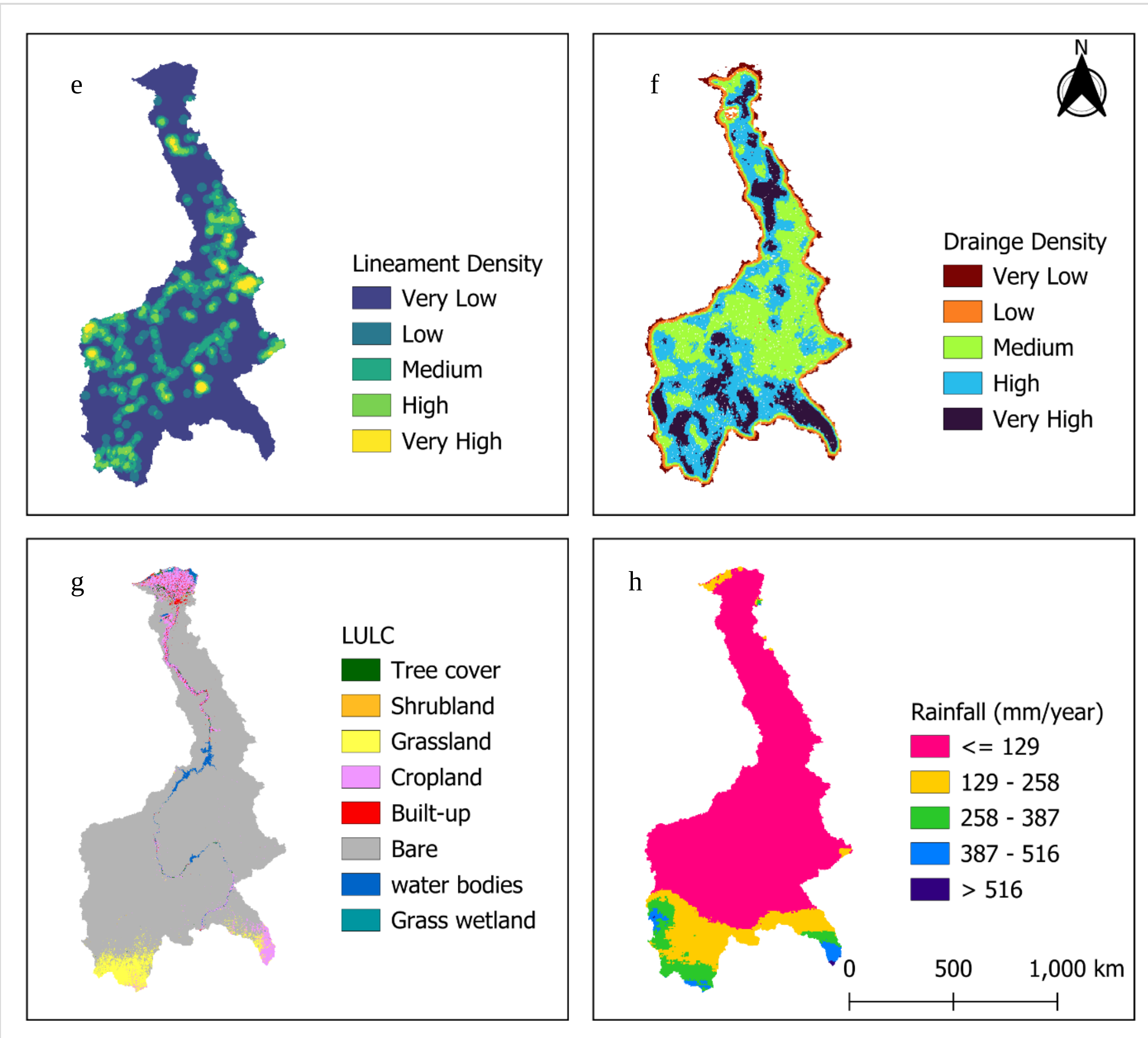


Figure 20: Additional thematic layers for the Main Nile sub-basin: (e) Lineament Density, (f) Drainage Density, (g) LULC (Land Use and Land Cover), and (h) Rainfall.

3.4. Multi-Criteria Decision Analysis (MCDA) with The Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) is a crucial component of the multi-criteria decision-making (MCDA) method, facilitating the systematic analysis and prioritization of multiple objectives (Jhariya et al , 2021). In GIS-based multi-criteria assessment, AHP is utilized to assign weights to thematic layers representing various influencing factors on groundwater potential. Saaty's AHP method (Saaty, 2004), proposed in 1980, provides a framework for decision-makers to allocate weights based on pairwise comparisons of criteria, considering their practical importance in a given area. This subjective approach involves selecting subunits and assigning weights based on comparisons derived from decision-making strategies.

In this study, AHP was employed to assign weights to each thematic layer, utilizing an Excel template developed by Goepel (2013). The assignment of weights was based on pairwise comparisons facilitated by experts from relevant institutions, ensuring a comprehensive and unbiased analysis of parameters. Table 2 displays the weights assigned to the thematic layers in the Main Nile sub-basin. The methodology outlined involves using GIS and AHP as MCDA techniques to delineate groundwater potential zones in the upper part of the Tekeze Atbara basin. Factors influencing groundwater occurrence and distribution were characterized, including geology, geomorphology, rainfall, lineament, land use/land cover, drainage density, soil type, slope, and soil texture. Pre-processing analysis of remote sensing data was conducted using ArcGIS 10.8 and QGIS 3.34.1.

The normalization of weights and determination of maximal eigenvalue and consistency ratios are essential steps in AHP, enabling the quantification of relative importance and ensuring the reliability of weight assignments. By employing AHP within MCDA, researchers can integrate multiple expert opinions without bias, facilitating a comprehensive analysis of groundwater potential zones. The AHP method is applied according to the calculation of weightage from a preference matrix representing map layers. The weightage is generated by the comparison of relevant criteria based on preference factors. The ability to manage a vast number of the data for required weightage, even for vast data in a straight forward manner, has made the method a popular one within various GIS methods (Jhariya et al , 2021).

3.4.1. Determination of weights in AHP

The AHP method is a decision-making process to judge a multilevel hierarchical classification system, which reveals the decision of each parameter (Anand et al. 2021b), it is a widely used MCDA technique. To ensure a fair weight distribution among the various factors employed, AHP uses pair-wise comparison. Greater relevance is indicated by a higher weighting assigned. The use of this technique also enables the integration of multiple expert opinions without bias (Sandoval and Tiburan 2019). According to (Saaty 1987), the element of each layer class of each raster was generally retrieved for the AHP calculation and will later be utilized to perform the pairwise comparison within the matrix. The normalized weight for each thematic layer was then determined using the pairwise comparison matrix (PCM), and the consistency of the judgment matrix was then determined (Hussaini et al. 2022). By using a pairwise comparison, the user can quantitatively rank each element in relation to each other to determine which most and least important (Table 7).

AHP is employed in this study to assign weights to each thematic layer. For this purpose, an Excel template developed by (Goepel 2013), available for free at the site "New AHP Excel template with multiple inputs – BPMSG" is used.

Table 7: Parameters scale*

intensity	Explanation
1	Two elements contribute equally to the objective
3	Experience and judgment slightly favor one element over another
5	Experience and judgment strongly favor one element over another
7	One element is favored very strongly over another, it dominance is demonstrated in practice
9	The evidence favoring one element over another is of the highest possible order of affirmation

*2,4,6,8 express intermediate values

Table 8: A matrix of pairwise comparisons

	Geology	Soil	Slope	LD	DD	LULC	RF	CR
Geology	1	2	3	2	5	5	5	0.08
Soil	1/2	1	2	3	6	7	5	
Slope	1/3	1/2	1	5	3	2	5	
LD	1/2	1/3	1/5	1	3	3	3	
DD	1/5	1/6	1/3	1/3	1	2	3	
LULC	1/5	1/7	1/2	1/3	1/2	1	3	
RF	1/5	1/5	1/5	1/3	1/3	1/3	1	

3.4.2. Checking for consistency

It is important to determine the maximal eigenvalue (max) before beginning to calculate the Consistency Ratio (*CR*). The Consistency Index (*CI*) is then determined using Eq. (1), where n is a number of variables. *CR* is obtained using Eq. (2). Using Saaty's scale of 1 − 9, (Table 7) the value of the Ratio Index (RI) is provided. The weights judgment is reliable and acceptable if the value is less than 0.1. We need to update the subjective assessment if the *CR* is higher than 10%. In this investigation, the computed consistency ratio is (*CR*=0.08), which > 10% indicates the provided weights were appropriate for further overlay analysis process.

$$CI = \frac{\lambda max - n}{n - 1} \quad (1)$$

where n is the number of criteria used in the study and λmax is the biggest or principal eigenvalue vector obtained by summing the products between each element of the priority vector and column totals in the matrix of (n £ n) type. This method takes into consideration the computation of normalized inputs of comparison scores Priority Vectors (PVs) which in turn determine the highest eigenvalue λmax in Eq (2) to yield the weights for each criterion

$$CR = \frac{CI}{RI} \quad (2)$$

Where *CR* is consistency ratio, *CI* is consistency index, and *RI* is random index (Table 9). *RI* also referred to as a random inconsistency index, involves averaging the *CI* that was generated at random and depends on the order (n) of the matrix (Saaty 1987).

Table 9: Random Index

Attributes	3	4	5	6	7	8	9	10
RI	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

All the input data/parameters (raster format) were assigned weights to their respective role and influence on MAR. The total score for each parameter was computed (Saaty 1987).

$$GPI = \sum_{w=1}^{m} \times \sum_{i=1}^{n} (w_i \times x_j) \quad (3)$$

$$\mathbf{GWP} = \sum Wp\,1 \times R\,p1 + Wp\,2 \times R\,p2 + Wp\,3 \times R\,p3 + Wp\,4 \times R\,p4 + Wp\,5 \times R\,p5 + Wp\,6 \times R\,p6 + Wp\,7 \times R\,p7 \quad (4)$$

Where GWP is groundwater potential, W is weight of the thematic layer, P is the parameter (thematic layer) and R is rank of the features.

3.4.3. Reclassification and standardization of factor criteria

The layers are standardized using an index, which ranges from 1−5 lowest to highest suitability (Table 10). It is important to highlight that when values are assigned to criteria, they primarily reflect the developer's preferences based on their own opinion, familiarity with the research topic, and the study area (Varouchakis et al. 2023b).

Table 10: Standardization of criteria and their suitability class*.

Value/Common scale	Suitability class
1	Very low
2	Low
3	Moderate
4	High
5	Very high

*In this study, seven thematic parameters were used and categorized for groundwater potential (GWP). Each parameter was reclassified, ranked, and weighted using AHP based on their influence on GWP.

