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Identification of Groundwater Potential Zones Using Remote Sensing and GIS Techniques: A Case Study in Jowhar, Somalia

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IDENTIFICATION OF GROUNDWATER POTENTIAL ZONES USING REMOTE SENSING AND GIS TECHNIQUES: A CASE STUDY IN JOWHAR, SOMALIA

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ABSTRACT

Groundwater is the principal source of water supply in Jowhar District, Middle Shabelle Region, Hirshabelle State, Somalia, yet borehole siting has proceeded with limited systematic assessment of the conditions governing its occurrence. This study identified and mapped groundwater potential zones in the district by integrating remote sensing, geographic information systems and the Analytical Hierarchy Process. Nine thematic layers, namely geology, rainfall, soil, drainage density, land use and land cover, slope, lineament density, elevation and the normalized difference vegetation index, were derived from Landsat 8 OLI/TIRS imagery, SRTM digital elevation data, CRU TS rainfall records for 2015 to 2025 and ancillary geological and soil datasets. Each layer was reclassified onto a five-point suitability scale and weighted by pairwise comparison on Saaty's scale. Geology at 26.22 per cent and rainfall at 26.17 per cent emerged as the dominant controls, together accounting for 52.39 per cent of the total weight, with a consistency ratio of 0.038 confirming the acceptability of the judgements. Weighted overlay analysis in ArcGIS produced a groundwater potential index classified into four zones: Good, covering 3,023.99 km² or 67.54 per cent of the district; Moderate, 1,306.52 km² or 29.18 per cent; Poor, 135.22 km² or 3.02 per cent; and Excellent, 11.66 km² or 0.26 per cent. The map was validated against 48 boreholes obtained from the Ministry of Energy and Water Resources of Hirshabelle State and verified in part by field inspection, giving an overall concordance of 47.9 per cent and an area under the receiver operating characteristic curve of 0.486. Because no borehole lay within the Poor or Excellent zones, two classes remained untested, and the map is accordingly recommended for regional planning rather than for site-specific borehole siting.

Keywords: groundwater potential zones; remote sensing; geographic information systems; analytical hierarchy process; weighted overlay; Jowhar; Somalia

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Fresh water makes up approximately 2.5 per cent of the total water on Earth, with many of the portions being locked up in glaciers and polar ice caps, and thus unavailable for instant consumption by humans (Shiklomanov & Rodda, 2003; UNESCO, 2024). The need for freshwater has been steadily increasing by nearly 1 per cent per year since the 1980s, according to the World Water Development Report 2024, compiled by the United Nations Educational, Scientific and Cultural Organization (UNESCO), with most of the demand stemming from population growth, expansion of agricultural land, urbanization, and rapid industrialization. Groundwater plays a pivotal role in rural economies, supporting livelihoods in nearly 90 per cent of these communities, and it is estimated that it provides about 25 per cent of the irrigation water and almost half of the world's drinking water supply (UNESCO, 2024; Famiglietti, 2021; Taylor et al., 2022).

The World Water Development Report (WWDR) published by UNESCO (2023) also estimated the water scarcity for at least one month a year in 2016 was around 930 million people, and by 2050, this figure could rise between 1.7 and 2.4 billion. The projections illustrate the need for systematic identification, mapping, monitoring and sustainable management of groundwater in order to ensure future water security.

Groundwater has become the most strategically important freshwater resource, especially in the arid and semi-arid countries where surface water resources are limited and unreliable, particularly in the face of growing climate variability. More than one-third of the world's largest groundwater systems are highly stressed as a result of groundwater overexploitation, contamination, reduced recharge and non-sustainable groundwater abstraction (UN-Water, 2024; Scanlon et al., 2023; Taylor et al., 2022). In addition, Scanlon et al. (2023) observed that groundwater is responsible for ~50% of the total groundwater withdrawn for domestic purposes globally and that systematic groundwater exploration and sustainable management is crucial to improve water security, especially when faced with extended droughts. Groundwater resources are even more important in low income and in post-conflict countries, where surface water infrastructure is often found to be inadequate or destroyed, meaning that

groundwater is the only, or main, source of water for people's livelihoods, agriculture and domestic water needs.

In the last decade, there has been a great deal of research interest in the international scientific community with regard to the assessment of Groundwater Potential Zone (GPZ) using Remote Sensing and Geographic Information System (GIS). The employment of GIS-based Analytical Hierarchy Process (AHP) in combination with remote sensing data from satellite imagery proved to be a successful approach to accurately delineate groundwater recharge zones in semi-arid agricultural landscapes in Europe, as shown by the study in the Uckermark district of Brandenburg, Germany (Rothe et al., 2022). These hydrogeological and land use parameters were overlaid and zone maps were calculated using the weighted overlay technique; the zone maps were further checked based on long-term groundwater level monitoring data. In Asia, GWPZ has been categorized in the Jinan Karst Spring Basin of China using an integration of hydrogeological datasets, GIS, remote sensing and AHP techniques to classify GWPZ in the basin as good groundwater potential (67 per cent of the basin) (Shen et al., 2024). Similarly, Yousaf et al. (2024) applied the remote sensing technique through GIS in Lahore, Pakistan and identified the groundwater potential recharge zones in the study area with five classes ranging from extremely poor to extremely good, and concluded that most of the study area is in poor to mediocre category because of high impervious cover and groundwater depletion in the study area. In general, these global studies have demonstrated that the RS GIS approach used for field surveys is an alternative that can be reproduced, is economical and provides a comprehensive response to the spatial context that cannot be achieved with conventional hydrogeological field surveys, which are often too costly in developing countries and post-conflict situations.

The application of remote sensing and GIS in GWPZ mapping has been significantly increased at the regional level in Africa, but there are critical data deficits particularly in data poor countries. A geospatial assessment was carried out in the Igede area of Ekiti State in West Africa that used a combination of the Analytical Hierarchy Process (AHP) and Geographic Information Systems (GIS) based Multi-criteria analyses to derive the thematic layers such as geology, rainfall, Digital Elevation Model (DEM) data, land use and land cover (LULC), Normalised Difference Water Index (NDWI), slope and lineament density that were subsequently used in the creation of GWPZ maps, which were verified against the borehole records (Odesola et al., 2024). The study supported the validity of the proposed method AHP weighted overlay to delineate GWPZ in the geologically complex regions, which is an effective and

practical approach. In the study area in Central African Republic (CAR), groundwater potential zones map was created using AHP method and GIS, groundwater was found to be highly controlled by the lithology, drainage density, slope and land use in the areas of limited groundwater access in rural Central African Republic. A study in the Buffalo Catchment in the Eastern Cape province of South Africa used GIS, remote sensing and AHP to classify the GWPZ into five classes ranging from very poor to good covering an area of about 1,237 km², which revealed that the area with high GWPZ values corresponds to an environment that is semi-arid, with low drainage density and favorable geological structures (Moodley, 2022). These regional studies demonstrate the robustness and adaptability of the RS-GIS-AHP framework in different geological conditions and climatic zones in sub-Saharan Africa.

In the East Africa context, there is significant research literature to guide GWPZ mapping through remote sensing and GIS in countries like Ethiopia and Kenya. There is significant research literature in the East Africa context that can guide GWPZ mapping using remote sensing and GIS in countries like Ethiopia and Kenya. The applications of weighted overlay analysis of thematic layers, such as geology, lineament density, soil type, drainage density, slope, rainfall and LULC, have been consistently shown to be able to effectively delineate groundwater potential at the watershed scales in the Gorezen Watershed, the Muger Watershed, Abay Basin and the Teji River Catchment of southwest Shewa Zone in Ethiopia (Mulu et al., 2024; Duguma, 2025; Workie et al., 2024). In Ethiopia, Melese and Belay (2022) achieved an accuracy of 82.9 per cent in the prediction of GWPZ using borehole yield data and in Baringo County, Kenya, Ombasa et al. (2022) showed that GWPZ mapping was done with good reliability. Somalia is situated in the Horn of Africa region which has an adverse climate and hydrogeological profile and Somalia is an area with a pronounced and well-documented water insecurity, but has received comparatively little systematic attention in the scholarly literature on geospatial GWPZ mapping.

Somalia is one of the water-stressed countries globally. The country experiences an arid to semi-arid climate, very little perennial surface water and extreme rainfall variability (Ismail *et al.,* 2026). According to the Food and Agriculture Organization Somalia Water and Land Information Management Program (FAO SWALIM, 2024), Jubba and Shabelle Rivers are the only perennial water sources in Somalia, and the vast majority of the people (about 95 per cent) rely on groundwater resources for domestic water supply, livestock watering and small-scale irrigation. The main equipment used for abstraction of groundwater is borehole, shallow wells and springs, with borehole depths of 90 to 250 metres and the yield ranging from 5 to 20 cubic metres per hour based on the different aquifer systems.

Groundwater resources in Somalia are however largely restricted in availability due to poor water quality in parts of the country, as well as a lack of hydrogeological information, and the almost complete destruction of water sector infrastructure caused by decades of civil conflict (FAO SWALIM, 2024; ReliefWeb, 2024).

Jowhar, the administrative capital of the Middle Shabelle Region and Hirshabelle State of Somalia, presents significant potential for systematic groundwater potential zone mapping. The town and its surrounding areas are situated along the middle reaches of the Shabelle River, which serves as the principal source of water for domestic consumption, irrigation, and livestock production. However, the river exhibits marked seasonal variability, characterized by recurrent flooding during the rainy seasons and substantially reduced flows or complete drying during prolonged droughts, thereby affecting water availability and agricultural productivity (Ministry of Energy and Water Resources [MoEWR], 2022; Food and Agriculture Organization [FAO], 2023). According to the National Bureau of Statistics (NBS) Somalia Population Estimation Survey 2022, Jowhar District continues to experience population growth, increasing demand for reliable water resources and underscoring the importance of identifying sustainable groundwater sources (National Bureau of Statistics [NBS], 2022).

The groundwater system underlying Jowhar District is associated with Quaternary alluvial deposits bordering the Shabelle River together with deeper sedimentary aquifer systems. Nevertheless, the spatial distribution, depth, recharge characteristics, storage potential, and productivity of these aquifers remain inadequately documented in the available scientific literature. Consequently, groundwater potential mapping using Remote Sensing (RS) and Geographic Information Systems (GIS) has become an important scientific approach for identifying suitable groundwater development zones to support sustainable water resource management in the district.

Groundwater recharge, occurrence, storage, and movement are controlled by several interrelated hydrogeological and environmental factors. These include geology and lithology, which determine the nature and permeability of aquifer materials; lineament density, which influences groundwater infiltration through fractures and faults; geomorphology, which controls landforms and infiltration characteristics; soil type, which affects infiltration and water retention capacity; land use and land cover, which influence surface runoff and groundwater recharge; drainage density, which determines runoff concentration and infiltration opportunities; slope, which regulates runoff velocity and infiltration rates; and rainfall, which provides the primary source of groundwater recharge (Saaty, 1980; Freeze & Cherry,

1979; Fetter, 2018; Ismail et al., 2026). These factors collectively determine groundwater availability and are therefore widely adopted in groundwater potential zone mapping studies.

The integration of thematic layers extracted from satellite imagery, Digital Elevation Models (DEMs), geological maps, and ancillary spatial datasets constitutes the foundation of Remote Sensing and GIS-based groundwater potential zone (GWPZ) mapping. In GWPZ studies, thematic parameters such as geology and lithology, lineament density, geomorphology, soil type, land use and land cover, drainage density, slope, and rainfall are integrated using the Analytical Hierarchy Process (AHP), a structured multi-criteria decision-making technique developed by Saaty (1980). AHP assigns relative weights to the groundwater conditioning factors through pairwise comparisons before integrating them using Weighted Index Overlay (WIO) analysis within a GIS environment to produce a composite groundwater potential map. The resulting maps are commonly classified into groundwater potential zones ranging from very poor to very high and are subsequently validated using borehole yields or well productivity data.

Although Remote Sensing, GIS, and AHP have been widely applied for groundwater potential mapping in many parts of Africa and other regions of the world, their application in Somalia remains limited. Existing groundwater investigations in Somalia have largely focused on hydrogeological surveys, borehole exploration, and groundwater resource assessments with limited integration of spatial multi-criteria decision analysis for groundwater potential delineation. Furthermore, no comprehensive GIS–Remote Sensing–AHP-based groundwater potential zone mapping study has been undertaken specifically for Jowhar District despite its increasing water demand, climate variability, and dependence on groundwater resources. This study therefore seeks to fill this knowledge gap by integrating Remote Sensing, GIS, and the Analytical Hierarchy Process to delineate groundwater potential zones in Jowhar District, Middle Shabelle Region, Somalia. The study aims to generate a scientifically reliable groundwater potential map that will support groundwater exploration, sustainable water resource management, and evidence-based planning in the district.

1.2 Statement of the Problem

In the East African region there is a significant amount of literature of GWPZ mapping in Ethiopia and Kenya with the help of Remote Sensing and GIS. A weighted overlay analysis of thematic layers like geology, lineament density, soil type, drainage density, slope, rainfall, and LULC have been proven to

be effective in identifying groundwater potential at watershed level in various studies in Ethiopia, namely in the Gorezen Watershed, the Muger Watershed in Abay Basin, and the Teji River Catchment of southwest Shewa Zone (Mulu et al., 2024; Duguma, 2025; Workie et al., 2024). In Ethiopia, Melese and Belay (2022) reported a mapping accuracy of 82.9 per cent for GWPZ prediction using borehole yield data, and Ombasa et al. (2022) proved that mapping was reliable in Baringo County, Kenya. Given the challenge of this region, with Somalia sharing this climate and hydrogeological condition, Somalia has been a region of relative neglect in scholarly literature on geospatial GWPZ mapping despite the well-attested and acute water insecurity in the region.

Somalia is among the water stressed countries in the world. The country has an arid to semi-arid climate, with a lack of perennial surface water and high rainfall variability. According to the Food and Agriculture Organization Somalia Water and Land Information Management Programme (FAO SWALIM, 2024), in the country, the only perennial water bodies are the Jubba River and Shabelle river with majority of the population (estimated at around 95 per cent) relying on groundwater for drinking water, livestock watering and small scale irrigation. The main groundwater abstraction facilities are boreholes, shallow wells and springs, the borehole depths are generally in the range of 90–250 meters and the groundwater abstraction rates of springs and shallow wells are between 5 and 20 cubic meters per hour depending on the aquifer system. New groundwater resources development in Somalia, however, is significantly hampered by low water quality in certain areas, lack of hydrogeological data, almost complete destruction of infrastructure in the water sector over many years of civil conflict, and lack of systematic groundwater mapping programmes at the district or regional level (FAO SWALIM, 2024; ReliefWeb, 2024).

Jowhar is the administrative capital of the Hirshabelle Federal Member State and the Middle Shabelle region, and appears to be a good candidate for systematic groundwater potential zone mapping. The town and the surrounding district are located along the middle course of the Shabelle River, which is the main source of water for agricultural, domestic and livestock activities in the area. The Shabelle River, however, is very episodically affected by flooding, with one of the most extreme floods on record occurring in May 2023, and occasionally affected by droughts when it dries up (Ministry of Energy and Water Resources, Somalia, 2022). The groundwater system permeating the Jowhar District is linked to alluvial deposits of the Quaternary age along the margins of the Shabelle River and the deeper geologic aquifer deposits, but the distribution, depth and yield of these aquifer systems are not sufficiently

understood in the published scientific literature. Given the estimated population of the district of 622,700 and the anticipated urbanization in the Jowhar district, which is likely to increase its water demand, the systematic identification of groundwater potential zones in the Jowhar District using remote sensing and GIS techniques is a scientific and humanitarian imperative.

The integration of various thematic layers obtained from satellite images, digital elevation models, geological maps and ancillary spatial data is the basis of the GWPZ mapping through remote sensing and GIS. The themes normally used in the GWPZ studies are generally geology, lithology, lineament density, geomorphology, soil type, land use and land cover, drainage density, slope, and rainfall. These parameters have been assigned relative weights using methods like Analytical Hierarchy Process (AHP) (Saaty, 1980), a structured multi-criteria decision-making method that quantifies the relative importance of each parameter by comparing one by one, and is integrated in a weighted index overlay (WIO) analysis within a GIS environment to create composite groundwater potential index maps. These maps are then subdivided into areas with different groundwater potentials, usually in the range of very poor to very good, and checked with existing borehole or well yield data, if available. Although this method has been used and tested in many geological and climatic environments, it has not been used systematically in the Jowhar District and has not been applied to the Middle Shabelle area of Somalia as a whole, which is a gap in knowledge that is being addressed by this study.

1.3 Research Questions

1. What is the spatial distribution pattern of groundwater potential zones in the Jowhar District of the Middle Shabelle region, Somalia?
2. Which remote sensing and GIS-derived thematic layers including geology, lineament density, soil type, drainage density, slope, land use and land cover, geomorphology, and rainfall most significantly influence the delineation of groundwater potential zones in the study area?
3. How does the integrated weighted index overlay analysis informed by the Analytical Hierarchy Process perform in generating a reliable and internally consistent groundwater potential zone map for the Jowhar District?
4. To what extent does the groundwater potential zone map produced by this study align with observed data from existing boreholes and wells in the district, and what does this validation indicate about the reliability of the model output?

1.4 Research Objectives

The study is to identify and map groundwater potential zones in the Jowhar District, Middle Shabelle region, Somalia, using remote sensing and GIS-based techniques.

1.4.1 Specific Objectives

1. To assess the relative influence variables on the occurrence and distribution of groundwater in the study area.
2. To integrate the derived thematic layers using weighted overlay analysis informed by the Analytical Hierarchy Process (AHP) to produce a composite groundwater potential index map for the Jowhar District.
3. To validate the derived groundwater potential zone map against available borehole and well yield data in the study area to determine the accuracy and reliability of the RS-GIS-AHP model output.

