The Federal Democratic Republic of Ethiopia
Minstry of Water and Energy

Consultancy Service for Hydrogeological Mapping Using Remote Sensing, GIS and Geophysical Surveying

Lot – 3

Procurement Reference Number:
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PHASE II

FINAL MAIN REPORT

DEVELOPING GROUNDWATER POTENTIAL MAP OF 14 WOREDAS (LOT-3)

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Acronyms/Abbriviation

AHP	=	Analytical Hierarchy Process
BDA	=	Basin Development Authority
CTI	=	Compound Topographic Index
CSA	=	Central Statistical Authority
DEM	=	Degital Elevation Model
DFID	=	Department for International Development
GIS	=	Geographic Information System
GWPI	=	Groundwater Potential Index
IC	=	Infiltration Coefficient
MDG	=	Milinuem Development Goal
MoWE	=	Ministry of Water and Energy
NGO	=	Non-Governmental Organization
RS	=	Remote Sensing
SNNP	=	Southern Nations Nationalities People
SRTM	=	Shuttle Radar Topography Mission
TWI	=	Topographic Wetness Index
USGS	=	United States Geological Survey
UTM	=	Universal Transverse Mercator
WASH	=	Water, Sanitation &Hygien
WDC	=	Water Development Comission

EXECUTIVE SUMMARY

The main objective of the work is to increase access to safe and sustainable water for the people in selected Woredas of the lot-3 by producing hydrogeological maps at woreda level, select potential sites and recommend two drilling sites i.e. one optimal drilling site and one alternative or optional drilling site, using these maps and geophysical field investigation and recommend the type of drilling.

The phase II scope of the work covers groundwater mapping using remote sensing and GIS approach with some ground truthing so as to produce groundwater potential map of the cluster and each Woreda within the cluster that will help identify the most suitable areas for further hydrogeological and geophysical investigation. The detailed scope of the work at this stage is to process the data obtained from remote sensing resource analysis and combine geological maps, lineament density maps, and wetness index maps and recharge zonation maps into one layer which displays different groundwater potential zones. To check the overlay analysis results by using information from secondary data (boreholes, springs and dug wells to prioritize the selection of the Target areas and conduct ground-truthing and identify two target areas in the woreda from areas highlighted with a high groundwater potential to priority population targets.

Mapping of the groundwater potential zones using integrated GIS and RS techniques in conjunction with review of previous geological and hydrogeological works has been performed. To have a broader view and understand the overall geological and hydrogeological settings of the study woredas and produce reliable thematic layers, a synoptic view of the continuity of Lithology, Lineaments, Recharge and storage area is essential. A Synoptic view of geology, lineament, topographic wetness index and recharge were prepared for the target woredas.

The Topographic wetness index, also known as the compound topographic index, is commonly used to quantify topographic control on hydrological processes. The index is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. Topographic Wetness Index (TWI) requires basically slope (in degree), flow direction and flow accumulation which are generated from elevation maps (DEM) extracted from SRTM (30m resolution) as an input.

Lineaments of the study woredas were extracted amnually from a mosaicked Senitel-2 imagery of January, 2020 series combined with hybrid geomorphology of woredas and mapped using ArcGIS 10.8 software, and subsequently lineament density map was computed.

Finally, recharge map layer was produced by calculating raster map of annual rainfall with infiltration coefficient of each geological unit in ArcGIS 10.8 platform. The mean annual rainfall raster data set were obtained from open sources of CHIRPS satellite imageries of 10 years from 2011 to 2020 mean annual rainfall on geological survey of America (USGS) official website (https://chc.ucsb.edu/). All the layers were resampled into 100 m cell size rastar maps.

A weighted index GIS overlay analysis technique has been employed for the groundwater potential mapping using an integration of 4 major thematic layers namely Lithology, Lineament density, Topographic Wetness Index and Recharge. Weights assigned to each class in all these thematic maps are based on the influence of each thematic layer on groundwater potential capacity through analytical hierarchical process techniques (AHP) method.

Thus, the groundwater potential zone maps of target woredas obtained have been qualitatively classified into four classes as very high, high, moderate and low. In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map of each target woreda, data on existing wells (yield) were collated and used to check the potential zones Identified.

CHAPTER 1 : - Background

1.1. Introduction

The arid, semi-arid and dry sub-humid areas of Ethiopia account for about 70 % of the total land mass and 46% of the total arable land. Drought and flood events, loss of grazing land, range land degradation, change in eco systems and biodiversity, loss of livestock, water & food insecurity, increased temperatures and aridity, deforestation and desertification, treats to health and general wellbeing, displacement and resource based conflicts are the common risks and vulnerability caused by extreme climates (Eli no and la Nina) recurring for decades as extreme changes in rainfall patterns in these areas. Therefore, to create resilient community to climate change impacts and bring about sustainable development, ensuring water security through assessing and utilizing the water resources potential (both surface and subsurface) of the areas for domestic and livestock purpose is an urgent local coping strategic priority.

Drought is the major natural disaster affecting the livelihood of Ethiopians, resulting in water insecurity which in turn causes disruption of livelihoods and loss of life. A significant proportion of the Ethiopian population still lacks access to clean water, despite the fact that Ethiopia successfully achieved the Millennium Development Goal (MDG) target of halving the number of people without access to improved drinking water. At the national level, 60 to 80 per cent of communicable diseases are attributed to limited access to safe water, and inadequate sanitation and hygiene services.

As part of its engagement, the Basin Authority of Ethiopia is committed in undertaking water resources study and mapping groundwater resources towards developing groundwater resources for the water needy community of Ethiopia. In line with this, the Basin Authority of Ethiopia in collaboration with the UK Department for International Development (DFID) has decided to undertake groundwater resources assessment using remote sensing and Geophysical surveying in selected drought prone areas of Ethiopia. The purpose of this undertaking is to identify priority water needy areas and locate potential groundwater sites that can be sources for water needy communities. Accordingly, a consultancy service agreement has been signed between FDRE, Basin Development Authority and DH Consult in JV with Golder Associate UK Ltd to undertake Hydrogeological Mapping using Remote Sensing, GIS and Geophysical Survey in selected 14 woredas of Ethiopia. As part of the assignment, this phase II work presents approaches and methods that has been undertaken to develop groundwater potential map that woud further help hydrogeological investigation emplying classical methods.

1.2. Objective

1.2.1. General objective

The main objective of the work is to increase access to safe and sustainable water for the people in 14 Woredas by producing hydrogeological maps at woreda level and recommend drilling sites which the Government of Ethiopia and other partners can use for developing groundwater resources of the woreda

1.2.2. Specific Objectives

The specificobjectives of this project include the following:

-Create detailed groundwater potential maps for the Woreda,

-Identify one optimal drilling site and one alternative or optional drilling site for the woreda, using these maps and geophysical field investigation and recommend the type of drilling methodology to be employed,

-Build the capacity of WDC, BDA, Regional Governments and NGOs to use overlay analysis techniques for groundwater potential mapping in Ethiopia

1.3. Scope

This study/ GW characterization, mapping and advanced mapping work/ will take place in four (4) Lots in Amhara, Afar, Oromia, SNNP, Tigray, Gambela and Somali regions. The total project covers 53 woredas selected for groundwater mapping under the Terms of Reference. Lot-3 comprises 14 Woredas and produce 14 hydrogeological maps (one map per woreda) to identify the most suitable site for borehole drilling. A critical first step for this project will be the initial identification of target sites for borehole drilling. The scope of the assignment for the woredas for Phase II Developning Groundwater Potential Map is as indicated hereunder.

i. Organize, coordinate, and facilitate a workshop with the Peer Review Committee to finalize overlay analysis weighting criteria

ii. Process the data provided by remote sensing analysis.

- For the woredas, the Consultant will use a GIS overlay analysis tool to combine remote sensing layers into one layer which displays the groundwater potential.
- In order to refine target areas, the Consultant will check the overlay analysis results by using information from secondary factors (Type 2 and Type 3 layers).
- At woreda level and in consultation with the Regional Water Bureaus and other partners, identify priority population targets and estimate water demand.
- Select two target sites in the woreda from areas highlighted with a high groundwater potential and close to priority population targets.
- Carry out field visits to all the woredas to ground-truth the information obtained from the input layers and the results from the overlay analysis.
- Carry out National Groundwater Risk Mitigation Strategy study and make recommendations
- Following the ground-truthing works and population targeting, select areas for detailed studies (detailed study areas)
  - Submission of groundwater potential maps at woreda level (1:100,000).
  - Development of conceptual models (hydrogeological cross-sections) of the Woredas for a better understanding of climate resilient groundwater system and the remote sensing and overlay analysis outputs,

- Submitting a final report per Priority woreda detailing groundwater potential maps for each woreda with ground-truthed analysis of drilling potential.
- Dissemination workshop of the groundwater potential resources mapping exercise and results among the main WASH stakeholders in Ethiopia.

1.4. Location map of the target Woredas under Lot-3

Fourteen Woreda in two Administrative Regions (9 woreda in Oromiya and 5 woredas in Somali) have been selected under LOT 3. The geographic location of the target Wordas is presented in Figure 1-1, and list of woredas with their woreda, Population and demographic map, existing water supply situation, climate, physiographic and demographic information is shown in the next chaper in detail.

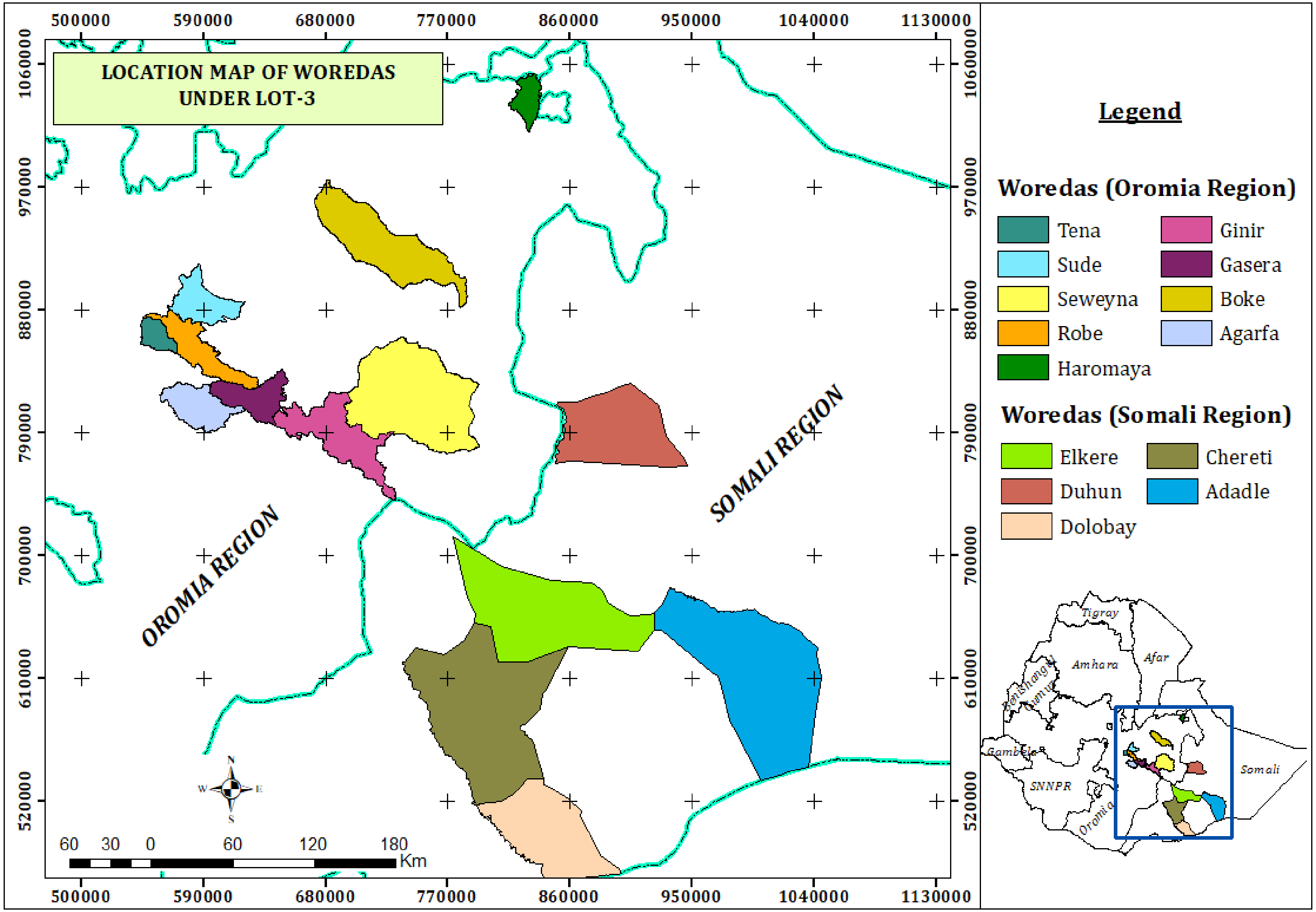

Figure 1-1:-Location map of target woredas under Lot-3

CHAPTER 2 : - REVIEW OF PREVIOUS WORKS

The ongoing review includes available literature on similar topic, interpretation of physical features from satellite images, geological reports, hydrogeological reports and existing water well data and well completion reporst. Basic data necessary for the assignment has been collected from Basin Authority, Regional Water Bureau, Public and private organization engaged in water works to help planning field work in subsequent project phases to get data gaps filled for further hydrogeological analysis.

Literatures and previous relevant studies have been assessed to learn more on major issues to be addressed as well as methods to be applied in describing hydrogeological framework and aquifer system of the project target areas. Satellite images have been used as baseline to identify major geological structures, relief features and topographic slopes to understand geospatial hydrological factors. Major geological structures including faults, lineaments and fissures controlling groundwater movement have been traced from from existing previouse work. Hydrological data including meteorology and river discharge have been collected to be used to assess the hydrological system of the target areas. Previouse reviewed documents and details of methodology have been discussed under their respective chapters and sections,

Most of the previous studies focused at regional scale area and generate more general information. The hydrogeological characteristics, geological set-ups and main lithological units and structures important for controlling groundwater occurrence and movement have been described in these work at a regional scale.

CHAPTER 3 : -BACKGROUND OF THE PROJECT WOREDAS

3.1. Haromaya Woreda

3.2.1. Population and demographic map

Haramaya woreda has 34 Kebeles with 310,416 populations for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 220,986 populations). Ifa Haromaya kebele has highest population with 18,552 whereas kersa Qajima kebele has the least population number with 3,086. Demographic map of Haromaya by kebele is shown in the figure below (Figure 3-1)

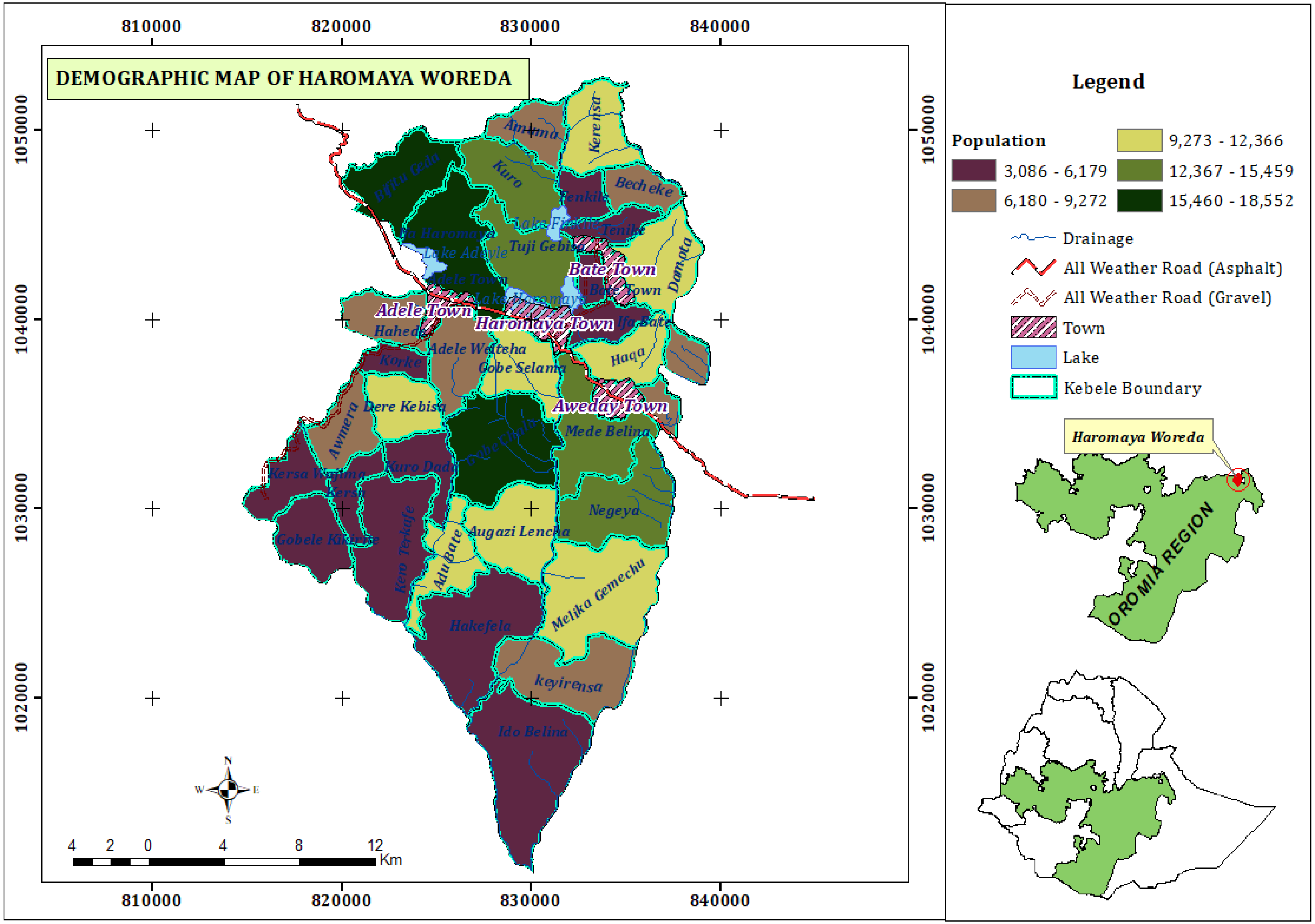

Figure 3-1:-Demographic map of Haromaya woreda

3.2.2. Existing water supply situation

A number of boreholes have been drilled in the northern part of the woreda around Lake Haromaya. Theses wells belong to Haromaya University, Harar Beer, Haromaya town and communities around. As far as the data we have is concerned, boreholes and dug wells with a depth range of 30m to 80m having shallow depth to the groundwater (1m to 11m) are available in this area. Well yields vary from 0.5 l/s to 8 l/s. The dominant aquifer material observed at some of these wells is alluvial deposits underlain by weathered and slightly fractured basement roacks. These wells are located at places having relatively low relief.

3.2.3. Climate

The annual rainfall in Haromaya area ranges from 769.6 to 1090 mm/yr (annual mean of 800 mm) as indicated by Eba Muluneh, 2017. The annual mean maximum and minimum temperatures of Haramaya area are, 24 °C, and 10°C, respectively.

3.2.4. Physiography

An attempt has been made to study the geomorphological details of the Haromaya area and to demonstrate their relationship to aquifer geometry in the area. In this study a systematic analysis of varriations in elevations of different land forms and their relationship with lineaments, drainage pattern and rock units have been made by integrating DEM and satellite immageries. The approach involved regional and local interpretation of features exposed at the surface. Erosional reminants of sedimentary rocks form localized redges overlying the basement rock units. Elluvial, aluvial and lacustrine sediments overlies the basement along perrenial and non perrrenial stream courses.

Sediment deposits are expected to have varying thickness and composition in the area having subsurface features of importance in groundwater storage favourable aquifer disposition and various subsurface geomorphic features which are potential sites for ground water development are identified. The geomorphologic evidences (map) will help to infer groundwater potential zones showing structural, lithological, geological, topographic and hydrological features of the area (Figure 3-2).

The drainage pattern depends on the rock types and geologic structures underlying a given area or catchment. Some types of rock are harder and more resistant to erosion than others. Some areas are impacted more by tectonic forces than other areas. Erosion usualy modifies land forms at large. The pattern of the drainage system of the area is commulative effect of these processes (Figure 3-3). In Haromaya Woreda domain bedrock lithology and geologic structure dominantly determine patterns of drainage net work. The crystalline basement dominantly composed of granites display parallel and rectangular drainage patterns in the area.