3.5.Layers overlay with GIS

All the thematic layers are integrated using ArcGIS to generate the Groundwater Potential Index (GPI) for assessing the Groundwater Potentiality Zone (GWPZ). The GPI is calculated using the Weighted Overlay method, as shown in Eq1.

Where, w_i is the normalized weight of the i_{th} thematic layer, which was prepared using AHP in an Excel sheet template, x_j is the rank value of each class within the j_{th} layer, m is the total number of themes, and n is the total number of classes in theme. The concept behind Eq1 is illustrated in Figure 19, which shows the values used to overlay the layers.

InRas1 (influence 75%)

2	2	3
2	1	1
1	2	2

InRas2 (influence 25%)

3	3	2
1	3	1
2	1	1

=

OutRas

2	2	3
2	2	1
1	2	2

Figure 21: Layers overlay concept

3.6. Sensitivity Analysis for the layers

This section explores the concept of Sensitivity Analysis (SA) and its application in the study. SA is a technique employed to assess the vulnerability of a model's outputs to variations within its input parameters (Saltelli et al, 2008). Sensitivity analysis helps to evaluate the effect of individual input parameter on the output model of the MAR potential zone. Based on this sensitivity analysis was conducted to evaluate the impact of each input parameter (Gebeyehu et al. 2023). It investigates how changes in the model's inputs can influence its final results. SA essentially gauges the robustness of a model's outputs when its input variables are manipulated. It provides valuable insights into the individual significance of each input parameter on the model's overall output by quantifying the changes in the output map corresponding to each input variation (Heuvelink et al, 1989). Several factors can influence the impact of input parameters on model outputs. These factors include: The total number of input parameters involved in the model, the degree of uncertainty associated with the input data, the weights or ranks assigned to different input parameters and the specific overlay operations performed within the model (Heuvelink et al, 1989).

The analysis leverages ArcGIS software to generate a statistical summary of the ratings assigned to each parameter. These results are subsequently presented in a table format. Map Removal Sensitivity Analysis is a technique used to assess the sensitivity of input parameters in a suitability analysis (Thapa et al , 2018). Generally, Map Removal Sensitivity Analysis offers a valuable approach to understanding the sensitivity of both individual input parameters and the interactions between them in a suitability analysis see figure 3 (a-g) below. This analysis employed a map-removal technique as described by (Lodwick, Monson, and Svoboda 1990). This method provides insights into the robustness of the analysis and helps researchers identify the most critical data layers and operations influencing the final suitability map. The removal process was computed using the formula of sensitivity index. Each input layer was systematically eliminated one at time while the remaining parameters were calculated by using (Eq. 5). The resulting sensitivity index (*SI*) values were then utilized to assess the significance of removing each layer in delineating the GWP potential zone map.

$$\boldsymbol{SI} = [[(\boldsymbol{GWPI} / \boldsymbol{N}) - (\boldsymbol{GWPI'} / \boldsymbol{n})] / \boldsymbol{GWPI}] * \mathbf{100} \quad \mathbf{(5)}$$

Where SI is sensitivity index of the removed layer GWPI is the GWP potential index calculated considering all input layers, GWPI′ is the GWP potential index obtained by excluding each input parameter at a time, and N and n are the numbers of input parameters used to delineate GWP zone and GWP′, respectively. A removed input layer with the highest SI indicates the most sensitive parameter while a parameter with the lowest *SI* is considered the least sensitive layer in delineating the GWPI map of the basin.

4. Results and discussion

4.1. Groundwater suitability map

4.1.1. BAS

The final stage of the suitability analysis was produced by the weight sum overlaying of the reclassified maps to produce the final suitability map for the. The obtained map resulted from multi-criteria analysis based on seven thematic maps. Each thematic map created for these factors was reclassified into five suitability classes: very low, low, moderate, high, and very high. This process involved assigning suitability scores to different ranges of values within each factor's map. For example, areas with highly permeable rock formations in the geology map have been assigned a high suitability score, while areas with low permeability were assigned a low score and this was done for all the layers. ArcGIS software was used to overlay the reclassified thematic maps. A weighting scheme was applied during the overlay process. This means the thematic layers were assigned different weights based on their perceived importance for groundwater occurrence in the Eastern Nile Basin which was adopted for Baro-Akobo-Sobat Sub-basin.

Areas with a combination of factors favorable for groundwater (e.g. highly permeable geology, sand soil, low drainage, flat slope, high lineament, and high rainfall) received a higher overall suitability score compared to areas with less favorable combinations as shown in the figure 21. The distribution for the Suitability Classes shows; Moderate Potential (44.93%, 231,618 sq km): This covers the largest area of the sub-basin, indicating that a significant portion has moderate potential for groundwater development. The High Potential (17.10%, 88,038 sq km) and Very High Potential (14.97%, 77,169 sq km): These areas hold promising potential for groundwater exploration and development due to favorable combinations of hydrogeological factors, while Low Potential (12.82%, 66,093 sq km) and Very Low Potential (10.21%, 52,648 sq km): These areas might have limited groundwater resources due to factors like low permeability or low rainfall. However, further investigation might be necessary to determine site-specific suitability.

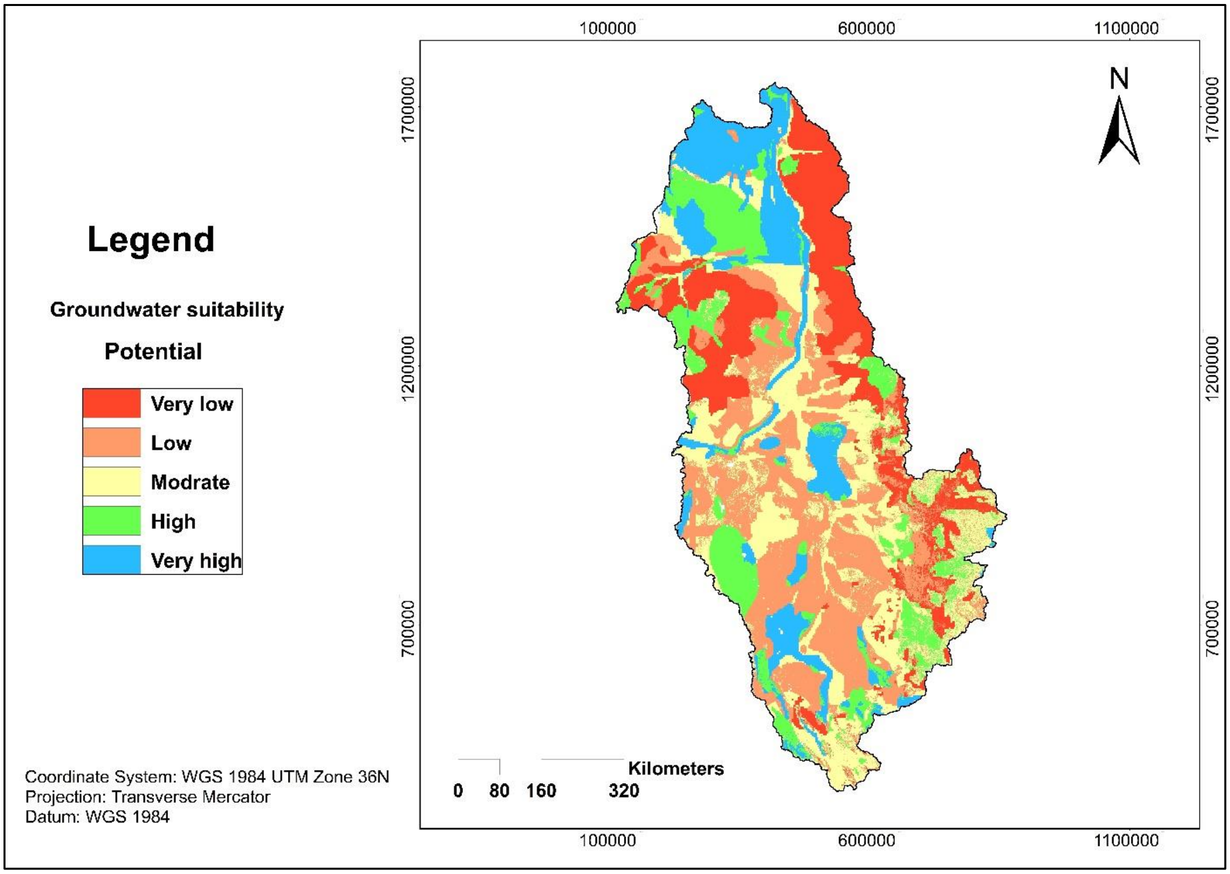


Figure 22:Groundwater Suitability Map of BAS

4.1.2. Blue Nile

In the present study, the importance of factors governing the GWP suitability mapping is assigned based on experts' opinions and personal judgment as there is no standard scale (Mengistu et al. 2022). The thematic layer's relative weight is defined using AHP based on expert judgment. These criteria were weighted based on GWP potentiality by constructing pairwise assessments in MCDA. The thematic maps were reclassified into five classes based on GWP potential zones, and a weighted index map of the catchment was created using seven thematic layers utilizing AHP (Anand et al. 2021). To consider relative significance from a GWP perspective, weights have been assigned to the raster layers and their corresponding weights. Potential GWP areas are divided into five different categories: very high, high, moderate, poor, and very poor (Fig. 22). According to the final suitability map, the Blue Nile basin north eastern portion, along with small portion of its southwestern and central parts exhibited the highest suitability for groundwater potential (GWP).