1.5 Scope and Limitations of the Study

This study will be conducted in Jowhar District, Middle Shabelle Region, Hirshabelle State, Somalia, focusing on delineating groundwater potential zones using Remote Sensing (RS), Geographic Information Systems (GIS), and the Analytical Hierarchy Process (AHP). The analysis will cover the district's administrative boundaries and the hydrogeomorphic characteristics of the Middle Shabelle River Basin within the study area. Spatial datasets, including Landsat 8 and Landsat 9 imagery, Sentinel-2 imagery, the 30 m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), and published geological and soil maps, will be used to derive thematic layers influencing groundwater occurrence. The study will primarily rely on geospatial analysis and will not include groundwater quality analysis, aquifer pumping tests, or continuous groundwater level monitoring.

The study may be constrained by limited availability of borehole logs and groundwater yield data for validating the groundwater potential map. The spatial resolution of freely available satellite imagery and DEM data may also limit the identification of fine-scale geological and structural features. In addition, security challenges in some parts of Jowhar District may restrict field verification of remotely generated outputs. Finally, although the AHP is a widely accepted multi-criteria decision-making technique, the assignment of factor weights involves expert judgment, which may introduce some degree of uncertainty. These limitations will be minimized through the use of validated geospatial datasets,

established AHP procedures, and comparison of the results with available secondary data and published literature.

CHAPTER TWO

LITERATURE REVIEW

2.1 Groundwater Occurrence and Hydrogeology

2.1.1 Principles of Groundwater Occurrence and Movement

Groundwater is the water that fills the voids, fractures and pores in subsurface geologic formations and flows from areas of recharge to areas of discharge because of gravity and hydraulic gradients (Freeze & Cherry, 1979). Groundwater occurrence in any locality is controlled by a combination of geological, climatic/weather, geomorphological and land-use factors, all of which help to define the capacity of the subsurface to receive, store, and transmit water. These parameters are fundamental in determining the potential zones of groundwater systematics because each one of them is a physically meaningful proxy of one or more hydrogeological processes.

Groundwater is found in two major subsurface zones; the unsaturated zone (vadose zone) where pores are partially filled with air and water, and the saturated zone where all the available pore spaces are occupied by water. The top of the saturated zone is known as the water table in unconfined aquifer systems and piezometric surface in confined systems. The vertical infiltration of precipitation to the water table is the main source of aquifer recharge and is facilitated by the intensity of precipitation, duration of precipitation, soil texture and structure, slope gradient, land cover type, and depth and permeability of the overlying geologic units (Scanlon et al., 2023). Recharge is typically episodic, spatially variable and is strongly controlled by localized geological and geomorphological features and structures such as permeable alluvial channels, fractured rock outcrops and pediment surfaces in arid and semi-arid regions with low and highly variable annual rainfall.

The capacity to yield water to wells depends on the two most important characteristics of an aquifer, the transmissivity and the storability, which are dependent upon the porosity, permeability, and thickness of the water-bearing formation. Primary porosity is the porosity of the original fabric of the rock or sediment, and is generally high in alluvial sediments, sandstones and gravels, these being productive aquifer in many semi-arid parts Africa. Post-depositional processes like fracturing, faulting, and chemical dissolution create secondary porosity, which is the primary source of groundwater storage and transmission in hard rock areas including crystalline basement rocks and carbonates, and is the primary source of groundwater in hard rock areas (Mulu et al., 2024). The groundwater potential in a basement

rock environment is thus very much dependent on the orientation, density and connectivity of fracture systems that are commonly mapped as lineaments from remote sensing data.

2.1.2 Hydrogeological Settings of Arid and Semi-Arid Regions in East Africa

The East African region comprises very complex hydrogeological settings, ranging from the deeply weathered crystalline basement rocks of the East African Rift System and the uplands, through to the sedimentary aquifer systems of the Somali-Ethiopian plateau and the alluvial systems in the main river valleys. The annual rainfall in most parts of Kenya, Ethiopia, Djibouti, Somalia and Eritrea ranges from less than 100 millimeters in the driest areas to about 600 millimeters at the sub-humid margins. In such settings, contamination of the water resources in the form of high salinity and fluoride concentrations is often observed as a result of the physical water scarcity, which makes it challenging to identify and develop practical freshwater aquifer systems hydrogeologically (Kebede, 2022).

In Kenya and in northern Ethiopia, groundwater is closely related to the rift valley geological framework, with fault-bounded sedimentary basins and volcanic features containing productive aquifers, reached by deep boreholes. In lowland areas of Ethiopia and Somalia, the alluvial aquifers are the main source of accessible groundwater, while groundwater is present in the Quaternary floodplain sediments at relatively shallow depths. The studies were carried out in the Ewaso Ng'iro–Lagh Dera Basin (EGB) of Kenya that spanned arid hard rock terrain and showed that integrated RS, GIS and AHP techniques could be used to effectively delineate groundwater recharge zones, where it was found that the most influential parameter in determining spatial groundwater potential was geological lineaments followed by drainage network characteristics (Ombasa et al., 2022). This discovery supports the broad conclusion that the density and connectivity of fracture systems in the basement rock are the most important factors determining groundwater occurrence and accessibility in this type of environment, as has been shown in many other studies.

The general East African literature also supports the view that the potential of groundwater resources in alluvial and floodplain environments, as in the Shabelle River valley of Somalia, depends mainly on the thickness, lateral extent, and hydraulic connectivity of permeable alluvial sediments, and on the depth of the water table below the land surface. The World Bank (2022) groundwater assessment for Somalia included a description of shallow (Quaternary) aquifers connected to the Shabelle and Jubba Rivers,

characterized by groundwater at depths below 15 metres in some areas along the river, and the most strategically available in southern Somalia.

2.1.3 Aquifer Types Relevant to Somalia and the Jowhar Geology

The geology of southern Somalia (i.e. Middle Shabelle, the area where Jowhar is located), involves a layer of sedimentary rocks that overlie older basement rocks. The subsurface geology in the southern part of Somalia consists of Quaternary alluvial and aeolian deposits, Neogene and Palaeogene sedimentary rocks including the sandstones of the Jesomma Formation, and the limestones and evaporites of the Mustaxiil Formation, and deeper Mesozoic sedimentary rocks (World Bank, 2022). Hydrogeological attributes and characteristics of each of these formations are unique which control their potential as a water-bearing aquifer system.

The most readily available aquifer system in the study area is the Quaternary alluvial deposits that are adjacent to the Shabelle River in the Jowhar District. These deposits are composed of unconsolidated sands, silts and clays deposited by the river during cycles of flooding over many thousands of years, and are generally more than 10 metres thick in the most favourable areas (World Bank 2022). These sediments normally have adequate permeability and specific yield to allow groundwater abstraction by shallow dug wells or hand dug boreholes and in the district are generally the most targetted for community water supply development. Hydraulic connectivity to the river system is known for moderately productive aquifers with high storage capacity that under high water table conditions maintain low flows in the Shabelle river, in deeper sedimentary aquifer systems, especially the Jesomma sandstone formation as identified in the larger Somali-Ethiopian basin (Awulachew et al., 2012).

The aquifer system of the Jowhar District can be classified into three major types: unconfined alluvial aquifers in the floodplain sediments of the Quaternary, semi-confined sediments of the Neogene and fractured or karstic limestone where it is close to the surface (Mustaxiil). Existing literature lacks information about the spatial distribution and hydrogeological characteristics of these aquifer systems, especially at the district scale, which makes GWPZ mapping a systematic study using GIS and RS a necessity.

2.2 Remote Sensing for Groundwater Exploration

2.2.1 Overview of Satellite Data Used in Hydrogeological Studies

In the last 30 years, the use of satellite remote sensing for hydrogeological studies has grown rapidly due to the progress in spatial image processing and GIS related analysis coupled with the progressive improvement of data quality and availability of multi-spectral and radar satellite data. A number of remote sensing methods have significant advantages over traditional hydrogeological field survey methods, especially in the post-conflict Somalia where field operations are highly restricted, such as: synoptic spatial coverage, temporal repeatability, cost-effectiveness and the ability to produce spatially continuous data over large and physically inaccessible areas (Ashraf et al., 2024).

The Landsat satellite series co-owned by NASA and the United States Geological Survey (USGS) has been one of the most widely used multispectral data sources in GWPZ mapping studies around the world. The Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS) are multispectral instruments on both Landsat 8 (launched in 2013) and Landsat 9 (scheduled for launch in 2021) with 30-metre spatial resolution, covering the visible wavelengths to shortwave infrared and thermal infrared, respectively. These bands are especially useful for geological and structural mapping, LULC classification, the extraction of spectral indices (e.g. Normalized Difference Vegetation Index, NDVI and Normalized Difference Water Index, NDWI) and the identification of soil and surface lithology. Ethiopia (Workie et al., 2025) and Nigeria (Odesola et al., 2024) studies have established the use of Landsat 8 imagery for effective derivation of GWPZ thematic layers for these semi-arid environments.

The European Space Agency (ESA) Copernicus Earth Observation programme operates the Sentinel-2 satellite, which offers multi-spectral data at a spatial resolution of 10 meters in the visible and near-infrared spectral bands and 20 meters in the shortwave infrared spectral bands, and a revisit time of about five days at the equator. The superior spatial and spectral resolution of Sentinel-2 compared to Landsat renders it very useful for detailed applications in geological and land cover mapping. In addition, Sentinel-1 SAR data was found to be more effective than optical data for extracting structural lineaments, with higher lineament densities, in Egypt, where Ashraf et al. (2024) conducted their research.

The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) is a topographic dataset, with a spatial resolution of approximately 30 meters globally, and is the most commonly used one in the mapping studies within GWPZ. It is the main data source from which morphometric parameters such as slope, drainage density, drainage pattern, stream order and watershed boundaries are calculated. The ASTER Global Digital Elevation Model (ASTER GDEM), which has a similar resolution of 30 m, is an alternative or complement to the topographic data set, and has better vertical

accuracy in some types of terrain. Mulu et al. (2024) and Duguma (2025) conducted studies in Ethiopia, which found that SRTM-derived DEM data can serve as a valuable foundation for morphometric analysis in semi-arid watersheds and produce drainage network maps and slope maps that are useful for capturing the spatial controls on groundwater recharge and flow.

2.2.2 Lineament Extraction from Satellite Imagery

One of the most important uses of remote sensing in groundwater exploration is the delineation of lineaments, which are zones of increased secondary permeability in the subsurface where groundwater infiltrates, migrates, and accumulates, such as faults, fractures, joints and shear zones. Lineament density is a widely used parameter that is a good indicator of rock fracturing and, therefore, the potential for productive groundwater in an area. In crystalline basement rock areas, high lineament density is always correlated with high groundwater potential, but in sedimentary formations, the lineaments can point to higher groundwater potential zones where fracture zones cut through low permeability stratigraphy (Ashraf et al., 2024).

Lineaments are generally generated from satellite imagery by a combination of multispectral or radar information directional filtering and automatic or semi-automated line detection algorithms that can be implemented within a GIS environment. Studies have shown that optical sensors (e.g. Sentinel-2 and Landsat 8) are very effective at mapping longer lineaments with clear tone variation, whereas radar sensors (e.g. Sentinel-1 SAR) are more effective at detecting shorter lineaments because they are less sensitive to solar illumination conditions and more to surface roughness and topographic shadowing (Ashraf et al., 2024). Hill shade and slope images derived from the DEM are also commonly employed in lineament mapping to help highlight subtle lineations that can be seen with SRTM at different azimuths of illumination, related to fault zones and fracture sets. This has been confirmed by studies in Ethiopia which revealed that the geology and lineament density and geomorphology are always the most important variables in the AHP-weighted GWPZ analysis, and thus, the primary step in the remote sensing workflow is lineament mapping (Bekele et al., 2025).

2.2.3 Drainage Pattern Analysis Using DEM

Analysis of drainage network patterns generated from the DEM data is a basic part of GWPZ mapping because drainage patterns also give indirect information of the underlying geology, topographic controls on water movement, and relative ability of different terrain units to produce surface runoff or

groundwater recharge. Groundwater recharge potential decreases with increasing drainage density in most geological conditions because high drainage density results in high surface runoff and low infiltration and vice versa for low drainage density (Mulu et al., 2024).

Drainage network extraction is done by DEM based method through hydrological processing tools available in GIS software (i.e. ArcGIS or QGIS) by following standard methodology of Stream Ordering (Strahler method). The hydraulic response of watersheds and the susceptibility of their watersheds to surface runoff and/or groundwater recharge is described by the drainage network, the stream order hierarchy and basin morphometric parameters such as bifurcation ratio, elongation ratio and basin form factor. The theme of drainage density in terms of the spatial variability in the study area is an important theme for GWPZ mapping in semi-arid environments as they are areas with low drainage density, which are assigned the highest groundwater potential rating in the weighted overlay analysis, as indicated by Workie et al., 2025.

2.2.4 Land Use and Land Cover Classification and Its Influence on Recharge

Land use and land cover (LULC) is an important thematic parameter in the mapping of GWPZ since it directly controls the amount of infiltrating precipitation for recharging the groundwater system and the amount of surface runoff and evapotranspiration. Dense vegetation cover (forests, woodlands and grasslands) slows surface water, reduces the energy of raindrops, increases soil organic matter and structure, and promotes moderate infiltration rates; agricultural lands with seasonal crops and crop residues also promote moderate infiltration. However, the urban and peri-urban regions with higher impervious surfaces like roads, buildings and concrete structures result in a significant reduction in infiltration capacity and increase in surface runoff, thereby causing groundwater depletion in rapidly urbanizing regions (Sreerama Naik et al., 2024; Shaikh et al., 2024).

LULC maps are generated from a supervised or unsupervised classification of multispectral satellite data (typically Landsat 8/9 or Sentinel-2) using classification algorithms like Support Vector Machine, Random Forest or Maximum Likelihood, within GIS or remote sensing software. Confusion matrix is a method that is commonly used to estimate the accuracy of LULC classification from ground truth points collected independently, and an overall classification accuracy of > 85% is regarded as acceptable in the literature for use in GWPZ analysis (Odesola et al., 2024). It was found that in the East African context, LULC changes such as increasing the extent of agricultural land at the cost of forest have a significant

impact on groundwater recharge rates, and current and accurate LULC data is important to incorporate into GWPZ assessments over a 20-year time period (Gashaw et al., 2022).

2.3 GIS-Based Methods for GWPZ Delineation

2.3.1 Weighted Index Overlay Analysis

he GIS-based technique most widely used in the spatial integration of multiple thematic layers in GWPZ mapping studies is the weighted index overlay (WIO) analysis. The general concept of WIO is to combine multiple spatial data layers representing different hydrogeological parameters together in a GIS environment and perform arithmetic operation (sum, difference, product) with the individual layers to produce a single composite groundwater potential index map by assigning a weight that reflects the relative influence of the individual layers on groundwater occurrence (Adugna & Awoke, 2024). The groundwater potential index (GPI) is then classified into a finite number of groundwater potential ordinal classes (usually 4-5) ranging from very poor to very good, according to the statistical distribution of the groundwater potential index over the study area.

The mathematical expression of WIO analysis can be written as the sum of the product of the weights of the thematic layers and the standardized score for each thematic layer at each spatial unit (pixel). Each parameter should have a percentage weight that adds up to 100 percent or unity, meaning that each parameter makes its share in the overall index. The weight assignment to each thematic layer is the most conceptually and methodologically important step, because it is the least consistent with varying weights, which creates significantly different GWPZ maps. Weights are usually established using the AHP framework or through expert opinion, but other methods, such as the frequency ratio method, weight of evidence, and machine learning algorithms have been used in the literature. The numerous studies that have been conducted have consistently shown that the WIO analysis using weights derived from AHP can generate GWPZ maps with a level of validation accuracy that is comparable to the more computationally expensive machine learning techniques, yet with greater methodological transparency and reproducibility (Mihret & Wuletaw, 2025).

2.3.2 The Analytic Hierarchy Process in Groundwater Studies

The Analytic Hierarchy Process (AHP) is a structured multicriteria decision making method, which was introduced by Saaty in 1980, is used to systematically quantify the relative importance of multiple

decision criteria by using pairwise comparisons (Saaty, 1980). The AHP framework is used to determine the weights of the various thematic layers (geology, lineament density, drainage density, slope, LULC, soil type, rainfall) in the context of the GWPZ mapping, as they are deemed by expert judgement or by empirical evidence from the literature to be of relative hydrological significance. The pairwise comparison process consists of assigning a rating between 1 and 9 to the parameters of each pair on Saaty's nine-point comparison scale, which represents the importance of the parameters, ranging from 'equal importance' (1) to 'extremely dominant' (9).

The AHP framework generates a pairwise comparison matrix which is then normalized to produce a priority vector (AHP weight) for each parameter using the eigenvalue analysis. The Consistency Ratio (CR) is used to test the internal consistency of the pairwise comparison matrix to be less than 0.10 (10 per cent) for the weightings to be deemed to be acceptably consistent. If the CR is more than 0.10, it means that the pairwise comparisons made are not consistent enough and the judgements should be adjusted. The internal coherence of the weight assignment process has been confirmed by studies that have used AHP in the mapping of GWPZ in Ethiopia, with consistently CRs below 0.10 even in well-designed studies (Diriba et al., 2024; Adugna & Awoke, 2024). Rainfall and geology/lithology are the two main factors that are most frequently given the highest weight in GWPZ studies in sub-Saharan Africa, with geology/lithology being the primary factor in determining capacity of the geology to store water and rainfall in determining groundwater recharge rates (Mulu et al., 2024; Bekele et al., 2025).

Many of the practical benefits of AHP seen in GWPZ studies are as follows: conceptually understandable, relatively easy to calculate using readily available GIS software, flexible to incorporate a range of qualitative and quantitative information, and the ability to aggregate multiple expert sets of weights into a consistent set of weights. The groundwater potential is generally similar for all the models, with AHP-based models appearing to be slightly more conservative in identifying high groundwater potential areas when compared to other MCDA based methods such as Fuzzy AHP, the Multi-Influencing Factor (MIF) method and machine learning methods like Random Forest (Workie et al., 2025; Mihret & Wuletaw, 2025).