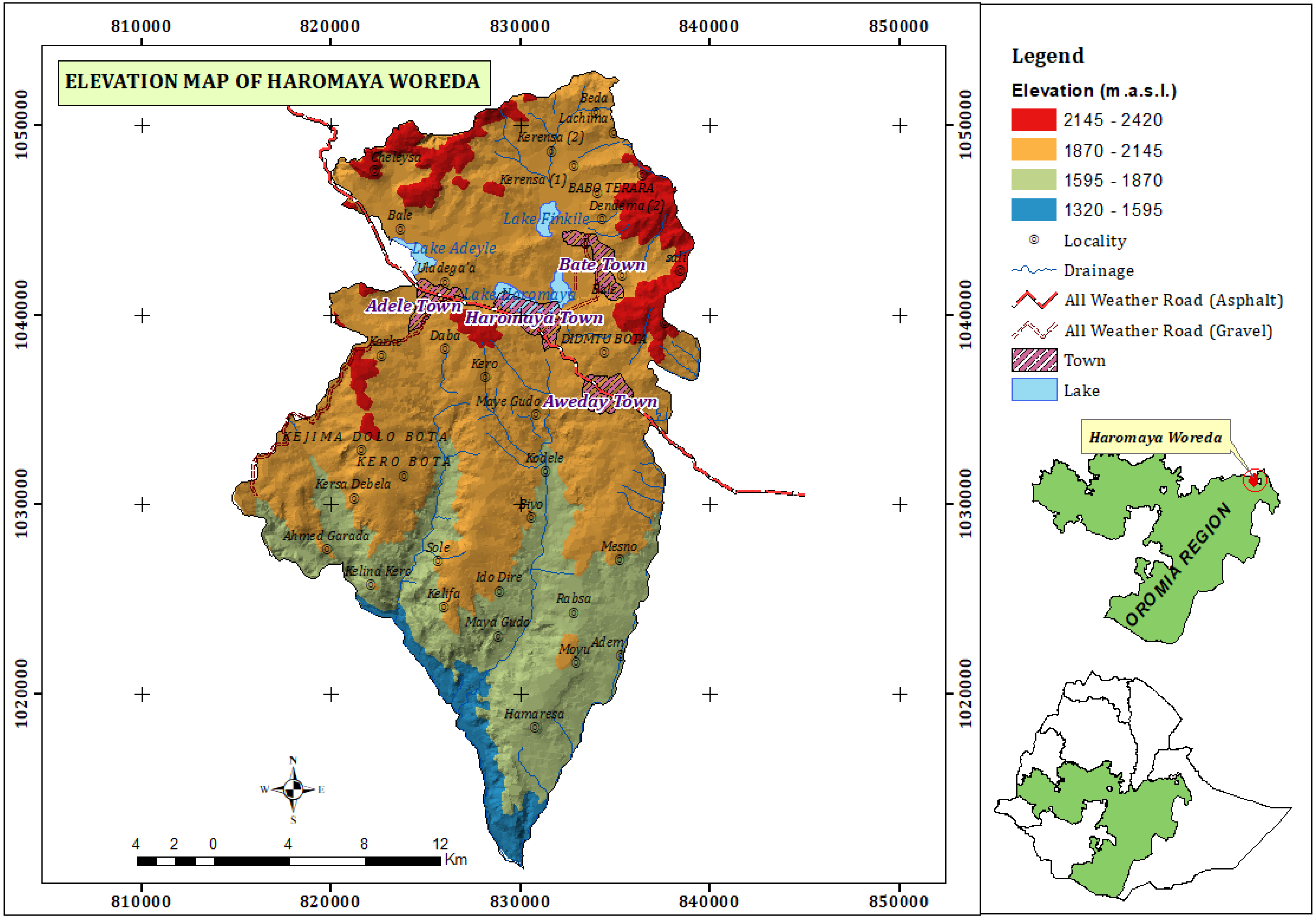

Figure 3-2. Physiography of Haramaya woreda

3.2. Boke Woreda

3.2.1. Population and Demographic Map

Boke woreda has 34 Kebeles with 202,921 populations for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 144,460 populations). Tefe Kebele has highest population with 13,499 whereas Madda Jalala kebele has the least population number with 525. Population map of Boke by kebele is shown in Figure 3-3.

3.2.2. Existing Water Supply Situation

About 15 boreholes have been drilled in the northern part of the woreda around Boke town. Theses wells belong to Boke town and local communities around. As far as the data we have is concerned, boreholes with a depth range of 153 m to 341 m having relatively a deeper groundwater level rangin between 13.2 and 269 m.b.s.l. Well yields vary from 1 l/s to 30 l/s with mean value of 6.1 l/s. A borehole with the highest yield is found at southeast of Boke town, around Laga Labu locality while the lowest yield borehole is located at west of Boke town, around Lebu locality. The dominant aquifer material observed at these wells is limestone rocks intercalated with marls. These wells are located at places having relatively low relief.

Apart from these, three high discharging springs which are mainly serving as a water supply and for irrigation purpose for the local communities are found at the northern regions of the woreda. The discharge of these springs ranges from 29.8 l/s to 241 l/s with mean value of 114.7 l/s. The high yield spring which is emanating from contacts and fractures of sandstone and basement rocks is located at south of Boke town, around Meda Gurati locality. This spring is mainly serving for irrigation purpose for the local area. Whereas, the low yielding spring which is emanating from fractured limestone and serving as a water supply and irrigation for the local community is found at northeast of Boke town, around Meda Mussa locality.

3.2.3. Climate

Review existing litrature and analysis of DEM reveal that Boke woreda is characterized by Boke is entirely characterized by arid to semi-arid physiography with altitude range from 600 masl in southeastern peripheries to 2000masl in northwestern. The annual rainfall in Boke area ranges from 769.6 to 1090 mm/yr (annual mean of 800 mm) as indicated by Eba Muluneh, 2017. The maximum and minimum temperatures of Boke area ranges 4 °C to 16°C with average of 16°C, while average mean annual rainfall is 963 mm/year.

3.2.4. Physiography

The Bena woreda is situated within the Wabis Shebele River basin. The present physiographic setting of the woreda is the result of mainly volcano-tectonic and erosional activities. The majority area of the study woreda is mainly characterized by plain topography while some rugged topography dissected by numerouse drainages found at limited area northern and southern peripheries of the woreda with an elevation range from 950 m.a.s.l. at southeastern to 2000 m.a.s.l., at northwestern regiont of the woreda (Figure 3-4). The plain landform occupies mostly central and central eastern part of the woreda which is characterized by flat low lying topographic surfaces. The rugged terrain found mostly at limited peripherial areas of the woreda is characterized by steep slopes, small ridges, hills and alternating valleys. This land form is mainly shaped by erosion activities which produced badland, rugged terrain and rolling topography. V-shaped streams are common with deep gorge.

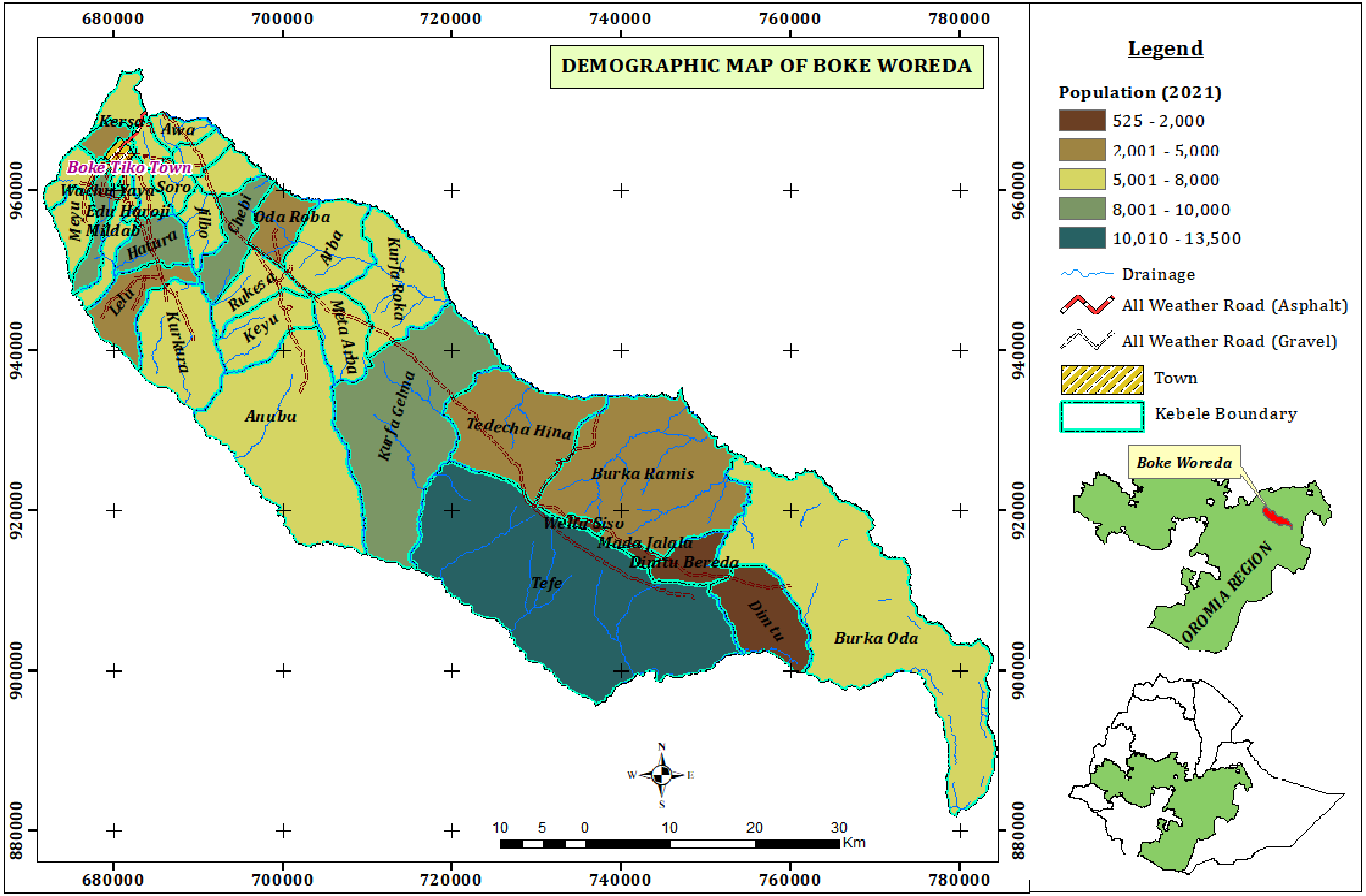

Figure 3-3:-Demographic map of Boke woreda

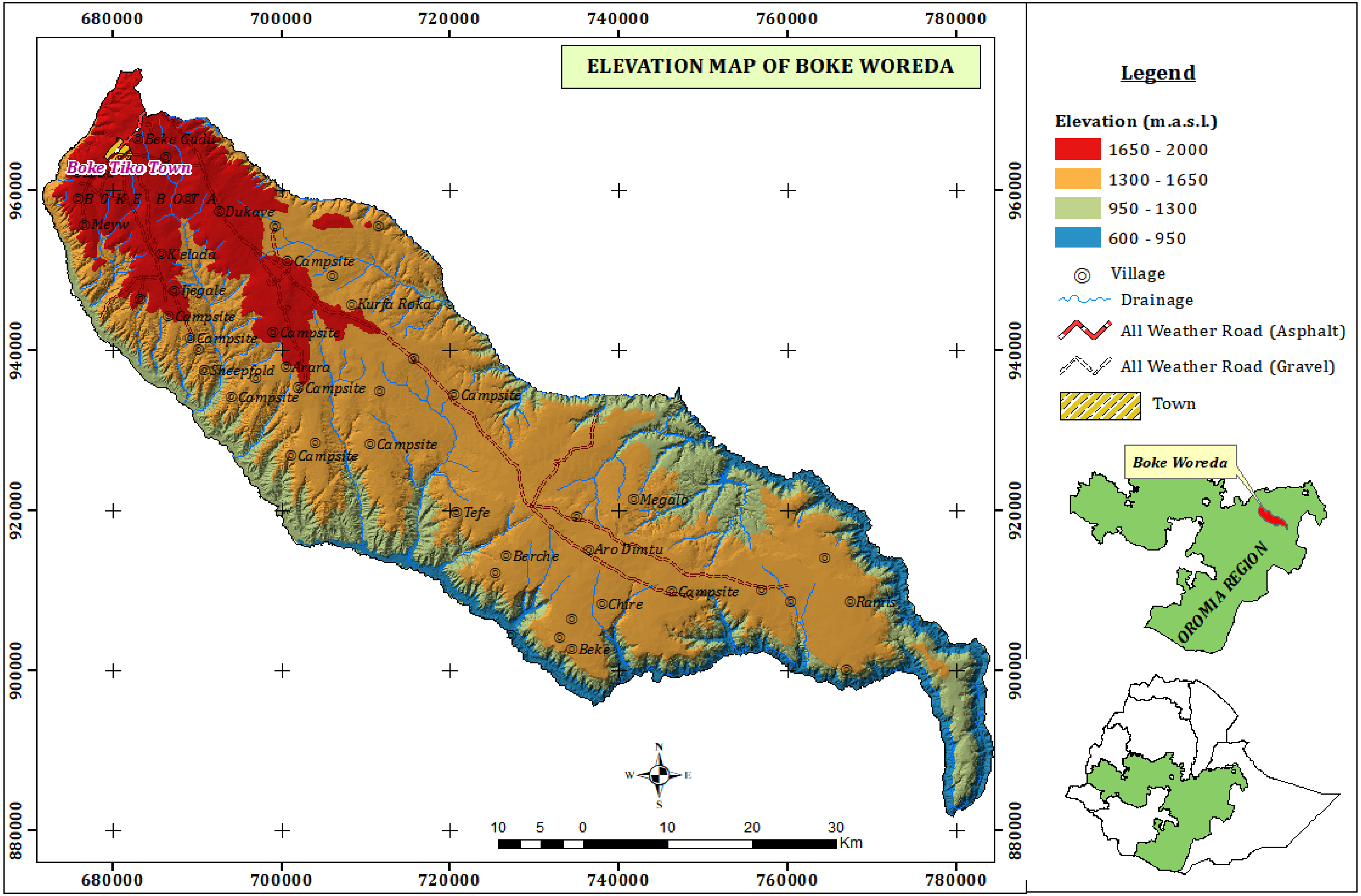

Figure 3-4. Physiography of Boke woreda

3.3. Gasera Woreda

3.3.1. Population and Demographic Map

Gasera has 21 Kebeles with 104,021 populations for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 74,053 populations). Awichache Birbirsa kebele has highest population with 8,511 whereas Wetechemo kebele has the least population number with 1,542. Population map of Gasera woreda by kebele is shown in Figure 3-5.

3.3.2. Existing Water Supply Situation

Only one shallow well having a depth of 75 m is found at east of Gasera town, around Abugure locality. This well belongs to Gasera town and serving as a domestic water supply. The dominant aquifer material observed at this well is volcanic rocks of fractured basalt.

Apart from this, 5 springs which are mainly serving as a water supply for the local communities are found also within the woreda, around southeast of Gasera town. These springs are fractured springs that emanating from fractured basaltic rocks.

3.3.3. Climate

Review existing litrature and analysis of DEM reveal that Gasera woreda is characterized by different physiographic features with elevation range from 1020 meters above sea level in the north to 2440 meters above see level in the south. The climate in Gasera is warm and temperate. The average annual temperature in Gasera is 14.9 °C. The rain in Gasera falls mostly in the winter, with relatively little rain in the summer. The annual mean rainfall is 677 mm.

3.3.4. Physiography

The Gasera woreda is situated within the Wabi Shebele River basin. The present physiographic setting of the woreda is the result of mainly volcano-tectonic and erosional activities. Generally, the study area in the north is mainly characterized by rugged topography deeply dissected by numerouse drainages. This landform occupies the Wabe River bank associated deep gorges in the peripheral northern parts of the woreda. This part of the woreda is comprised of faulted tertiary volcanics dominantly basalt underlain by Hamanile limestone.

The southern part of the woreda is characterized by plain landform gently sloping towards north. Surface elevation gradually fall from southwest towards north within the woreda domain. This eastern part of the woreda is comprised of plateau basalts and flows later slightly shaped by erosional process.

Elevation within the woreda boundary ranges from 1020 meters above sea level in the north to 2440 meters above see level in the south (Figure 3-6).

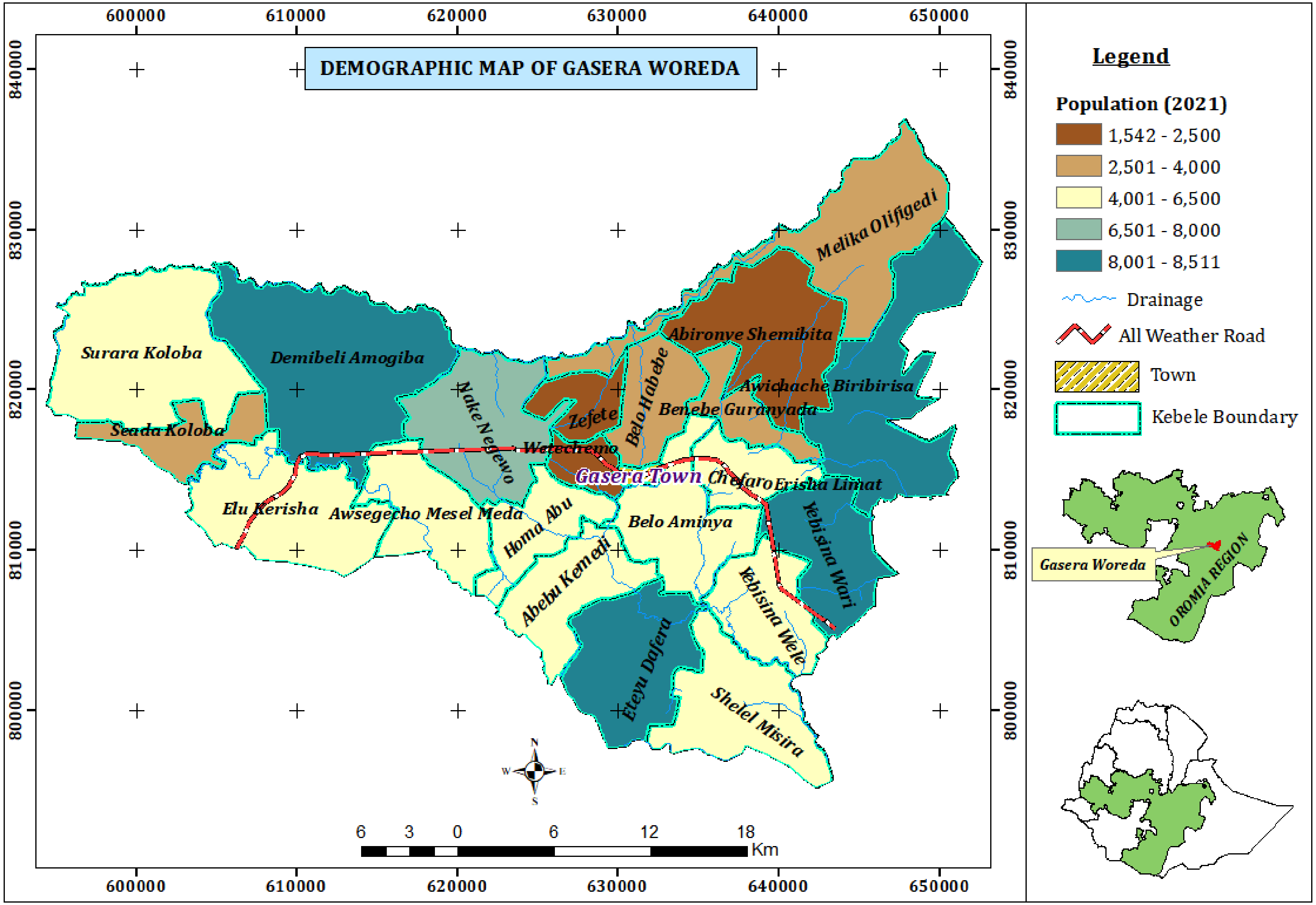

Figure 3-5:-Demographic map of Gasera woreda

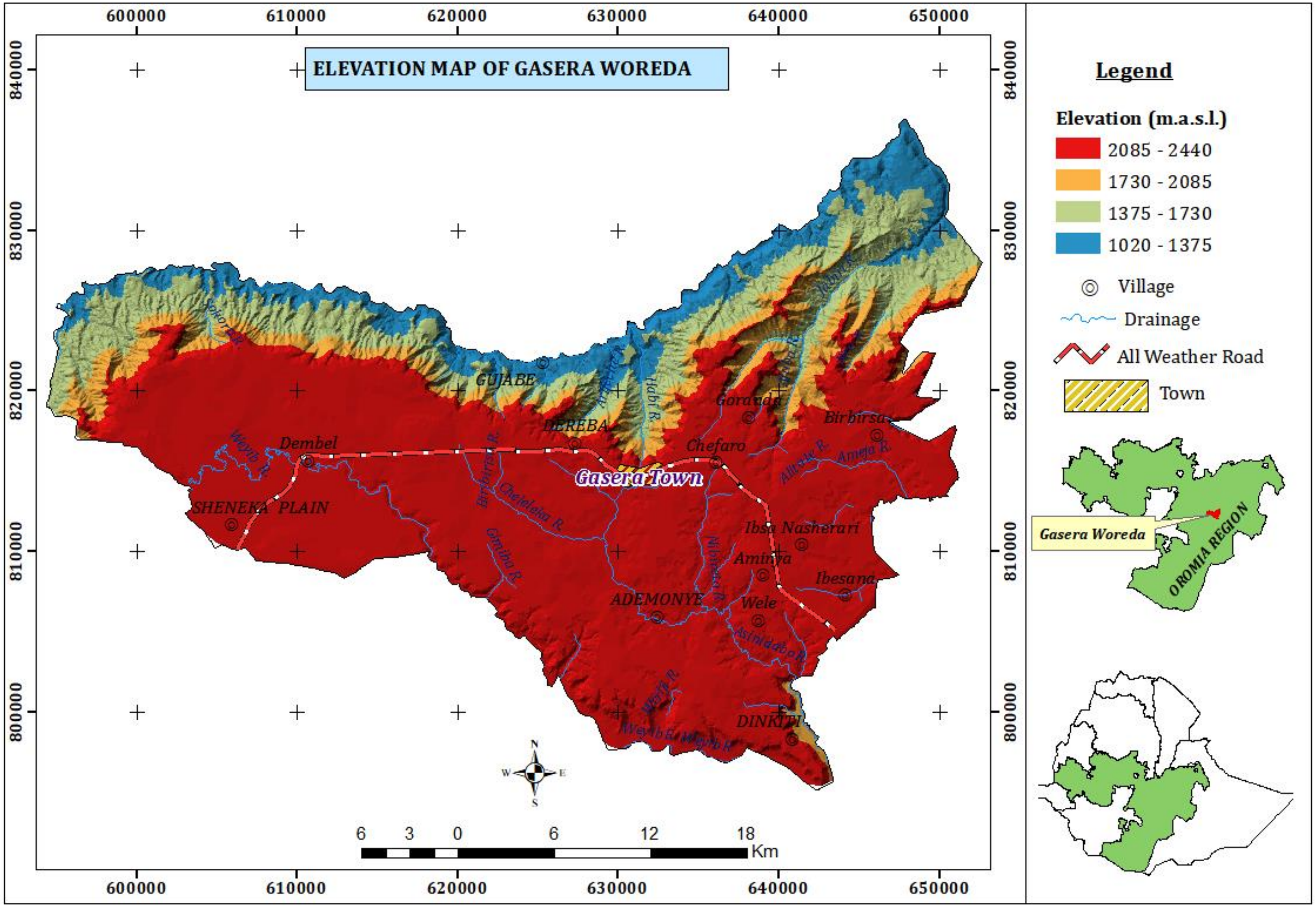

Figure 3-6. Physiography of Gasera woreda

3.4. Ginir Woreda

3.4.1. Population and Demographic Map

Ginir has 31 Kebeles with 167,578 populations for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 119,299 populations). Karadano kebele has highest population with 12,955 whereas Mehammed Ali Ersha Limat has the least population number with 3. Population map of Ginir by kebele is shown in Figure 3-7. However, there are some places in the Cenral and Northwest which are not covered by census to 2007.