The Blue Nile basin falls about 2.1% (very high), 14.89 % (high), 47.6 % (moderate), and 34.7 % (low), and 0.6 % (very low) potential areas for GWP. The unsuitable zones are mainly concentrated in the western, and south western, and the central part's unsuitable zones correspond to the slope constraint for steeper slopes, the nature of geology, and soil texture are the governing factors. The north eastern portion, along with small portion of its southwestern and central parts shows relatively very high to moderate GWP suitability due to the nature of the slope and the texture of the soil type. Geologically the area is covered with recent alluvial deposit, quaternary alluvial deposit, quaternary, Volcanic rock and tertiary Igneous Ashenege formation, which is suitable for GWP. On the other hand, land use is crucial in choosing appropriate sites for GWP (Hussaini et al. 2022). Based on this the water bodies, herbaceous wet land, tree cover and the croplands are appropriate land-use types are the major LULC classes that have importance for GWP occurrence in the Blue Nile basin. The gentle slope part of the area and high liniment density distribution is also the major contributing criteria for the highly suitable GWP area. Generally, the GWP potential suitability in the Blue Nile basin is associated with the combination of the above factor

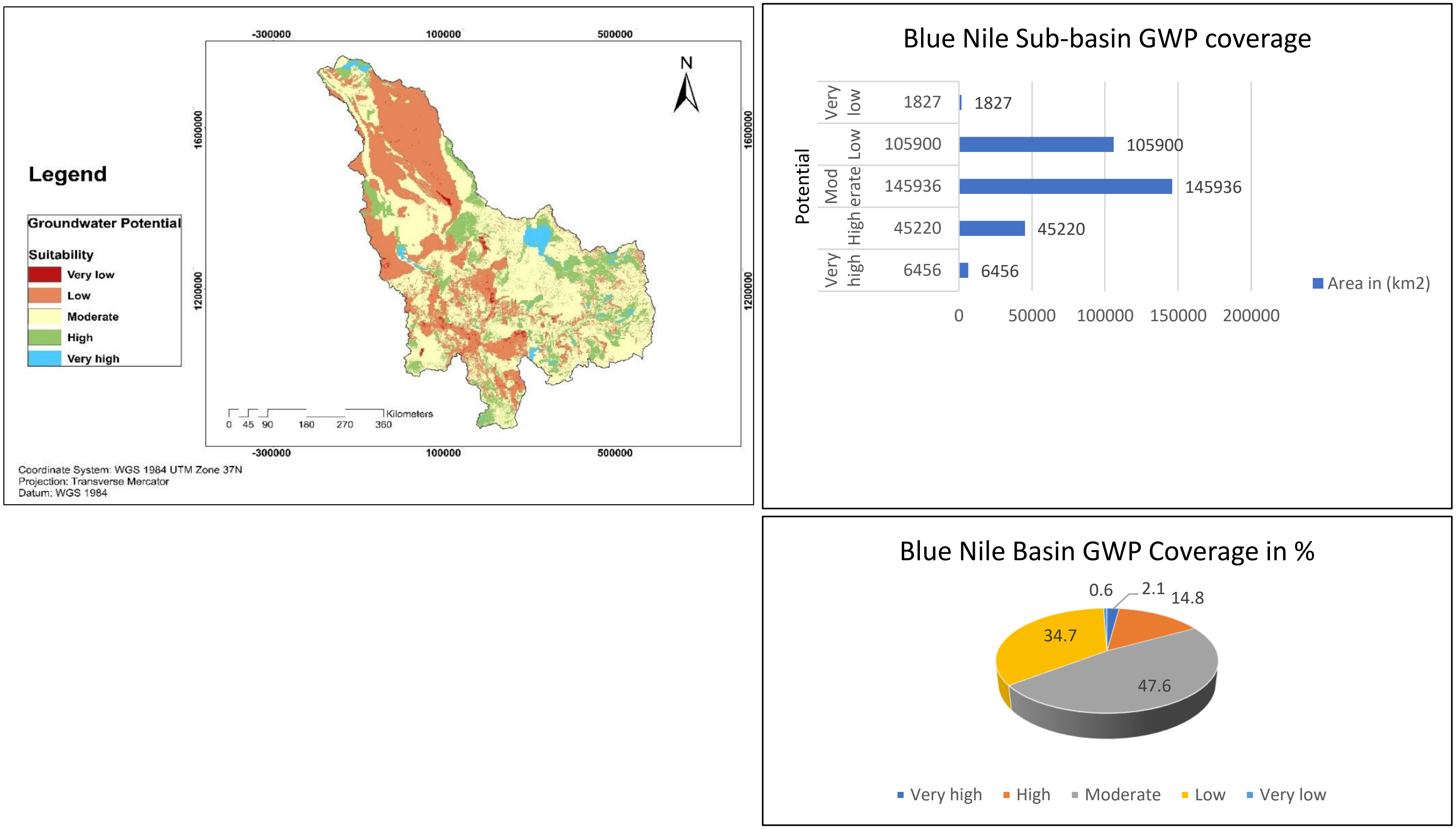


Figure 23: a) Groundwater suitability map (GWP) of Blue Nile Basin b) area coverage please avoid the repetitive numbers in the bar chart

4.1.3. Tekeze-Atbara

Application of AHP techniques by considering the weighted parameters for demarcation of potential zones involves calculations in the raster format module and development of potential maps in the GIS environment. The adopted weight results from the normalization of individual parameters by considering the ratio of weight assigned to the specific parameter and the corresponding layer's geometric mean. Normalized weight derived from the thematic layers' individual features considered for producing a potential groundwater index map was created (Figure 23). According to the spatial variation of groundwater potential, the study area was split into five zones, very low, low, moderate, high and very high, whose spatial distribution and extents 1503.67 km2 (0.74%), 5183.88 km2 (25.63), 87685.35 km2 (43.36%), 54110.87 km2 (26.76 %), and 7106.07 km2 (3.5%) as showing table 11.

Table 11: Groundwater Potential Zone

Class	Area (sq.km)	Area in percent %
Very low	1503.67	0.74
Low	5183.88	25.63
Moderate	87685.35	43.36
High	54110.87	26.76
Very high	7106.07	3.5

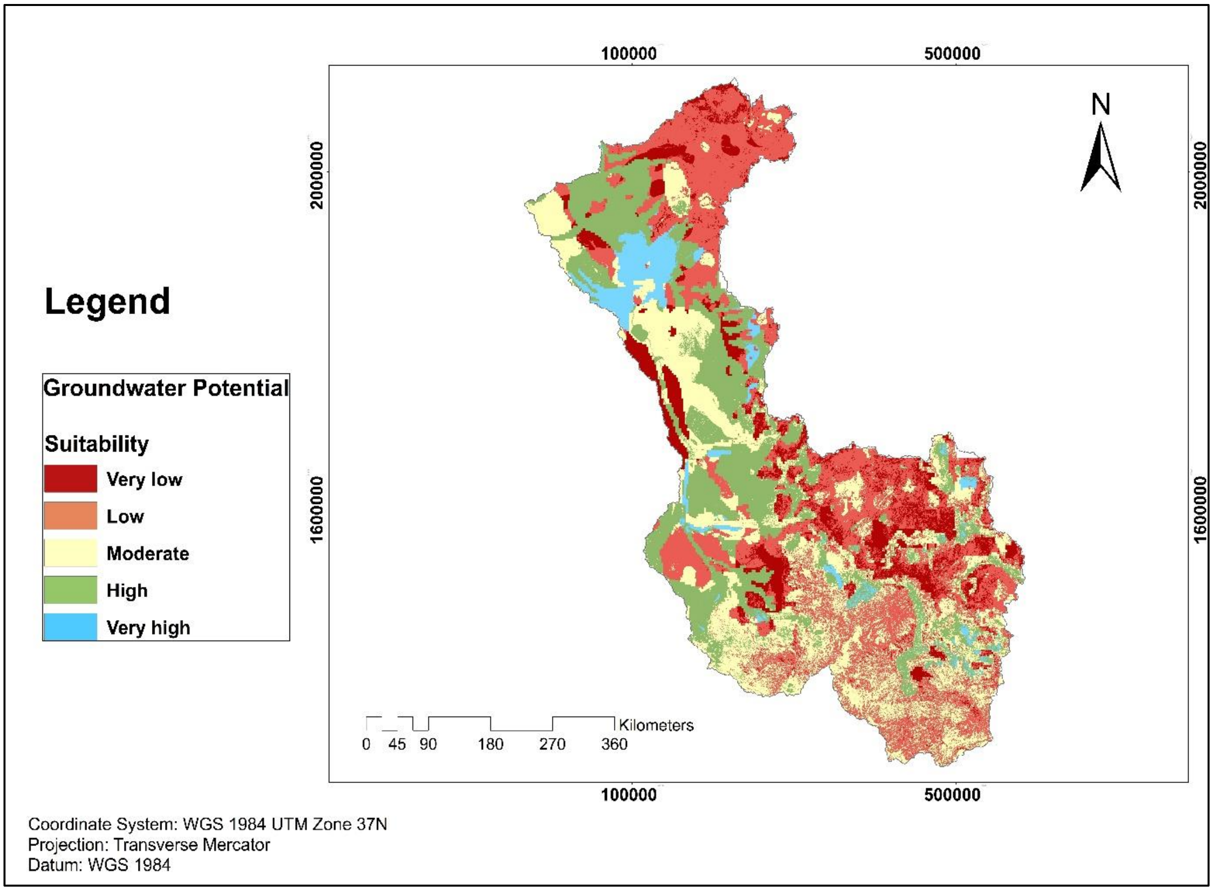


Figure 24: Groundwater potential Map of TAS

4.1.4. Main Nile

The groundwater potential map was created using GIS-based AHP and layer overlay techniques (Fig. 24). The GWPZ map of the Main Nile basin identifies five distinct zones (Figure 3). These zones, indicating high, moderate, and low groundwater potential, cover 0.15 million sq. km, 0.44 million sq. km, and 0.3 million sq. km, respectively. The very low and very high zones have much smaller areas, approximately 4400 sq. km and 1250 sq. km, respectively. Zones of high groundwater potential typically coincide with areas of a high groundwater table, influenced by various factors (Allafta and Opp 2021). In this study, the high GWPZ is primarily located in the northwestern part, while the moderate GWPZ spans the upstream area near Khartoum in the southern part of the basin. The low and very low GWPZs are found in the western parts of the study area and part of the northern region (Figure 24).