2.3.3 Multi-Criteria Decision Analysis Frameworks

Multi-criteria decision analysis (MCDA) is a family of structured decision-making methods that, in cases of multiple criteria (often conflicting) and where a spatially differentiated evaluation of an attribute of

interest is required, can be used to reach a decision. Hydrogeological mapping can be used to integrate the multi-dimensional nature of the groundwater occurrence in a systematic framework, such as a MCDA framework, of which AHP-based WIO analysis is the most common. However, other MCDA frameworks have been used in GWPZ mapping such as MIF method, Fuzzy AHP approach, logistic regression, weight of evidence (WOE), frequency ratio analysis and, more recently, machine learning classifiers like Random Forest, Boosted Regression Trees, and Artificial Neural Networks.

Unlike AHP, the MIF method is based on the number of factors each parameter is directly and indirectly affected by to assign weights to thematic layers, thus reflecting the interconnection of each parameter with the entire hydrogeological system in an effective manner rather than just based on expert opinion. Mulu et al. (2024) conducted a study in the Gorezen Watershed, Ethiopia, which used both AHP and MIF methods, concluding that the fusion of the two methods led to a better spatial agreement of GWPZ classification when compared to single method use. The Fuzzy AHP method is an extension of the classical AHP that overcomes the discrete nature of the GWPZ maps by assigning triangular fuzzy numbers to the scores of pairwise comparisons of the experts' judgements and eventually producing smoother GWPZ maps that could better represent the inherent gradational nature of GWP distributions across the landscape (Workie et al., 2025).

Thematic Layers can be integrated using the following means:

The thematic layers are integrated into a GIS-based GWPZ map with the help of raster-based overlay analysis in ArcGIS or other GIS software, based on a standardized procedure which involves the following steps: data collection, data processing and map preparation, reclassification of each thematic layer into a uniform rating scale, application of weights using AHP or other MCDA approach, calculation of the weighted overlay, classification of the GWPZ, and validation. The computation of the overlays can only be done once each thematic layer is reclassified on a common rating scale on a ordinal scale ranging from 1 to 5, with the higher rating having a greater groundwater potential (Diriba et al., 2024).

The most frequently used thematic layers used in GWPZ mapping studies in East Africa and similar semi-arid areas are geology/lithology, geomorphology, lineament density, drainage density, slope, rainfall, soil type and texture and LULC. These 8 parameters are consistently included in the studies analyzed for this review and, in some cases, supplementary parameters like the Topographic Wetness Index (TWI), Topographic Position Index (TPI) and Elevation are also added as indicators of surface

hydrological behavior. For example, studies undertaken in Ethiopia (Mulu et al., 2024; Workie et al., 2025; Bekele et al., 2025), Nigeria (Odesola et al., 2024) and South Africa (Moodley, 2022) all include these 8 parameters.

2.3.4 Integration of Thematic Layers

The integration of multiple thematic layers in the mapping of GWPZs is achieved by using a standardized process of data collection, data processing, map preparation, reclassification of each thematic layer into a uniform rating scale, weight assignment (either by AHP or other MCDA approach), weighted overlay computation, GWPZ classification and validation, carried out in GIS (ArcGIS or equivalent), by raster-based overlay analysis. To enable computation of overlay, each thematic layer has to be reclassified to an ordinal rating scale, usually 1 to 5, with 5 being the most groundwater potential and 1 being the least (Diriba et al., 2024).

The most frequently used thematic layers used for GWPZ mapping studies in East Africa and similar semi-arid regions are geology, lithology, geomorphology, lineament density, drainage density, slope, rainfall, soil type and soil texture, and LULC. All of the studies analyzed for this review also contain these eight parameters, but the extra layers (Topographic Wetness Index (TWI), Topographic Position Index (TPI) and elevation as a supplementary indicator of surface hydrological behavior) are sometimes added to the study. The studies were conducted in Ethiopia (Mulu et al., 2024; Workie et al., 2025; Bekele et al., 2025), Nigeria (Odesola et al., 2024) and South Africa (Moodley, 2022).

2.4 Thematic Parameters and Their Hydrogeological Significance

2.4.1 Geology

The geology of the aquifer are the most universally accepted thematic parameters used in the construction of GWPZ, since the physical and chemical characteristics of the rock or sediment of which an aquifer is composed will directly impact the porosity, permeability and water-storage capacity of the aquifer. The hydrogeological properties of the different lithological units are vastly different: unconsolidated sediments (sands and gravels) have high primary porosity and permeability; sandstones or limestones have intermediate primary porosity and permeability and weathered or fractured zones are also sources of secondary porosity in these rocks; crystalline basement rocks such as granite, gneiss and schist have little primary porosity, but may contain significant secondary porosity through weathered zones or fracture systems. Geology always has the highest or second highest weight in AHP-based

GWPZ analysis across East Africa indicating its first or second consideration in controlling the spatial distribution of groundwater potential (Mulu et al., 2024; Eshetu et al., 2024).

2.4.2 Geomorphology and Landforms

The recognition of landform types with different occurrence characteristics of groundwater is a key element of geomorphology in providing critical hydrogeological information. High groundwater potential is associated with geomorphological units such as pediment surfaces, valley fills, alluvial fans, floodplains and buried channels which are areas of active or historical sediment deposition where permeable materials are deposited. Rocky hills, ridges and elevated plateaus, on the other hand, are related to high surface runoff and low groundwater recharge. Commonly, geomorphological thematic layers used for GWPZ mapping are generated using the analysis of DEM coupled with interpretation of satellite imagery and in most studies from East Africa, the AHP weight range is between 15 and 22 per cent (Eshetu et al., 2024; Bekele et al., 2025).

2.4.3 Lineament Density

Lineament density is the linear density of the structural lineaments and is the most prominent remote sensing indicator of secondary porosity and permeability in the subsurface. In crystalline basement rock areas, a high lineament density is correlated with a well-connected fracture network that improves groundwater infiltration, storage and transmissivity. However, low lineament density, especially in impermeable rock types, are more likely to be associated with poor groundwater potential. The findings from numerous studies conducted in Ethiopia, Kenya and South Africa have been consistent in that the two or three most important groundwater parameters in the mapping exercise are lineament density and that zones of high lineament density correspond to high borehole yield in the validation exercise (Moodley et al., 2022; Mulu et al., 2024).

Quantitatively, lineament density is defined as the total length of lineaments per unit area, calculated using the equation:

$$LD = \frac{\sum_{i=1}^{n} L_i}{A}$$

where LD is the lineament density (km/km²), Li is the length of the ith individual lineament segment, n is the total number of lineament segments within the study area or cell, and A is the area of the designated

cell or the total region under consideration (in km²). In some hydrogeological contexts, a secondary count-based density (Dn = n / A) is also used to highlight areas with a high frequency of lineament intersections, which are particularly favorable for groundwater flow due to enhanced fracture connectivity.

For manual extraction of lineament density often conducted for validation purposes or in areas lacking advanced GIS software a systematic grid-overlay method is employed. A transparent grid of uniform cell size (commonly 1 km × 1 km, though the dimensions depend on the scale of the satellite imagery and the target aquifer scale) is overlaid onto the printed or digitized lineament map. Within each grid cell, the cumulative length of all visible lineament traces is carefully measured using a calibrated ruler, a cartographic wheel measure, or a digital scale. This measured total length is then divided by the actual ground area represented by the grid cell to derive the local lineament density value. The computed value is assigned to the centroid of each respective grid cell, and these point-values are subsequently interpolated and contoured to generate the final lineament density surface used in the GWPZ mapping exercise.

2.4.4 Drainage Density

As described in Section 2.3.3, the drainage density is inversely proportional to the potential of groundwater recharge; and low drainage density is considered as a permeable substrate which favors infiltration, rather than runoff generation. For GWPZ mapping studies, the hydrologically conditioned drainage network derived from a DEM is used to complete a kernel density estimation (KDE) in a GIS environment and this is reclassified into the rating classes such that the lowest drainage density will capture the highest groundwater potential score. The study in the Muger Watershed (Chala et al., 2025) and Gorezen Watershed (Mulu et al., 2024) of Ethiopia showed that the areas of low drainage density in permeable geological formations strongly have higher yields of boreholes than the areas of high drainage density in impermeable crystalline rocks.

Fundamentally, drainage density is determined using the following equation:

$$DD = \frac{\sum_{j=1}^{m} L_{sj}}{A}$$

where DD is the drainage density (km/km²), L_{sj} is the length of the j^{th} stream segment, m is the total number of stream segments within the watershed or kernel, and A is the total area of the watershed or the specific GIS raster cell (in km²). In modern GWPZ analysis, this conventional arithmetic calculation is replaced or supplemented by kernel density estimation (KDE). The KDE applies a moving window of a specified radius across the stream network, employing a smoothing kernel function (e.g., quartic or Gaussian) to compute the density per unit area for each output raster cell. This approach produces a continuous, spatially-smoothed drainage density surface that effectively captures the spatial variability of stream network concentration, which is then reclassified into the appropriate groundwater potential scoring classes.

2.4.5 Slope and Topography

Slope gradient is one of the basic factors that determine the distribution of precipitation between surface runoff and groundwater recharge. Steep slopes tend to cause surface water to flow rapidly and erode, decreasing the time that surface water has to infiltrate, and thus the probability of infiltration into the soil and eventual groundwater recharge; gentler slopes allow surface water to pond or to flow slowly, increasing the likelihood of infiltration into soil and subsequent infiltration to groundwater. The slope is generally calculated from the DEM and is derived from the rate of change of elevation in the horizontal (x) and vertical (y) directions. The slope angle is mathematically expressed as:

$$\theta = \arctan\left(\sqrt{\left(\frac{\vartheta z}{\vartheta x}\right)^2 + \left(\frac{\vartheta z}{\vartheta y}\right)^2}\right) x \frac{180}{\pi}$$

where θ is the slope in degrees and z is the elevation. It is usually divided into categories of gentle to very steep slope (less than 5 degrees to 90 degrees). Slopes less than 5 degrees will have the highest groundwater potential rating in GWPZ mapping. The findings of this study in the Gidabo Watershed in Ethiopia (Diriba et al., 2024) showed that most of the high groundwater potential zones were located at gentle slopes which also coincided with fine-textured soils and high-density lineament networks.

2.4.6 Rainfall and Precipitation

Groundwater recharge is primarily controlled by rainfall in most semi-arid environments and thus the spatial and temporal variations in rainfall is the prime determinant of the spatial pattern in groundwater

potential. The depth and permeability of the vadose zone, slope, soil type and land cover will modulate the impact of rain as a recharge driver, but it is better able to recharge areas with higher mean annual rainfall. The rainfall data for GWPZ mapping studies are usually derived from interpolated rainfall surfaces created from rain gauge station readings or derived from satellite observations of precipitation like CHIRPS (Climate Hazards Group InfraRed Precipitation with Stations) and PERSIANN, which are especially useful in regions with limited ground-based rain gauges (Eshetu et al., 2024). The thematic parameters of a GWPZ study in an AHP context is usually dominated by the weight of rainfall (20-25%), which is the recharge source in Ethiopia (Eshetu et al., 2024; Bekele et al., 2025).

2.4.7 Soil Type and Texture

Soil physical properties significantly influence the speed with which infiltrating water moves through the vadose zone to the water table, especially the texture (the relative amounts of sand, silt and clay); the structure (the arrangement of soil particles); and the hydraulic conductivity (the ability of water to pass through the soil). The hydraulic conductivity of the coarse textured sandy soils is high, allowing for high infiltration rates, and thus high groundwater recharge rates, while the fine textured clay rich soil has a low hydraulic conductivity and will allow for water to pond on the surface of the soil or to surface run off. Soil texture data are usually obtained from national or international soil maps (such as the FAO World Soil Database and the USDA Soil Taxonomy) and classified as to ground water permeability and ground water recharge potential in GWPZ mapping. In the Muger Watershed (Duguma, 2025) it was found that low matrix permeability of the soil on gently sloping terrain with high numbers of lineaments showed high groundwater potential, even though the lineaments facilitated preferential pathways for recharge.

2.4.8 Land Use and Land Cover

The relationship between LULC and groundwater recharge and infiltration have been outlined in Section 2.3.4. LULC usually has a moderate weight (8 to 15 per cent) in the AHP analysis, given the fact that it is not a primary geologic control of groundwater occurrence, but rather a surface modifier of the recharge process when considering the thematic parameter significance for groundwater mapping. Areas heavily dominated by vegetation, such as forests, woodlands, and shrublands are always rated as having the highest potential for groundwater whereas urban and bare land areas are always rated as having the lowest potential for groundwater. Land Use and Land Cover (LULC) maps are created from recent

satellite data to reflect the temporal dynamism of LULC, which is a result of continuous process of land degradation, agricultural expansion and urbanization within the study area, as indicated in the literature (Gashaw et al., 2022; Kawara et al., 2024).

2.5 Review of Similar Studies in Africa and Comparable Regions

2.5.1 Case Studies from East and Northeast Africa

GIS and RS-based GWPZ mapping has become the most prolific research area in sub-Saharan Africa and data collection has been progressing rapidly in Ethiopia, with several peer-reviewed research studies for a variety of geological, climatic and hydrological environments. The studies undertaken by Kindie et al. (2019), Melese and Belay (2022), Godif and Manjunatha (2023) and Manderso et al. (2024) used the GIS-based MCDA methods to delineate GWPZ using seven to nine thematic layers all found lithology and rainfall to be the most influencing factor in the Lake Tana Basin. Good to excellent agreement with yields obtained from borehole records was achieved in these studies, with the agreement index being higher than 75 per cent in most of the cases.

Mulu et al. (2024) used the AHP and MIF methods in the Gorezen Watershed which is semi-arid and dominated by basalt rocks, and the GWPZ was obtained by overlaying nine thematic layers, resulting in five GWPZ categories. The fractured basalt zones that had high lineament density were identified as the most critical groundwater potential zones and were supported by the results of similar studies in the Ethiopian and Kenya Basalt terrains. Based on the GIS-AHP, the GWPZ delineation in the Teji River Catchment of Southwest Shewa Zone was conducted, revealing that around 30.88 per cent of the catchment was classified as good groundwater potential zone; the spatial distribution of GWPZ indicated a good correlation with alluvial landform and low slope terrain. The validity of the RS-GIS-AHP approach was validated by research conducted in the Gidabo Watershed in the Main Ethiopian Rift (Diriba et al., 2024) which showed a GWPZ model accuracy of 76.8 per cent on the basis of spring and well data using the Receiver Operating Characteristic (ROC) curve method, indicating the validity of the approach in a structurally complex rift valley environment.

Studies in Baringo County, Kenya, by Ombasa et al. (2022) showed that there is a good spatial correlation between high and very high groundwater potential areas and the location of productive boreholes. The study highlighted the specific relevance of adding geological lineament data to alluvial formation maps in semi-arid areas underlain by basement rocks, where secondary permeability

controlled by lineaments is the main option for groundwater access. Studies have shown the applicability of AHP and WIO analysis for delineation of GWPZ in sedimentary and mixed geological environments respectively with drainage density as the controlling parameter in alluvial formations and lithology in sandstone formations in the Sudan and in the entire Nile basin region.

2.5.2 Methodological Comparisons and Lessons Learned

The methodological strategies used in the reviewed studies share some common features and can be generalized to the present study. There are several commonalities and lessons to be learned from the studies reviewed for this chapter when it comes to methodological approaches that were utilized. In the first instance, the validation accuracy of GWPZ mapping produced by the RS-GIS-AHP framework ranges from 75% to 88% in various geographical, geological and climatic conditions, indicating the applicability and reliability of the RS-GIS-AHP framework as a GWPZ mapping methodology (Adugna & Awoke, 2024; Diriba et al., 2024; Pial et al., 2025). Second, the spatial pattern and level of accuracy of the generated GWPZ map are highly dependent on the number and nature of the thematic layers included in the analysis: studies with a sufficient number (8 or more) of carefully selected thematic layers, which cover the various geological, morphological, hydrological, and land use aspects of groundwater occurrence tend to achieve higher validation accuracy than studies with fewer layers. Third, the method of validation (based on borehole yield data, spring discharge, ROC curve analysis or agreement index calculations) has a significant impact on the accuracy estimates reported for GWPZ maps, and is not standardized across studies, which makes it difficult to make direct comparisons of accuracy across studies.

From the East African literature, the critical methodological lesson is the need to consider the weight assignment process in the specific study area geological and hydrogeological setting and conditions, not necessarily to blindly use weights from studies carried out in different hydrogeological settings. Lithological formations in alluvial areas like the Shabelle river valley in the Jowhar District may be differently weighted in terms of geology and drainage density as compared to basement rock areas where groundwater is more likely to occur in fracture controlled secondary porosity. A key strength of the AHP is the ability to incorporate expert judgements which are relevant to the local setting, and where borehole data is limited for calibration of parameter weights.

2.6 Study Area Context

2.6.1 Geology and Hydrogeology of the Jowhar and Middle Shabelle Region

Jowhar the administrative centre of the Middle Shabelle region lies in the southern lowlands of Somalia at an altitude of about 100 metres above sea level. The region has an area of about 22,663 sq km, and is bounded by the Shabelle River which flows for about 150 km through the region and then goes south into the coastal swamps to reach its confluence with the Jubba River and final loss in coastal swamps near Jilib. Quaternary alluvial deposits of the floodplain of the Shabelle River dominate the regional geology of the Middle Shabelle, overlying Neogene and Palaeogene sedimentary rocks of the Somali Basin, including the sandstones of the Jesomma Formation, and the limestones and evaporite lithologies of the Mustaxiil Formation (World Bank, 2022; Awulachew et al., 2012).

The most readily available and most important aquifer system in the study area is the Quaternary alluvial deposits in the Jowhar District along the corridor of the Shabelle River. The deposits are laterally extensive beds of sand and gravel interbedded with fine-grained, silty and clayey horizons that formed during successive flood events, the coarser-grained deposits comprising productive unconfined aquifers thicker than 10 meters. Groundwater found in these alluvial deposits is relatively shallow (usually < 15 meters below ground surface) and is hydraulically linked to the Shabelle River and so has a dynamic and variable relationship with river stage in the immediate floodplain surroundings. The World Bank (2022) geologic assessment also identified alluvial Quaternary sands as the main shallow aquifer that could be tapped for community water supply borehole drilling in the Shabelle River corridor in the south of Somalia.