3.4.2. Existing Water Supply Situation

Only five boreholes (one shallow well and four deep wells) are found in the northwestern part of the woreda, at northwest of Ginir town. The depth of the wells ranges between 60 m and 300 m while the groundwater level and discharge of these wells ranges between 3 and 176 m.b.s.l. and from 3 l/s and 5.6 l/s, respectively. The deep borehole (depth = 300m) with high yield (Q = 5.6 l/s) is located at western part of the woreda, at Harewa-3 village. All the wells are serving for domestic water supply for the local communities and Ginir town. The dominant aquifer material observed at these wells is volcanic rocks of fractured basaltic rocks.

Apart from this, about 26 springs are found mostly at central and central western regions of the woreda. They are mainly serving as a water supply for the local communities found within the woreda. The discharge of the springs varies between 0.1 l/s and 50 l/s. The high discharging spring with yield of 50 l/s is located at central part, south of Ginir town at Chancho locality. It serves mainly as a water supply for the local community. All the springs are emanating from fractured basaltic rocks.

3.4.3. Climate

Ginir Woreda falls within two agro-climatic zones namely 25% temperate (Woyinadega) and 75% lowland (kola). Ginir Woreda receives mean annual rainfall of about 918 mm. The Woreda receive rain in two seasons such as Belg (autumn) season (March to May) and Tsedey (spring) season (September to November). Bega (winter) season (December- February) is the driest season in the area. Unlike highland part of the country, Kremit (June to August) is dry season with only small rainfall. In the Woreda the highest rainfall amounts recorded in months of April, May and October and the lowest amount recorded in months of January and February.

The temperature data from 1982-2023 indicates that the higher monthly mean maximum temperature was recorded in the Woreda during month of 21 December to February where as the lowest monthly mean minimum temperature recorded during months of December and January . In these years (1982-2012) the recorded average mean maximum, minimum and average temperature were 24.2^{0}c, 13.3^{0}c and 18.7^{o}c, respectively.

3.4.4. Physiography

The Ginir woreda is situated within the Wabis Shebele River basin. The present physiographic setting of the woreda is the result of mainly volcano-tectonic and erosional activities. The study area is mainly characterized by plain topography at central eastern regions and rugged topography with some hills which is dissected by numerouse drainages with some elevated plateaue at central western parts of the woreda area with an elevation range from 920 m.a.s.l. at southeastern to 2560 m.a.s.l., at western part of the woreda (Figure 3-8). The plateau landform occupies mostly central western part of the woreda which is characterized by flat low lying topographic surfaces and consists of down faulted tertiary volcanics plateau basalt that has been shaped by erosion forming smooth rolling topography. The rugged terrain found mostly at central southern peripheries of the woreda is characterized by steep slopes, parallel to sub parallel ridges and alternating valleys. This land form is mainly shaped by erosion activities which produced badland, rugged terrain and rolling topography. V-shaped streams are common with deep gorge. The south eastern area is characterized by plain land form with flat slopes mainly underlain by slightly dissected Masozoic sedimentary rocks of upper sandstones.

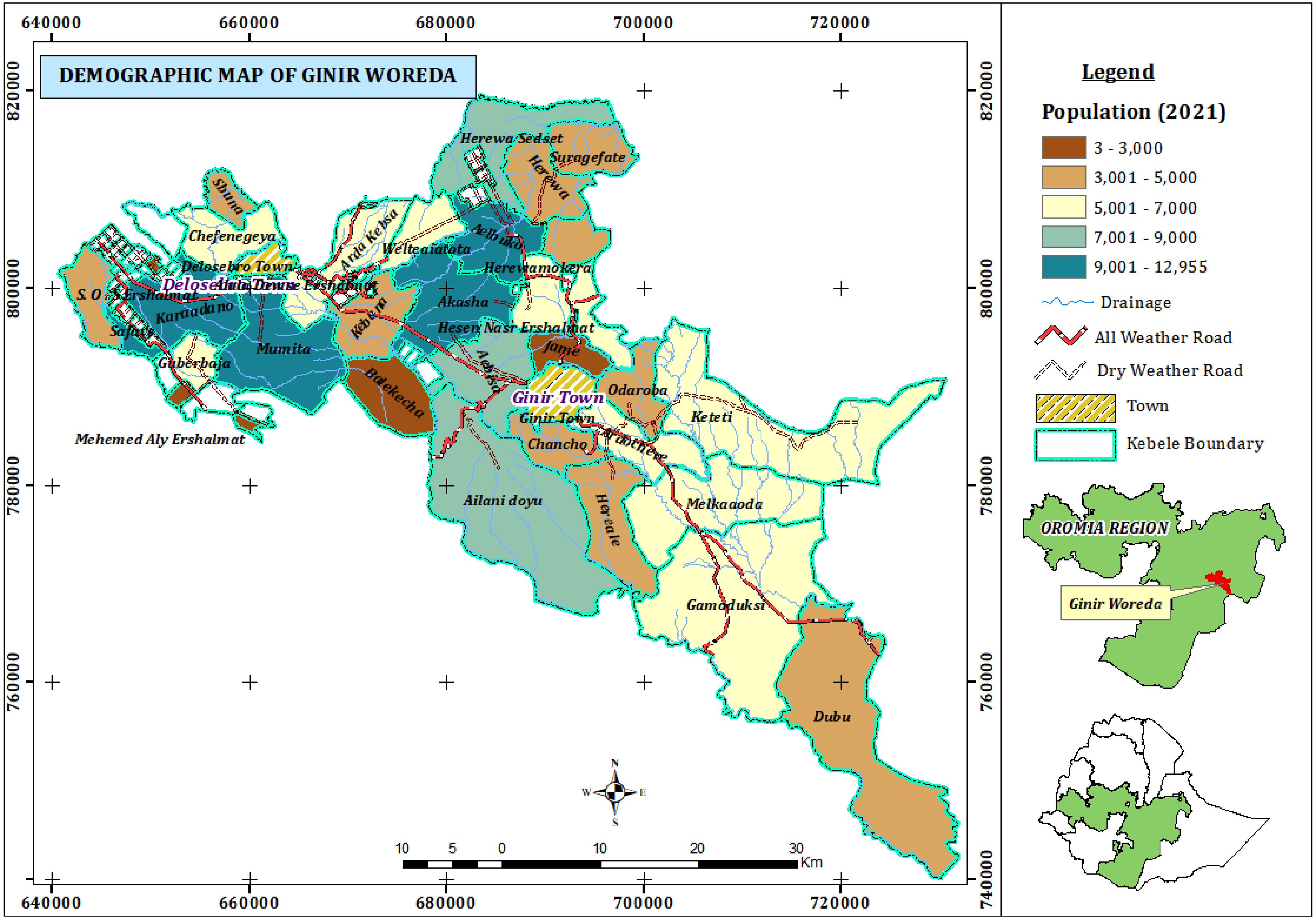

Figure 3-7:-Demographic map of Ginir woreda

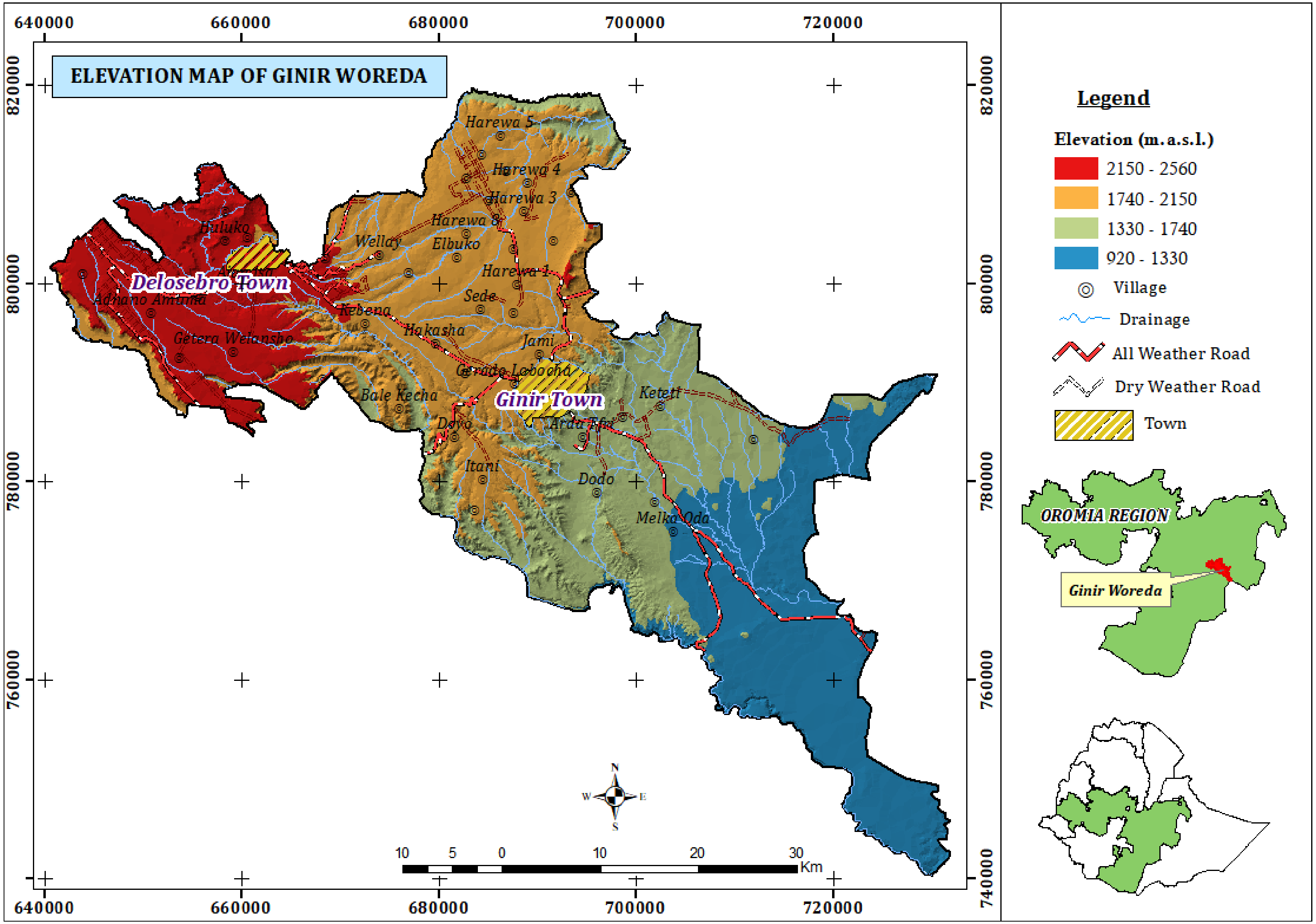

Figure 3-8. Physiography of Ginir woreda

3.5. Agarfa Woreda

3.5.1. Population and Demographic Map

Agarafa has 21 Kebeles with 125,302 populations for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 89,203 populations). Walite Wegerege has highest population with 10,850 whereas Soba kebele has the least population number with 2,191. Population map of Agarafa by kebele is shown in Figure 3-9. However, there are some places in the south east which are not covered by census in 2007.

3.5.2. Existing Water Supply Situation

About 51 boreholes (28 shallow wells and 23 deep wells) are found in the central eastern regions of the woreda. The depth of the wells ranges between 24 m and 207 m while the groundwater level of these wells ranges between 10 and 58.9 m.b.s.l. The wells are serving for domestic water supply for the local communities, Agarfa and Ali towns. The dominant aquifer material observed at these wells is fractured basaltic rocks.

Apart from this, only five low yielding springs are mostly found around southeastern parts of the woreda. They are mainly serving as a water supply for the local communities within the woreda. The discharges of these springs vary between 0.27 l/s and 2 l/s. The springs are mainly emanating from fractured basaltic rocks.

3.5.3. Climate

Review existing litrature and analysis of DEM reveal that Agerfa woreda is characterized by different physiographic features with elevation range from 1240 meters above sea level in the north to 3760 meters above see level in the south. The climate in Agarfa is warm and temperate. The average annual temperature in Agarfa is 14.9 °C. The rain in Agarfa falls mostly in the winter, with relatively little rain in the summer. The annual mean rainfall is 677 mm.

3.5.4. Physiography

The Agarfa woreda is situated within the Wabi Shebele River basin. The present physiographic setting of the woreda is the result of mainly volcano-tectonic and erosional activities. Generally, the study area in the west is mainly characterized by rugged topography dissected by numerouse drainages with some small elevated plains. This landform occupies the down slopes mountain ranges in the south, the northeastern up to the deep gorges in the peripheral parts of the woreda. This part of the woreda is comprised of faulted tertiary volcanics dominantly basalt flows which has been shaped by erosional process.

The eastern part of the woreda is characterized by plain landform with gentle slope. Surface elevation gradually falls from southwest towards north and east within the woreda domain. This eastern part of the woreda is comprised of plateau basalts and flows later shaped by erosional process.

Elevation within the woreda boundary ranges from 1870 meters above sea level in the north to 3760 meters above see level in the southwest (Figure 3-10).

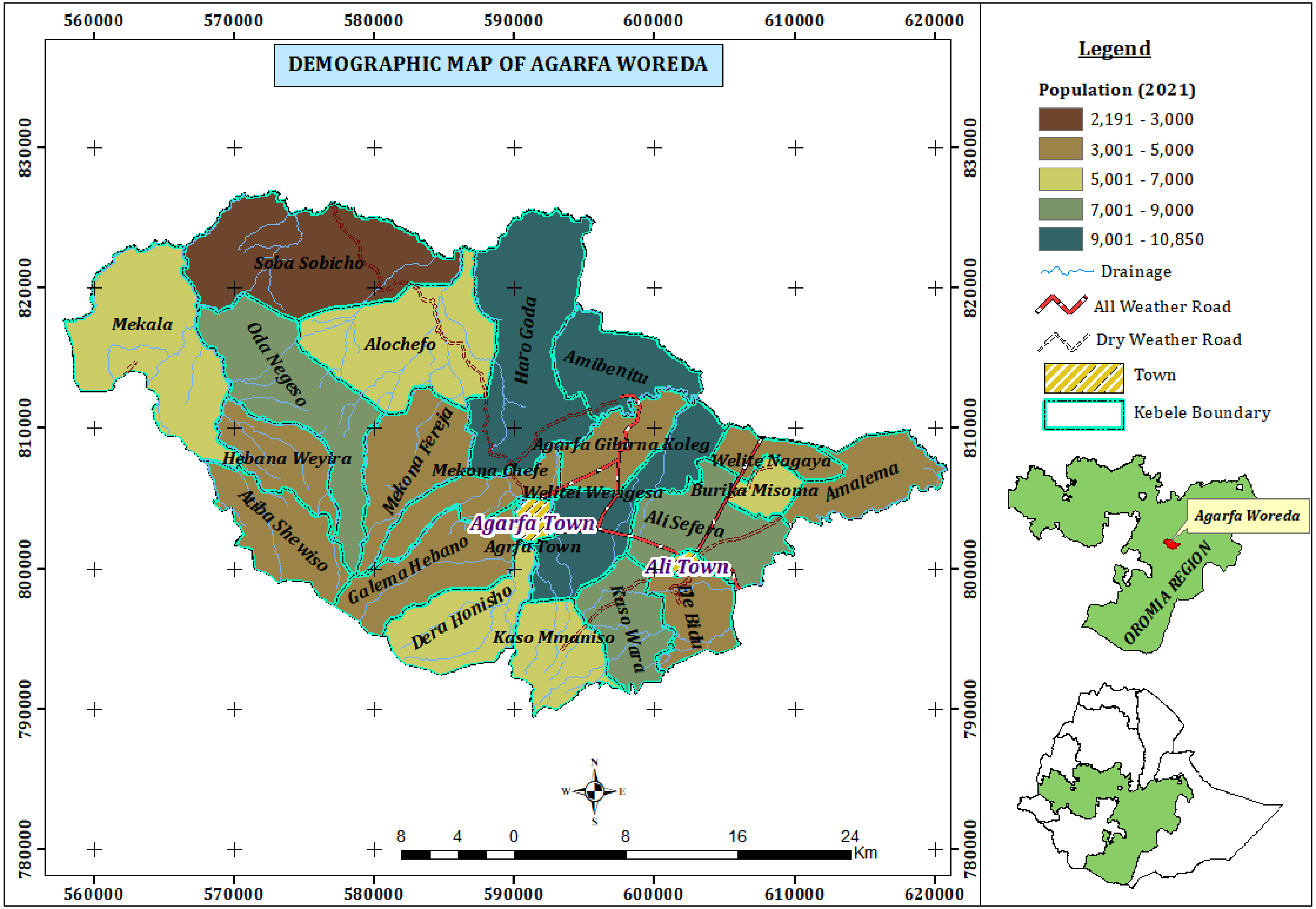

Figure 3-9:-Demographic map of Agarfa woreda

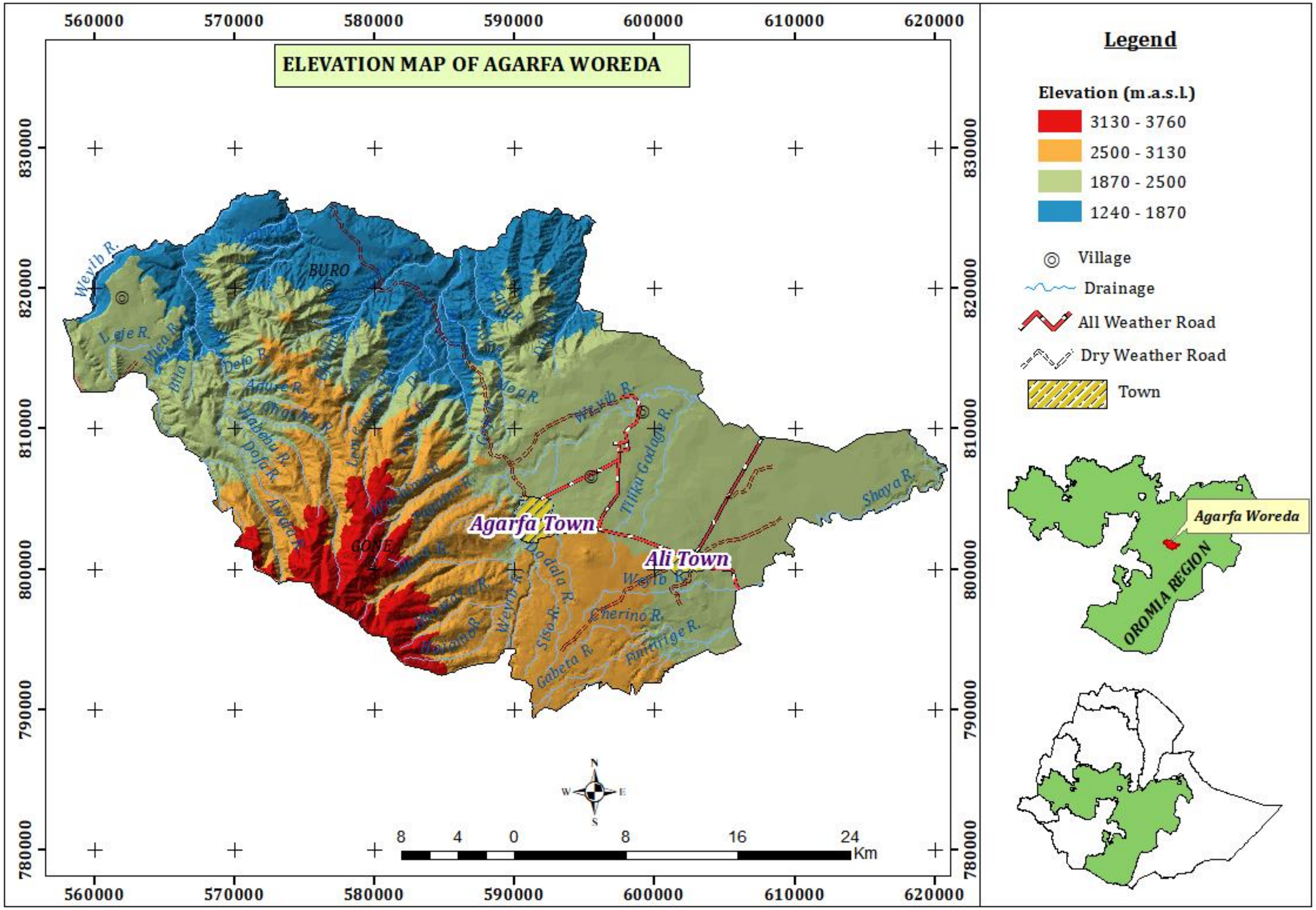

Figure 3-10. Physiography of Agarfa woreda

3.6. Robe Woreda

3.6.1. Population and Demographic Map

Robe has 28 Kebeles with 203,019 populations for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 144,530 populations). Sebro Chefa kebele has highest population with 11,384 whereas Sadiqua Atuche kebele has the least population number with 3,593 Population map of Robe by kebele is shown in Figure 2.46. However there are some places in the North which are not covered by cencese to 2007 (Figure. 3-11).