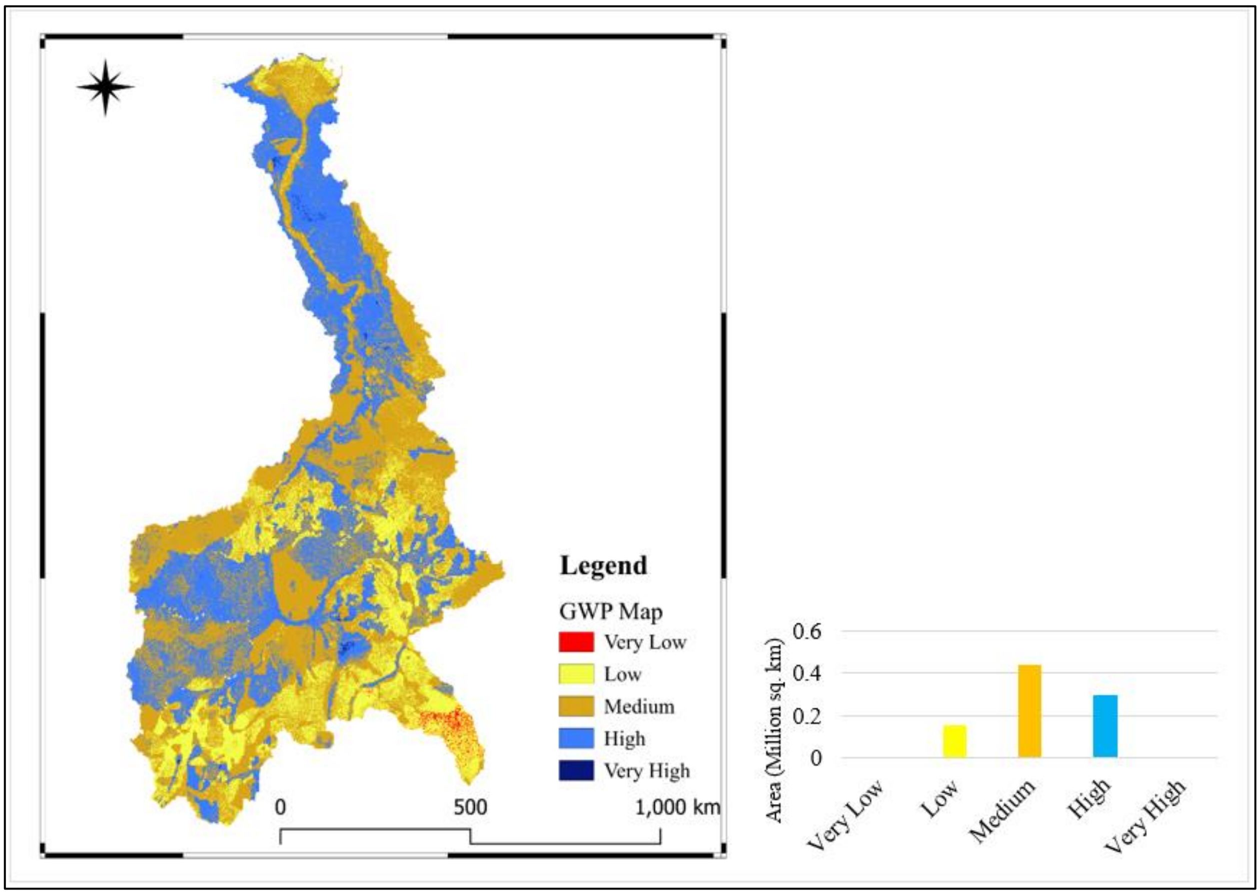


Figure 25: Groundwater potential of the Main Nile

4.2. Sensitivity analysis maps

4.2.1. Baro-Akobo-Sobat

The analysis on the Baro-Akobo-Sobat Sub-basin revealed that slope is the most sensitive parameter, followed by drainage density. The present study utilizes a specific type of SA called "Map Removal Sensitivity Analysis" to evaluate the sensitivity of various parameters (Thapa et al, 2018). The analysis leverages ArcGIS software to generate a statistical summary of the ratings assigned to each parameter. These results are subsequently presented in a table format.

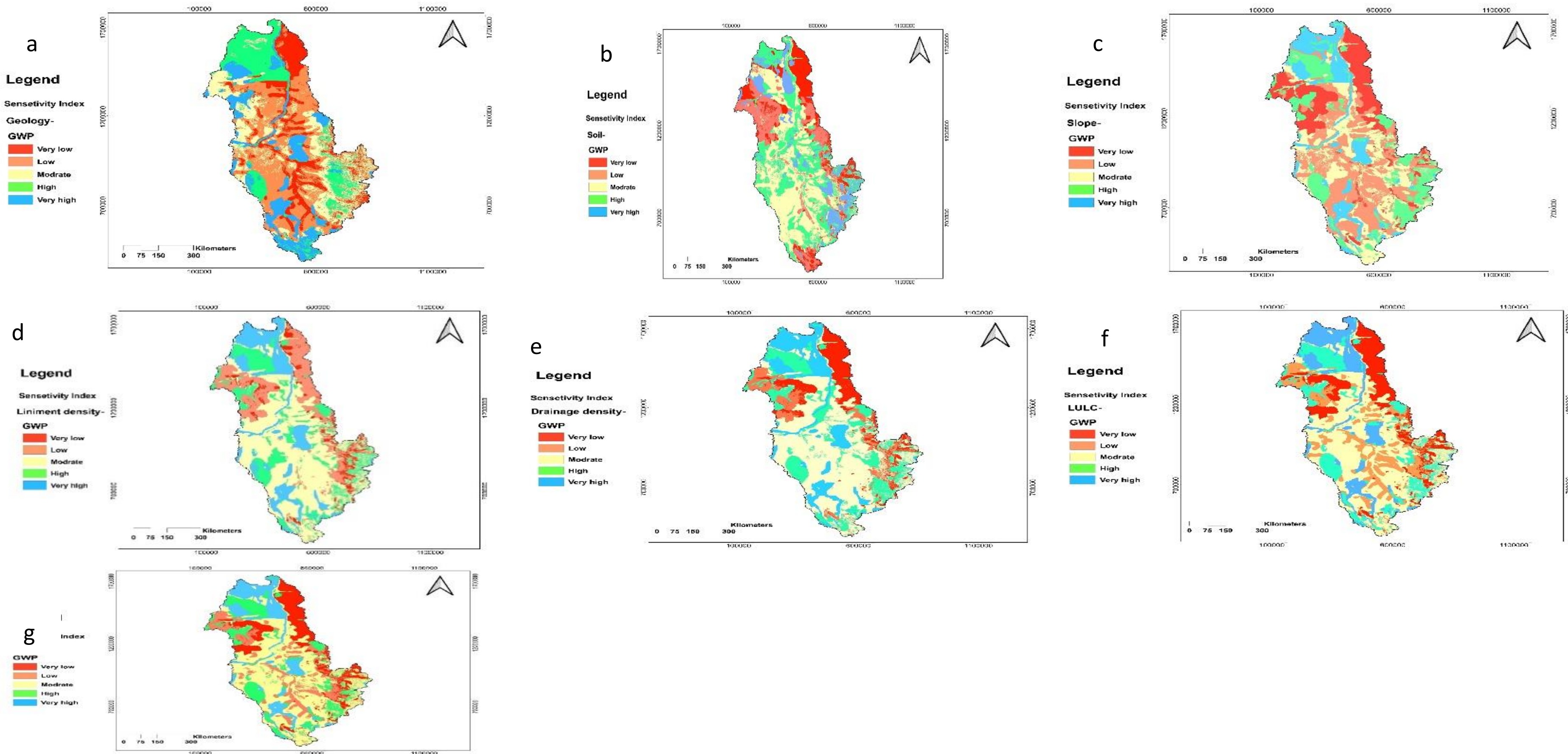


Figure 26: sensitivity index: a) geology b) soil c) slope d) liniment density e) drainage density f) LULC g) rainfall

Table 13: The sensitivity analysis of BAS.

Layer name	Sensitivity variation index (SI) in %			
	Min	Max	Mean	StD
Geology-	-7.33	8.78	**2.37**	2.06
Soil texture-	-1.18	6.87	**0.22**	-1.34
Slope-	-1.54	6.26	**2.49**	-1.59
Liniment density-	-1.89	2.8	**-1.21**	0.68
Drainage density-	-2.14	-1.6	**-0.81**	0.56
LULC-	-2.18	0.92	**-1.26**	0.34
Rainfall-	-2.25	-0.29	**-1.82**	0.25

4.2.2. Blue Nile

Table 12: Sensitivity Index

Layer removal	Min	Max	Average	Standard Deviation
Geology	-20.81	5.18	-3.31	2.54
Soil	-8.13	4.32	-4.6	2.38
Slope	-6.42	4.14	-0.25	1.24
Lineament	-4.54	0.62	3.2	0.64
Drainage Density	-3.37	0.89	-1.81	0.46
LULC	-3.35	-0.5	-2.25	0.31
Rainfall	-2.93	-1.03	-2.48	0.22

The sensitivity result shows most of the thematic maps are sensitive to slope and geology with a mean SI value of 2.49% and 2.37%, respectively. The slope with a mean SI value of 2.49%, and rainfall (mm/year) with a mean of −1.8% are the most and least sensitive parameters in delineating the GWP sites map, respectively (Table 13). The geology layer significantly influences the spatial distributions of GWP availability in the Blue Nile basin. The rainfall is the least influential factor on the basin GWP availability, and removing it from the delineation of the GWP map resulted immeasurable effect on the spatial extents of the potential zones.

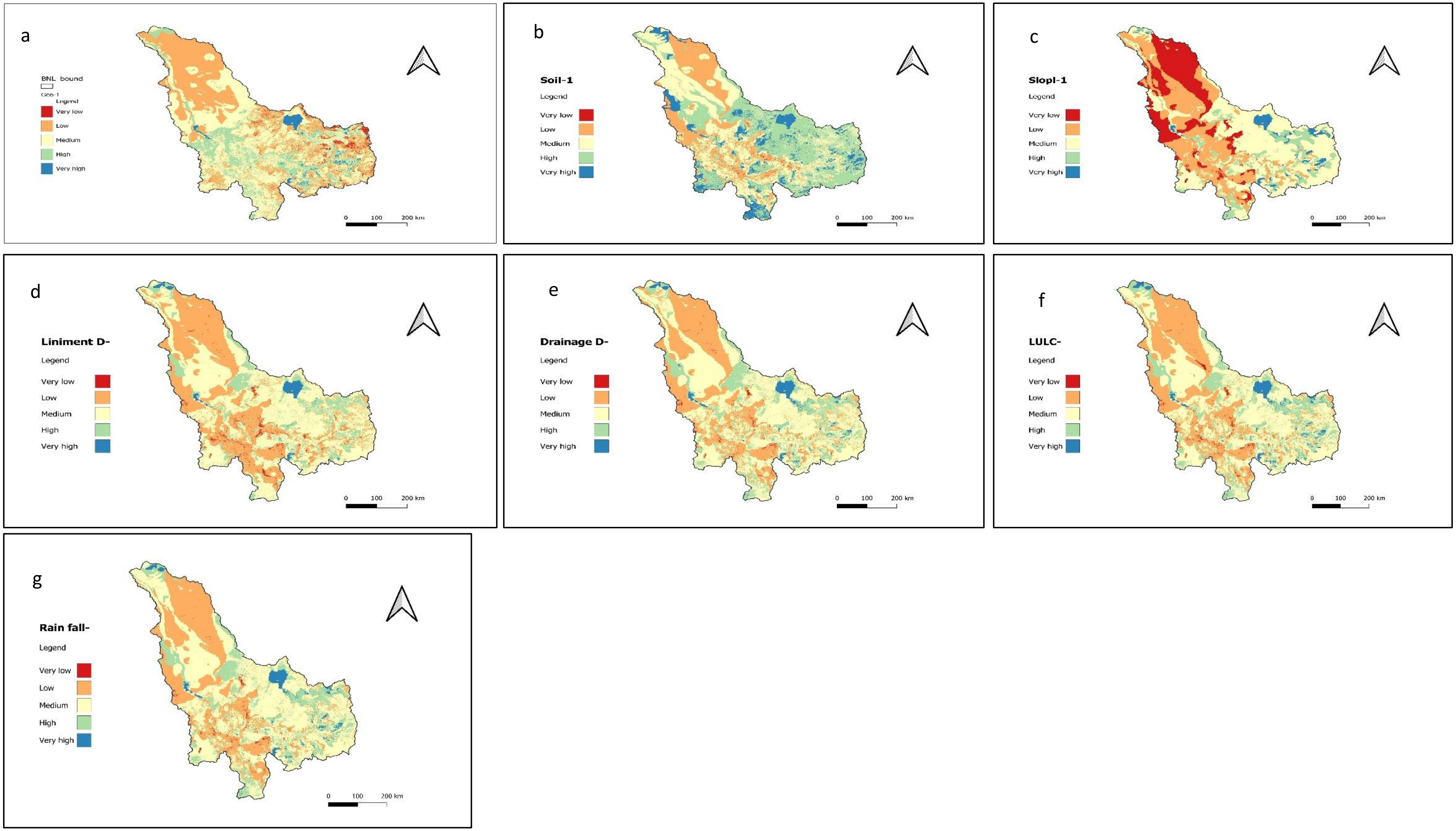


Figure 27: Model sensitivity- a) geology- b) soil- c) slope- d) liniment density- e) drainage density- f) LULC- g) rainfall- where is a, b, c and d in the figures