The core of the Middle Shabelle region has relatively deeper sedimentary sequences such as the sandstones of the Jesomma Formation that are known to host moderately productive confined aquifers with good storage capacity to support base flows in the Shabelle River during the dry season (Awulachew et al., 2012). The Mustaxiil Formation made up of Limestones, Gypsums and related evaporite lithologies is known to form karstic aquifer systems in the Somali-Ethiopian border area but may also occur in the subsurface of the Middle Shabelle at depth. Spatial distribution, thickness and hydraulic properties of these deeper formations are not well characterised in the Jowhar District and a systematic borehole database of the hydraulic properties is not available.

2.6.2 Climate and Hydrology of the Study Area

The Middle Shabelle region has an arid to semi-arid climate with bimodal rainfall pattern characterized by two rainy seasons: Gu (long rains) during April to June and Deyr (short rains) during October to December. The rainfall amount in the region is about 150-500 mm per year, with 150 mm to the north and interior part of the district and 500 mm towards the coastal fringe where it is influenced by the Indian Ocean monsoon system. Precipitation levels are highly variable both geographically and from one year to the next, with years of severe droughts and floods, such as the prolonged drought from 2016–2022 (five consecutive below-average rainy seasons), followed by years of extreme floods due to above-average precipitation in the highland areas of Ethiopia that feed the Shabelle River (FAO SWALIM, 2024; Ministry of Energy and Water Resources, Somalia, 2022).

The most significant surface water resource in the Middle Shabelle region is the Shabelle River in which water is used for irrigated agriculture, livestock watering, recharge of the floodplain aquifers by flooding and replenishment of groundwater. The Shabelle River has also a strong inter-annual and seasonal flow variability, however: during the rainy seasons (Gu and Deyr), the discharge can increase rapidly with the rainfall in the highland areas of Ethiopia, resulting in a very high discharge of the river in low-lying areas of the district, which can lead to severe flooding; during the dry seasons (January-March and July-September), the river discharge can drop to very low levels or even become zero in certain years, leaving communities completely reliant on groundwater source. The Middle Shabelle and southern Somalia regions received below-average seasonal rainfall in late 2024, and the FAO SWALIM Groundwater Monitoring Bulletin (2024) revealed a chronic vulnerability of the water supply in the region to climatic variability, as expected under the influence of La Niña, with a 60 to 80 per cent below normal rainfall forecast for the 2024 to 2025 dry season.

2.6.3 Existing Water Resources and Usage Patterns

Three main sources of water supply exist in the Jowhar District: Shabelle River, Dug wells and scoop holes in the floodplain alluvium and deep borehole that taps into the confined sedimentary aquifers. The Somali population, including residents of Jowhar and its nearby rural area, mainly depend on groundwater for their year round drinking water supply while the Shabelle River is mainly an irrigation water source during the flood season, according to the FAO SWALIM (2024) groundwater monitoring programme. Generally, the boreholes in Middle Shabelle region produce 5-20 cubic meters per hour/discharge from available aquifer formations while shallow dug wells produce 2.5-10 cubic meters per hour/discharge but are prone to contamination and may go dry during extended dry season periods.

The International Crisis Group (2025) reported that water access and control over irrigation and borehole facilities has been a major aspect of the political economy of conflict in the Middle Shabelle region, and non-state actors in the Middle Shabelle have taken advantage of the region's water scarcity for resource extraction and population control. This conflict situation has greatly hampered systematic collection of data on groundwater resources, and has made a significant contribution to the lack of reliable hydrogeological databases for Jowhar District. Humanitarian organizations like UNICEF, OCHA, and the Water, Sanitation and Hygiene (WASH) cluster have installed boreholes for emergency water supply in Jowhar and the surrounding areas, but the location, depth and yield of these boreholes, along with the geological log, are not systematically documented in any publicly accessible database, creating significant difficulties for the validation of GWPZ maps in this study area through borehole-based methods.

2.7 Research Gaps and Conceptual Framework

2.7.1 Identified Gaps in Existing Literature

Based on the above literature search, the present study is justifiable as it has identified some major gaps and significance of the study. The lack of published peer-reviewed research using remote sensing and the GIS-based GWPZ mapping methodologies in the Jowhar District or in the Middle Shabelle region, Somalia, in general is the most basic disparity. The RS-GIS-AHP methodology has been validated in many similar lowland river basin environments in the semi-arid regions of East Africa, such as Ethiopia, Kenya and Sudan, but has not been documented for any application in the settings of river basins in the South of Somalia. This is an important knowledge gap, both because of the critical water insecurity situation for the area and because there is the potential to generate evidence from geospatial GWPZ mapping that can be used to inform investment in groundwater infrastructure in a post conflict recovery scenario.

A second gap is the lack of systematic hydrogeological data both for the Jowhar District and for the whole of southern Somalia. In Somalia, borehole logs have been produced for decades and are becoming increasingly scarce, with the majority of performance data for boreholes being lost and the country's hydrogeological maps almost nonexistent, in comparison to similar countries in East Africa, specifically Ethiopia and Kenya, which have produced significant borehole logs through government geological surveys and international development organizations. The current global and regional hydrogeological databases, such as the World Bank (2022) groundwater assessment, and the FAO SWALIM monitoring

programme, only offer coarse scale data regarding aquifer systems at the national or regional level, which is inadequate for mapping the GWPZ for siting boreholes and planning water supplies for the district scale in Jowhar.

A third gap is related to the methodological literature about GWPZ mapping in data-poor conflict-stressed contexts. The application and validation of the RS-GIS-AHP approach in areas that lack comprehensive hydrogeological databases, e.g. Somalia, is challenging because of methodological difficulties that have not been addressed in the literature. Further research is needed to address questions related to the selection of the most relevant thematic parameters when detailed geological maps are not available, as well as to the calibration of AHP weights when borehole yield data is not available in the country to facilitate cross-reference, and to development of alternative validation methodologies using proxy indicators of groundwater occurrence, which are frontier challenges to the applicability of geospatial GWPZ methods in post-conflict humanitarian situations.

2.7.2 Theoretical and Analytical Framework

This study is based on three converging theoretical frameworks: hydrogeological systems theory, geospatial multi-criteria decision analysis and integrated water resource management. The hydrogeological systems theory is rooted in the assumption that the occurrence, storage and transmissivity of groundwater are spatialized functions of the geology, morphology, hydrology and land use of the landscape, and that these variables can be mapped, quantified, and combined to create a spatialized model of groundwater potential (Freeze & Cherry, 1979; Scanlon et al., 2023). From geospatial MCDA theory, the study follows AHP-WIO framework as the major analytical tool for amalgamating the various thematic layers into a composite groundwater potential index based on the theoretical arguments presented by Saaty (1980) and rigorously validated in the GWPZ mapping literature discussed in this chapter.

The study is motivated by the theory of integrated water resource management, which outlines that a spatially explicit evidence base, based on the principle of maximising groundwater development in areas of highest hydrogeological potential, can be used to target infrastructure investments for the most efficient and equitable groundwater access minimising the risk of dry borehole failures and resources being depleted. Operational context is crucial in this study, as it is both a post-conflict and data-scarce semi-arid district with predominantly groundwater as the most critical and vulnerable freshwater

resource, and reflects the need to achieve universal access to safely managed drinking water as stated in the Sustainable Development Goals by 2030.

The analytical framework of the study, which is conceptually illustrated in this chapter and operationalized in Chapter Three involves the sequential derivation of eight thematic layers from the satellite remote sensing data and ancillary spatial data, namely geology, lineament density, geomorphology, drainage density, slope, rainfall, soil type, and LULC; the assignment of weights to the thematic layers through the AHP pairwise comparison process guided by the published literature and hydrogeological expert knowledge; computation of a composite groundwater potential index using WIO analysis in a GIS environment; classification of the groundwater potential index into five groundwater potential zones; lastly, validation of the resulting groundwater potential zone map against available borehole and well yield data from the Jowhar District. This framework follows the best practice in GWPZ mapping literature, and is customized to the data availability limitations and hydrogeologic conditions in the study area

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Study Area

Jowhar District is situated in the Middle Shabelle region of south-central Somalia, some 90 kilometers north of Mogadishu. The district is located between latitude 2°00', 3°00' N and longitude 45°00', 46°00' E. This is estimated to cover an area of about 2,600 square kilometers and it includes a low-lying alluvial plain that is crossed by the Shabelle River, one of the two permanent rivers in Somalia (SWALIM, 2012). The Shabelle River corridor is historically important with regard to the agricultural economy of the district, but the annual floods and droughts have caused a lack of stability in livelihoods.

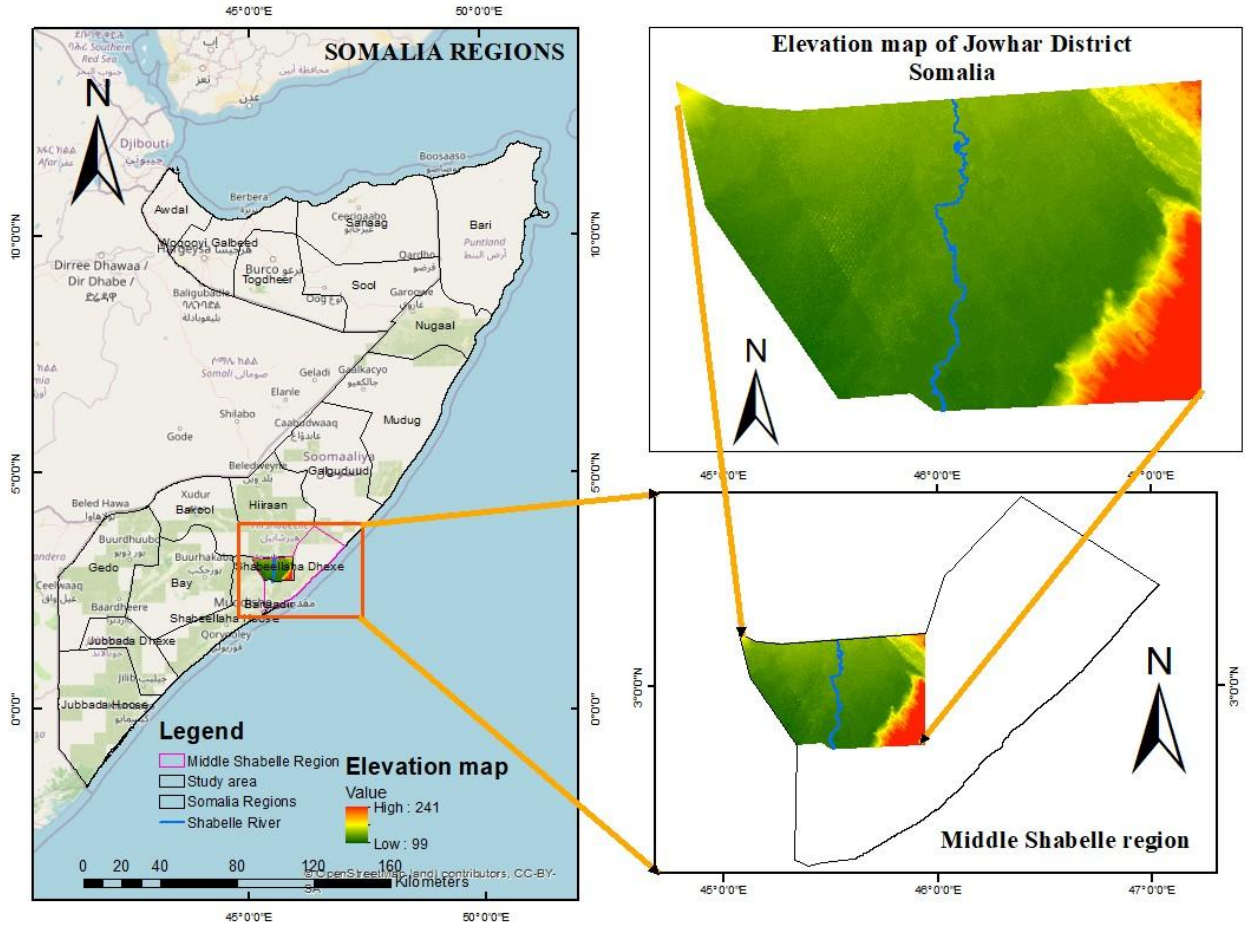


Figure 1: location map of the study area

The climatic zone of Jowhar District is a semi-arid to arid climate having a bi-modal rainfall pattern. The two main rainy seasons locally referred to as the Gu (April-June) and Deyr (October-December) bring mean annual rainfall of 300 to 450 mm not enough to cater for the increasing domestic and agricultural water needs of the populace (FAO-SWALIM, 2017). The temperatures are also high, throughout the entire year, with annual averages between 25°C to 35°C, adding to the scarcity of surface water due to high evapotranspiration rates.

The geology of the district is largely Quaternary alluvial deposits of Shabelle River flood plain deposits underlain by the older sedimentary sequences, including limestone, of the Oligocene to Miocene age. From a hydrogeological point of view, these geological units are regarded as very important because they might contain unconfined and semi-confined aquifer systems. Even with this potential, there are still limited systematic hydrogeological studies and borehole data to support the assessment of groundwater resources and the development of groundwater plans, and remote sensing and GIS are being used to support groundwater development planning.

1.2 Data Sources

The datasets employed in this study are summarized in Table 1. Landsat 8 OLI/TIRS imagery covering path 162 and row 052 was retrieved from the United States Geological Survey (USGS) and served as the basis for deriving lineament density (LD), the normalized difference vegetation index (NDVI), and land use/land cover (LULC) maps of the study area. Existing geological information was revised using data supplied by the Ministry of Water Resources and Energy (MOWRE), from which the lithological units of the area were delineated. A Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) at 30 m spatial resolution was likewise acquired from the USGS website on the same date and used to extract slope, drainage density, and elevation layers. Precipitation records spanning 2015–2025 were sourced from the CRU TS v. 4.10 database, which supplies gridded estimates at a 0.5° × 0.5° resolution. Finally, soil information obtained from the Ministry of Water and Energy was supplemented with FAO soil data to characterize the soil types of the study area.

Table 1. Summary of Data Sources and Specifications

Data Types	Data Source	Data type and acquisition data	The function of the data	Reference

SRTM DEM (30 m)	USGS	Grid 2025-03-10	SL, DD, and EL, maps	https://earthexplorer.usgs.gov/
Rainfall	CRU TS v. 4.10/	0.5° × 0.5°/2015–2025	Rainfall map	https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.10/cruts.2604091129.v4.10/pre/
Soil data	FAO	Polygon/2023	Soil map	Digital Soil Map of the World v.3.6 - Datasets - "FAO catalog"
Landsat 8 OLI/TIRS	USGS	2026/02/09	LULC, LD, and NDVI maps	https://earthexplorer.usgs.gov/
Geological data	USGS	Polygon 1:250,000/2020	Lithology map	https://www.usgs.gov/centers/central- energy-resources-science-center/science/world-geologic-maps

Note: USGS –United States Geological Survey; CRU TS vs. 4.10 –Climatic Research Unit gridded Time Series version 4 data; MOWRE –Ministry of Water Resources and Energy; SL –Slope; DD –Drainage density; EL –Elevation; LULC –land use land cover; NDVI-Normalized Difference vegetation Index; LD –Lineament density.