3.6.2. Existing Water Supply Situation

Only three boreholes drilled at Robe town, Habe town and Sediqa town, respectively. Theses wells belong to and serving as a water supply for Robe town, Habe town and Sediqa town, respectively. As far as the data we have is concerned, the depth of one borehole found at Sediqa town is 85 m. The dominant aquifer material observed at these wells is volcanic rocks of basalt.

Apart from this, two low yielding springs which are mainly serving as a water supply for the local communities of Harkesa and Wanga Goya villages, respectively are also found within the woreda. The low yielding springs located at Wanga Goya locality, in northwest of Sediqa town has a discharge of 0.21 l/s while the other low discharging spring found at Harkesa locality, southeast of Sediqa town has a discharge of about 1 l/s. These springs are emanating from fractured volcanics of basaltic rocks.

3.6.3. Climate

Review existing litrature and analysis of DEM reveal that Robe woreda is characterized by different physiographic features with elevation range from 1080 meters above sea level in the north to 4120 meters above see level in the south. The climate in Robe is warm and temperate. The average annual temperature in Robe is 14.9 °C. The rain in Robe falls mostly in the winter, with relatively little rain in the summer. The annual mean rainfall is 677 mm.

3.6.4. Physiography

The Robe woreda is situated within the Wabi Shebele River basin. The present physiographic setting of the woreda is the result of mainly volcano-tectonic and erosional activities. Generally, the woreda domain is bounded by deeply incised Robe River in the north Wabe River courses oriented in the NW to SE. Other than the deeply incised parts along the two river courses and associated river bank, the dominant part of the woreda domain is mainly characterized by flat topography slopping down towards southeast. This flat landform occurs between the two rivers and associated deep gorges. In these peripheral northern and eastern parts of the woreda within the gorges, Hamanile Limestone and sandstone units outcropped forming cliffs.

In the central gently sloping plain landform the dominant lithologic unit is plateau basalt and flows. This central part of the woreda is comprised of plateau basalts and flows later slightly shaped by erosional process. Surface elevation gradually falls from northwest towards southeast within the woreda domain. Elevation of the woreda ranges from 1080 m.a.s.l., in the north to 4120 m.a.s.l., in the south (Figure 3-12).

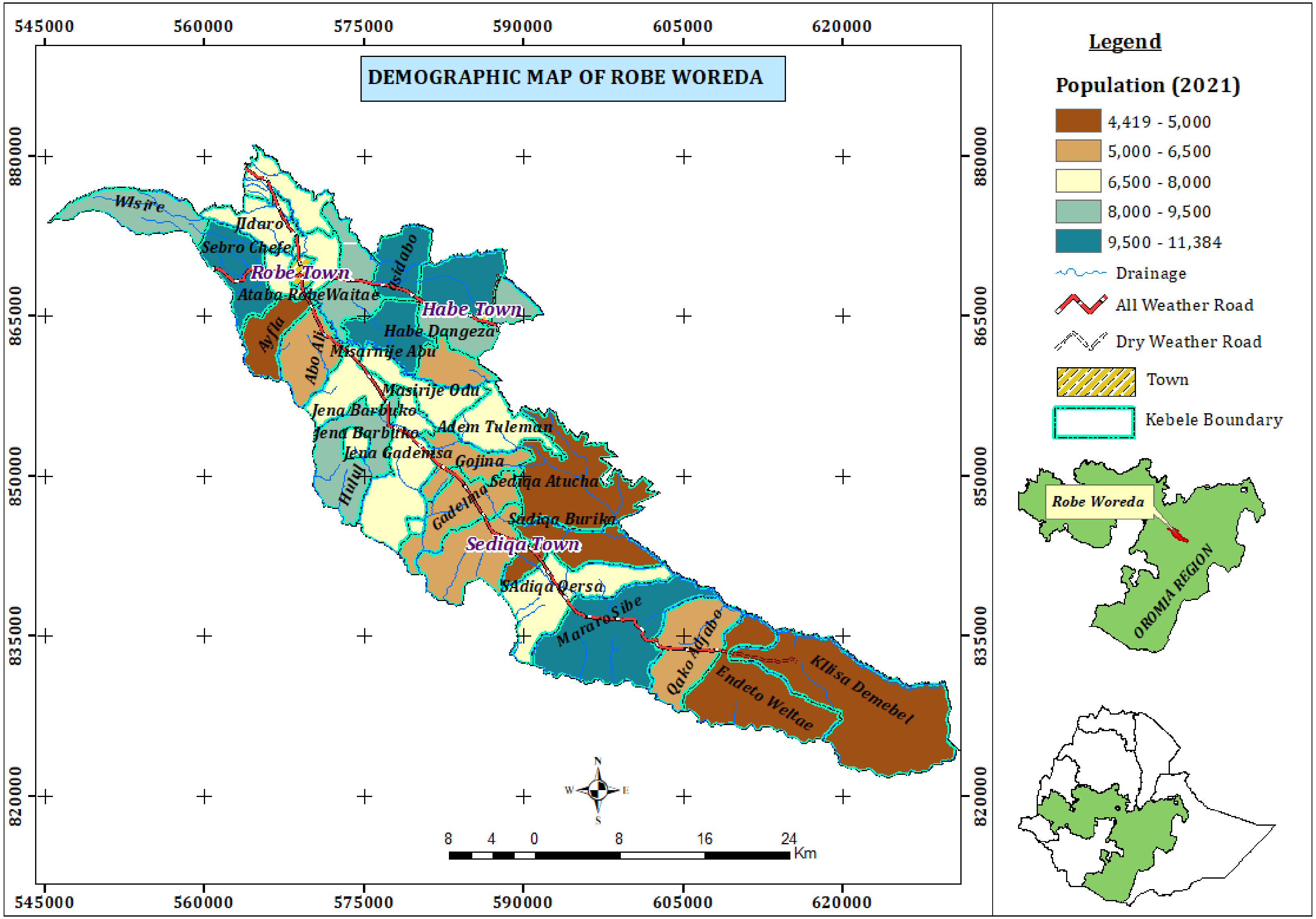

Figure 3-11:-Demographic map of Robe woreda

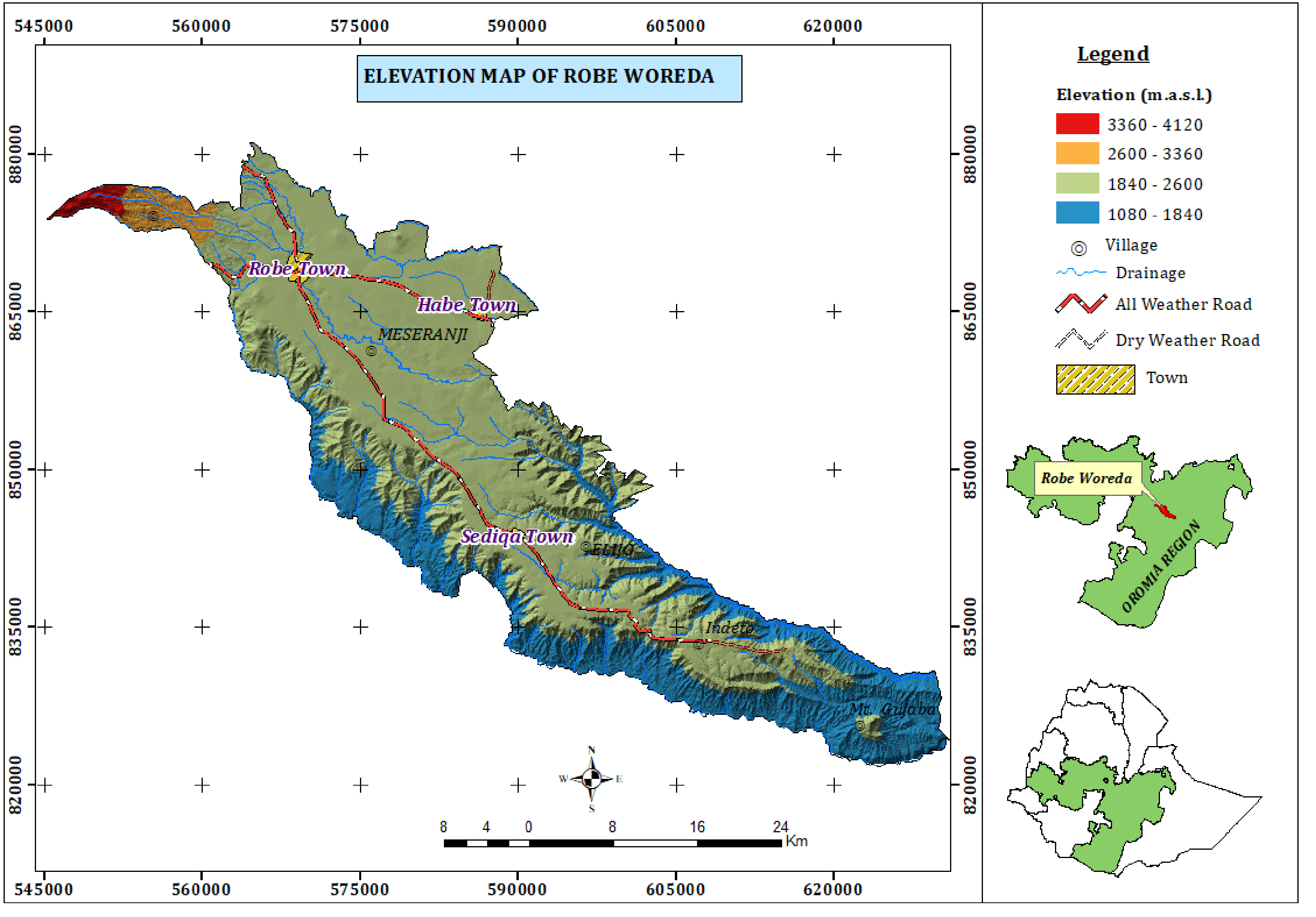

Figure 3-12. Physiography of Robe woreda

3.7. Seweyna Woreda

3.7.1. Population and Demographic Map

Seweyna has 25 Kebeles with 87,190 populations for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 62,071 populations). Sheku kebele has highest population with 5,315 whereas Boditi kebele has the least population number with 1,648. Population map of Seweyna by kebele is shown in Figure 3-13. However, there are some places in the west which are not covered by cencese 2007.

3.7.2. Existing Water Supply Situation

About 14 boreholes (1 shallow well and 13 deep wells) are found in the central and western regions of the woreda. The depth of the wells ranges between 74 m and 235 m while the groundwater level and discharge of these wells ranges between 28 and 69.4 m.b.s.l. and from 2 l/s and 6.7 l/s, respectively. The deep borehole (depth = 180 m) whith high yield (Q = 6.7 l/s) is located at central western part of the woreda, at Micha Biliso town. All the wells are serving for domestic water supply for the local communities and Micha Biliso town. The dominant aquifer material observed at these wells is fractured limestone rocks.

Apart from this, only two springs are found around southwest of Micha Biliso town. They are mainly serving as a water supply for the local communities found within the woreda. The discharges of these springs are about 0.75 l/s and 12 l/s. The high discharging spring having a yield of 12 l/s is located at southwestern boundary of the woreda. It serves mainly as a water supply for the local community. The high yileding springs is mainly emanating from fractured basaltic rocks while the low yielding spring is emanating from fractured sandstone rocks.

3.7.3. Climate

Seweyna Woreda falls within two agro-climatic zones namely 25% temperate (Woyinadega) and 75% lowland (kola). Seweyna Woreda receives mean annual rainfall of about 918 mm. The Woreda receive rain in two seasons such as Belg (autumn) season (March to May) and Tsedey (spring) season (September to November). Bega (winter) season (December- February) is the driest season in the area. Unlike highland part of the country, Kremit (June to August) is dry season with only small rainfall. In the Woreda the highest rainfall amounts recorded in months of April, May and October and the lowest amount recorded in months of January and February.

The temperature data from 1982-2023 indicates that the higher monthly mean maximum temperature was recorded in the Woreda during month of 21 December to February where as the lowest monthly mean minimum temperature recorded during months of December and January. In these years (1982-2012) the recorded average mean maximum, minimum and average temperature were 24.2^{0}c, 13.3^{0}c and 18.7^{o}c, respectively.

3.7.4. Physiography

The Seweyna woreda is situated within the Wabis Shebele River basin. The present physiographic setting of the woreda is the result of mainly volcano-tectonic and erosional activities. The majority area of the study woreda is mainly characterized by plain topography while some rugged topography with some hills and ridges which is dissected by numerouse drainages found at limited area southwestern parts of the woreda with an elevation range from 700 m.a.s.l. at southeastern to 2180 m.a.s.l., at southwestern regiont of the woreda (Figure 3-14). The plain landform occupies mostly central and eastern part of the woreda which is characterized by flat low-lying topographic surfaces and consists of Mesozoic sedimentary rocks of upper sandstone and upper Gabredarre limestone. The rugged terrain found mostly at limited southwestern area of the woreda is characterized by steep slopes, small ridges, hills and alternating valleys. This land form is mainly shaped by erosion activities which produced badland, rugged terrain and rolling topography. V-shaped streams are common with deep gorge.

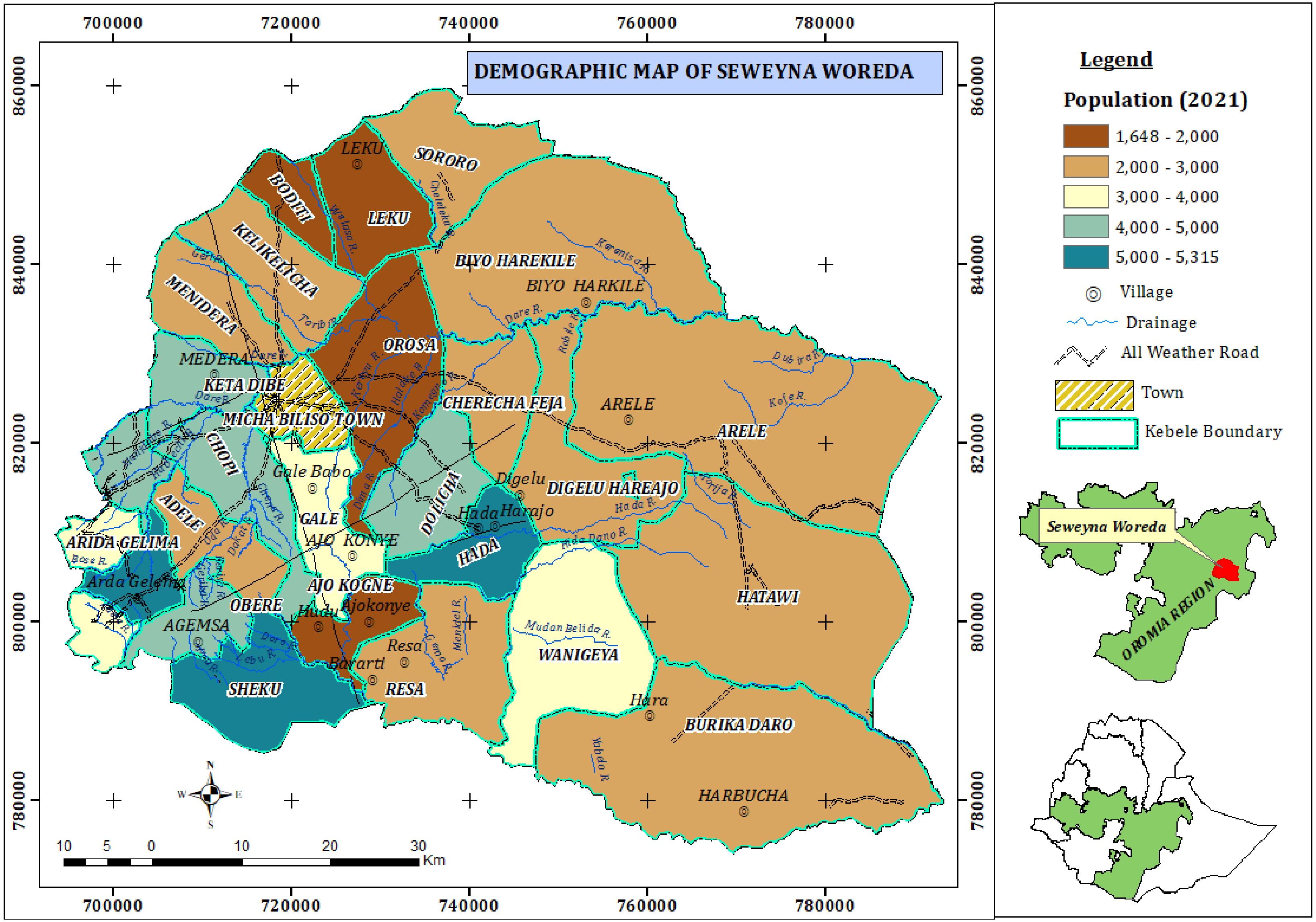

Figure 3-13:-Demographic map of Seweyna woreda

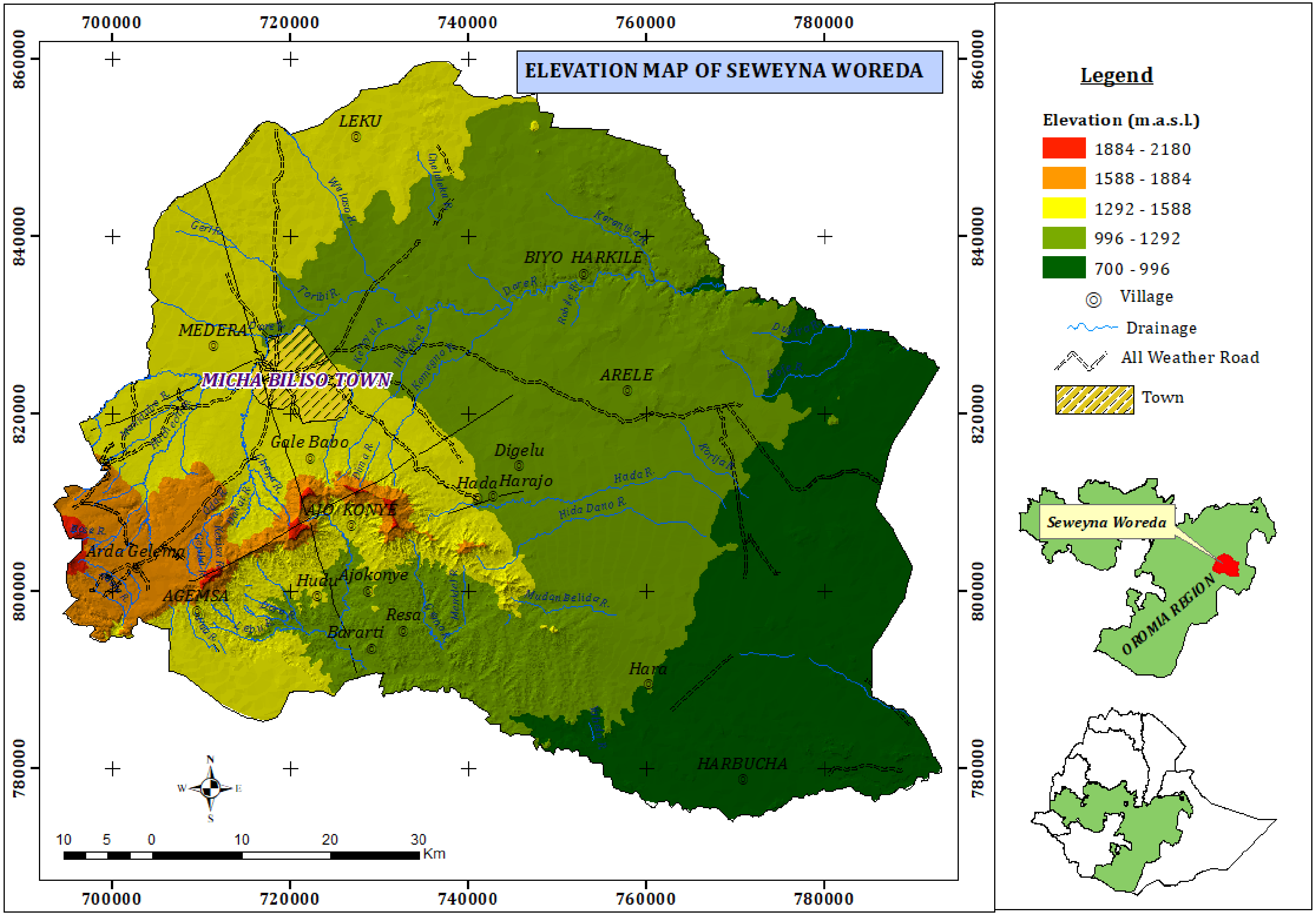

Figure 3-14. Physiography of Seweyna woreda

3.8. Sude Woreda

3.8.1. Population and Demographic Map

Sude has 28 Kebeles with 218,055 populations for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 155,234 populations). Deksis Ersha kebele has highest population with 16,078 whereas Semar Abdaye kebele has the least population number with 4,151. Population map of Sude by kebele is shown in Figure 3-15.