4.2.3. Tekeze-Atbara

Sensitivity analysis (SA) measures the uncertainty or variation in the output results obtained from models applied (Saltelli et al., 2008). In more general term it measures the robustness associated with the model output with manipulated input variables. It helps to understand the influence of individual input parameters on the model's output by estimating the change in output map with each change in inputs. Researchers have studied the impact of input parameters on the model output which is influenced by several factors such as a number of input parameters, inaccuracy related to inputs, weights, and ranks assigned, nature of overlay performed (Heuvelink et al., 1989). In the present study, Map removal sensitivity analysis (Lodwick et al., 1990) to test the sensitivity of the various hydrogeological parameters. The statistical summary of rating of each parameter used in the study are obtained from in ArcGIS 10.2 software using symbology and classification statistics options of layer properties and the results are represented in table 14.

Table 14: Sensitivity Analysis result

Layer removal	Min	Max	Average	Standard Deviation
Geology	-19.05	8.73	-2.25	4.69
Soil	-19.05	5.95	-3.83	3.45
Slope	-19.05	5.95	**-0.96**	2.96
Lineament	-19.05	5.95	-3.4	2.73
Drainage Density	-2.38	5.95	-1.8	1.53
LULC	-10.71	5.95	-2.44	1.59
Rainfall	-9.71	5.95	-2.5	1.54

4.2.4. Main Nile

According to the sensitivity analysis (Table 15), the lithology factor shows the largest variation index at 3.64%. Similarly, the lineament density layer significantly influences the GWPZs assessment, with a variation index of 3.51%. The elimination of the LULC layer also impacts the GWPZs assessment, with a variation index of 3.01%. The GWPZs are sensitive to the removal of slope and rainfall, showing variation indices of 2.98% and 2.88%, respectively. The omission of soil and drainage density also contributes to sensitivity variations, with mean values of 2.81% and 2.43%, respectively (Table 15).

The exclusion of each factor from the assessment alters the percentage areas of very low, low, moderate, high, and very high GWPZs. Lineament density is a critical parameter in identifying the GWPZs, as its removal significantly decreases the "Very High" GWPZ area by 17.65% (Table 9). Similarly, the exclusion of LULC and rainfall reduces the "Very High" GWPZ area by 3.77% and 3.39%, respectively. Furthermore, the "Very Low" GWPZ areas are sensitive to the omission of soil and drainage density, with their removal decreasing the zone area by 2.42% and 1.59%, respectively (Table 16). The removal of other factors does not significantly influence the area zones, as their impacts are less than 1% for both decreases and increases.

Table 15: Map elimination sensitivity analysis (one layer is removed each scenario)

Factor eliminated	**Variation index (%)**			
	Min	Max	Mean	STD
Lithology	0.95	52.38	3.64	3.12
Soil	0.95	19.05	2.81	1.91
Slope	0.95	19.05	2.98	2.02
Lineament Density	0.95	19.05	3.51	2.59
Drainage Density	0.95	10.71	2.43	0.52
LULC	0.95	19.05	3.01	1.96
Rainfall	1.79	19.05	2.88	1.71

Table 16: Area zone changes under each scenario of elimination

Factor eliminated	Area changes ((+/-) %)				
	Very low	Low	Moderate	High	Very High
Lithology	-0.21	0.06	-0.09	0.22	0.79
Soil	-2.42	-0.75	-0.12	0.59	0.87
Slope	0.42	-0.31	0.09	0.02	0.90
Lineament Density	0.74	0.24	0.10	-0.21	-17.65
Drainage Density	-1.59	-0.21	-0.03	0.17	0.54
LULC	0.13	0.13	0.09	-0.19	-3.77
Rainfall	-0.45	0.10	0.08	-0.16	-3.39

The analysis on the Main Nile Sub-basin revealed that geology and soil is the most sensitive parameter for the area zone distribution and slight changes when lineament density is removed as shown in figure 27 below. On the other hand, the removing of slope, drainage density, LULC, and rainfall is less sensitive.

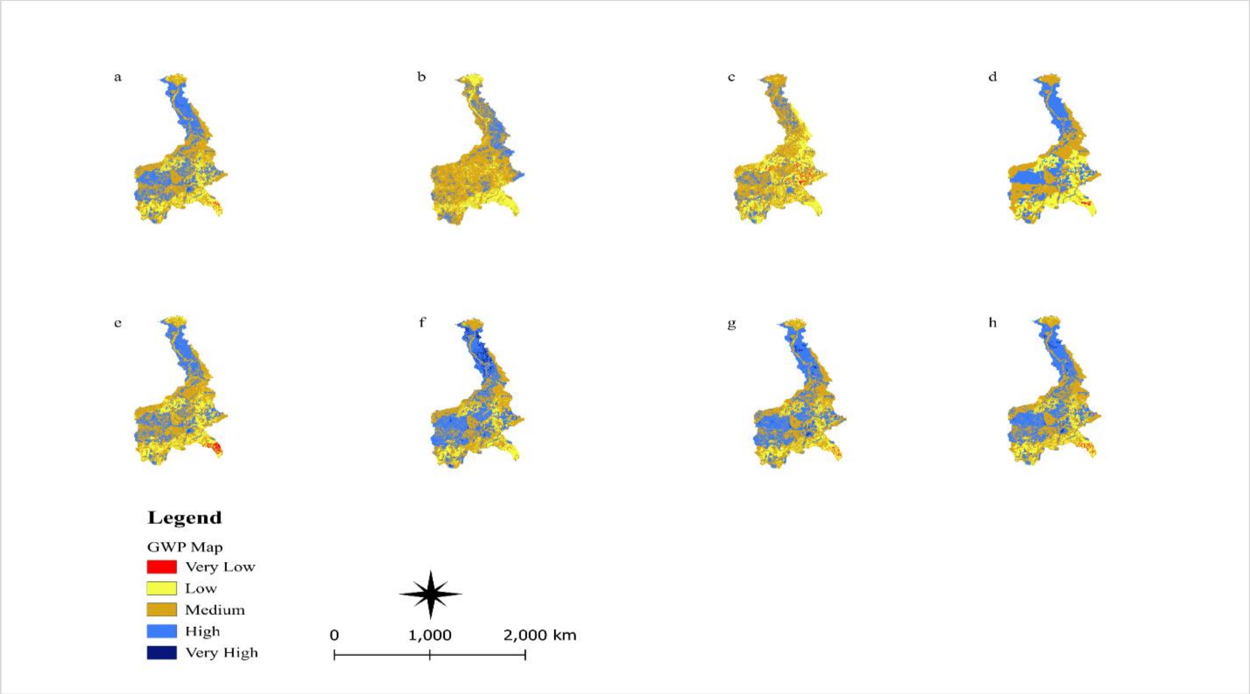
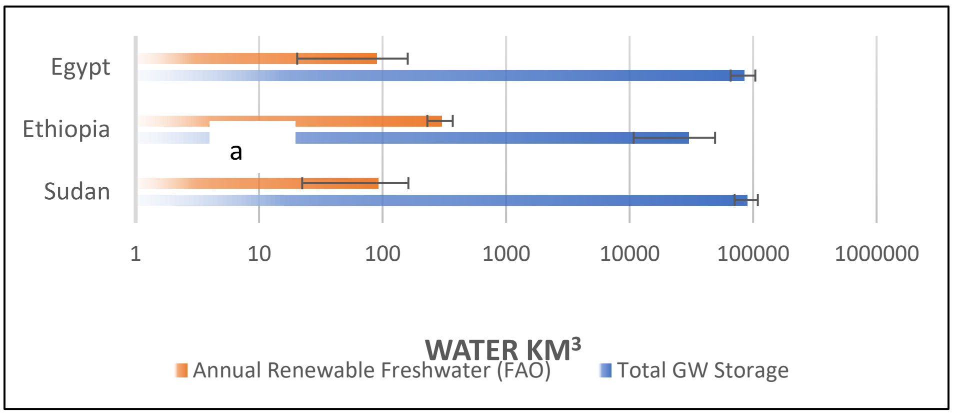
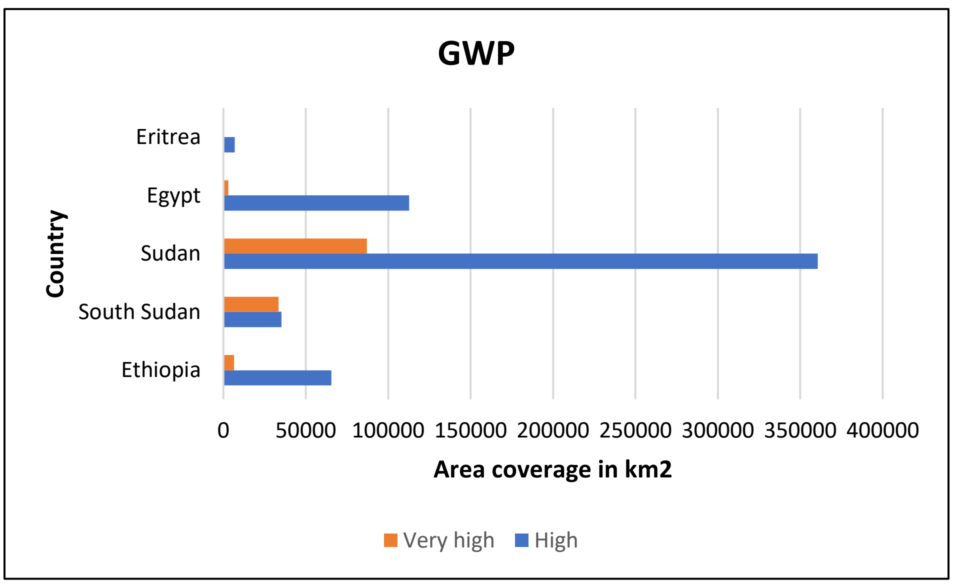