3.3 Research Method

Various criteria were employed to identify groundwater potential zones. Raster maps of the relevant variables were generated using GIS (version 10.8) and Envi (version 5.6) from remote sensing data. These thematic layers included land use/land cover, slope, elevation, NDVI, lineament density, drainage density, soil texture, and geology. Atmospheric and radiometric corrections were applied with the Semi-Automatic Classification Plugin. In GIS, processes such as conversion, interpolation, categorization, reclassification, augmentation, and filtering were used to process the satellite data. Elevation data from the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM), with a 30 m ×30 m resolution, improved accuracy in both vertical and horizontal measurements. This data was used to produce an elevation map in ArcGIS. The elevation information was then used to generate slope raster data for each grid cell by calculating the maximum rate of change between neighboring cells. Slope classes were classified using the Slope Spatial Analyser tool. Drainage density, inferred from the slope data, was calculated to measure the spacing of stream channels, defined as the total stream length per unit area (Sar et al., 2015). The stream order was determined through flow accumulation and flow direction operations in ArcGIS. The drainage lines were assessed by evaluating stream lengths greater than 1000 units ("value > 1000"), and drainage density (km/km ^{2}) was calculated as shown in **Eq. (1).**

$$\mathbf{D_D} = \sum_{i=1}^{n} \frac{Di}{A} \quad \textbf{(1)}$$

where D_i is the total stream length in stream order i^{th} (km), and A is the basin area (km^2). Utilizing PCI Geomatics 2016, the Landsat 8 OLI/TIRS image (path 163, row 58), exhibiting 5% cloud cover, was extracted to compute the lineament density of the study region. In recent years, high-resolution satellite imagery has proven to be an effective technique for mapping groundwater in arid and semi-arid regions. The thematic layer for lineament density (LD) is defined as the cumulative length of all identified lineaments relative to the area of the catchment under consideration (Das, 2019a). The calculation of lineament density was done using **Eq. (2).**

$$\mathbf{L_D} = \sum_{i=1}^{n} \left(\frac{Li}{A}\right) \quad \textbf{(2)}$$

where L_i is the length of the i^{th} lineament, $\sum L_i$ is the sum length of all lineaments in kilometers, and A is the grid size in square kilometers. Lineament extraction was performed with random lines in various regions based on hillshade analysis. Subsequently, lineaments were extracted using ArcMap 10.8. The manual extraction of lineaments is more dependable than alternative automated techniques (Alshehri and Abdelrahman, 2023). The geological, or lithological, thematic map of the study area was downloaded from USGS and updated with the latest (2015) geological maps of the Garowe district from the Ministry of Water Resources and Energy, Somalia (MOWRE, 2015). The ESRI land cover of Sentinel-2, at a 10-meter resolution, was used to determine the recent (2024) LULC map of the study area. We obtained the soil map of the study area from FAO (2003) data and MOWRE's Somalia soil map (Table 1). A rainfall map of this research was created using the inverse distance weighting (IDW) interpolation approach. The NDVI assesses the greenness of vegetation and serves as a strong indication of temporal changes in vegetation within a specific area. The NDVI layer was created using the Near Infrared and Red bands in the Raster Calculator of ArcGIS 10.8 **Eq. (3) .**

$$\boldsymbol{NDVI} = \frac{\boldsymbol{NIR-RED}}{\boldsymbol{NIR+RED}} \quad \textbf{(3)}$$

where NIR represents the near-infrared band, whereas RED signifies the red band in the reflectance values of the electromagnetic spectrum. Finally, the delineation of the groundwater potential zone involved converting all data layers into raster format, maintaining a uniform spatial resolution of 30 m ×30 m. The relative importance of each element influencing groundwater potential was assessed by a pairwise comparison of all features. Each map was categorized using computed weights. The weighted overlay module in ArcGIS 10.8 was used to create a groundwater potential map by integrating all

thematic layers. The groundwater potential zones identified through GIS and RS techniques were assessed against existing ground data from boreholes, springs, and hand-dug wells to confirm the validity of the qualitative results. This enhanced confidence in the application of qualitative results derived from GIS and RS analysis. The overall framework for data processing and analysis is illustrated in **Fig. 2**

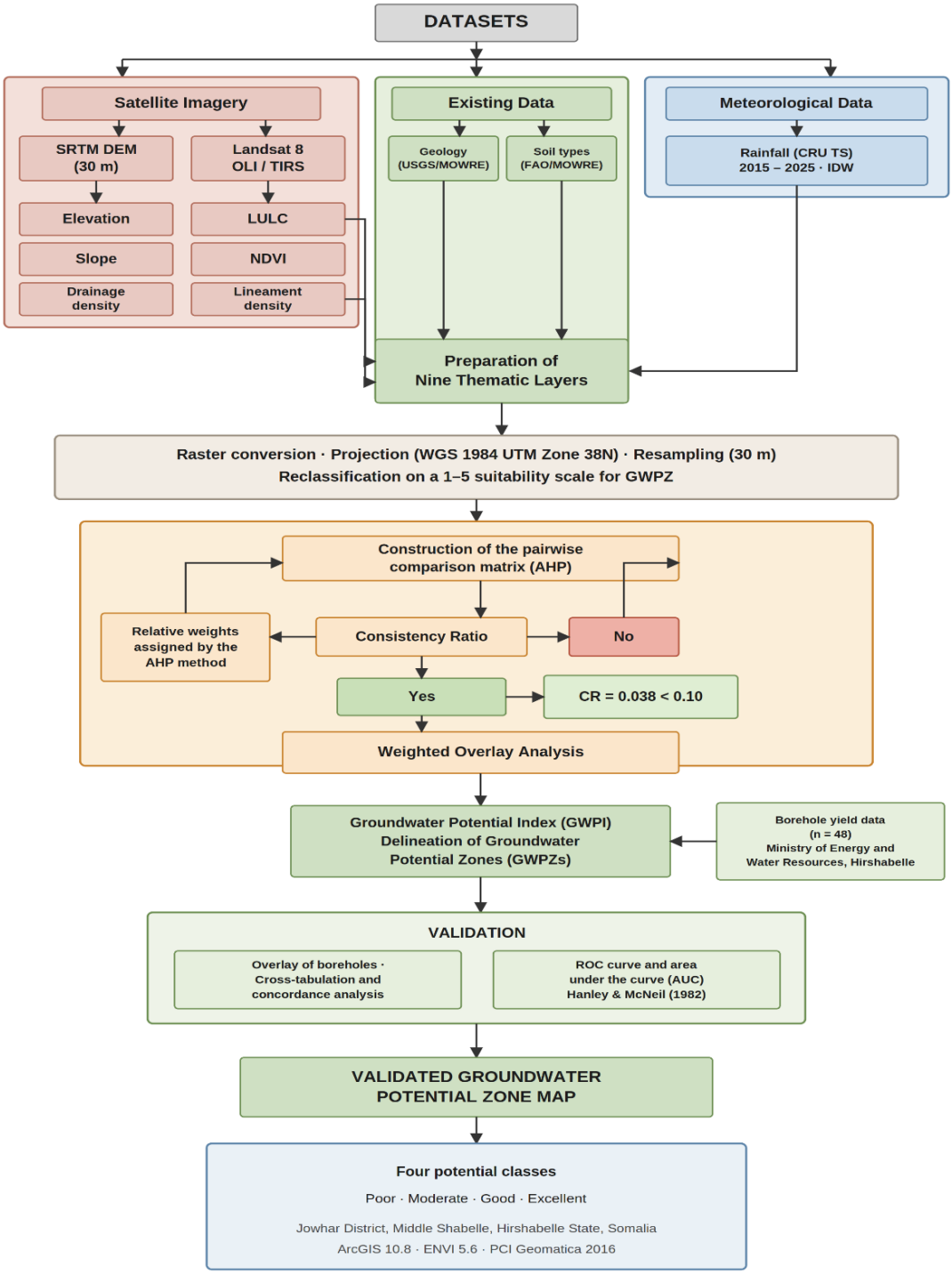


Figure 2. Flowchart for the identification of groundwater potential zones (GWPZs).

3.3.1 Thematic Layer Derivation

Nine thematic layers will be developed to represent the spatial factors used in groundwater potential zone (GWPZ) mapping. These include geology, lineament density, drainage density, slope, geomorphology, land use/land cover (LULC), soil type, and rainfall. Each thematic layer will be prepared from the corresponding spatial dataset using ArcGIS 10.8, ENVI, and Google Earth Engine where appropriate. All datasets will be projected to the Universal Transverse Mercator (UTM) coordinate system, clipped to the study area boundary, converted to raster format with a common spatial resolution of 30 m, and reclassified into groundwater suitability classes. The resulting standardized raster layers will subsequently be integrated using the Analytic Hierarchy Process (AHP) and weighted overlay analysis to generate the Groundwater Potential Zone (GWPZ) map.

3.3.3 Classification, Rating, and Scoring of Thematic Layers

Each thematic layer will be reclassified into five discrete classes representing a continuum of groundwater potential influence, from Very Low (score = 1) to Very High (score = 5). This five-point ordinal rating scale is consistent with established practice in GIS-based groundwater potential mapping and enables comparability and integration of diverse parameter types within the weighted overlay framework (Magesh et al., 2012; Das & Mukherjee, 2020). The classification of each parameter will be informed by published hydrogeological criteria, local geological knowledge, and the specific environmental characteristics of the Jowhar District.

Reclassification will be performed using the ArcGIS Reclassify tool within the Spatial Analyst extension. The resulting reclassified rasters will each carry integer values ranging from 1 to 5, where 5 represents conditions most conducive to groundwater occurrence and 1 represents conditions least conducive. These standardized reclassified layers will then serve as inputs to the AHP-weighted overlay analysis.

3.3.4 Analytical Hierarchy Process (AHP) and Weight Assignment

The Analytical Hierarchy Process (AHP), originally developed by Saaty (1980), is a structured multi-criterion decision-making (MCDM) technique that enables the derivation of objective numerical weights for decision criteria based on pairwise comparison matrices. The AHP has been extensively applied in

groundwater potential mapping studies globally due to its ability to incorporate expert knowledge, handle multiple interacting variables, and produce a quantifiable consistency measure that validates the internal coherence of the weight assignment process (Saaty, 1980; Magesh et al., 2012; Rahmati et al., 2015).

In this study, the AHP will be applied to determine the relative weights of the eight thematic layers. A pairwise comparison matrix will be constructed in which each parameter is compared to every other parameter using Saaty's nine-point scale of relative importance, where 1 indicates equal importance and 9 indicates extreme importance of one criterion over another as illustrated in Table 2. Expert opinion from hydrogeologists and GIS specialists familiar with the Horn of Africa hydrogeological context will be solicited to inform the pairwise comparisons, in addition to the weight hierarchies reported in comparable peer-reviewed studies.

Table 2. The one-to-nine scale of parameters significance

Strength of significance	Explanation
1	Equal significance
3	Medium significance
5	Strong
7	Very strong significance
9	Maximum significance
2,4,6, and 8	Interim number between two adjacent numbers

Source: (Satty, 1980).

Following the construction of the pairwise comparison matrix, the normalized principal eigenvector will be computed to derive the final weights for each thematic layer. The consistency of the pairwise judgments will be evaluated using the Consistency Ratio (CR), calculated using Eq. (4).

$$\mathbf{CR} = \frac{\boldsymbol{CI}}{\boldsymbol{RI}} \qquad \textbf{(4)}$$

where CI is the Consistency Index computed as CI = (λmax − n) / (n − 1), λmax is the principal eigenvalue, n is the number of criteria, and RI is the Random Index for the given matrix order (Saaty, 1980). A CR value of ≤ 0.10 (10%) is considered acceptable, indicating that the pairwise comparisons are sufficiently consistent for the derived weights to be used reliably in the overlay analysis. If the CR exceeds this threshold, the pairwise comparisons will be revisited and revised accordingly.

3.3.5 Weighted Overlay Analysis and GWPZ Map Generation

The Groundwater Potential Index (GPI) map will be generated through the application of the Weighted Index Overlay (WIO) method in ArcGIS Spatial Analyst. This method involves the mathematical combination of all reclassified thematic raster layers, each multiplied by its AHP-derived normalized weight, to produce a single composite index surface representing the overall groundwater potential of each pixel in the study area. Calculated using Eq. (5):

$$GPI = \Sigma (Wi \times Ri) \quad (5)$$

where GPI is the Groundwater Potential Index at any given pixel, Wi is the normalized AHP weight assigned to the ith thematic layer, and Ri is the reclassified rating (1–5) of the ith thematic layer at that pixel location. The summation is performed across all eight thematic layers, ensuring that the relative hydrogeological importance of each parameter is preserved in the composite output.

The resulting continuous GPI raster will then be reclassified into five discrete GWPZ categories using the Natural Breaks (Jenks) classification method, which minimizes within-class variance and maximizes between-class variance, thereby producing hydrogeologically meaningful and spatially distinct zones (Magesh et al., 2012; Tehrany et al., 2019).

3.3.6 Validation of the Groundwater Potential Zone Map

The credibility of any groundwater potential GIS-based map depends on the strength of the data used to validate it with independent empirical data. In this study the borehole and well yield data will be used as the comparative dataset for validating the models and their ability to correspond to the actual groundwater productivity in the field, in terms of the GWPZs. The most appropriate and scientifically sound way of validating GWPZ maps in literature is to follow this approach (Das & Mukherjee, 2020; Lee et al., 2020; Arshad et al., 2020).

3.3.7 Borehole Data Overlay

Locations of available boreholes and wells with yield and/or water level data will be digitized and plotted on the final GWPZ map in ArcGIS. The Extract Values to Points tool will be used to extract a GWPZ category for each borehole point. A cross tabulation will then be carried out, to calculate the percentages of the high yielding boreholes classified under the Very High and High GWPZ, and the percentages of

the dry and low yielding boreholes classified under the Low and Very Low GWPZ. Model accuracy and reliability will be better if there is a greater degree of concordance between the predicted GWPZ category and the observed borehole yield.

3.3.8 Receiver Operating Characteristic (ROC) Analysis

A Receiver Operating Characteristic (ROC) curve analysis and Area Under the Curve (AUC) will be performed whenever possible based on the borehole data, to quantify the discriminating power of the GPI model. The AUC value ranges from 0.5 (no discriminative ability) to 1.0 (perfect discrimination) and values more than 0.70 were considered as acceptable and values more than 0.80 were good predictive values for groundwater potential mapping (Pradhan et al. 2009; Lee & Pradhan 2007). This validation approach by means of statistics will give a model objective and standardized measure of its performance.

CHAPTER FOUR

RESULTS & DISCUSSION

4.1 Geology

Geology, or lithology, is among the most decisive controls on groundwater occurrence because the composition, degree of consolidation and pore structure of the underlying rocks determine how readily water infiltrates, how much can be stored and how freely it moves through the subsurface (Ibrahim-Bathis & Ahmed, 2016; Ismail et al., 2026). Unconsolidated sediments with high primary (intergranular) porosity form productive aquifers, whereas compact or well-cemented rocks transmit and store water mainly through secondary openings such as fractures and solution cavities.

The lithological map of the study area in Figure 3 comprises five units: Quaternary alluvium (Q), Quaternary–Tertiary sediments (QT), Cretaceous (K), Lower Cretaceous (Kl) and Jurassic limestone (J). Quaternary alluvium is by far the most extensive unit, occupying the entire central and eastern part of the district; it consists of unconsolidated sand, silt and gravel laid down by the Shabelle River and possesses the highest primary porosity, making it the most favorable host for groundwater. The Quaternary–Tertiary sediments occupy the south-central sector and are also comparatively favorable, whereas the Jurassic limestone, Lower Cretaceous and Cretaceous units are confined to the north-western margin, where consolidation reduces primary porosity, and groundwater is restricted largely to fractured or weathered horizons. The units were therefore reclassified from very high suitability for Quaternary alluvium (5) to very low for the Jurassic limestone (1), as shown in Table 3.

Table 3: Reclassification and rating of layer suitability for the identification of groundwater potential zones.

Thematic Layers	**Description**	**Reclassification values and layer suitability for the identification of groundwater potential zones**					**Source**
	Ranking Classification	**1**	**2**	**3**	**4**	**5**	
		Very poor	Poor	Moderate	High	Very High	
Geology	Types of geological units *Category*	J: Jurassic limestone *Very low*	Kl: Lower Cretaceous *Low*	K: Cretaceous *Moderate*	QT: Quaternary–Tertiary *High*	Q: Quaternary alluvium *Very high*	Lavanya & Muthukumar, 2024; Ismail et al., 2026
Rainfall	Rainfall (mm, 2015–2025) *Category*	4,290–4,440 *Very low*	4,450–4,580 *Low*	4,590–4,730 *Moderate*	4,740–4,880 *High*	4,890–5,020 *Very high*	Ibrahim-Bathis & Ahmed, 2016; Ismail et al., 2026

Thematic Layers	Description	Reclassification values and layer suitability for the identification of groundwater potential zones					Source
	Ranking Classification	1	2	3	4	5	
		Very poor	Poor	Moderate	High	Very High	
Soil texture	Soil type *Category*	Zo: Orthic Solonchaks (saline) *Very low*	Vc: Chromic Vertisols (clay) *Low*	– –	Rc: Calcaric Regosols *High*	Qc: Cambic Arenosols (sandy) *Very high*	Ibrahim-Bathis & Ahmed, 2016
Drainage density	Value (km/km²) *Category*	2.44–3.04 *Very high*	1.83–2.43 *High*	1.23–1.82 *Moderate*	0.609–1.22 *Low*	0–0.608 *Very low*	Nigussie et al., 2019; Berhanu & Hatiye, 2020
LU/LC	Type *Category*	Built area *Very low*	Bare soil *Low*	Vegetation *Moderate*	Agriculture *High*	Water & wetlands *Very high*	Alshehri & Abdelrahman, 2023; Sahoo et al., 2024
Slope	Degree *Category*	3.98–18.7 *Very steep*	2.44–3.97 *Steep*	1.41–2.43 *Moderate*	0.516–1.4 *Gentle*	0–0.515 *Flat*	Rather & Andrabi, 2012; Ismail et al., 2026
Lineament density	Density (km/km²) *Category*	0–0.066 *Very low*	0.067–0.13 *Low*	0.14–0.20 *Moderate*	0.21–0.27 *High*	0.28–0.33 *Very high*	Sar et al., 2015; Mishra & Singh, 2019
Elevation	Mean above sea level (m) *Category*	192–241 *Very high*	162–191 *High*	133–161 *Moderate*	114–132 *Low*	99–113 *Very low*	Ally et al., 2024; Tesfa & Sewnet, 2025
NDVI	Degree *Category*	0.083–0.118 *Very low*	0.119–0.148 *Low*	0.149–0.201 *Moderate*	0.202–0.291 *High*	0.292–0.557 *Very high*	Alshehri & Abdelrahman, 2023

4.2 Rainfall

Rainfall is the ultimate source of groundwater recharge, and its magnitude and distribution govern the quantity of water available to percolate to the water table; areas of higher rainfall are therefore generally associated with greater recharge potential (Ibrahim-Bathis & Ahmed, 2016; Ismail et al., 2026). In semi-arid environments such as the study area, where potential evapotranspiration is high, the spatial pattern of rainfall strongly influences where recharge is most likely to occur.

The rainfall surface in Figure 4, interpolated from CRU TS gridded data for 2015–2025 using the inverse distance weighting (IDW) method, shows cumulative totals of 4,290–5,020 mm over the period (390–456 mm per year), consistent with the bimodal Gu and Deyr seasons of the region. Rainfall increases progressively from the north-east, which records the lowest totals, towards the south and south-west, where the highest totals occur. The wetter southern sector was therefore assigned the highest recharge suitability (5) and the drier north-eastern corner the lowest (1), as shown in Table 3.

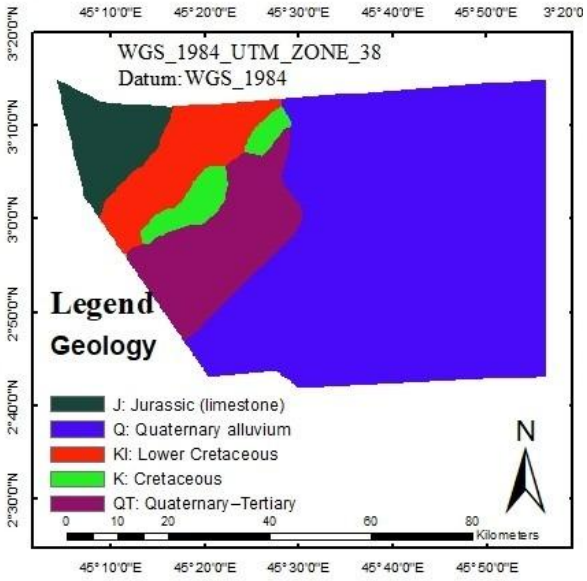


Figure 2: Geology (lithology) map of the study area.