3.8.2. Existing Water Supply Situation

Only two shallow wells are found in the western part of the woreda at Kula town and Derba locality. Theses wells belong to Kula town and local communities of Derba village, respectively. As far as the data we have is concerned, the depth boreholes are 77 m and 45 m having relatively shallower groundwater level of about 73 and 26.6 m.b.s.l., respectively. The dominant aquifer material observed at these wells is volcanic rocks of pyroclstics. These wells are located at places having relatively low relief.

Apart from these, one high discharging and three low yielding springs which are mainly serving as a water supply for the local communities are found also within the woreda. Three low yielding springs located at Kersa locality, in southern part, at Laku locality, in central region, and at Abukoy Burkitu area, west of Kula town have a discharge of 2 l/s, 2 l/s & 3 l/s, respectively. These springs are fractured springs emanating from fractures basaltic rocks.. Whereas, the high yielding spring having a discharge of 50 l/s is a depressionla spring emanating from fractured volcanics. It serves mainly as a water supply for the local community.

3.8.3. Climate

The annual rainfall in Sude area is about 1916mm and the Minumum rainfall is during the month of December and January while the Maximum rainfall is during the month of July and August. The annual mean maximum and minimum temperatures of Arrea Varies from 23°C, and 12°C, respectively.

3.8.4. Physiography

The Sude woreda is situated within the Wabis Shebele River basin. The present physiographic setting of the woreda is the result of mainly volcano-tectonic and erosional activities. The study area is mainly characterized by rugged topography dissected by numerouse drainages with some elevated plateaue at northernrn and at western parts of the woreda area with an elevation range from 1640 m.a.s.l. at eastern extrem to 2780 m.a.s.l., at western part of the woreda (Figure 3-16).

The plateau: **-** This landform occupies the down slopes of Galema mountain ranges in the south, the northeastern part of Galema Mountain up to the altitude of Torso area at northern part of the woreda. The western plateau is characterized by flat low-lying topographic surfaces and consists of down faulted tertiary volcanics; basalts, ignimbrites and pyroclastic which has been shaped by erosion forming smooth rolling topography.

The rugged terrain: - Northern, central and southern parts of the woreda forms rugged topography extending to the east is characterized by steep slopes; parallel to sub parallel ridges and alternating valleys. This land form is mainly shaped by erosion activities which produced badland, rugged terrain and rolling topography. V-shaped streams are common with deep gorge. Elevation varies from 1640m to more than 2400m. The central area mainly underlain by highly dissected Tertiary volcanics basalt and Masozoic sedimentary rocks of upper limestones. It forms ragged topography with parallel to sub parallel ridges and alternating valleys. Further to the eastern part of the woreda is underlain by slightly dissected Mesozoic sedimentary rocks of upper sandstone. This part of the area is mainly affected by E-W and NW- SE trending lineaments.

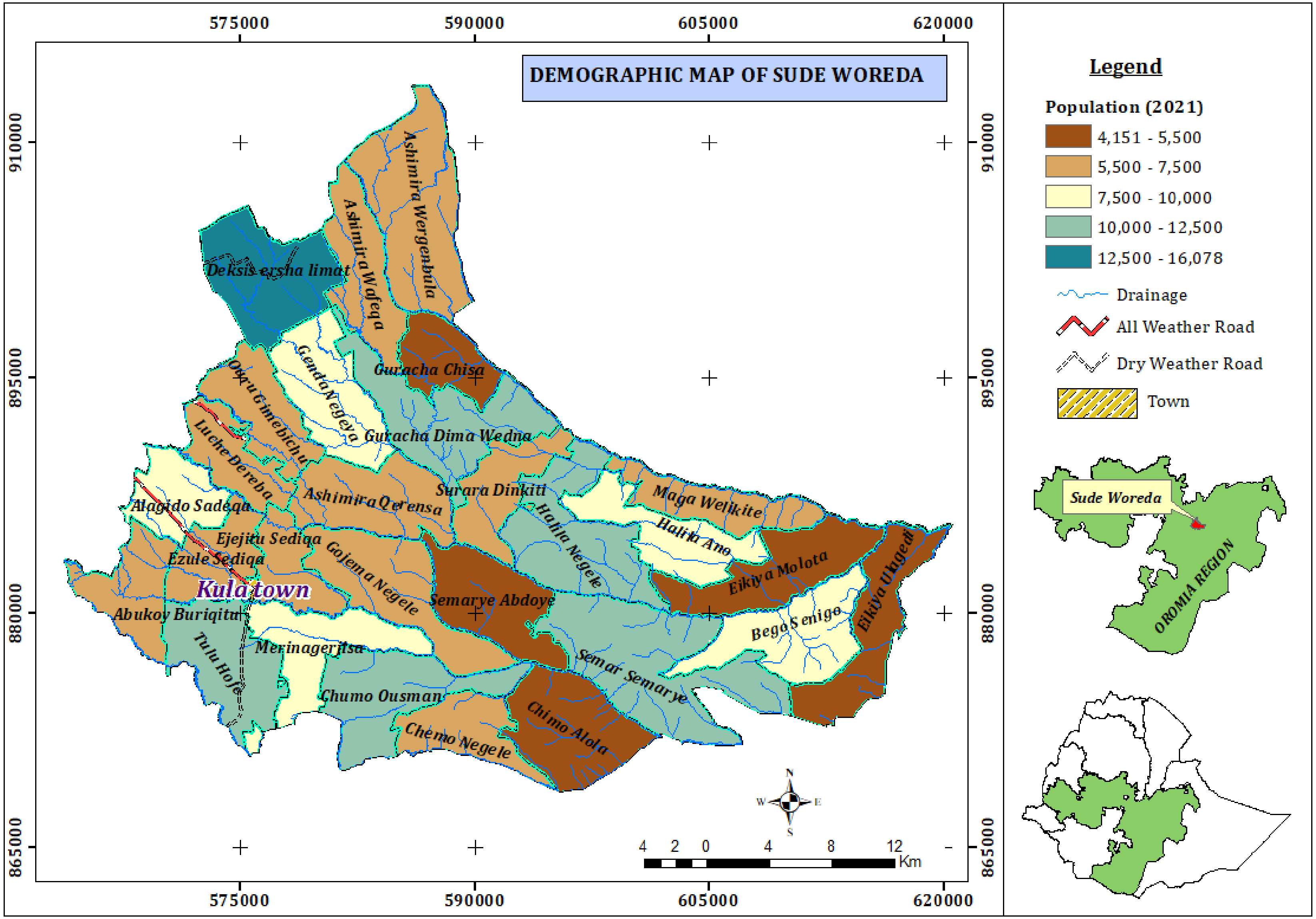

Figure 3-15:-Demographic map of Sude woreda

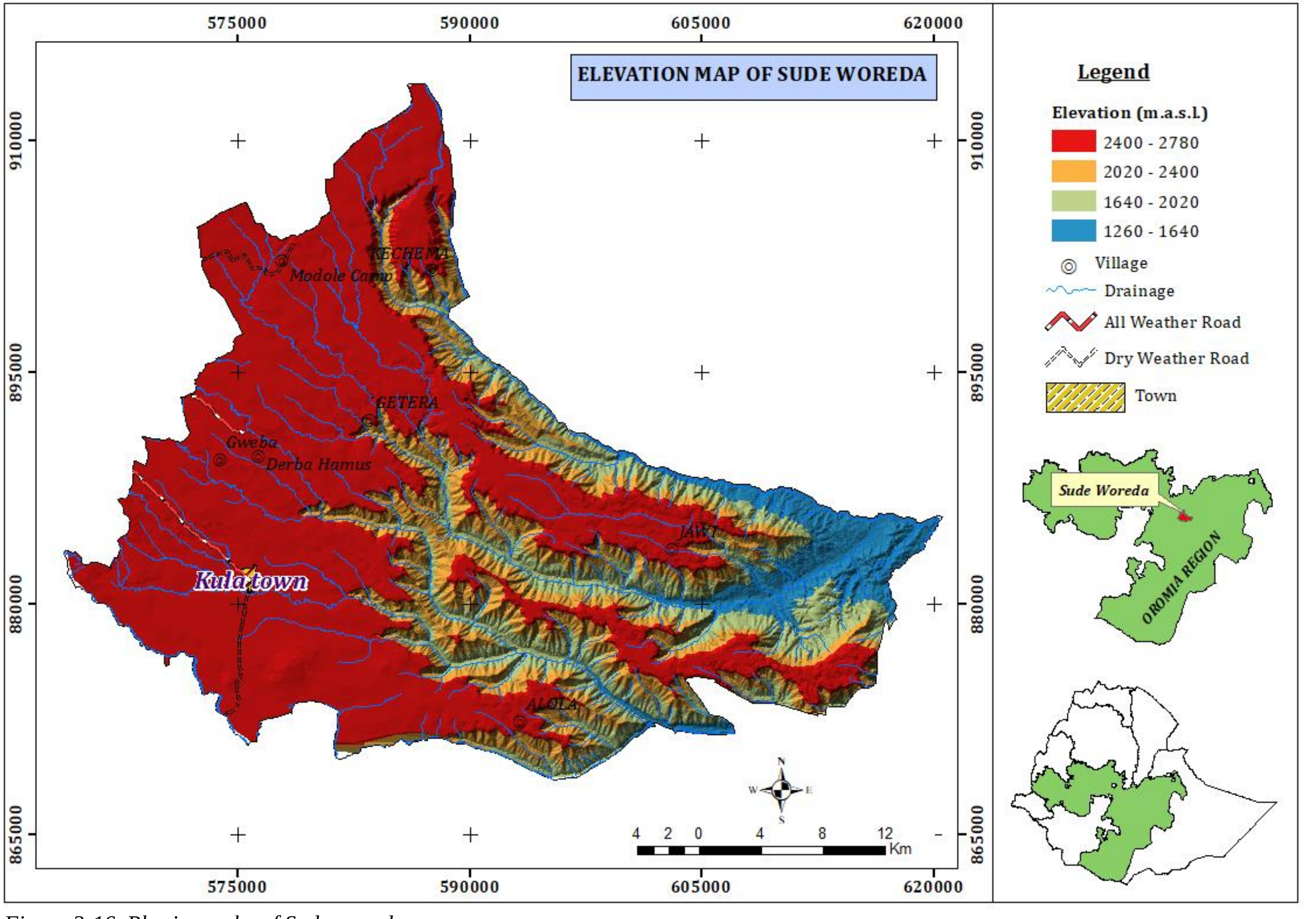

Figure 3-16. Physiography of Sude woreda

3.9. Tena Woreda

3.9.1. Population and Demographic Map

Tena woreda has 11 Kebeles with 84,212 populations for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 59,951 populations). Wadagomsa kebele has highest population with 12,160 whereas Haja shale kebele has the least population number with 3,059. Population map of Tena by kebele is shown in Figure 3-17.

3.9.2. Existing Water Supply Situation

Only one deep borehole is found in the southeastern region of the woreda, around Amaraba Indato locality. The depth, groundwater level and yield of the well is 196 m, 65 m.b.g.l., and 22 l/s, respectively. The well is serving for domestic water supply of Ticho town. The dominant aquifer material observed at this well is fractured scoraceous basaltic rocks.

Apart from this, 7 low yielding springs are also found and distributed throughout the woreda. They are mainly serving as a water supply for the local communities within the woreda. The discharg of thee springs ranges between 0.21 l/s and 4.5 l/s with mean value of 1.8 l/s. All the springs are emanating from fractured basaltic rocks in the area.

3.9.3. Climate

The climate in Tena is warm and temperate. The average annual temperature in Tena is 14.9 °C. The rain in Tena falls mostly in the winter, with relatively little rain in the summer. The annual mean rainfall is 677 mm.

3.9.4. Physiography

The Tena woreda is situated within the Wabis Shebele River basin. The present physiographic setting of the woreda is the result of mainly volcano-tectonic and erosional activities. The majority area of the study woreda is mainly characterized by elevated plain topography while some rugged topography with some hills and ridges which is dissected by numerouse parallel to sub-parallel drainages at majority area of the woreda with an elevation range from 1560 m.a.s.l. at southeastern to 4100 m.a.s.l., at northwestern region of the woreda (Figure 3-18). The plain landform occupies mostly central western part of the woreda which is characterized by flat high elevated topographic surfaces. The rugged terrain found mostly at limited southeastern low-lying areas of the woreda is characterized by steep slopes, small ridges, hills and alternating valleys. This land form is mainly shaped by erosion activities which produced badland, rugged terrain and rolling topography. V-shaped streams are common with deep gorge.

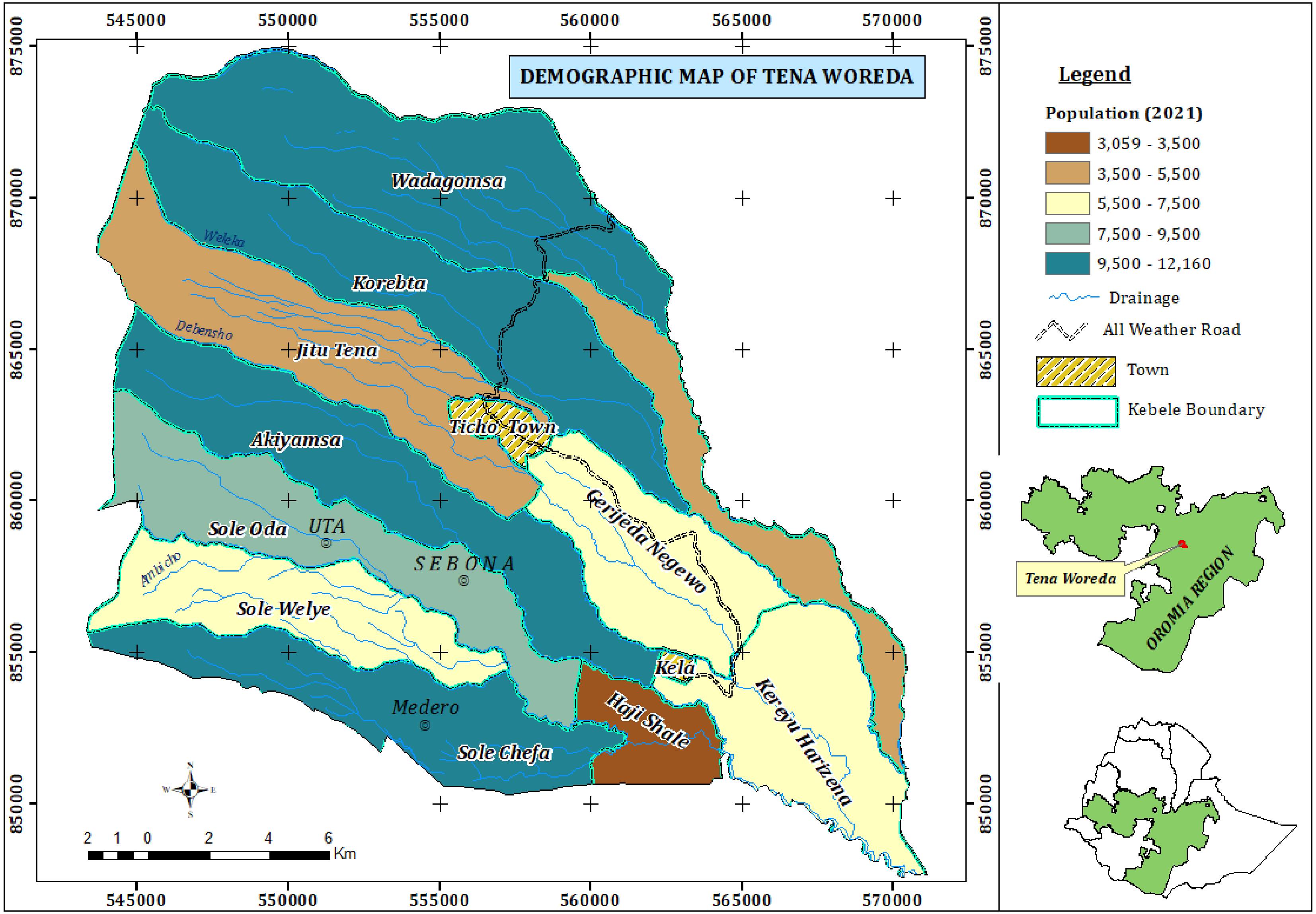

Figure 3-17:-Demographic map of Tena woreda

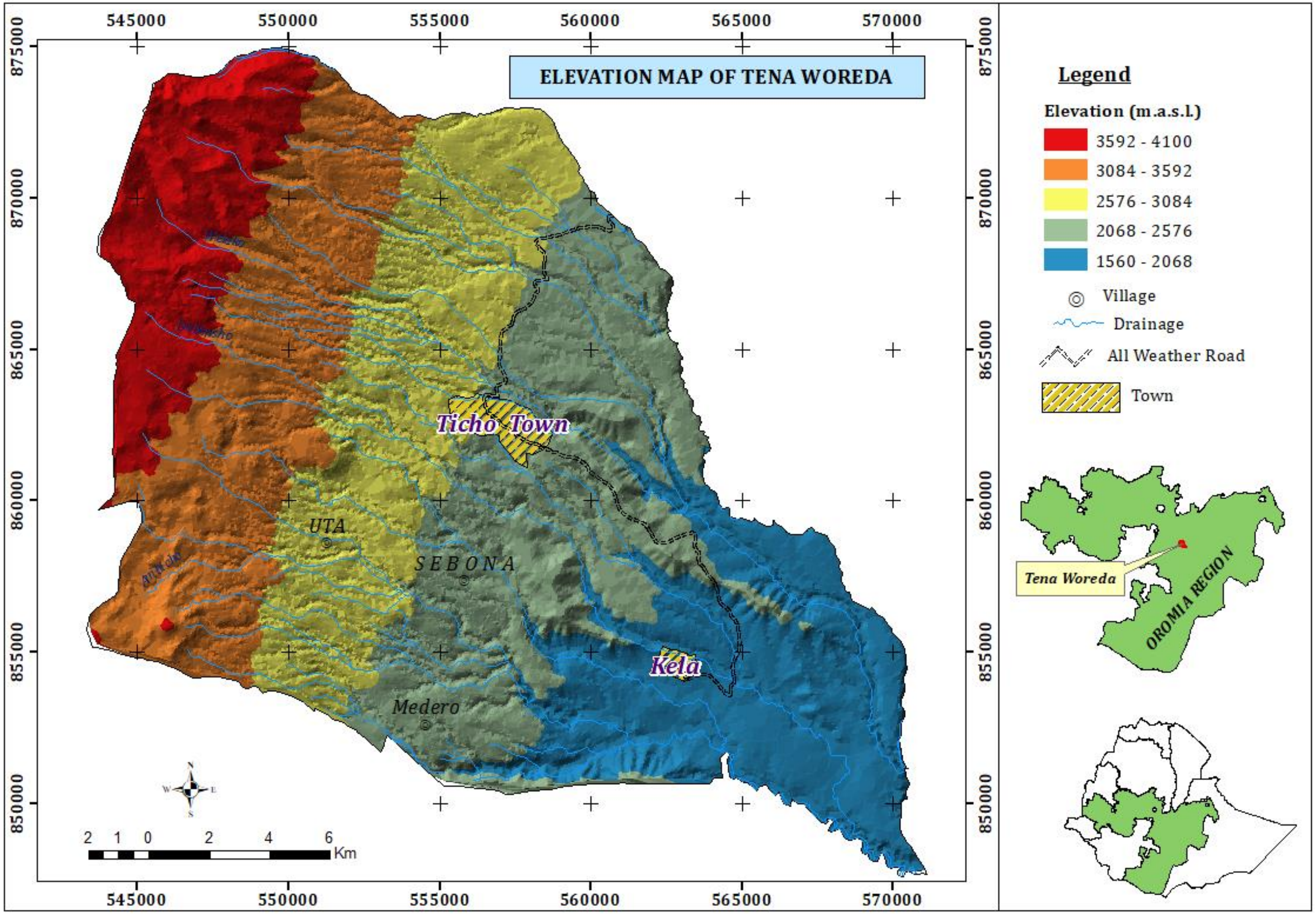

Figure 3-18. Physiography of Tena woreda

3.10. Adadle Woreda

3.10.1. Population and demographic map

Adadleworedahas 11Kebeles with 123,259 populations, for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 99,487 populations).

As per the forcasted population data for the year 2021, Bolihagare have highest population 23,745whereasHilogaDudokebele has the least population number with 5,644. Population map of Adadleworedais shown in the figure below (Figure 3-19)

3.10.2. Existing water supply situation

Well and related water schemes datascould notbe obtained in this woreda, hence the study findings of this project with the combined effect of overlay analysis and geophysical investigation thougt to be considered as an aid for the site selection of groundwater development in this woreda.