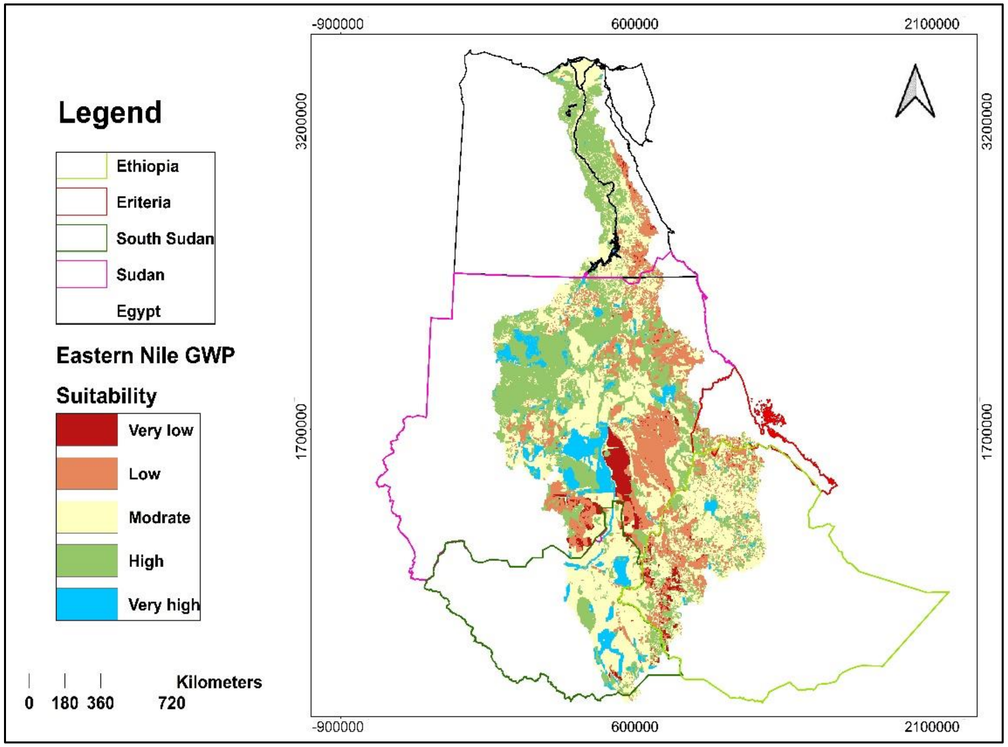
Figure 28: Model sensitivity: b) geology- c) soil- d) slope- e) liniment density- f) drainage density- g) LULC- h) rainfall-

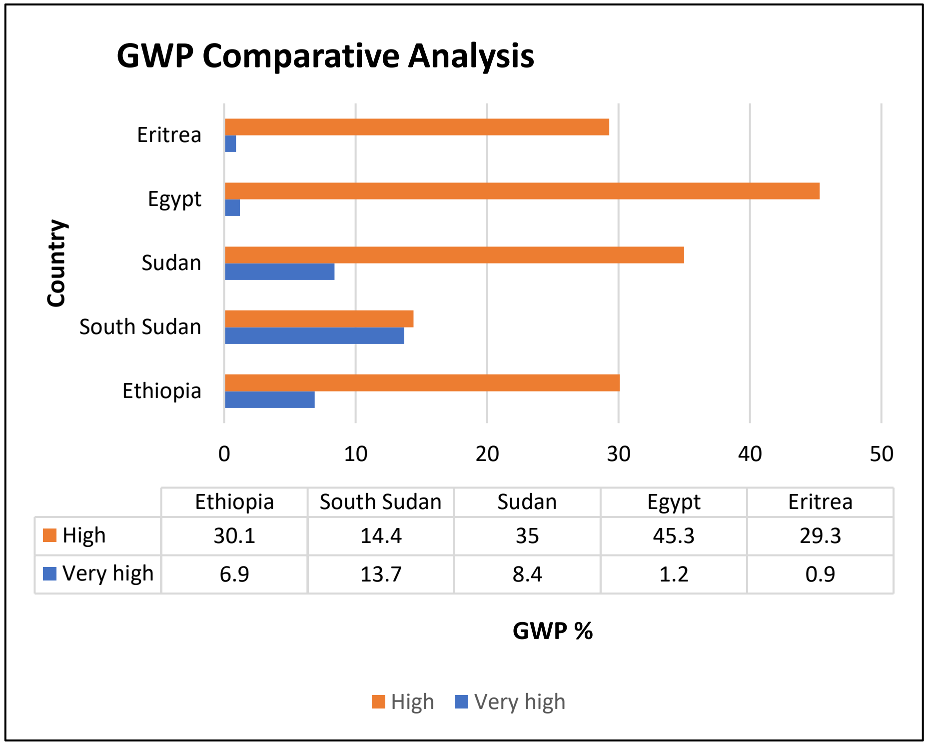
4.3.GWP Comparative Analysis in Eastern Nile Basin

The comparative studies of the groundwater potential in the Eastern Nile Basn showed that; South Sudan has very high groundwater potential (13.7%) with an area of 33487 KM^2 followed by Sudan with 8.4% that covers 87000.45 KM^2, Ethiopia has about 6.9% covering 65549.29 KM^2, while Egypt and Eritrea have 1.2% (3006.23 KM^2) and (0.9%) 223.21 KM^2 respectively. The study has also shown that Egypt has greater high potential area 45.3% (112683.8 KM^2), Sudan (35%) 360644.9 KM^2, Ethiopia with 30.1% (65549.29 KM^2) while South Sudan and Eritrea have (14.4%) 35209.96 KM^2 and (29.3%)6857.03 KM^2 fig b below. This is in conformity wityh the studies done by (MacDonald et al. 2012). As shown in fig a below.

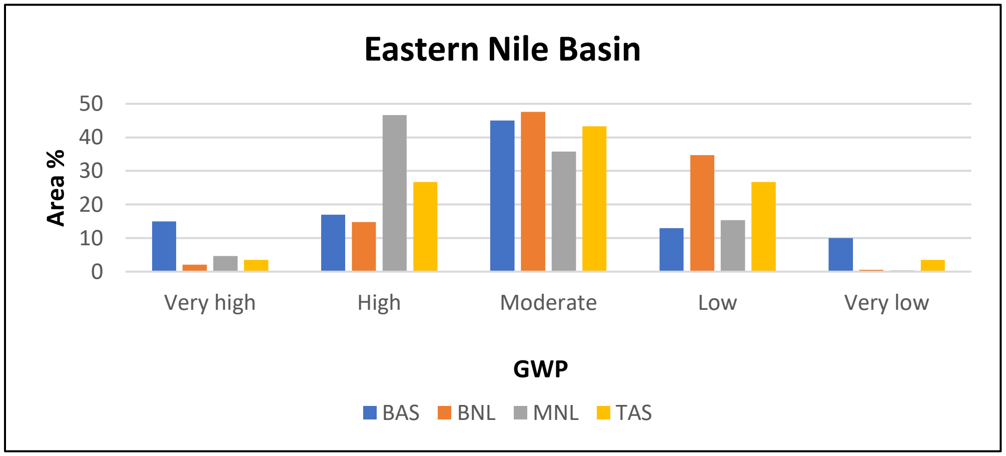








	Ethiopia	South Sudan	Sudan	Egypt	Eritrea
High	30.1	14.4	35	45.3	29.3
Very high	6.9	13.7	8.4	1.2	0.9



5. Validation

5.1. Baro-Akobo-Sobat

While the groundwater suitability map for the Baro-Akobo-Sobat Sub-basin provides valuable insights, a crucial limitation exists, the absence of validation well data. The analysis relied on seven thematic maps (geology, soil, slope, etc.) to estimate groundwater potential. However, it's important to acknowledge a limitation of the Lack of Validation Well Data. The analysis relies on existing spatial data and have not been validated with actual groundwater measurements from wells. This absence of ground truth data from wells means that the suitability classes (very low to very high potential) require verification through site-specific investigations. While the map offers a powerful planning tool, drilling and geophysical surveys are necessary to confirm groundwater presence and yield at specific locations within the identified potential zones. Despite this limitation, the suitability map remains a valuable tool for guiding groundwater exploration efforts in the Baro-Akobo-Sobat Sub-basin. By incorporating validation data in the future, the model's accuracy and effectiveness can be significantly improved.

5.2.Blue Nile

In most cases, existing inventory data is compared to the probability of MAR zone determined by GIS approaches (Anand et al. 2021b). By superimposing the inventory well point data with the created MAR potential map, the validity of the potential GWP map was tested (Gebeyehu et al. 2023b). Additionally, the outcome has been verified using the data on pumping wells or available inventories in some portion of the basin with 63 well data with high to moderate yield (Figure 5a). The majority of the wells are situated in very high-to-high (64.5%), and moderate (75.7%) designated GWP potential zones with a productivity rate range of 1 − 54 L/s, according to the validation points of the GWP potential site. The aquifer productivity of already-existing pumping wells was added to the created GWP potential zones suitability map based on the distribution of wells and the corresponding yield values. Most African aquifers are categorized as extremely high (>20), high (5 − 20), moderate (2 − 5), low moderate (1 − 2), low (0.1 − 0.5), or very low (0.1) in L/s, based on their productivity (Mengistu et al. 2022b). However, out of the total inventory of wells in some portion of the Blue Nile basin, there are very high to high (49.2 %), moderate (50.7%), and yield production wells, which correspond to the productivity classification. As a result, the production wellfields and the developed GWP map correspond in most part of the area. This emphasizes the importance of the weighted influencing parameter threshold values through GIS-based overlay analysis (Gebeyehu et al. 2023b), for identifying potential GWP zones.