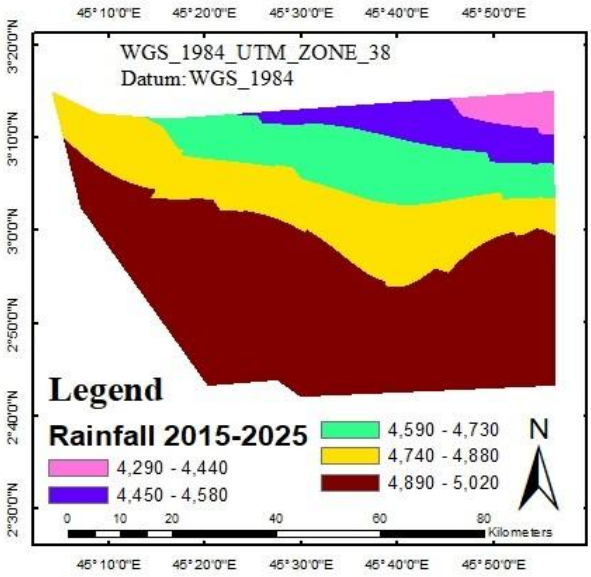


Figure 1: Rainfall map for the study area.

4.3 Soil

Soil texture and structure regulate the partitioning of precipitation between infiltration and surface runoff, and thus the volume of water that ultimately reaches the aquifer (Berhanu & Hatiye, 2020; Ismail et al., 2026). Coarse-grained, well-drained soils encourage infiltration, whereas fine-textured, compacted or saline soils impede percolation and promote runoff and evaporation.

Four soil units occur in the study area as shown in Figure 5, which are Cambic Arenosols (Qc), Calcaric Regosols (Rc), Chromic Vertisols (Vc) and Orthic Solonchaks (Zo). Chromic Vertisols dominate the central plain; these heavy, swelling clays develop very low permeability when wet and therefore restrict recharge, and were rated low (2). The sandy Cambic Arenosols that occupy the eastern part of the district have the highest infiltration capacity and were rated very high (5), while the Calcaric Regosols in the north-west were rated high (4). The Orthic Solonchaks, confined to a small saline tract in the west, were rated very low (1), reflecting both their poor permeability and the associated risk of saline groundwater Table 3. The prevalence of clay-rich Vertisols across the floodplain is characteristic of the Shabelle system and locally offsets the otherwise favorable alluvial lithology.

4.4 Drainage Density

Drainage density is the total length of stream channels per unit area and is an inverse indicator of groundwater potential (Das, 2019; Nigussie et al., 2019). High drainage density reflects low-permeability ground and efficient runoff, which shortens the time available for infiltration, whereas low

drainage density indicates permeable terrain where more water is retained and recharged (Ismail et al., 2026).

Drainage density derived from the SRTM DEM ranges from 0 to about 3.04 km per km² (Figure 6). Most of the district falls within the low to moderate range, indicating generally permeable alluvial ground, with localised zones of higher drainage density scattered through the south-central sector. Areas of low drainage density were rated most favourable for groundwater (5) and areas of high drainage density least favourable (1), as shown in Table 3.

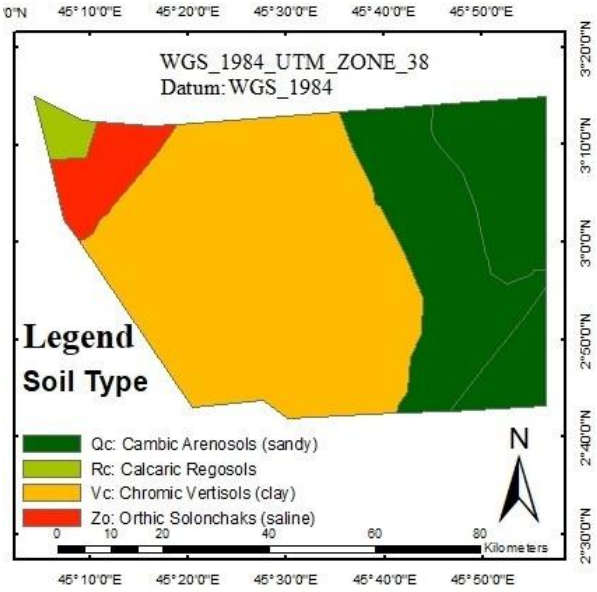


Figure 4: Soil map of study area

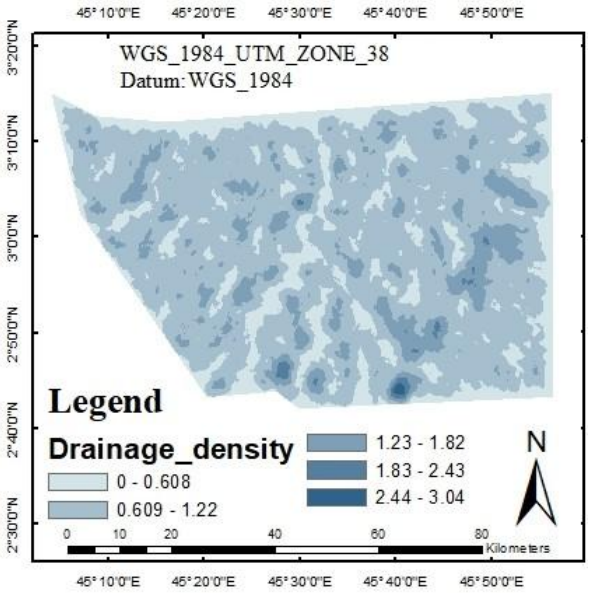


Figure 3: Map showing Drainage Density

4.5 Land Use / Land Cover (LULC)

Land use and land cover influence recharge by controlling interception, evapotranspiration, infiltration and runoff (Berhanu & Hatiye, 2020; Ismail et al., 2026). Surface water, wetlands and cultivated or vegetated land tend to promote infiltration, whereas built-up and bare surfaces increase runoff and reduce recharge.

The land-cover map identifies six classes: water, wetlands, agriculture, vegetation, bare soil and built-up land as shown in Figure 7 and Table 4. Open water and associated wet ground occupy an extensive tract in the central and western part of the district along the Shabelle corridor, while a large block of irrigated agriculture dominates the east; bare soil is most widespread across the north, and vegetation and built-up land occur as smaller, scattered units. Water and wetlands were assigned the highest suitability (5), followed by agriculture (4) and vegetation (3), with bare soil (2) and built-up land (1)

rated lowest Table 3. The concentration of water and cropland along the river reinforces the corridor as the most recharge-favourable part of the district.

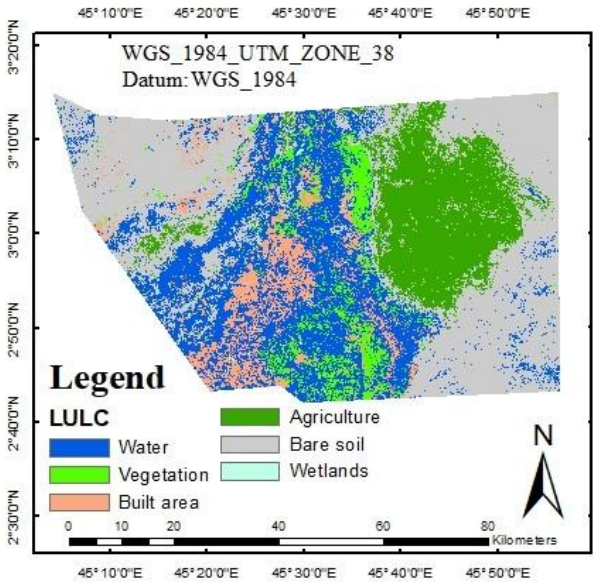


Figure 7: Showing Land use land cover (LULC)

Table 4: Land-use/land-cover types and coverage of the study

No.	LU/LC Class	Area (km²)	Percentage (%)
1	Agriculture	798.22	16.88
2	Bare soil	1947.43	41.19
3	Built area	426.75	9.03
4	Vegetation	283.89	6.00
5	Water	1260.40	26.66
6	Wetlands	11.77	0.25

4.6 Slope

Slope governs the balance between runoff and infiltration: on steep ground water drains rapidly and has little time to infiltrate, whereas on flat to gently sloping ground it is retained longer and recharge is enhanced, giving slope an inverse relationship with groundwater potential (Yeh et al., 2016; Ismail et al., 2026).

Slope generated from the SRTM DEM ranges from 0 to about 18.7 degrees but is overwhelmingly low: the great majority of the district lies below 1.4 degrees, confirming the near-level character of the Shabelle floodplain, with steeper pixels occurring only sporadically as shown in Figure 8. The flattest terrain was rated most favourable (5) and the limited steep ground least favourable (1), as shown in Table 3.

4.7 Lineament Density

Lineaments are the surface traces of faults, fractures and joints that create secondary porosity and permeability, so higher lineament density generally corresponds to greater groundwater potential, particularly in consolidated rocks (Das, 2019; Ismail et al., 2026).

Lineament density extracted from Landsat 8 imagery and DEM hill shading ranges from 0 to 0.33 km per km² as shown in Figure 9. The highest densities form a distinct cluster in the south-east of the district,

with a secondary zone in the north-west, while the central area records the lowest values. Zones of high lineament density were rated most favorable (5) and those of low density least favorable (1), as shown in Table 3. Because the district is dominated by unconsolidated alluvium, in which primary porosity prevails, lineament density plays a smaller role here than it would in hard-rock terrain, although the fractured south-eastern zone may enhance local storage where it coincides with the older lithologies.

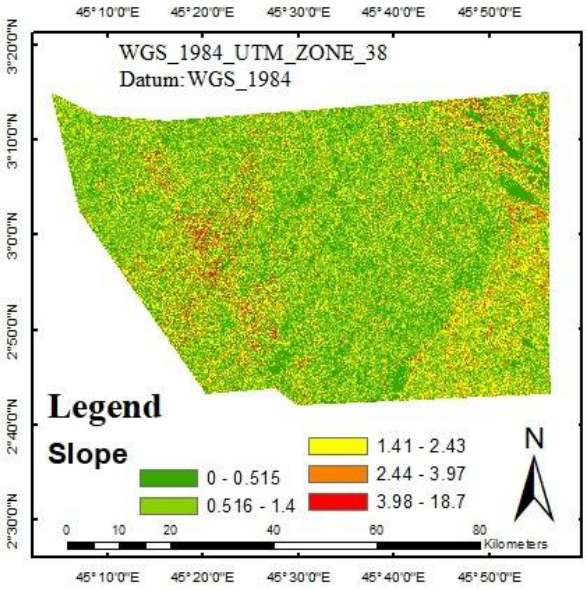


Figure 8: Showing Slope

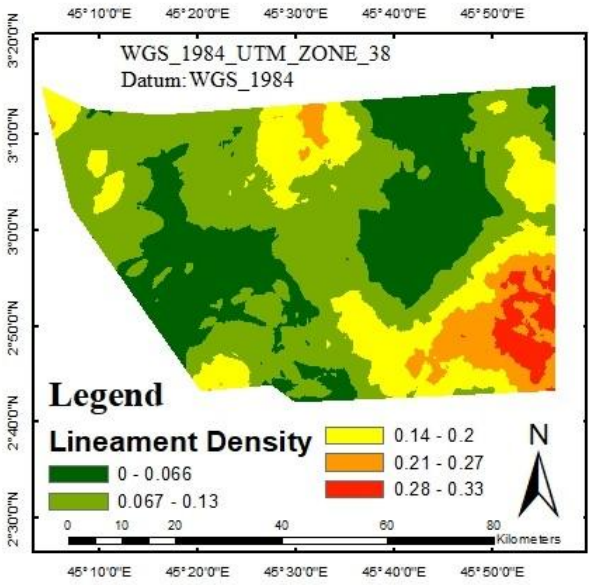


Figure 9: showing Lineament density

4.8 Elevation

Elevation reflects topographic position and is inversely related to groundwater potential: low-lying areas receive and retain water draining from higher ground and tend to have shallower water tables and greater percolation, whereas elevated areas shed water and recharge less (Ismail et al., 2026).

Elevation in the study area ranges from 99 to 241 m above sea level as in Figure 10. The lowest ground occupies the central and western plain, while the land rises gently towards the east and south-east, reaching its maximum in the south-eastern corner. The low-lying central and western plain was therefore rated most favorable for groundwater (5) and the elevated south-east least favorable (1), as shown in Table 3. This gentle west-to-east rise is consistent with the regional configuration of the Shabelle plain.

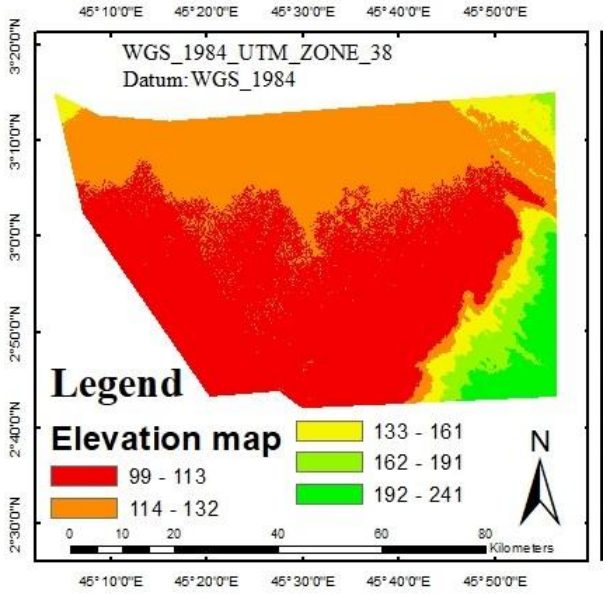


Figure 10: Showing Elevation of study area

4.9 Normalized Difference Vegetation Index (NDVI)

NDVI is an indicator of vegetation vigor and, indirectly, of soil moisture and shallow groundwater availability; denser, healthier vegetation often marks areas of greater water availability and recharge (Ismail et al., 2026).

NDVI values range from about −0.08 to 0.56 as shown in Figure 11. The highest values form a central strip corresponding to irrigated and riparian vegetation along the Shabelle corridor, whereas the lowest values occur over bare and sparsely vegetated ground in the central-west. High-NDVI areas were rated most favorable (5) and low-NDVI areas least favorable (1), as shown in Table 3.

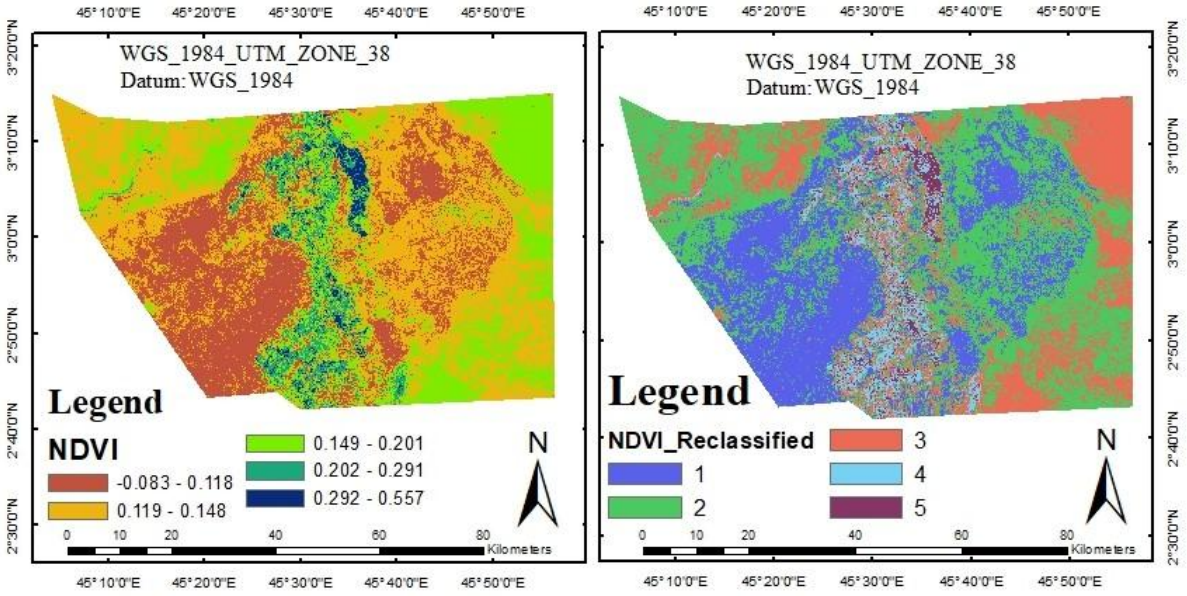


Figure 11: NDVI (a) and reclassified NDVI (b).

4.10 Assignment of Weightages to the Thematic Layers Using AHP

The relative importance of the nine thematic layers controlling groundwater occurrence in Jowhar District was determined using the Analytical Hierarchy Process (AHP), a multi-criteria decision-making technique that converts expert judgement into a set of numerical weights through systematic pairwise comparison (Saaty, 1980, 1990). Rainfall, geology, slope, drainage density, land use/land cover, lineament density, soil, NDVI and elevation were compared two at a time using Saaty's nine-point scale, on which a score of 1 indicates that two factors are equally important and a score of 9 indicates that one factor is of extreme importance relative to the other. Each comparison was guided by the hydrogeological role of the two factors in the study area — as established in the interpretation of the individual thematic layers in Sections 4.1 to 4.8 — and cross-checked against the weighting patterns reported for comparable semi-arid and alluvial settings (Ismail et al., 2026; Diriba et al., 2024). The 36 pairwise judgements required for nine factors were assembled into the comparison matrix presented in Table 5, with unity along the diagonal and the lower triangle populated by the reciprocals of the corresponding upper-triangle entries.