3.10.3. Climate

Adadleworedais entirely characterized by arid to semi-arid physiography with altitude <2000masl. Theannual rainfall in Cheretiworedaranges from 15.8 to 95.6 mm/yr (annual mean of 55.5 mm) as indicated by EbaMuluneh, 2017.

3.10.4. Physiography

Adadleworedais entirely characterized by arid to semi-arid physiography with altitude <2000masl. (Figure 3-20)

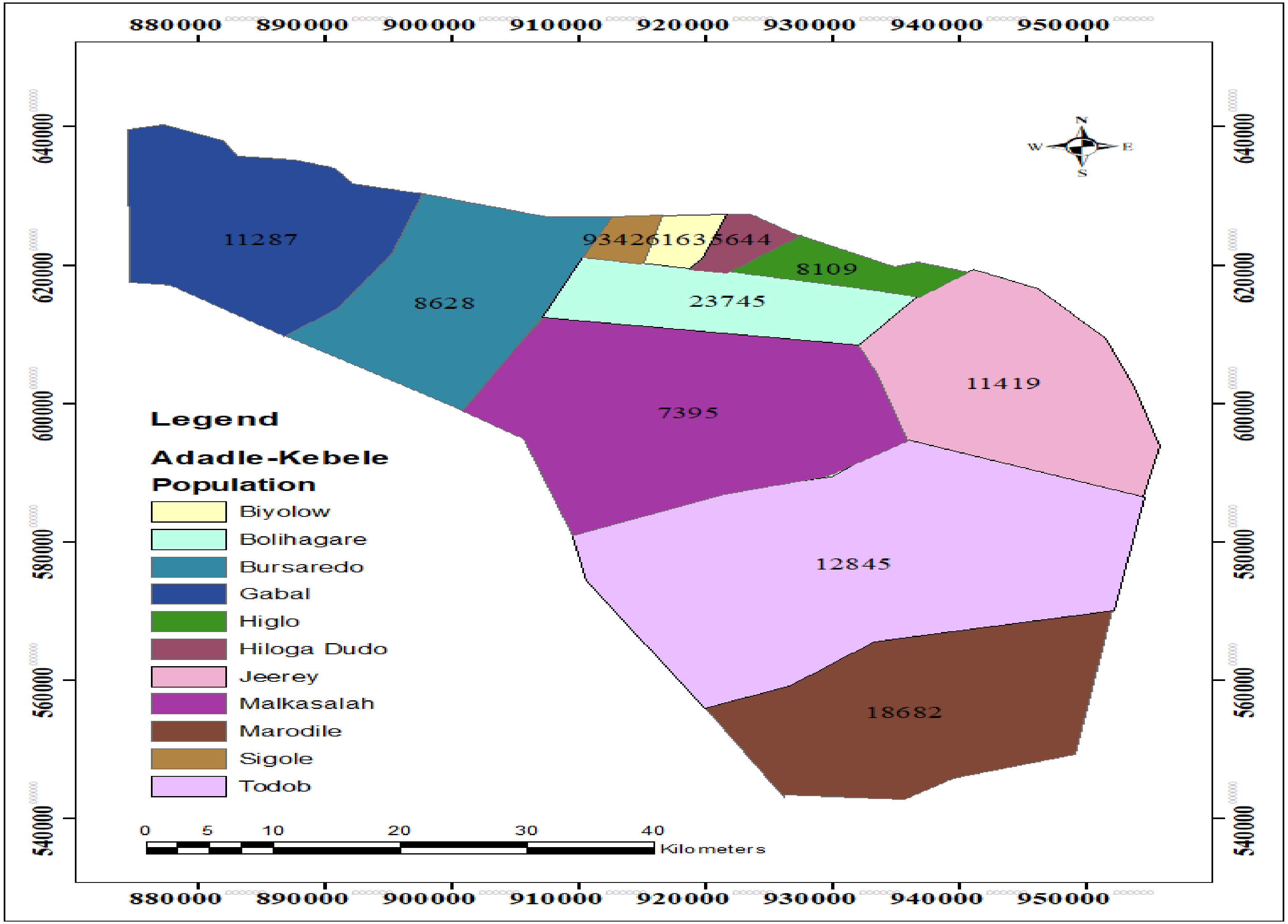

Figure 3-19:-Demographic map of Adadle woreda

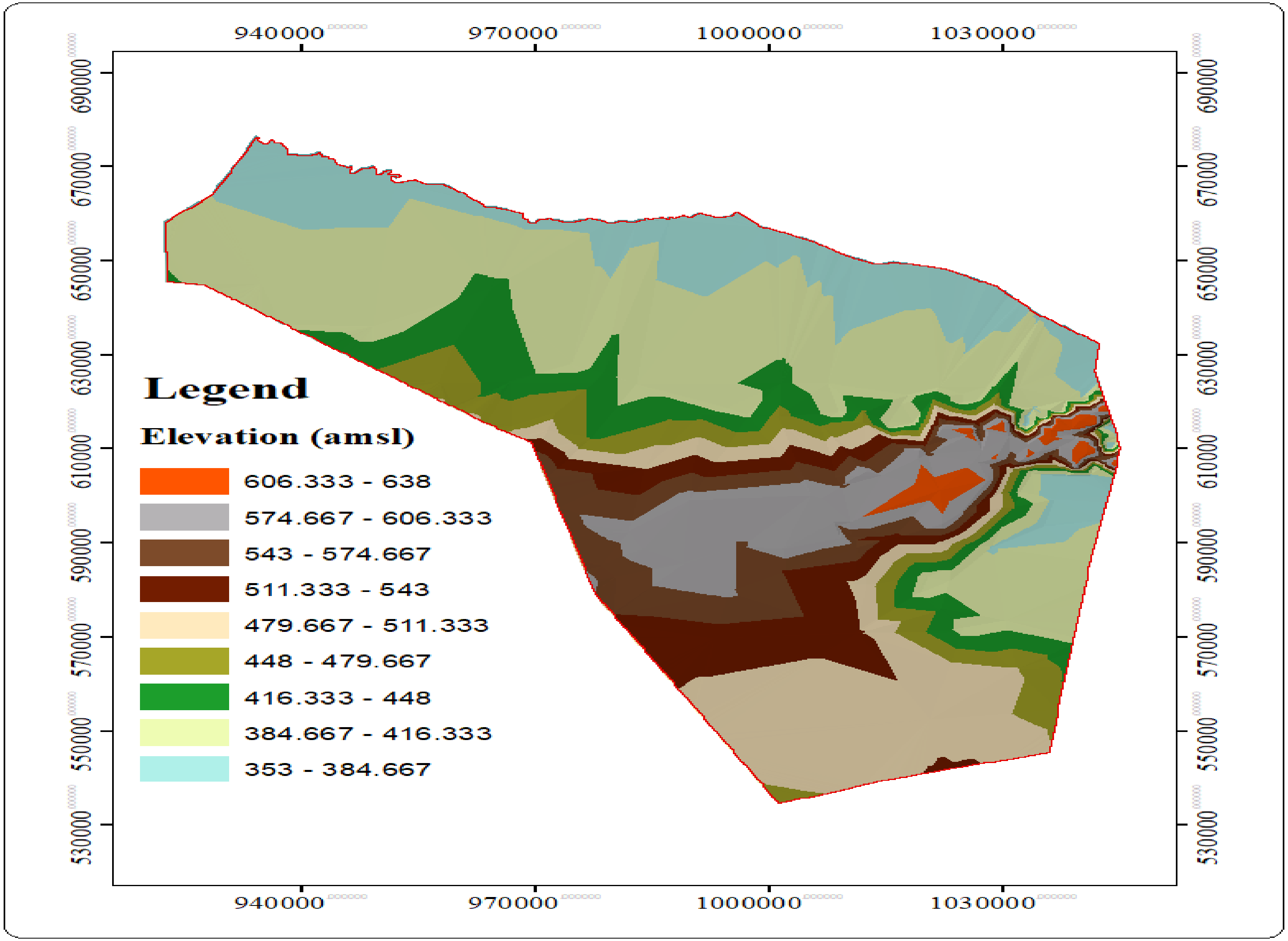

Figure 3-20.Physiographyof Adadle woreda

3.11. Dihun Woreda

3.11.1. Population and demographic map

Duhun woreda has 5Kebeles with 37,145.02 populations. As per the forcasted population data for the year 2021, Duhun town has highest population 12,259 whereas Ayun and karchachabo kebeleshave the least population number with 5,200. Population map of Duhun woreda is shown in the figure below (Figure 3-21)

3.11.2. Existing water supply situation

Well and related water schemes datas could notbe obtained in this woreda, hence the study findings of this project with the combined effect of overlay analysis and geophysical investigation thougt to be considered as an aid for the site selection of groundwater development in this woreda.

3.11.3. Climate

Duhun woreda is entirely characterized by arid to semi-arid physiography with altitude <2000masl. Theannual rainfall Duhun woreda woreda ranges from 14.53 to 78. 87 mm/yr (annual mean of 55.5 mm) as the monthly rainfall raster maps were obtained from open sources of CHIRPS satellite imageries of 2020 monthly series (from January to December, 2020) on geological survey of America (USGS) official website (https://chc.ucsb.edu/).

3.11.4. Physiography

Duhun woreda is entirely characterized by arid to semi-arid physiography with altitude <2000masl. (Figure 3-22)

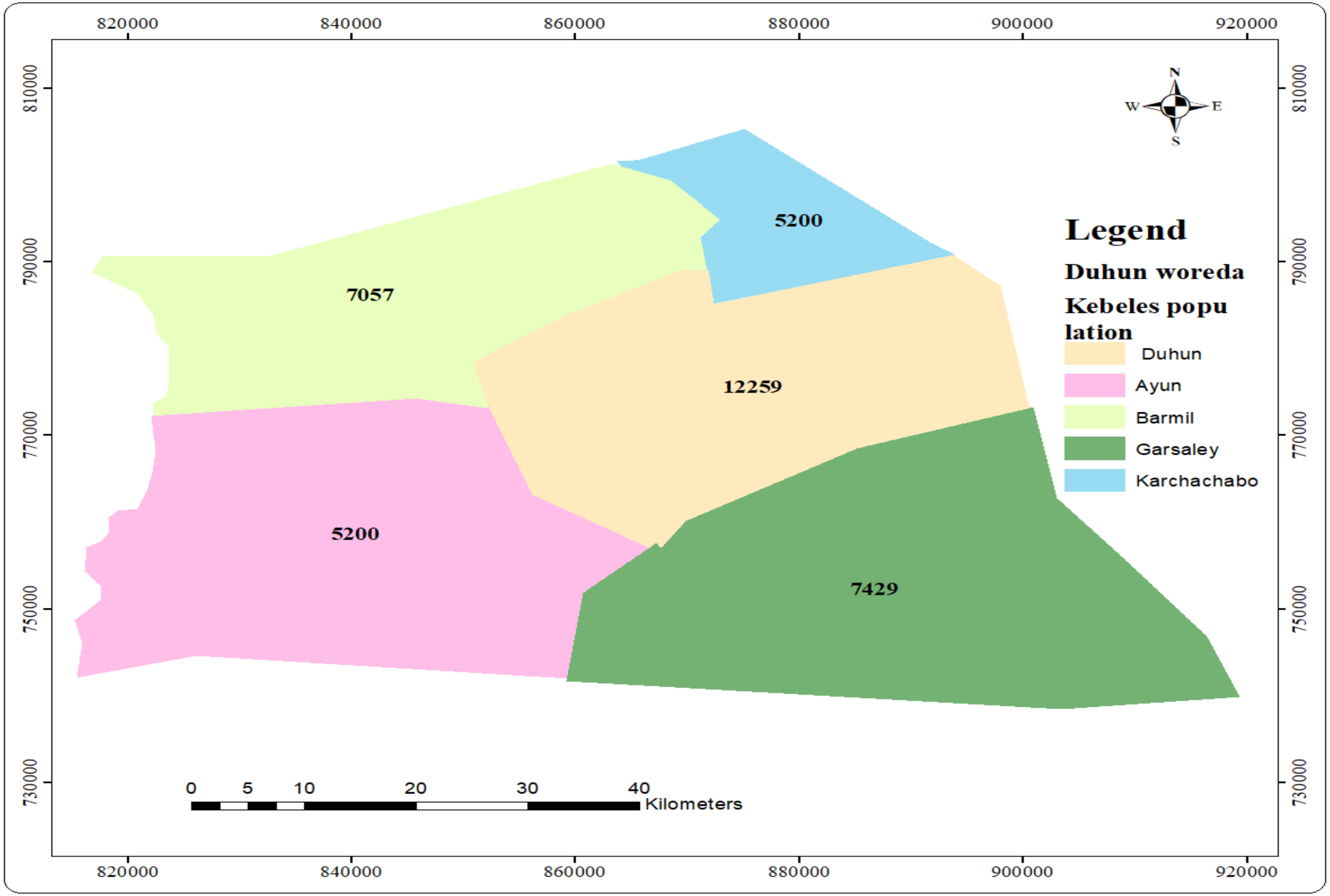

Figure 3-21:-Demographic map of Duhun woreda

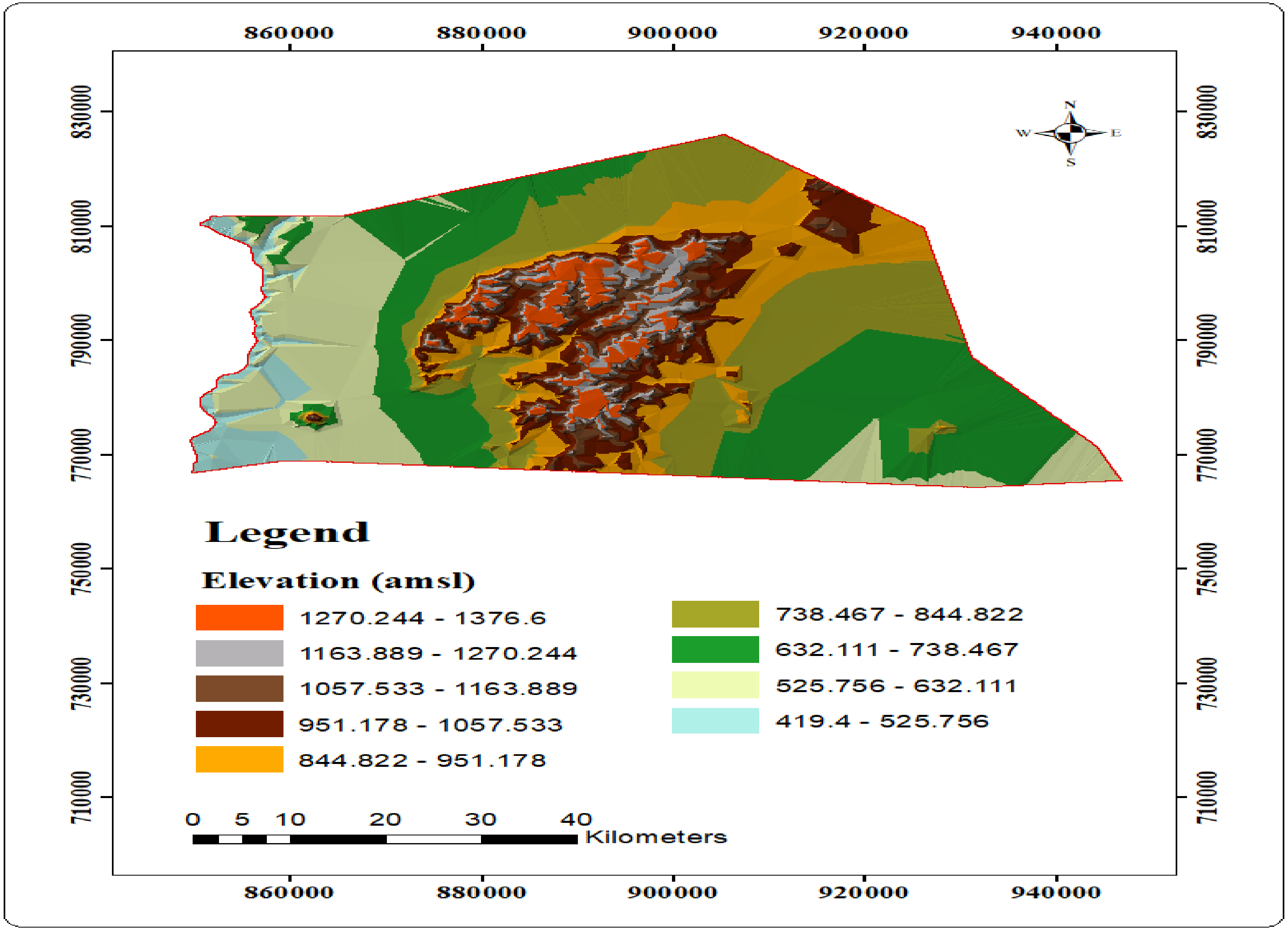

Figure 3-22.Physiography of Duhun woreda

3.12. Elkere Woreda

3.12.1. Population and demographic map

Elkere woreda has 13Kebeles with 68,944 populations. As per the forcasted population data for the year 2021, Elkari town has highest population 9,766 whereas Awraga kebele has the least population number with 4,270. Population map of Elkere woreda is shown in the figure below (Figure 3-23)

3.12.2. Existing water supply situation

Well and related water schemes datas could notbe obtained in this woreda, hence the study findings of this project with the combined effect of overlay analysis and geophysical investigation thougt to be considered as an aid for the site selection of groundwater development in this woreda.

3.12.3. Climate

Elkere woreda is entirely characterized by arid to semi-arid physiography with altitude <2000masl. Theannual rainfall in Elkere woreda ranges from 14.88 to 99.07 mm/yr (annual mean of 55.5 mm) as indicated by Eba Muluneh, 2017.

3.12.4. Physiography

Elkere woreda is entirely characterized by arid to semi-arid physiography with altitude <2000masl (Figure 3-24).