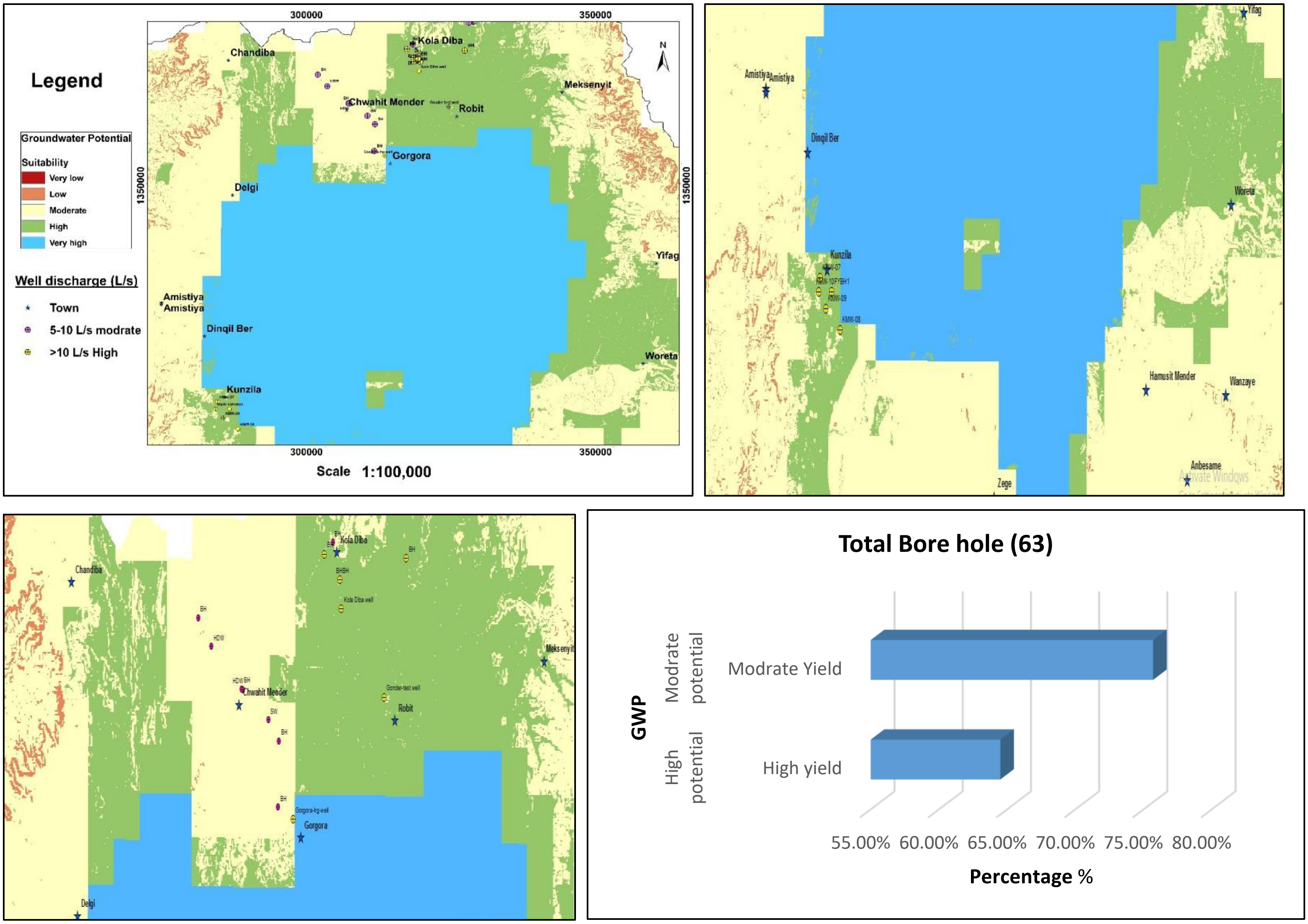


Figure 29: GWP Validation using borehole Yield

5.3.TAS

5.3.1. Validation using wells data

An accuracy check of the prediction model is highly essential to prevent errors and improve environmental studies' decision-making. The obtained potential zones derived by integrating different techniques like RS, GIS, and MCDA were validated with correlation studies of data collected from ten wells in the study area (Abdallah, 2014) (Table 17 and Figure 29). Locations of the selected wells, The static water level (SWL) is the distance from the land surface to the water in the well under non-pumping (static) conditions prediction map, Less value (SWL) it nearest to the land surface it is mean there are match groundwater more than big value of SWL, in the (Figure 29) most lowest value of static water level in portion of high groundwater potential and the high value of water level in moderate of groundwater portion

Table 17: Wells Data

Well	Longitude	Latitude	Static water level (m)
1	35.94489	15.0901	32.07
2	35.91566	15.11684	33.97
3	35.84306	15. 17684	34.69
4	35.84987	15.15689	38.77
5	35.92666	15.16273	31.36
6	35.9047	15.17665	11.5
7	35.90514	15.1782	12.44
8	35.90493	15.17735	12.24
9	35.83273	15.29014	40.83
10	35.78878	15.33465	27.43
11	36.3405	15.6441	9.8
12	36.3405	15.6456	9.95
13	36.3405	15.6456	-
14	36.3348	15.6683	7.6
15	36.3391	15.6724	-
16	36.337	15.6694	9.2
17	36.3338	15.6663	11.3
18	36.3318	15.6652	-
19	36.3253	15.6873	13.2
20	36.3286	15.2359	16
21	36.3207	15.7133	14.6
22	36.3196	15.7157	16
23	36.3371	15.7173	14
24	36.3372	15.7347	7
25	36.109	16.1599	-

26	36.2067	16.1579	11
27	36.2067	16.1579	11.5
28	36.2067	16.1579	9.3
29	36.2072	16.1577	11
30	36.2095	16.1514	15.4
31	36.1297	16.1453	10.5
32	36.1286	16.1456	13.4
33	36.1197	16.1583	34.6
34	36.1206	16.1826	10
35	36.1212	16.1828	8.8
36	36.1206	16.1827	44
37	36.3773	15.5	25
38	15.4481	36.3903	18.75
39	35.94489	15.0901	32.07

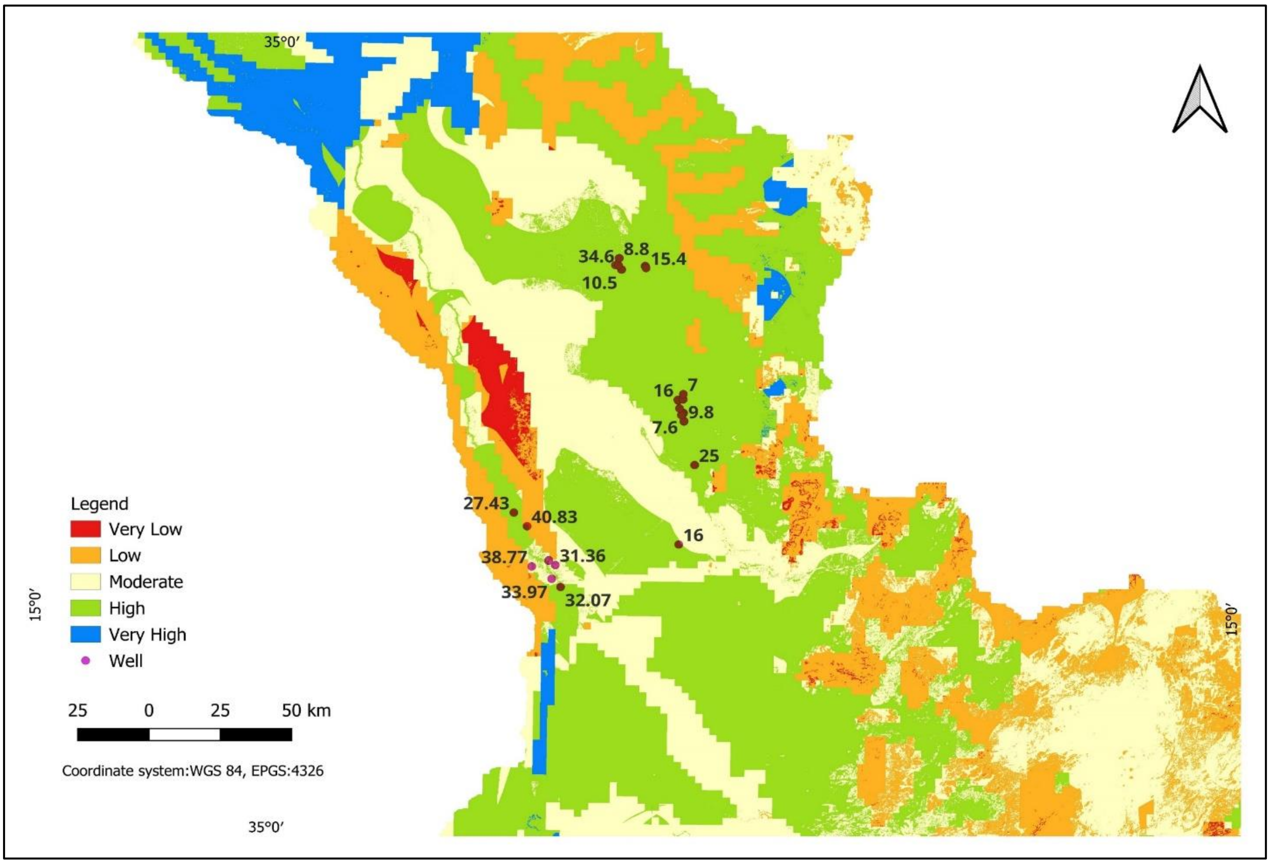


Figure 30: Wells Map of TAS

5.4. Main Nile

The results obtained from the Global Land Data Assimilation System (GLDAS) showed that groundwater potential storage in the Main Nile is very high at the eastern end near Khartoum, moderate storage is seen along the sub-basin from north of Khartoum to Egypt. This is confirmed by the current study where groundwater potential is very high in the middle and south west of the sub-basin. Low potential is distributed throughout the sub-basin.