The weight of each layer was derived from the normalized principal eigenvector of the pairwise comparison matrix, obtained by dividing every entry by its column total and averaging the normalized values across each row (Table 6). Geology (26.22%) and rainfall (26.17%) emerged as the dominant factors, together accounting for more than half of the total weight (52.4%); this outcome reflects the semi-arid, alluvial setting of the Shabelle floodplain, in which precipitation is the ultimate source of

recharge and the primary porosity of the underlying lithology governs how readily that recharge is stored and transmitted. Soil (11.94%) and drainage density (11.52%) received the next highest weights, consistent with their direct control over infiltration and surface-water retention, while elevation (7.82%) was assigned a moderate weight reflecting its influence on the hydraulic gradient across the floodplain. Land use/land cover (5.33%) and NDVI (4.89%) received comparatively low and closely similar weights, since both are indirect, vegetation-related proxies for moisture conditions rather than direct hydrogeological controls. Slope (3.67%) and lineament density (2.44%) were the least influential factors: the near-total absence of relief across the district leaves little contrast between slope classes, while the dominance of unconsolidated alluvium, in which primary intergranular porosity rather than fracture-controlled flow governs groundwater movement, limits the discriminating power of lineament density in this setting.

The internal consistency of the pairwise judgements was evaluated using the consistency ratio (CR), following Equation (4). The principal eigenvalue of the nine-factor matrix was $\lambda max = 9.440$. The consistency index was calculated as $CI = (\lambda max - n)/(n - 1) = (9.440 - 9)/(9 - 1) = 0.055$, where $n = 9$ is the number of compared factors, and the consistency ratio was obtained as $CR = CI/RI = 0.055/1.45 = 0.038$, using the random index $RI = 1.45$ corresponding to a ninth-order matrix (Saaty, 1980). Since the resulting CR of 0.038 is well below the widely accepted threshold of 0.10, the pairwise comparisons are considered sufficiently consistent, and the derived weights (Table 6) were therefore accepted for use in the subsequent analysis.

Table 5: Pairwise comparison matrix of the selected thematic layers and their weights.

Matrix	Rainfall	Geology	Slope	D D	LULC	LD	Soil	NDVI	EL	Normalized weight	Normalized principal eigenvector	Checking of consistency ratios (CR)
Rainfall	1	2	5	3	4	6	2	5	4	0.262	26.17%	
Geology	1/2	1	6	4	5	7	3	6	4	0.262	26.22%	λmax = 9.440
Slope	1/5	1/6	1	1/2	1/2	2	1/4	1/2	1/3	0.037	3.67%	CI = 0.055
Drainage density	1/3	1/4	2	1	2	4	2	3	2	0.115	11.52%	RI = 1.45
LULC	1/4	1/5	2	1/2	1	3	1/3	1	1/2	0.053	5.33%	CR = 0.0379
Lineament density	1/6	1/7	1/2	1/4	1/3	1	1/5	1/3	1/4	0.024	2.44%	CR < 0.1
Soil	1/2	1/3	4	1/2	3	5	1	3	2	0.119	11.94%	Consistency Ratio is acceptable
NDVI	1/5	1/6	2	1/3	1	3	1/3	1	1/2	0.049	4.89%	
Elevation	1/4	1/4	3	1/2	2	4	1/2	2	1	0.078	7.82%	
Total	**3.4**	**4.51**	**25.5**	**10.583**	**18.833**	**35**	**9.617**	**21.833**	**14.583**	**1.000**	**100%**	

Table 6: Normalized weight of the matrix.

Factor	Rainfall	Geology	Slope	Drainage density	LULC	Lineament density	Soil	NDVI	Elevation	Eigen vector	Weights
Rainfall	0.29	0.44	0.20	0.28	0.21	0.17	0.21	0.23	0.27	0.262	26.17%
Geology	0.15	0.22	0.24	0.38	0.27	0.20	0.31	0.27	0.27	0.262	26.22%
Slope	0.059	0.037	0.039	0.047	0.027	0.057	0.026	0.023	0.023	0.037	3.67%
Drainage density	0.098	0.055	0.078	0.094	0.11	0.11	0.21	0.14	0.14	0.115	11.52%
LULC	0.074	0.044	0.078	0.047	0.053	0.086	0.035	0.046	0.034	0.053	5.33%
Lineament density	0.049	0.032	0.020	0.024	0.018	0.029	0.021	0.015	0.017	0.024	2.44%
Soil	0.15	0.074	0.16	0.047	0.16	0.14	0.10	0.14	0.14	0.119	11.94%
NDVI	0.059	0.037	0.078	0.031	0.053	0.086	0.035	0.046	0.034	0.049	4.89%
Elevation	0.074	0.055	0.12	0.047	0.11	0.11	0.052	0.092	0.069	0.078	7.82%
Sum	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.000**	**100%**

4.11 Mapping of the groundwater potential zones

The groundwater potential zone (GWPZ) map of Jowhar District was produced by combining the nine standardized thematic layers described in Sections 4.1 to 4.8 — rainfall, geology, soil, drainage density, land use/land cover, slope, lineament density, elevation and NDVI — using the Weighted Overlay Analysis (WOA) tool in ArcGIS. Each raster had already been reclassified onto a common five-point suitability scale (Table 3), so the overlay simply multiplied every layer by its corresponding AHP weight (Table 8) and summed the results, following the Groundwater Potential Index (GWPI) formulation given in Equation (5).

Substituting the normalized weights derived in Section 4.9 into Equation (5) gives the explicit form of the model used for Jowhar District:

$$GWPI = 0.262(Rf) + 0.262(G) + 0.037(Sl) + 0.115(DD) + 0.053(LULC) + 0.024(LD) + 0.119(St) + 0.049(NDVI) + 0.078(El)$$

where Rf is rainfall, G is geology, Sl is slope, DD is drainage density, LULC is land use/land cover, LD is lineament density, St is soil type, NDVI is the normalized difference vegetation index, and El is elevation, with each term representing the product of a layer's AHP weight and its reclassified suitability score. Because rainfall and geology together carry over half of the total weight (52.4%), the composite

index responds most strongly to variation in these two layers, while slope and lineament density, the two most weakly weighted factors, have comparatively little influence on the final zonation.

The continuous GWPI surface was reclassified using the Natural Breaks (Jenks) method into four groundwater potential categories — Poor, moderate, Good and Excellent — as shown in Figure 12. The corresponding areal distribution of each class is summarized in Table 7.

Table 7: Groundwater potential zones and corresponding areal distribution.

No.	GWPZ Class	Area (km²)	Percentage (%)
1	Poor	135.22	3.02
2	Moderate	1306.52	29.18
3	Good	3023.99	67.54
4	Excellent	11.66	0.26
	Total	**4477.40**	**100.00**

The zonation is strongly asymmetric: a single class, Moderate, accounts for more than two-thirds of the district (67.54%, 3,024.0 km²), while the Poor and Excellent classes together occupy less than 3.3% of the total area. This pattern reflects the relatively uniform hydrogeological setting of the Shabelle floodplain, in which most of the district shares a broadly similar combination of favourable rainfall, alluvial geology and gentle slope, so that only comparatively small areas depart far enough from this baseline to be classified as either distinctly poor or distinctly excellent.

The Poor zone (3.02%, 135.2 km²) is confined almost entirely to the northwestern corner of the district, coinciding closely with the outcrop of the Jurassic limestone and Lower Cretaceous units identified in Section 4.1 (Figure 3). These consolidated formations have limited primary porosity compared with the surrounding alluvium and were assigned the lowest suitability ranks in Table 3; because geology carries the second-highest AHP weight (26.22%), its influence dominates the composite index in this corner of the district even where other layers, such as rainfall, are not themselves at their lowest.

Table 8 Summary of scores and weightage allocated to thematic layers influencing groundwater potential.

Thematic layer	Dominant feature	Suitability rank	Score	Weightage (%)
Geology	Q: Quaternary alluvium	Very High	5	26.22
	QT: Quaternary–Tertiary	High	4	
	K: Cretaceous	Moderate	3	
	Kl: Lower Cretaceous	Low	2	
	J: Jurassic limestone	Very Low	1	
Rainfall (mm, 2015–2025)	4,890–5,020	Very High	5	26.17
	4,740–4,880	High	4	
	4,590–4,730	Moderate	3	
	4,450–4,580	Low	2	

Thematic layer	Dominant feature	Suitability rank	Score	Weightage (%)
Soil type	4,290–4,440	Very Low	1	11.94
	Qc: Cambic Arenosols (sandy)	Very High	5	
	Rc: Calcaric Regosols	High	4	
	Vc: Chromic Vertisols (clay)	Low	2	
	Zo: Orthic Solonchaks (saline)	Very Low	1	
Drainage density (km/km²)	0–0.608	Very High	5	11.52
	0.609–1.22	High	4	
	1.23–1.82	Moderate	3	
	1.83–2.43	Low	2	
	2.44–3.04	Very Low	1	
Elevation (m a.s.l.)	99–113	Very High	5	7.82
	114–132	High	4	
	133–161	Moderate	3	
	162–191	Low	2	
	192–241	Very Low	1	
LULC	Water	Very High	5	5.33
	Wetlands	Very High	5	
	Agriculture	High	4	
	Vegetation	Moderate	3	
	Bare soil	Low	2	
	Built area	Very Low	1	
NDVI	0.292–0.557	Very High	5	4.89
	0.202–0.291	High	4	
	0.149–0.201	Moderate	3	
	0.119–0.148	Low	2	
	−0.083–0.118	Very Low	1	
Slope (degrees)	0–0.515	Very High	5	3.67
	0.516–1.4	High	4	
	1.41–2.43	Moderate	3	
	2.44–3.97	Low	2	
	3.98–18.7	Very Low	1	
Lineament density (km/km²)	0.28–0.33	Very High	5	2.44
	0.21–0.27	High	4	
	0.14–0.20	Moderate	3	
	0.067–0.13	Low	2	
	0–0.066	Very Low	1	
Total				**100.00**

The Moderate zone (29.18%, 1,306.5 km²) forms a broad arc immediately south and east of the Poor zone, corresponding to the transition from the Jurassic and Cretaceous outcrops toward the Quaternary–Tertiary and Quaternary alluvial units. In this belt, geology and rainfall are both moderately favourable but not optimal, and the combination is sufficient to lift the composite index into the Good class without reaching the higher categories.

The Good zone (67.54%, 3,024.0 km²) dominates the central and southern part of the district, encompassing most of the area underlain by Quaternary alluvium described in Section 4.1. Although this setting combines several individually favorable conditions — high primary porosity, near-flat slope and comparatively high rainfall in the south and southwest — the composite index is moderated by the extensive Chromic Vertisol (clay) cover identified in Section 4.3, which restricts infiltration once saturated, and by localized increases in drainage density. The result is a large, relatively homogeneous zone of moderate rather than excellent groundwater potential, illustrating how a single unfavorable layer can offset several favorable ones once all nine factors are combined.

The Excellent zone is the smallest and most fragmented class, covering only 0.26% (11.7 km²) of the district in scattered clusters within the southern and south-central part of the Moderate zone. These pockets most plausibly mark localized coincidences of the most favorable conditions across several layers simultaneously — sandy Cambic Arenosols, water or wetland land cover, high NDVI, and low drainage density — as described in Sections 4.3, 4.4 and 4.7. Because the AHP weighting requires several moderately-weighted layers to align favorably at once for a pixel to reach the Excellent class, such locations are inherently rare and spatially discontinuous rather than forming a single contiguous zone.

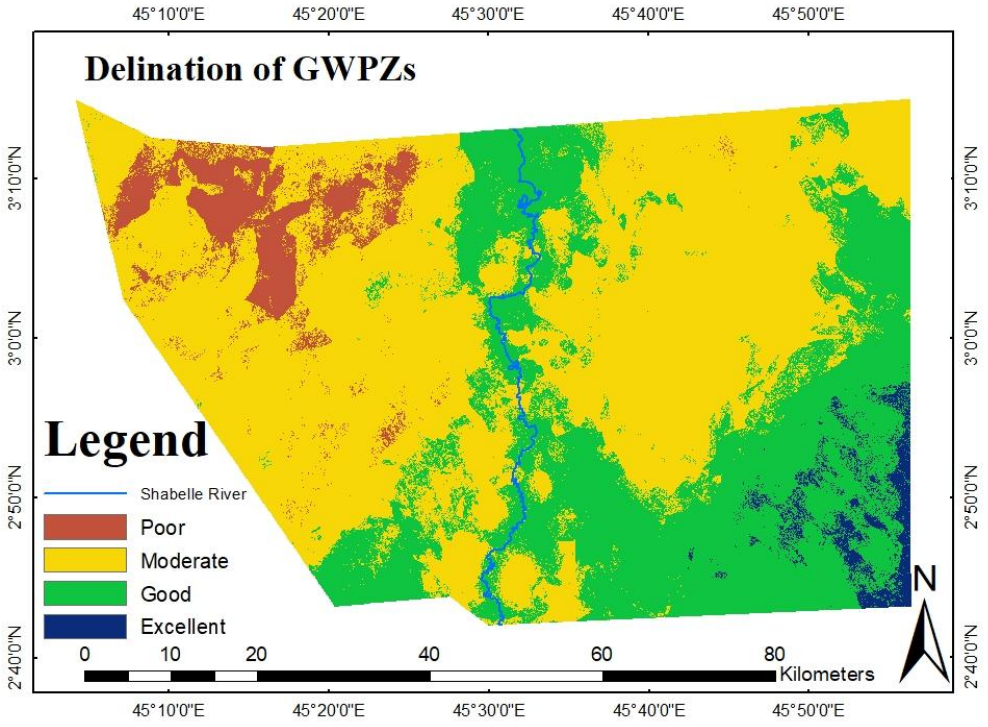


Figure 12: Mapping of groundwater potential zones (GWPZs).

4.11 Validation of the Groundwater Potential Zones

The groundwater potential zone map delineated in Section 4.10 was validated against independent field evidence in the manner set out in Sections 3.3.6 to 3.3.8. The validation dataset was obtained from the Ministry of Energy and Water Resources of Hirshabelle State, which maintains the official register of water supply infrastructure for Middle Shabelle and records the name, coordinates and measured discharge of each water source. Because secondary inventory data may carry positional or transcription errors that would pass directly into a spatial validation, the register was not accepted without independent checking: a subset of the recorded boreholes, selected according to accessibility and prevailing security conditions, was visited during the study period, the position being re-recorded with a handheld GPS receiver, the operational status confirmed and the recorded discharge checked against information supplied by the operators. The register proved consistent with the field observations and was accepted as a sound basis for validation, this verification addressing the concern that inventory data of unverified provenance may weaken an accuracy assessment (Congalton, 1991).

The inventory comprises 48 boreholes with recorded discharges, which constitute the complete set of records with measured yield available for the district at the time of the study. Groundwater data in Jowhar are limited by the sparse development of water supply infrastructure outside the main settlements, by incomplete and irregular record keeping, and by the access and security constraints that restrict field survey across much of Middle Shabelle, so that the validation dataset was necessarily determined by what exists rather than by any sampling design of the researcher. Recorded discharges range from 2.30 to 25.78 liters per second, with a mean of 7.72 L/s and a median of 5.30 L/s, the mean exceeding the median because a few high-capacity boreholes serving the urban supply raise the arithmetic average. Since no universally accepted scheme exists for classifying borehole productivity, published class limits reflecting the character of the areas concerned and the judgement of the investigators (Saranya & Saravanan, 2020), the boreholes were grouped into four productivity categories whose limits were determined from the observed distribution of the measured data. The classification is presented in Table 8 and corresponds in number to the four potential classes of Section 4.10, permitting a direct class-for-class comparison.

Table 9 Classification of the validation boreholes by measured yield.

Yield category	Yield range (L/s)	Boreholes	Percentage (%)
Poor	< 3.5	7	14.6
Moderate	3.5 – 9.9	29	60.4
Good	10.0 – 24.9	11	22.9
Excellent	≥ 25.0	1	2.1
Total		**48**	**100.0**

The verified records were imported into ArcGIS 10.8 through the Add XY Data function, the input coordinate system being specified as the geographic system WGS 1984 to correspond with the decimal-degree coordinates held in the register, exported to a permanent feature class and projected to WGS 1984

UTM Zone 38N, the system used for every thematic layer in this study. The Extract Values to Points tool of the Spatial Analyst extension was then applied, with the final groundwater potential surface as the input raster, appending to each borehole the potential class of the cell in which it lies, so that every borehole carried both an observed productivity category and a predicted potential class. Their spatial distribution upon the delineated map is shown in Figure 13.