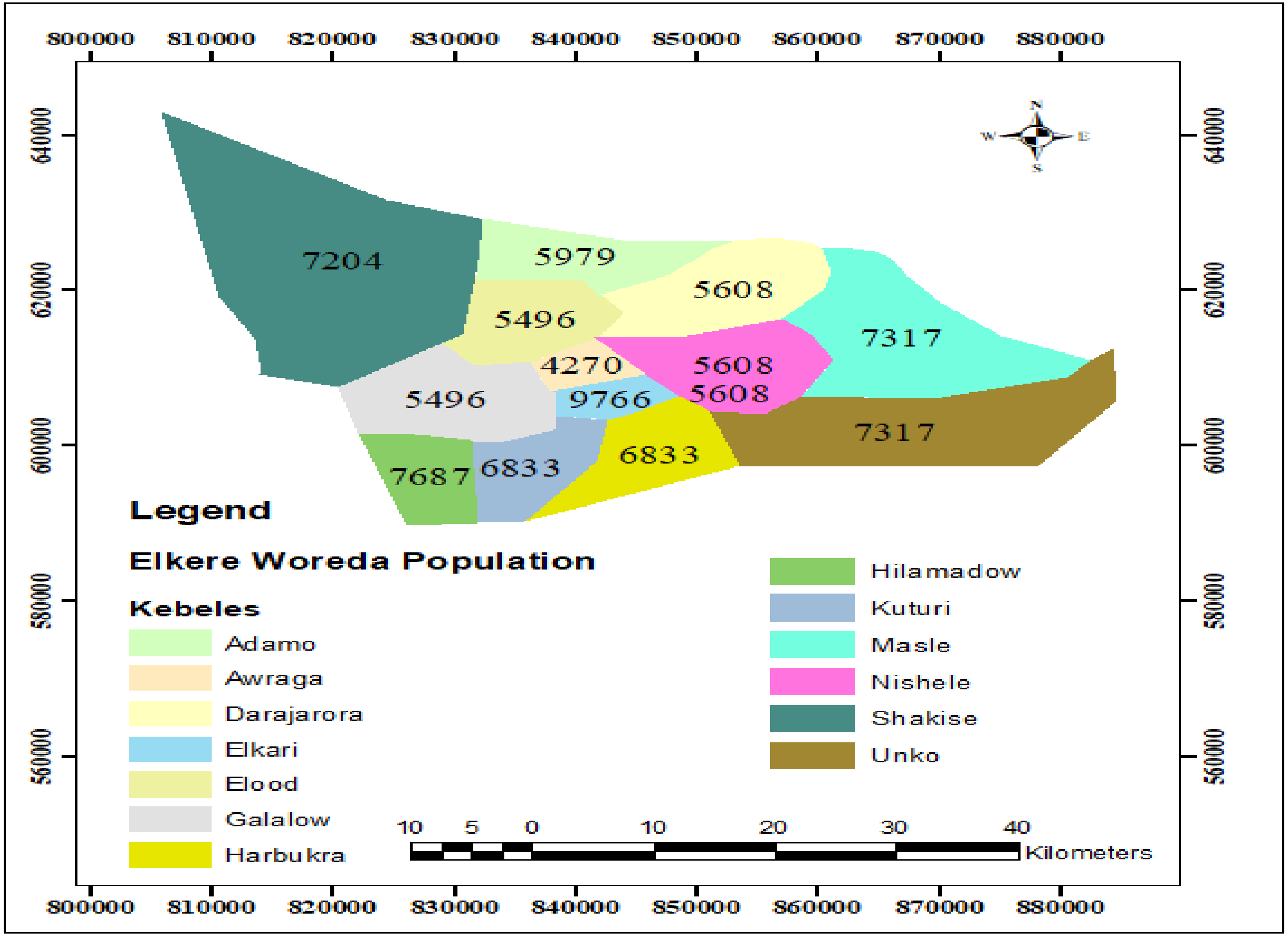

Figure 3-23:-Demographic map of Elkere woreda

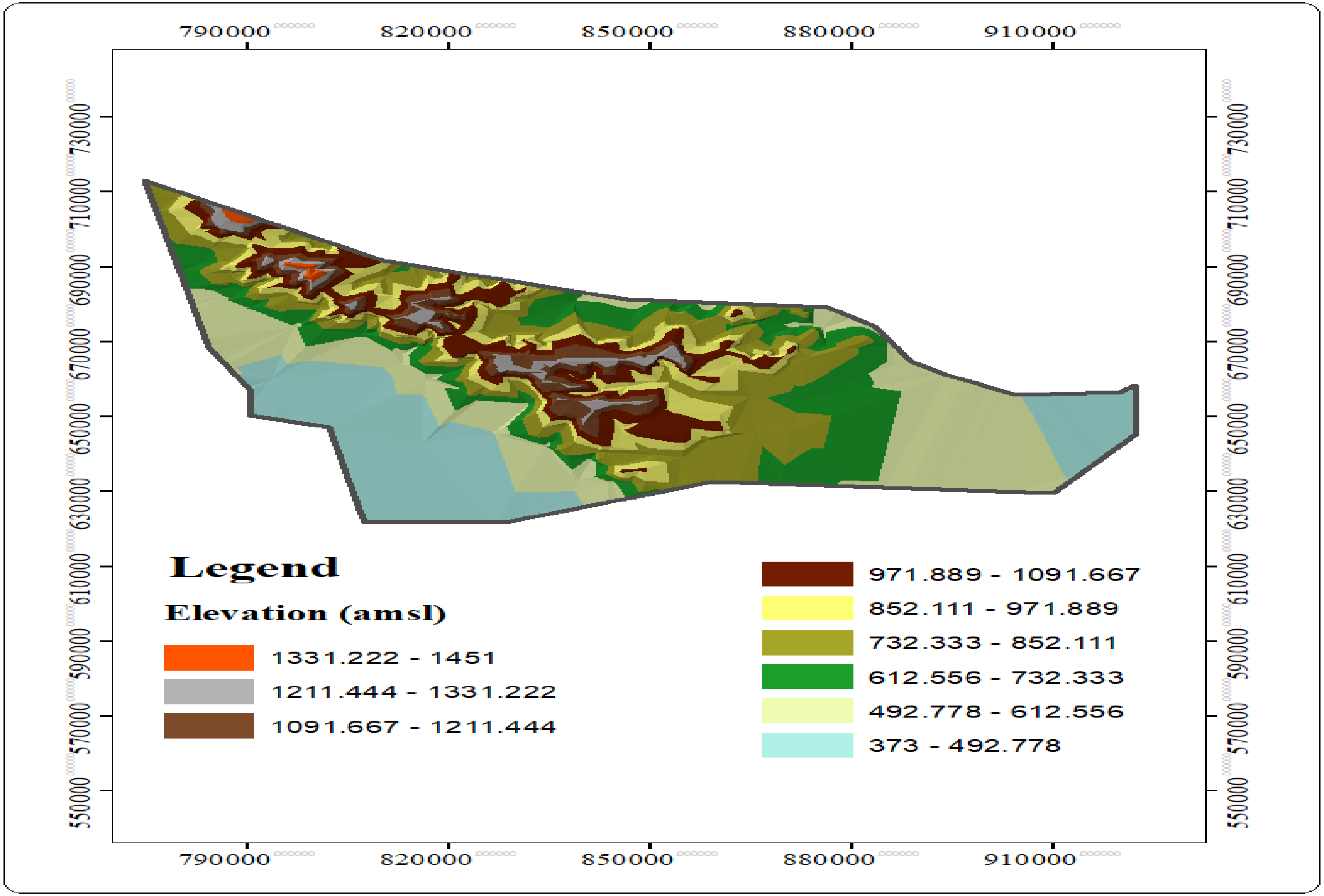

Figure 3-24. Physiography of Elkere woreda

3.13. Chereti Woreda

3.13.1. Population and demographic map

Chereti Woreda is found in the Somali Regional State, in Wabishebele River basin. It has 20 Kebeles with 182,824 populations for 2021 G.C. which was projected from 2007 G.C. CSA census data (i.e. 247,043 populations). Population map of Chereti woreda is shown in the figure below (Figure 3-25)

3.13.2. Existing water supply situation

Well and related water schemes datas could notbe obtained in this woreda, hence the study findings of this project with the combined effect of overlay analysis and geophysical investigation thougt to be considered as an aid for the site selection of groundwater development in this woreda.

3.13.3. Climate

Chereti woreda is entirely characterized by arid to semi-arid physiography with altitude <2000masl. Theannual rainfall in Chereti woreda ranges from 15.8 to 95.6 mm/yr (annual mean of 55.5 mm) as indicated by Eba Muluneh, 2017.

3.13.4. Physiography

Chereti woreda is entirely characterized by arid to semi-arid physioraphy with altitude <2000masl. (Figure 3-26)

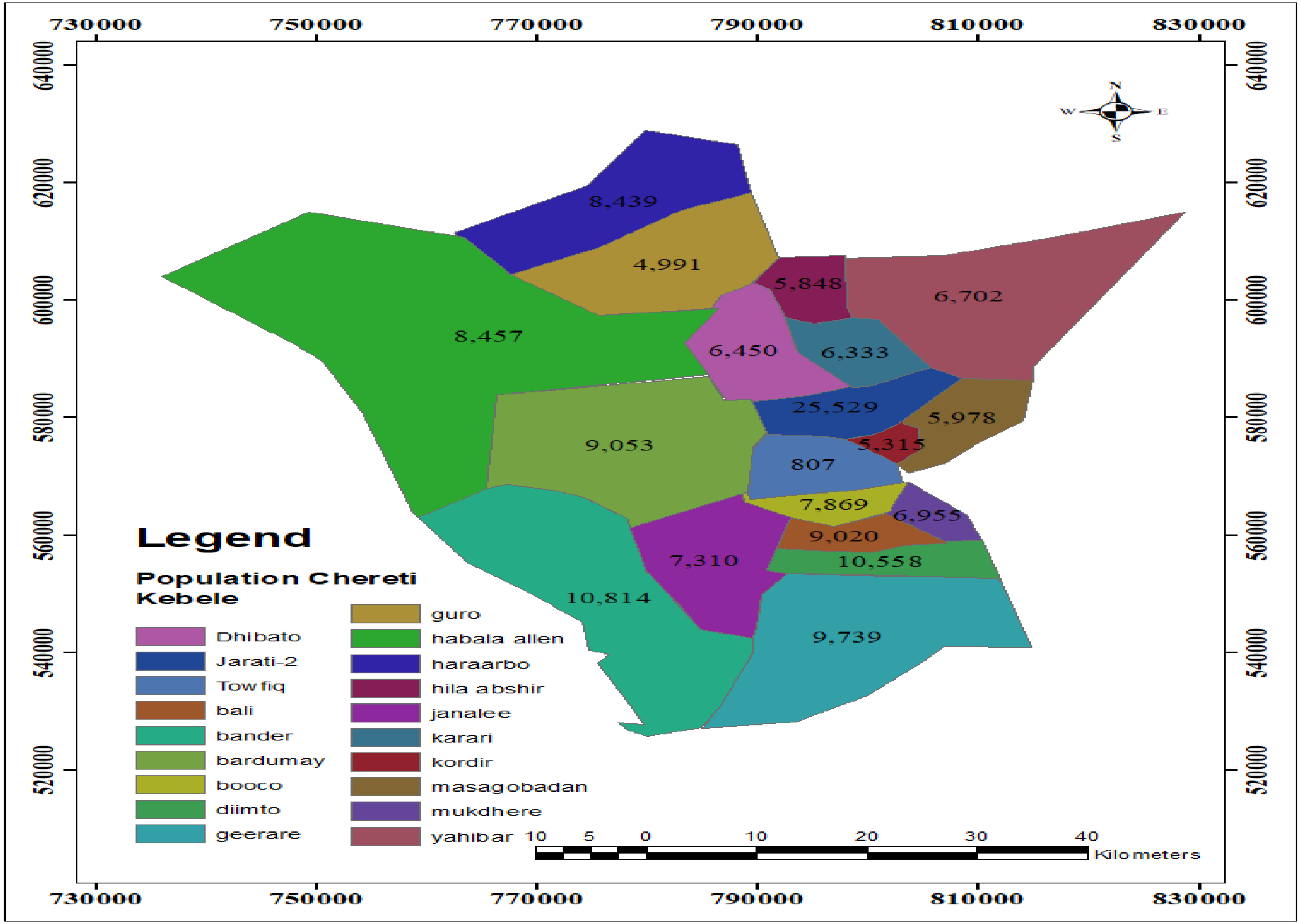

Figure 3-25:-Demographic map of Chereti woreda

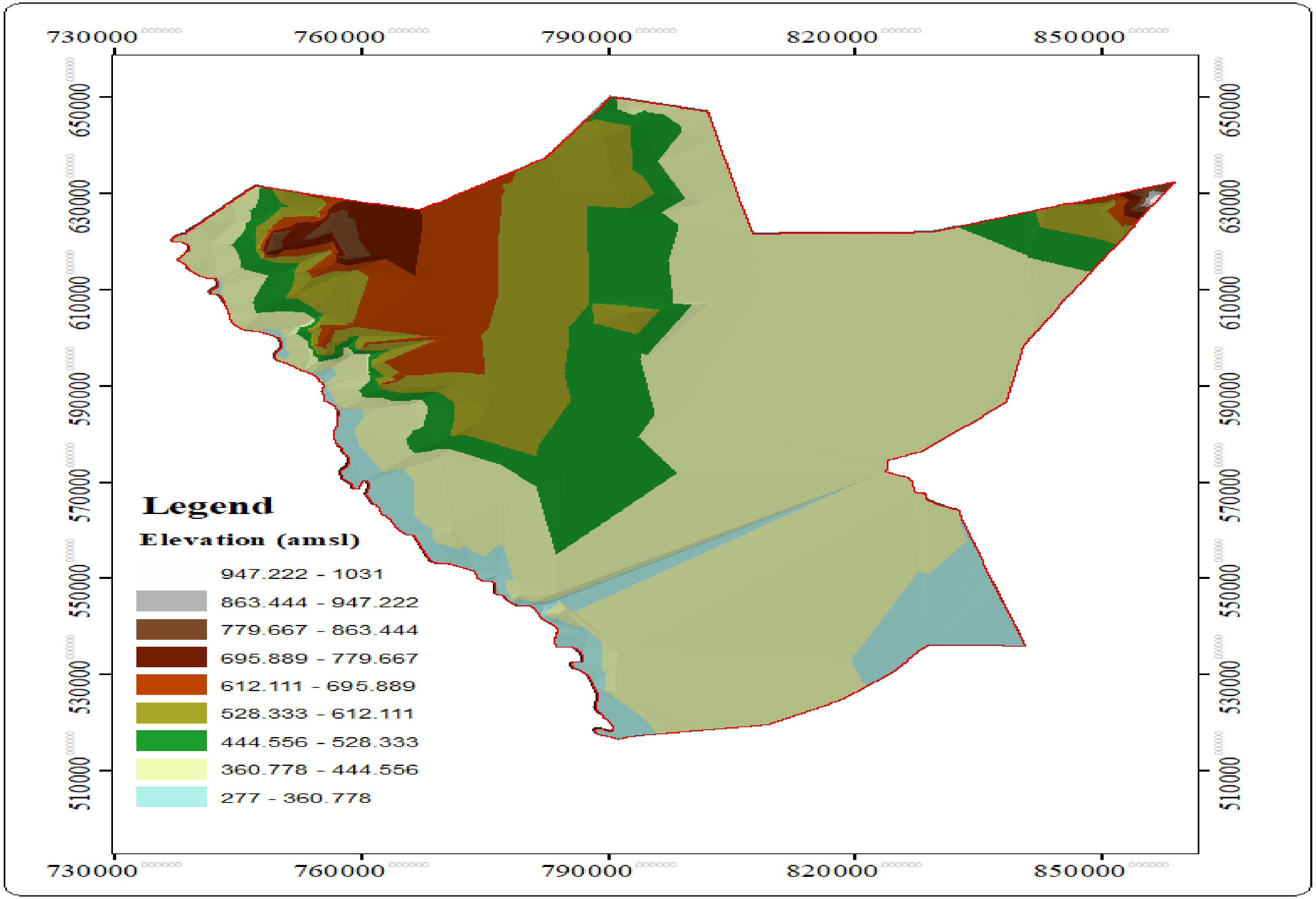

Figure 3-26. Physiography of Chereti woreda

3.14. Dolobay Woreda

3.14.1. Population and demographic map

Dolobay woreda has 17 Kebeles with 128,414 populations. As per the forcasted population data for the year 2021, Dolobay town has highest population with Dolobay town 13,173whereas HeloBuli kebele has the least population number with 6,899. Population map of Dolobay woreda is shown in the figure below (Figure 3-27)

3.14.2. Existing water supply situation

Well and related water schemes datas could notbe obtained in this woreda, hence the study findings of this project with the combined effect of overlay analysis and geophysical investigation thougt to be considered as an aid for the site selection of groundwater development in this woreda.

3.14.3. Climate

Dolobay is entirely characterized by arid to semi-arid physiography with altitude <2000masl. The Annual rainfall in Dolobay woreda ranges from 13 to 72 mm/yr (annual mean of 80 mm) as indicated by Eba Muluneh, 2017.

3.14.4. Physiography

Dolobay is entirely characterized by flat land with altitude <2000masl (Figure 3-28).

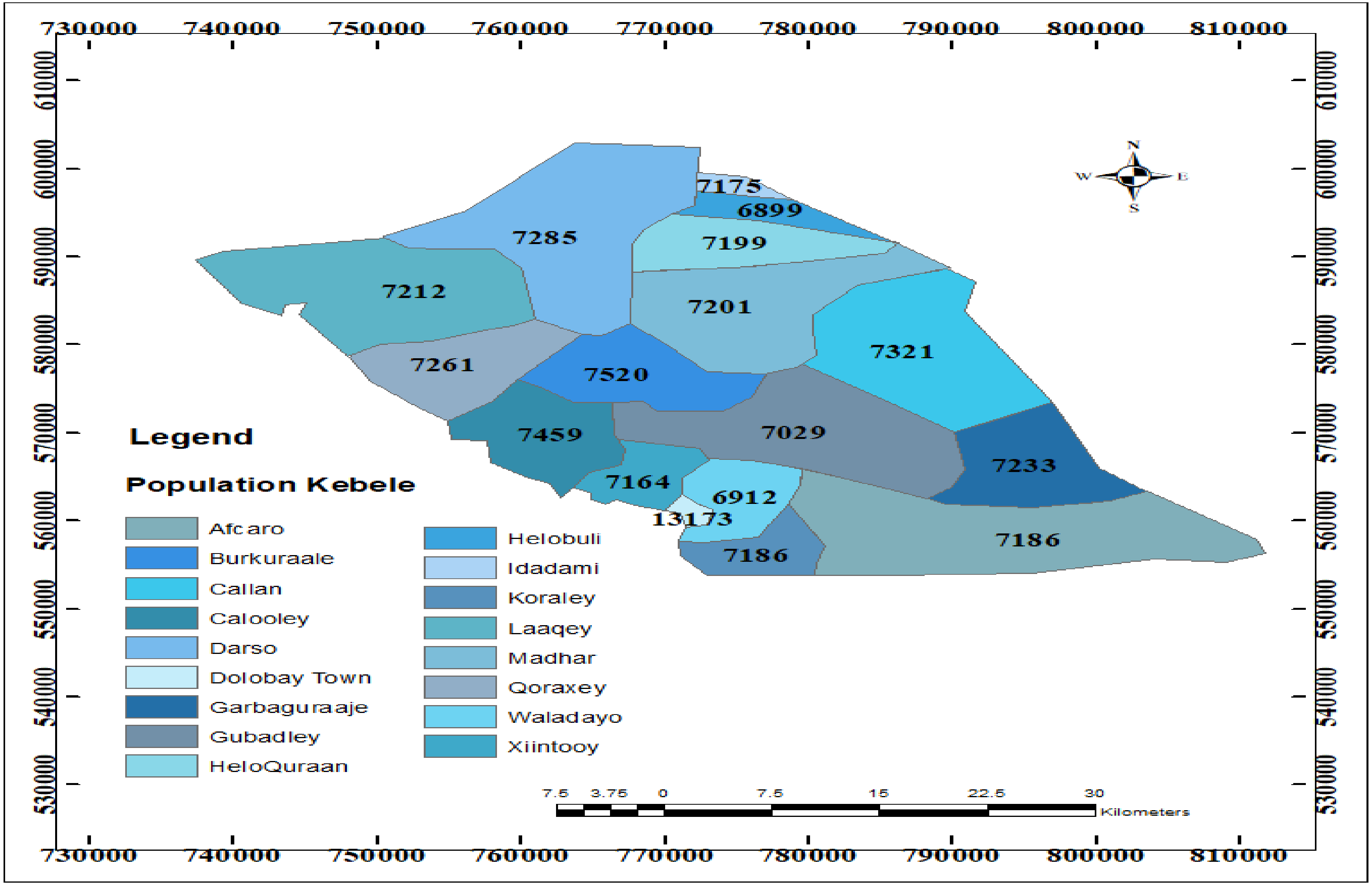

Figure 3-27:-Demographic map of Dolobay woreda

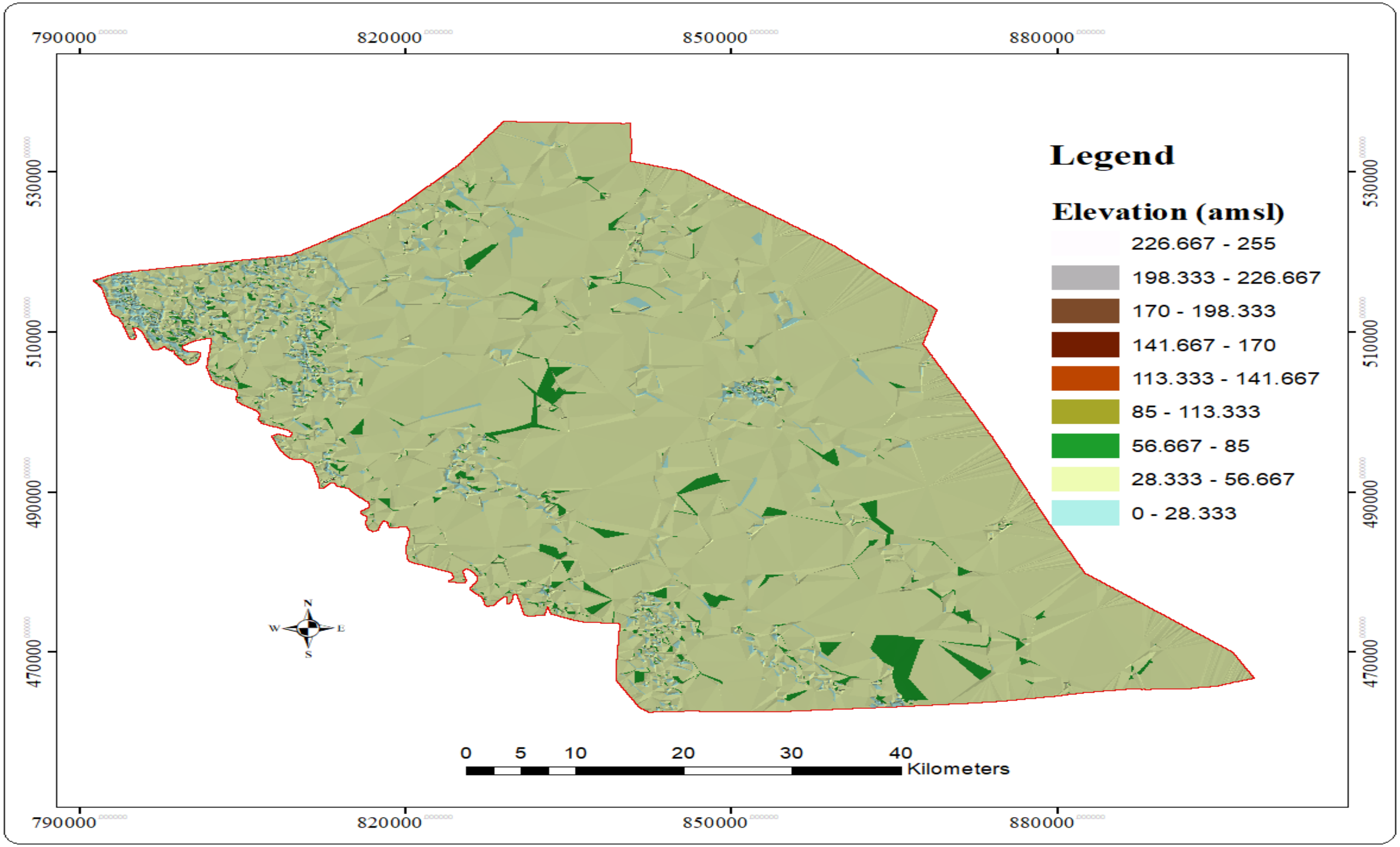

Figure 3-28. Physiography of Dolobay woreda

CHAPTER 4 : - PREPARATION OF THEMATIC LAYERS AND OVERLAY ANALYSIS

4.1. Methododology

The groundwater potential zones mapping is made using the GIS overlay analysis method using remote sensing and conventional input data. Existing hydrogeological and relevant data on geological/lithological units, structural features or lineaments, geomorphologic and climatic conditions of the target woredas were collated first. The overall study concept involved integration of four thematic layers.