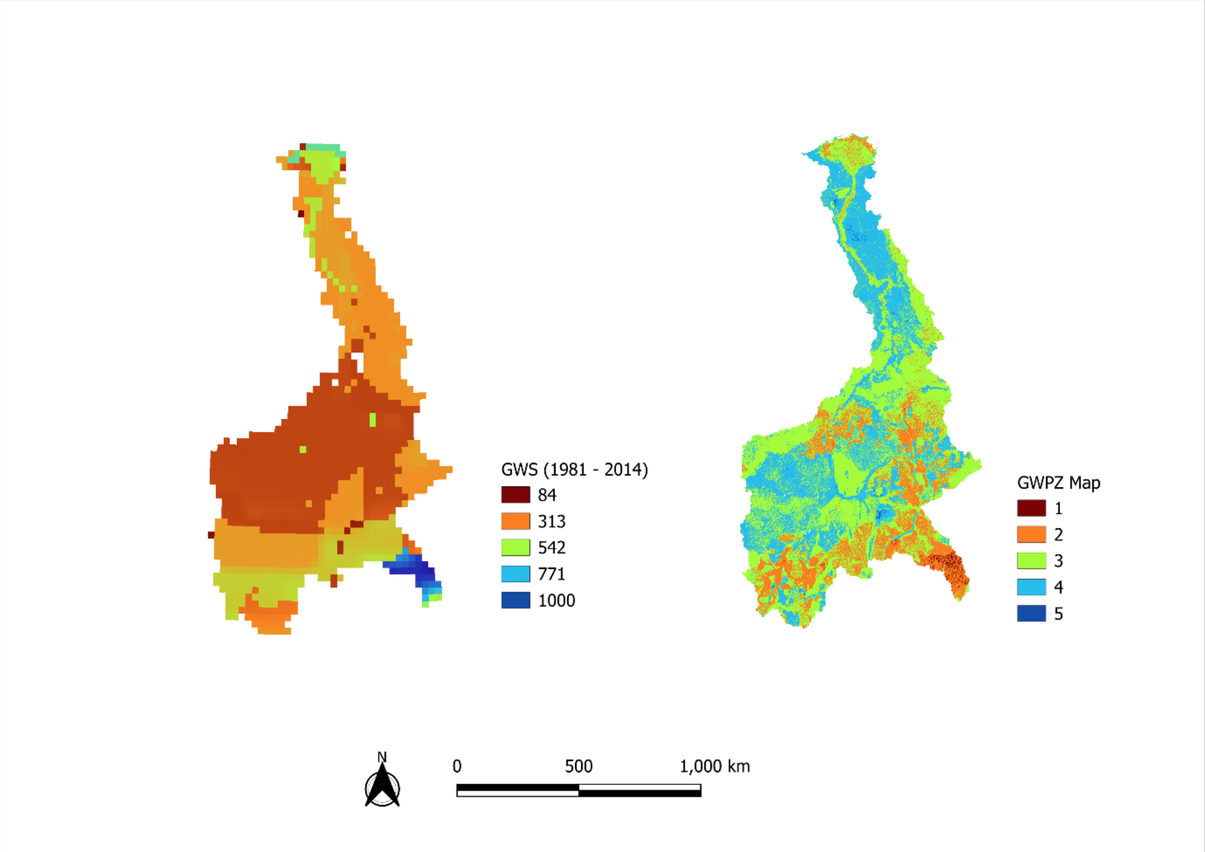


Figure 31: Result validation with GLDAS GW storage data for period (1981 - 2014) indicate the coordinate in the map

6. Conclusion

In all Sub-basins the multi-criteria decision analysis was conducted using ArcGIS and QGIS to generate a comprehensive groundwater suitability map. This analysis of groundwater potential in Baro-Akobo-Sobat incorporated seven thematic maps (geology, soil, slope, lineament density, drainage density, land use/land cover, and rainfall). The results of the analysis revealed a diverse distribution of groundwater potential in the sub-basin. The largest area (44.93% or approximately 231,618 sq km) is occupied by zones with moderate potential, indicating a reasonable chance of finding groundwater resources. Significant areas with high potential (17.10%) and very high potential (14.97%) cover over 31% combined, offering promising locations for groundwater exploration and development. Although smaller in extent, areas with low potential (12.82%) and very low potential (10.21%) contribute to the overall understanding of groundwater occurrence in the sub-basin. It is important to note that this map represents suitability, not an assurance of groundwater availability. The actual yield and quality of groundwater will vary based on site-specific geological formations and human activities. Furthermore, long-term groundwater resource protection requires the implementation of sustainable management practices, including monitoring groundwater levels, regulating extraction rates, and implementing measures to prevent contamination. The methodology and findings can also be applied to other basins in BAS to map GWP suitability. Overall, GIS-MCDA proved to be a useful tool for GWP suitability mapping.

In Blue Nile Sub-basin, seven thematic maps were created and assigned weights based on their influence, including geology, soil texture, slope, liniment density, drainage density, LULC, and rainfall (mm/year), using geospatial techniques. The results showed that slope and geology were the most influential parameters affecting GWP suitability in the study area, accounting for 50% of the suitability mapping. The final suitability map revealed that the highest GWP suitability in the basin is found in the northeastern portion, with smaller portions in the southwestern and central areas. The GWP suitability zone was determined through GIS-based weighted overlay analysis, and the study area was classified as 2.1% very high, 14.89% high, 47.6% moderate, 34.7% low, and 0.6% very low potential areas for GWP. Additionally, this GWP suitability mapping is important for future detailed studies in the basin. The findings of this study can be used as a basis for identifying potential GWP zones, improving groundwater management, and reducing uncertainty in decision-making and resource allocation. This study is the first attempt to develop potential GWP zones in the Blue Nile basin and has important implications for effective groundwater aquifer management and early planning phases. The methodology and findings can also be applied to other basins in Blue Nile Sub-basin to map GWP suitability. Overall, GIS-MCDA proved to be a useful tool for GWP suitability mapping.

In the TAS, several steps were executed which involved in the study included developing thematic layers, assigning weights to influencing factors using the AHP method, and overlay analysis to determine groundwater potential zones. Based on the groundwater potential, the study area was divided into five zones: very low, low, moderate, high, and very high. The spatial distribution and extents of these zones were as follows: 1503.67 km2 (0.74%) very low, 5183.88 km2 (25.63%) low, 87685.35 km2 (43.36%) moderate, 54110.87 km2 (26.76%), and 7106.07 km2 (3.5%) very high. The results reveal that the study's potential zones are categorized as very high and high in the southern to northern region and part of the northeastern portion. Conversely, the southern-east portion has low to very low groundwater potential, while the central and another part of the northeastern region demonstrate moderate groundwater potential. The derived groundwater potential results from the integrated operation of various factors, including slope, rainfall, lineament, drainage density, soil patterns, and geology. Additionally, the results highlight the significant role of soil and geology in the groundwater condition of the area.

In the Main;

To support the sustainable management of water resources, more multidisciplinary studies should be conducted in these areas. This approach can lead to the development of more precise, reliable, and useful groundwater potential zone mapping techniques. Furthermore, future research should investigate the impacts of climate change and urbanization on groundwater recharging and potential. The current study recommends the utilization of advanced remote sensing data, such as LIDAR, machine learning algorithms, groundwater-surface water interaction, real-time monitoring, capacity building, and an integrated approach, in order to create a groundwater potential zone map for a sustainable system. This investigation emphasizes the need for additional research that includes socioeconomic aspects, long-term monitoring, field evaluation of findings, and an expansion of the study to other regions.

Moreover, more extensive geophysical investigations should be conducted for the area under study.

7. Recommendation

Based on the generated groundwater suitability map, the following recommendations are suggested:

- **Prioritize Exploration:** Focus initial groundwater exploration efforts on areas classified as high and very high potential. These zones offer the most favorable conditions for encountering productive aquifers.
- **Sustainable Development:** While targeting high potential zones, ensure sustainable development practices are implemented throughout all sub-basins to protect groundwater quality and recharge.
- **Site-Specific Investigations:** The suitability map provides a valuable regional overview, but further investigations, including drilling and geophysical surveys, are crucial to confirm groundwater presence and yield at specific locations within each potential zone.
- **Water Resource Management:** Utilize the suitability map for informed water resource management strategies within the sub-basin. This includes allocating resources for groundwater development in suitable areas and implementing water conservation measures in areas with limited potential.
- **Model Refinement:** Consider incorporating additional data layers, such as historical groundwater extraction data or water quality information, to further refine the groundwater suitability model in the future.
- **Future Data Collection:** Drilling wells in various locations across the sub-basin, particularly in high potential zones, would provide crucial validation data to refine the groundwater suitability model.
- **Uncertainty:** Recognizing the limitations of the model due to missing validation data is important. Users should interpret the suitability map as a probability indicator, not an absolute guarantee of groundwater availability.

The suitability map may help determine the GWP zones within the Eastern Nile Basin. However, it was developed without considering decision-maker rules, economic benefits (cost-benefit analysis), risk assessment studies, or environmental benefits (environmental impact assessment). The accuracy of the GWP suitability mapping can be improved with more criteria, including groundwater level fluctuation, electrical conductivity, and recharge. However, data accessibility has an impact. The above factors were not taken into account in GWP suitability mapping due to limited data availability and the scope of the current investigation. Further comprehensive large-scale assessment of the basin's hydrogeological characteristics is important. The findings should be validated through ground truthing, which involves field investigations, direct measurements, and sampling. This will confirm the accuracy of remote sensing data and models used in the study. Additionally, detailed geophysical surveys should be conducted to obtain a comprehensive understanding of the subsurface geological formations and map groundwater potential zones. These surveys may include techniques such as electrical resistivity tomography (ERT) and vertical electrical sounding (VES).

The collected data should be integrated and analyzed, prioritizing zones based on groundwater availability, water quality, and proximity to demand centers. An implementation plan should be developed, including sustainable groundwater management strategies and guidelines for borehole siting based on the geophysical survey results. Additionally, recommendations for construction, operation, and maintenance should be provided.

It is crucial to engage stakeholders throughout the process, including local communities, water resource authorities, NGOs, and government agencies. This will ensure their participation, address concerns, and foster collaboration. To ensure the long-term sustainability of the implemented measures, a monitoring and evaluation framework should be established. This framework will regularly assess groundwater levels, water quality, and borehole performance, enabling adjustments as necessary.

In conclusion, this study provides a valuable tool for groundwater management in the Eastern Nile Basin. The findings support informed decision-making and resource allocation, contributing to the region's sustainable development. The methodologies and insights can be applied to other basins, promoting broader groundwater resource understanding and management.

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1. Annex

1.1. Sensitivity index matrix

Sub-Basin	Statistics	1 (Soil, Slope, LD, DD, LULC, RF)	2 (Geology, Slope, LD, DD, LULC, RF)	3 (Geology, Soil, LD, DD, LULC, RF)	4 (Geology, Soil, Slope, DD, LULC, RF)	5 (Geology, Soil, Slope, LD, LULC, RF)	6 (Geology, Soil, Slope, LD, DD, RF)	7 (Geology, Soil, Slope, LD, DD, LULC)
MN	min	0.95	0.95	0.95	0.95	0.95	0.95	1.79
	max	52.38	19.05	19.05	19.05	10.71	19.05	19.05
	avg	3.64	2.81	2.98	3.51	2.43	3.01	2.88
	STD	3.12	1.91	2.02	2.59	0.52	1.96	1.71
BN	min	-7.33	-1.18	-1.54	-1.89	-2.14	-2.18	-2.25
	max	8.78	6.87	6.26	2.8	-1.6	0.92	-0.29
	avg	2.37	0.22	2.49	-1.21	-0.81	-1.26	-1.8
	STD	2.06	-1.34	-1.59	0.68	0.5	0.34	0.25
BAS	min	-20.81	-8.13	-6.42	-4.54	-3.37	-3.35	-2.93
	max	5.18	4.32	4.14	0.62	0.89	-0.5	-1.03
	avg	-3.31	-4.6	-0.25	3.2	-1.81	-2.25	-2.48
	STD	2.54	2.38	1.24	0.64	0.46	0.31	0.22
TAZ	min	-19.05	-19.05	-19.05	-19.05	-2.38	-10.71	-9.71
	max	8.73	5.95	5.95	5.95	5.95	5.95	5.95
	avg	-2.25	-3.83	-0.96	-3.4	-1.8	-2.44	-2.5
	STD	4.69	3.45	2.96	2.73	1.53	1.59	1.54

Add another annexes that show the ranking and weights in the AHP you have applied.