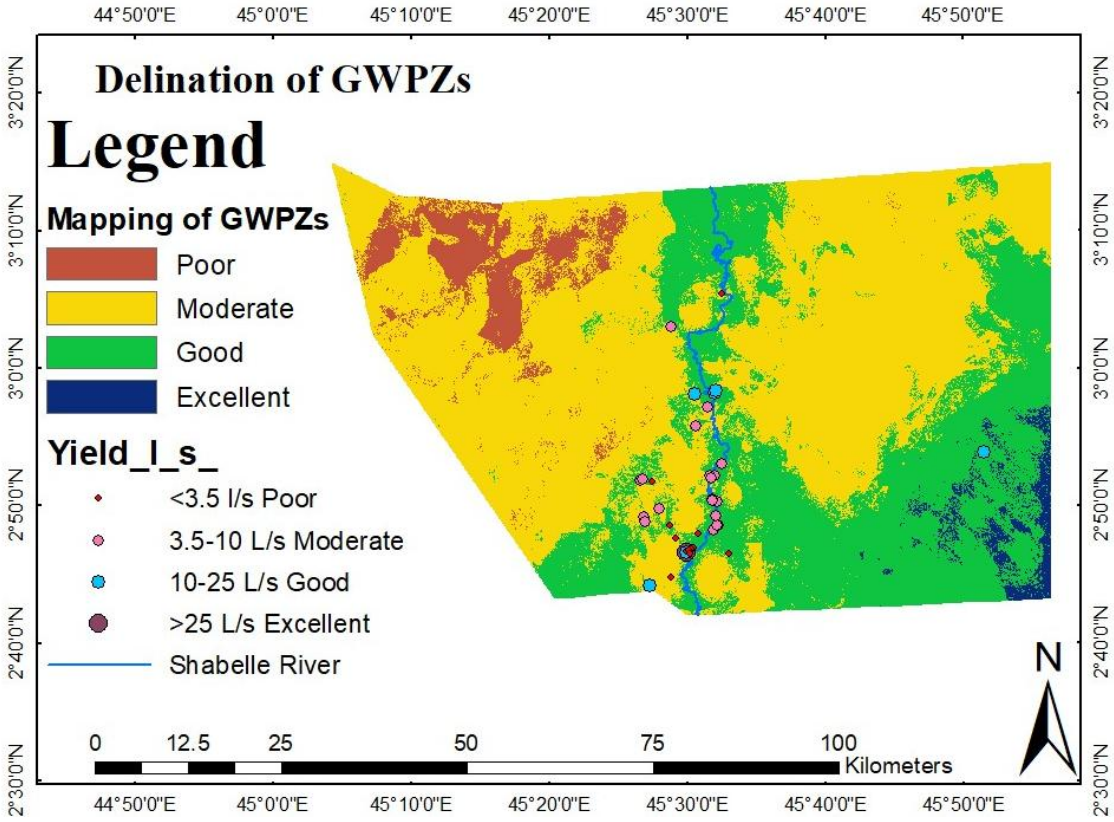


Figure 13: Validation borehole locations overlaid upon the delineated groundwater potential zones.

The cross-tabulation of the two attributes is presented in Table 9. The boreholes divide almost equally between two of the four predicted classes, 23 falling within the Moderate zone and 25 within the Good zone, while neither the Poor nor the Excellent zone contains any borehole. This follows from the areal composition reported in Section 4.10, in which those two classes together occupy barely 3.3% of the district, and from the concentration of water supply infrastructure in the central and southern plain where population and drilling access permit; the two classes in which the model advances its most distinctive predictions therefore remain untested. Within the Moderate zone 2 boreholes are of Poor productivity, 15 Moderate, 5 Good and 1 Excellent, while within the Good zone 5 are Poor, 14 Moderate and 6 Good, so that the proportion of boreholes of Good or better productivity is 26.1% in the Moderate zone against 24.0% in the Good zone, the two being for practical purposes indistinguishable. Comparing each predicted class with the observed category of the same name, 21 of the 48 boreholes, or 43.8%, are

correctly classified, while assessed by concordance in the aggregated form specified in Section 3.3.7, 6 of the 12 boreholes discharging 10 L/s or more and 17 of the 36 less productive boreholes are correctly placed, giving an overall concordance of 47.9%, a value indistinguishable from the 50% expected were productivity and predicted potential statistically independent.

Table 10 Cross-tabulation of observed borehole productivity against predicted groundwater potential class.

Predicted zone	Poor	Moderate	Good	Excellent	Total
Poor	0	0	0	0	0
Moderate	2	15	5	1	23
Good	5	14	6	0	25
Excellent	0	0	0	0	0
Total	**7**	**29**	**11**	**1**	**48**

The discriminating power of the model was quantified by receiver operating characteristic analysis as described in Section 3.3.8. The boreholes were divided into productive and non-productive groups at a discharge of 10 litres per second, the boundary separating the Good and Excellent categories from the Moderate and Poor, giving 12 positive and 36 negative cases, the potential class at each location serving as the model score on an ordinal scale ascending from Poor to Excellent. The resulting curve is presented in Figure 13. Because every borehole falls within either the Moderate or the Good zone the predictor assumes only two distinct values, so the curve consists of a single interior operating point with the two trivial endpoints, at which the model attains a sensitivity of 50.0% against a false positive rate of 52.8%. The area beneath the curve is 0.486, lying almost exactly upon the diagonal line of no discrimination; the 95% confidence interval, computed by the method of Hanley and McNeil (1982), extends from 0.297 to 0.676 and thus encompasses 0.500, and a test of the null hypothesis that the true area equals 0.500 returns a probability of 0.886. Judged against the criterion adopted in Section 3.3.8, under which values above 0.70 are acceptable and those above 0.80 good (Pradhan et al., 2009; Lee & Pradhan, 2007), and against the conventional bands in which 0.5 to 0.6 denotes poor discrimination (Yesilnacar & Topal, 2005), the value falls below the threshold of acceptability. Because the division into productive and non-productive groups depends upon the threshold adopted, the analysis was repeated at three alternative thresholds as a sensitivity test (Table 10); the area ranges from 0.387 to 0.509, every confidence interval encompasses 0.500 and no probability approaches significance, so the conclusion is robust to that choice.

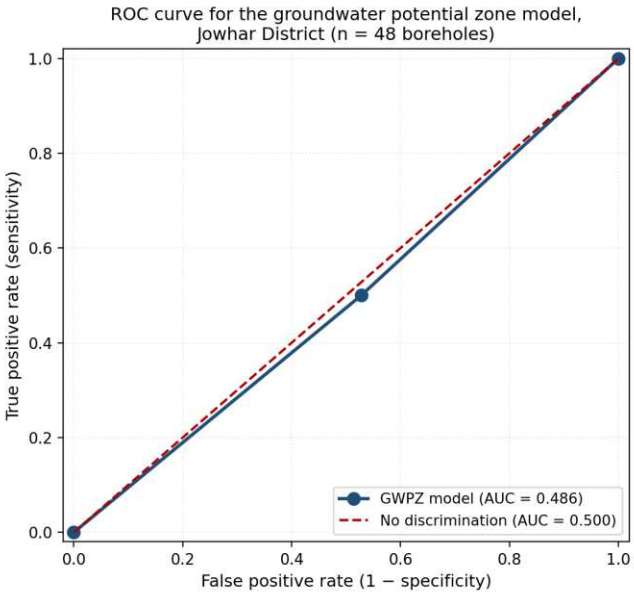


Figure 14: Receiver operating characteristic (ROC) curve for the groundwater potential zone model.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The Analytical Hierarchy Process established that the occurrence and distribution of groundwater in Jowhar District are governed principally by geology and rainfall. The pairwise comparison of the nine thematic layers yielded normalized weights of 26.22% for geology and 26.17% for rainfall, so that these two factors together account for 52.39% of the total influence, followed by soil type at 11.94% and drainage density at 11.52%. Elevation, land use and land cover, the normalized difference vegetation index, slope and lineament density were found to exert progressively lesser influence, receiving weights of 7.82%, 5.33%, 4.89%, 3.67% and 2.44% respectively. The consistency of these judgements was confirmed by a principal eigenvalue of $\lambda max = 9.440$, a consistency index of 0.055 and a consistency ratio of 0.038, the last being well below the accepted threshold of 0.10 and indicating that the weights derived are internally coherent and acceptable for multi-criteria analysis. The dominance of geology and rainfall is consistent with the hydrogeological character of the study area, in which the permeable Quaternary alluvium of the Shabelle floodplain constitutes the principal aquifer and in which recharge is limited chiefly by the quantity and distribution of precipitation. The low weights assigned to slope and lineament density likewise reflect the physical setting, the district being almost level throughout and its aquifer dominated by primary intergranular porosity rather than by fracture-controlled flow.

The weighted overlay of the nine reclassified layers produced a composite groundwater potential index which was classified into four zones. The Good zone occupies 3,023.99 km², or 67.54% of the district, and dominates the central and southern plain; the Moderate zone covers 1,306.52 km², or 29.18%, forming a broad arc to the north and west of it; the Poor zone accounts for 135.22 km², or 3.02%, and is confined almost entirely to the north-western margin where the consolidated Jurassic limestone and Cretaceous formations outcrop; and the Excellent zone comprises only 11.66 km², or 0.26%, in small scattered pockets within the southern plain. The delineated map therefore indicates that the greater part of Jowhar District possesses moderate to good groundwater potential, an outcome attributable to the extensive development of permeable alluvial deposits across the floodplain, and that the least favourable ground lies along the north-western margin where consolidated formations of low primary porosity predominate. The spatial pattern accords with the known hydrogeology of the Shabelle system and provides, at the regional scale, a systematic synthesis of the conditions governing groundwater occurrence in a district for which no such assessment had previously been undertaken.

Validation of the delineated map against measured borehole discharges did not establish that the model reliably distinguishes productive from unproductive locations. Of the 48 boreholes examined, 21, or 43.8%, fell within the potential class corresponding to their observed productivity category, while the aggregated concordance between predicted potential and measured yield was 47.9%, a value indistinguishable from the 50% that would be expected were the two statistically independent. Receiver operating characteristic analysis returned an area under the curve of 0.486, with a 95% confidence interval extending from 0.297 to 0.676 and an associated probability of 0.886, the curve lying almost exactly upon the diagonal line of no discrimination and the value falling below the threshold of 0.70 adopted in Section 3.3.8 as the criterion of acceptability. A sensitivity test conducted at four alternative discharge thresholds returned areas ranging from 0.387 to 0.509, in every case with a confidence interval encompassing 0.500, confirming that this outcome is not an artefact of the particular threshold chosen. It must be emphasized, however, that this finding is materially constrained by the validation data available, for no borehole in the inventory lies within either the Poor or the Excellent zone, so that the two classes in which the model advances its most distinctive predictions could not be tested at all, and the assessment was necessarily confined to the two intermediate classes between which the model itself predicts the least difference. The proper conclusion is therefore not that the map has been shown to be inaccurate, but that the data available were insufficient to demonstrate its accuracy across the full range of the classification.

5.2 Limitations of the Study

The principal limitation of this research was the scarcity of borehole data across the district as a whole. The validation inventory obtained from the Ministry of Energy and Water Resources of Hirshabelle State comprised 48 boreholes with recorded discharges, and these constituted the complete set of records with measured yield available for Jowhar District at the time of the study. Their distribution, however, was determined not by any sampling design of the researcher but by the historical development of water supply infrastructure, which has concentrated in and around the settlements of the central and southern plain where population is greatest and where access for drilling equipment is practicable. The consequence was that the validation sample did not extend across the full range of conditions predicted by the model. Not a single borehole was located within the Poor zone along the north-western margin, and none within the Excellent pockets of the southern plain, with the result that two of the four delineated classes, together occupying 3.3% of the district, could not be tested at all. A validation dataset that samples only part of a classification cannot demonstrate the performance of that classification as a whole, and the scarcity of borehole records therefore constrained not merely the statistical precision of the assessment but the very scope of what it was able to establish.

This constraint was compounded by three related features of the available data. The boreholes were spatially clustered rather than systematically distributed, 37 pairs lying within approximately 200 metres

of one another, so that the number of genuinely independent observations, and hence the statistical power of the validation, was appreciably smaller than the nominal sample size of 48. The register recorded discharge alone, without accompanying information on borehole depth, screen length and position, well development or installed pump capacity, so that the influence of borehole construction upon measured yield could be neither isolated nor controlled; a shallow or poorly developed borehole in favorable ground may yield less than a deeper and better constructed borehole in unfavorable ground, and a proportion of the scatter observed in the validation is attributable to this engineering variation rather than to any failure of the hydrogeological model. Field verification of the inventory, moreover, was necessarily partial, since access to parts of the district was restricted by prevailing security conditions, and only those boreholes that could be safely reached were visited and checked.

Three further limitations should be acknowledged. The spatial resolution of the freely available satellite imagery and digital elevation data constrained the identification of fine-scale geological and structural features, and lineaments extracted at this resolution represent only the more prominent structural elements of the district. The assignment of weights through the Analytical Hierarchy Process, although conducted in accordance with established procedure and verified by an acceptable consistency ratio, rests ultimately upon expert judgement and therefore carries an irreducible element of subjectivity. Finally, the study was confined to geospatial analysis and did not extend to groundwater quality assessment, aquifer pumping tests or continuous monitoring of groundwater levels, so that the potential zones delineated describe the likelihood of groundwater occurrence rather than the quantity that may be sustainably abstracted or its suitability for a given use. The physiographic uniformity of the district, in which elevation spans only 142 meters, more than four-fifths of the area lies below a slope of 1.4 degrees, a single lithological unit underlies the central and eastern sectors and rainfall varies by some 15% across the district, further limits the internal contrast upon which any weighted overlay depends, and constitutes a genuine constraint upon the discriminating power attainable by this method in such a setting.

5.3 Recommendations

On the basis of the findings and within the limitations set out above, the following recommendations are offered to water authorities, government agencies, NGOs, UN agencies and Researchers concerned with groundwater development in Jowhar District. The groundwater potential zone map produced by this study should be employed as a regional planning instrument, to guide the prioritization of areas for more detailed investigation and to identify ground where drilling risk is likely to be elevated, rather than as a direct basis for siting individual boreholes. The north-western margin of the district, underlain by consolidated Jurassic and Cretaceous formations and delineated here as the Poor zone, should be approached with caution in any drilling programme, and investment there should be preceded by geophysical survey. Conversely, the extensive Good and Moderate zones of the central and southern

plain, where the permeable Quaternary alluvium is most fully developed, represent the most promising ground for the expansion of water supply, subject in every case to site-specific confirmation.

Prior to any operational use of the map, the reclassification direction of the inverse thematic layers, namely slope, drainage density and elevation, in which low parameter values correspond to high groundwater suitability, should be verified and the weighted overlay recomputed should any inversion be found. These three layers together carry 23.01% of the total weight, and an error in their reclassification would propagate systematically through the composite index; this is the one potential source of systematic error lying wholly within the control of the analysis, and its elimination is a necessary precondition of confidence in the output.

It is further recommended that a systematic programme be established for the compilation and maintenance of groundwater records in Jowhar District and the wider Middle Shabelle Region. The limitations encountered in this study arose principally from the absence of such a record, and their resolution lies in its creation. Drilling contractors, non-governmental organizations and government agencies undertaking borehole construction should be required to record and deposit, in a standard format, the coordinates, total depth, lithological log, screen position, static water level, pumping test results and sustainable yield of every borehole completed. A register of this kind, maintained by the Ministry of Energy and Water Resources, would transform the evidential basis available to future groundwater studies in the region and would permit validation of a rigor not attainable from the data presently available.

5.4 Suggestions for Further Research

Four directions for further research follow directly from this study:

1. The validation should be repeated once a more complete borehole inventory becomes available, and in particular once yield observations can be obtained from within the Poor and Excellent zones. Targeted exploratory drilling in those areas, undertaken specifically for the purpose of model verification, would furnish a far more decisive assessment of reliability than the present sample permits, since it is precisely there that the model advances its strongest predictions.
2. The receiver operating characteristic analysis should be repeated upon the continuous groundwater potential index surface rather than upon the reclassified map, since the technique realizes its full resolving power only when the model score is continuous, and the coarse two-valued predictor available in this study necessarily limited the sensitivity of the test.
3. Future work in this and comparable floodplain districts should consider supplementing the present factor set with parameters that vary more strongly at the local scale, such as aquifer thickness, transmissivity or depth to the water table derived from geophysical survey, which

would be expected to improve discrimination in settings where the surface-derived factors are close to uniform.

4. The comparative performance of alternative multi-criteria and statistical techniques, including the multi-influencing factor method, frequency ratio, certainty factor and machine learning approaches, should be examined against the same dataset, so that the suitability of the Analytical Hierarchy Process to low-relief alluvial terrain may be assessed against alternatives rather than assumed.

Limitations

- *Sparse validation data. The validation inventory, obtained from the Ministry of Energy and Water Resources of Hirshabelle State, comprised 48 boreholes with recorded discharge, the complete set of records with measured yield available for Jowhar District at the time of the study.*
- *Incomplete coverage of classes. Borehole locations reflect the historical development of water supply infrastructure, concentrated in the central and southern plain, rather than any sampling design. No borehole lay within the Poor zone or the Excellent pockets, so two of the four classes, together covering 3.3% of the district, could not be tested. The validation therefore cannot demonstrate performance across the whole classification.*
- *Spatial clustering. Thirty-seven pairs of boreholes lay within about 200 m of one another, so the number of independent observations, and hence statistical power, was appreciably smaller than the nominal sample of 48.*
- *Missing construction data. The register recorded discharge only, without depth, screen length and position, well development or pump capacity. The effect of construction on yield could not be isolated, so some scatter in the validation reflects engineering variation rather than model error.*
- *Partial field verification. Security conditions restricted access to parts of the district, so only boreholes that could be safely reached were visited and checked.*

Abbreviations

Abbreviation	Meaning
AHP	Analytical Hierarchy Process
AUC	Area Under the Curve
CI	Consistency Index
CR	Consistency Ratio
DEM	Digital Elevation Model
DD	Drainage Density
EL	Elevation
FAO	Food and Agriculture Organization
FAO SWALIM	Food and Agriculture Organization Somalia Water and Land Information Management Programme
GIS	Geographic Information Systems
GPS	Global Positioning System
GWPI	Groundwater Potential Index
GWPZ	Groundwater Potential Zone
IDW	Inverse Distance Weighting
LD	Lineament Density
LUC	Lincoln University College
LULC	Land Use and Land Cover
MCDA	Multi-Criteria Decision Analysis
MoEWR	Ministry of Energy and Water Resources
MOWRE	Ministry of Water Resources and Energy
NBS	National Bureau of Statistics
NDVI	Normalized Difference Vegetation Index

NDWI	Normalized Difference Water Index
NIR	Near Infrared
OCHA	Office for the Coordination of Humanitarian Affairs
OLI	Operational Land Imager
RI	Random Index
ROC	Receiver Operating Characteristic
RS	Remote Sensing
SDG	Sustainable Development Goals
SL	Slope
SRTM	Shuttle Radar Topography Mission
TIRS	Thermal Infrared Sensor
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children's Fund
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WASH	Water, Sanitation and Hygiene
WGS	World Geodetic System
WOA	Weighted Overlay Analysis

Declarations

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Data availability

All data generated or analyzed during this study are included in this article.

Code availability: not applicable

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