Geological units/lithologies prepared for each woreda within a synoptic cluster rectangular boundary buffering the woredas area are grouped into different hydrolithological units taking their characteristics of hydrogeological significance into consideration.

Lineaments are manifestation of linear features that can be identified directly on the rock units or from remote sensing data while lineaments and their intersections play a significant role in the occurrence and movement of groundwater resources in sedimentary, volcanic and crystalline rocks. The presence of lineaments may act as a conduit for groundwater movement which results in increased secondary porosity and, therefore, can serve as groundwater potential zone (Rao, 2006; Prasad et al., 2008). Accordingly, detailed lineaments of the study woredas were extracted from Sentinel 2 series combined with geomorphology (DEM) of the areas and mapped using ArcGIS 10.8 software, and subsequently lineament density map laters were computed in using GIS algorithm and expressed in terms of length of the lineament per unit area (km/km^2).

In addition, Topographic Wetness Index (TWI) plays also important role in the occurrence and development of groundwater. The topographic wetness index (TWI), also known as the compound topographic index (CTI), is a steady state wetness index. It is commonly used to quantify topographic control on hydrological processes. The index is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. The index was designed for hill slope catenas. Accumulation numbers in flat areas will be very large.

In order to produce Topographic Wetness Index (TWI) requires basically slope (in degree), flow direction and flow accumulation which are generated from elevation maps (DEM) extracted from SRTM (30m resolution) as an input layers. The DEM with gaps/voids were initially filled and then all the input layers were resampled into 100 m cell size. Accordingly, TWI map layers were prepared for each woreda within the synoptic cluster boundary using a raster calculations algorithm in ArcGIS 10.8 software based on the following procedure.

1) fd = flow direction (DEM)
2) fa = flow accumulation (fd)
3) Slope (DEM)
4) Slope = (slope (DEM)*1.570796)/90

5) Tan_slp = con (slope > 0, tan (slope), 0.001)
6) fa_scaled = (fa + 1) *cell size; cell size = 100m
7) TWI = ln (fa_scaled/tan_slp)

Finally, recharge map layer was produced using equation 1 by calculating raster map of annual rainfall with infiltration coefficient of each geological unit identified within the project woredas in ArcGIS 10.8 platform.

R = RF*IC……………………………………………………………………...1

Where, R= Recharge (mm/y), RF = Annual Rainfall (mm/y), IC = Infiltration Coefficient

The mean annual rainfall raster data set were obtained from open sources of CHIRPS satellite imageries of 10 years from 2011 to 2020 mean annual rainfall on geological survey of America (USGS) official website (https://chc.ucsb.edu/). The infiltration coefficients of geological units were obtained from Abay River Basin Integrated Resources Development Master Plan Study report (MoWR, 1999). According to the master plan study, the IC of various lithological units could be assigned based on the results obtained from recharge estimations made using an integrated approaches including base flow separation and estimation of proportion of annual rainfall amount that to be percolated to the subsurface based on correlation made between each lithological unit identified within the basin using a developed mathematical equation. Therefore, for the current study, the IC values were extracted from the basin study that have similar properties of lithological units found in the current study woredas and accordingly assigned to each lithological unit. Then, the geological map converted to raster based on the assigned value of IC with cell size of 100m on ArcGIS platform. Finally, the raster maps of rainfall and IC of lithological units were multiplied using a raster calculation algorithm in ArcGIS in order to obtain spatial map of annual recharge amount for the project area.

Subsequent to the preparation of all the different thematic maps (including recharge, TWI, geology and lineament thematic maps) with varied attributes, the maps were converted into raster format and then assigned suitable weights in order of their hierarchy in groundwater potentiality using the analytic hierarchy process (AHP) (Saaty 1980, 1992). All the normalized weighted thematic layers were integrated and processed in ArcGIS 10.8 platform to demarcate the potential groundwater zone in the woredas. The details of the procedures adopted for this study is summarized graphically as flow-chart in Figure 4-1 (while further details on the AHP and weight assignments are highlighted in the following section.

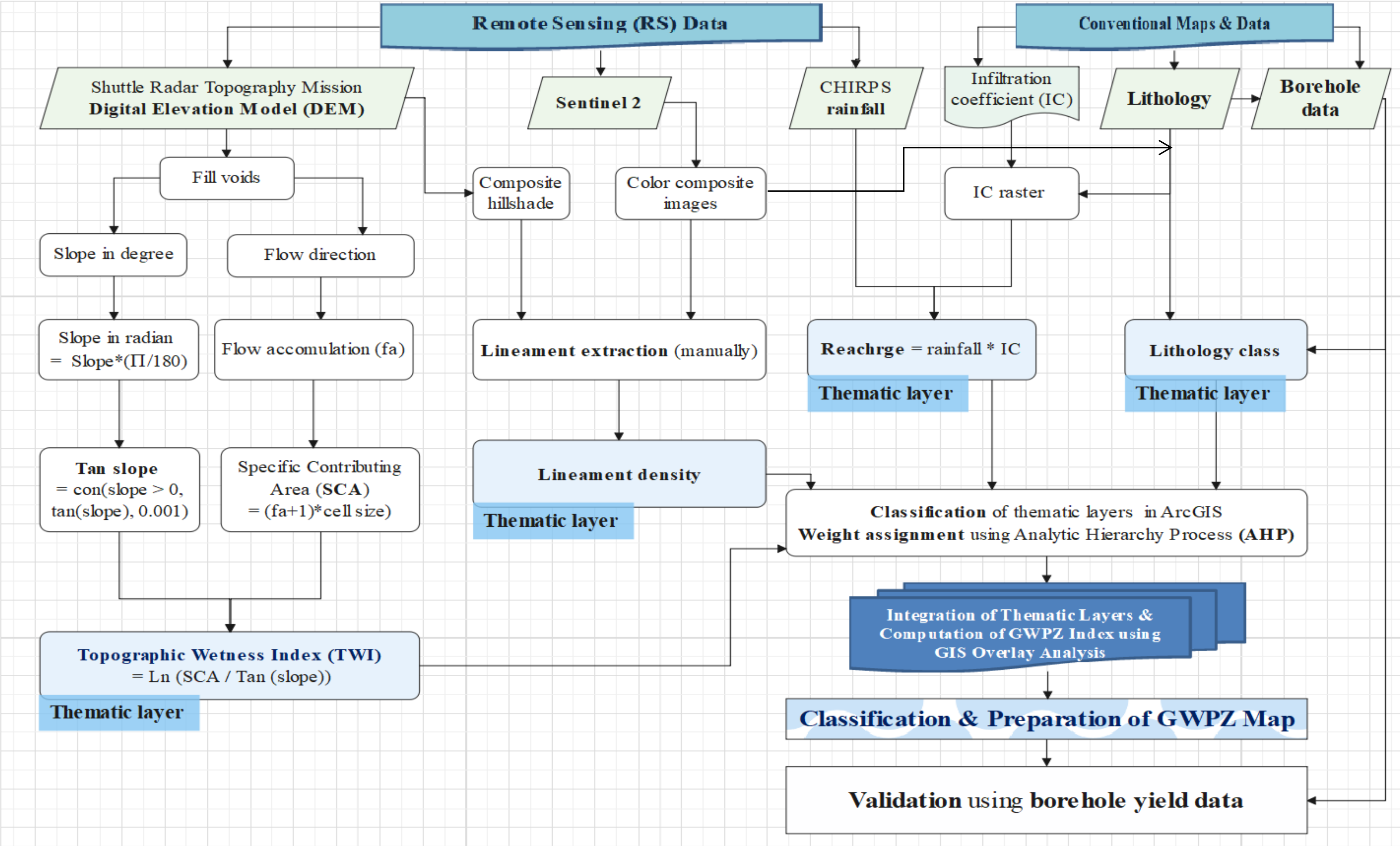

Figure 4-1 Flowchart for delineating groundwater potential zones using, GIS Overlay technique

4.2. Preparation of Thematic Map Layer

4.2.1 Synoptic Area Mapping

The present study addresses the aspect of characterization of the groundwater potential zones using integrated GIS and RS techniques in conjunction with review of previous geological and hydrogeological works. The overall study concept involved integration of four thematic layers (geology, lineament, topographic wetness index and recharge). To have a broader view and understand the overall geological and hydrogeological settings of the study woredas and produce reliable thematic layers for each woreda under Lot-3, a synoptic view of the continuity of lithology, lineaments, recharge and storage area is essential. A Synoptic area of rectangular boundaries buffering with minimum of 10 km from the woreda boundaries has been used to prepare each thematic layer map (i.e., Geology, TWI, Lineament density and Recharge). The groundwater potential maps of the woredas have been developed on GIS environment using overlay analysis of these thematic layers. All of the map themes were presented in UTM Projection Zone 37, Datum WGS84 with 100 metre resolution. The groundwater potential maps finally clipped for each woreda boundary. Accordingly, the following thematic map layers of project woredas were prepared using defined synoptic cluster boundaries.

4.2.1.1. Map Layers within Haromaya Synoptic Area

In this synoptic area, the four thematic layers and maps such as geology, grouped hydrolithological units, lineament and lineament density, TWI, and recharge were prepared for Haromaya woreda in particular.

I. Geology

In preparation of the geological map of the target woreda, major lithological units, their spatial coverage and geomorphological condition of the Haromaya wereda within the synoptic boundary has been assessed from existing data and previous studies and geological map sheets (i.e., Diredawa Sheet (NC 37-12) & Harar Sheet (NC 38-9)) from the Geological Survey of Ethiopia (GSE, 1972) and using sentnial 2 multispectral image for modification of the existing maps. This initial stage of the work encompasses extracting base map features, through the manipulations of topographic map in a GIS environment. The topographic map illustrates geographic references (Example, localities, names of rivers, road network and etc.) useful to mark widely distributed control points for accurate geo-referencing of previous geologic maps that is available in different scales. At regional and local scale, the following geological units are exposed in Haromaya Woreda within the synoptic boundary:

- Precambrian rock units that include - Undifferentiated gneisses, Syntectonic granite and Post-tectonic granite
- Mesozoic sediments that include - Lower and Upper sandstones, and Lower and Upper Hamanilie limestone formations
- Tertiary volcanics that include - lower, plateau and upper most basaltic flows
- Unconsolidated Quaternary sediments that include, Eluvium, Lake Sediments and alluvium

At local scale, Haromaya woreda in a rectangular synoptic view, the follwong geological units were identified:

Undifferentiated gneisses (Pugn) - This lithological unit is exposed at central and eastern parts of the area. Their outcrop form ridges, isolated hills, peaks and low-lying topography within streams, river beds and creeks. Lithological intercalations of biotite gneiss, quartzo-feldspathic gneiss, biotite-amphibole gneiss and migmatites form this mapping unit. Dolomitic marble calc-silicates and meta-ultramafic rocks also occur at places. Biotite-amphibole gneiss is frequently interlayered with biotite gneiss and often grades to amphibole gneiss and amphibolite. The biotite-amphibole gneiss is grey to black grey, medium grained foliated, and svc fft66how continuous parallel bands of mafic and felsic minerals.

Syntectonic granite (Pgt1) - This unit is exposed in central part of the area covering the dominant part of Haromaya Woreda proper. The unit forms rugged terrain with sharp cliffs. This rock is slightly deformed, less foliated and mainly composed of quartz, plagioclase, k-feldspars as well as minor amphibole minerals. The granite is pinkish, medium to coarse grained, massive and inequigranular to slightly deform. Here it contains diorite and granodiorite enclaves of variable size as well as granitic plutons and aplitic dikes.

Post-tectonic granite (Pgt2) - Post-tectonic granites is exposed in the northern parts (around Haromaya and Bate towns) of the Woreda map, and usually form small hills and ridges that occur in areas drained by Gobele River, north of Haromaya. This granite is pinkish in color, coarse grained, and massive in texture. In outcrop plagioclase, k-feldspar, quartz as well as white mica are the major composition.

Lower sandstone (Ja) - Lower sandstone rests unconformably on the Precambrian basement rocks in the dominant part of the area. Unconformity is defined by a meter to 5m basal conglomerate containing clasts of the basement rocks. The clasts are mainly subangular to angular with up to 5cm in diameter. The lower sandstone is exposed in many areas of the map sheet extending from western part to the northeastern part of the map area, and always lies below the lower limestone. The lower sandstone shows reddish, whitish, grey, pinkish and is usually friable. The contact with the overlying lower limestone is sharp and at places it grades to calcareous sandstone and also grades to limestone. The sandstone is coarse grained cross-bedded and shows general upward fining. Some beds are hard and compact showing through cross bedding. The cross-bedding ranges from 0.5 to 1m and at places it is as thick as 10 meters. The lower part of the unit is conglomeratic to pebbly sandstone and is medium to coarse grained and grades upward to fine/ medium grained sandstone which is capped by claystone. The contact with the overlying limestone is generally regular, parallel and horizontal.

Upper sandstone (Ka) – The upper sandstone is mostly exposed in the northwestern and southwestern parts of the map area. It attains a thickness of 15 to 30 m and is often faulted or fault bounded to the western part (Harar area). The thickness reaches up to 110 at places. Thin beds of limestone (4 to 5m) are recorded within dominant sandstone lithology. The upper sandstone is medium grained, light to light gray, reddish gray, yellow brown and is massive to thickly bedded. It shows planar and cross-laminations. NW-SE fractures are common, which are often filled with iron-oxides. At the base of the sandstone reddish brown to violet mudstone is intercalated. The mudstone is highly lithified, massive and is 5m thick. Disseminated pebbles & gravels form conglomerate and pebbly sandstone in the upper part of the sequence.

***Lower Hamanilie limestone (Jh1)* -** The lower limestone covers stratigraphically the uoverlying the sandstone. The limestones of the lower sequence cover wide area outside of the woreda boundary. This unit is creamy, light gray to light brownish gray. Invertebrate fossils within this limestone include bivalves, gastropods, and corals. Secondary alteration resulted to dissolution of the limestone and produced rough surfaces of weathered elephant skin structures.

***Upper Hamanilie limestone (Jh2)* -** The upper limestone covers stratigraphically the upper most of the limestone sequence of the map area that forms ridges in the area. The limestones of the upper sequence are thickly bedded often showing stylolites. Their thickness varies from place to place and the maximum is about 200m. It is comprised of various limestones such as micritic limestones with minor beds of dolomite, cherty limestone, black limestone and grainstone. Micritic limestone forms the major part of the upper limestone. This is creamy, light gray to light brownish gray. It is medium to thickly bedded. Invertebrate fossils within this limestone include bivalves, gastropods, and corals. Secondary alteration resulted to dissolution of the limestone and produced rough surfaces of weathered elephant skin structures.

***Lower Basalt (Tv1)* -** The lower basalt occupies small patchy area of northeastern part of the map area. The lower basalt comprises olivine-plagioclase phyric, plagioclase-olivine phyric and aphanitic basalts. At places, altered rhyolites and minor trachytes are associated with this unit. It shows columnar jointing at places. The lower basalts are often vesicular, amygdaloidal, aphanitic and scoriaceous basalt or scoria. The vesicular basalts are filled by calcite and chalcedony. Some vesicles are devoid of secondary minerals. Alteration of plagioclase to calcite, clay minerals and sericite is common.

***Plateau Basalt (Tv3)* -** occupies small patchy area of northeastern part of the map area. This unit forms horizontal to gently dipping layers or laminated volcanic units. Vesiculated quartz alkali trachyte is interlayered with alkali rhyolite, porphyritic alkali rhyolite, ash-fall deposit and at places with thin obsidian layers.

***The Highland Basalt flows (Tv4)* -** Highland basalt forms mainly the highlands of southeastern parts of the map area. These are central eruptions and exposed on top of upper pyroclasts. These lava flows form large plateau areas and are younger fresh basalts. The basalts are separated with thin paleosoils. The basalts are fine grained and at places columnarly jointed. The highland basalts are correlated to the Termaber Formation and there are minor trachyte flows on top of the basalts.

***Quaternary eluvium (Qel)* -** This unit occupies limited areas of the Haromaya Woreda plateau (around northeast and south of Aweday town), forming high flatland to slightly subdued topography. The eluvium consists of silty-clayey materials covering the granitic intrusive rocks.

Lake sediments (Qls) - The lake sediments are lacustrine origin and occupy limited area that mainly found around Haromaya and Bate towns and surrounding areas, and are restricted to lake processes in that area. The Qls occur around Lake Haromaya and Finkile. The sediments are clays and silts related to the fluctuation of lake levels. The sediments might be mixed with wash sediments of the nearby uplands.

Quaternary alluvium (Qal1) - This alluvium occurs both on the plateau and ín the rift zones along major river valleys. It shows varied thickness from place to place; which range from a meter to 10 m. or up to 20 m. in some river beds. Composition varies from silty mud to sandy-conglomerates. These loose materials often show bedding and cross-bedding which are not continuous. Quaternary alluvium (Qal1) forms relatively wide valley plains and at places even altered to new soil generation at their top part. Alluvial plain soil is mixed with scattered gravels and pebbles, moved from the surrounding uplands. Such deposits are assumed to be older than Holocene and are assumed to be Pleistocene pluvial deposits.

Quaternary alluvium (Qal2) - This alluvium is exposed along valley floors of Recent age. They are confined to river channel beds. They are compositionally variable from coarse sand, gravels, which are none stratified and at places mixed with cobbles and boulders. These are confined to channel cutting across the former wide valley floors low plains. Along some tributaries and creeks, they form wide areas with pro-alluvium. In the wide plains, they provide fertile soil rich in humus content; which are important for agriculture. Distributary channels are common along recent valleys due to variation in bed loads. In some places of the area, the thickness of this deposit reaches up to 15 m.

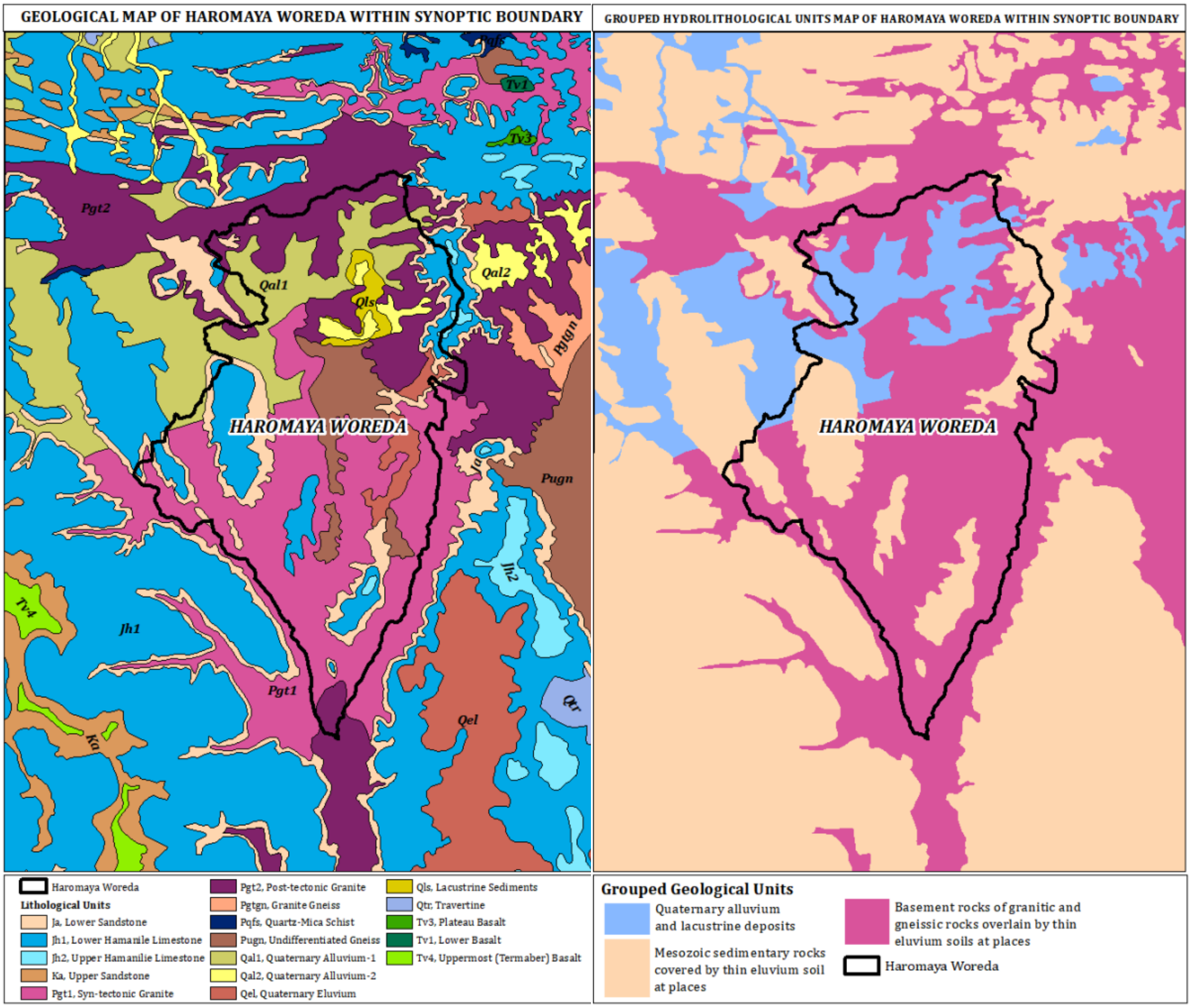

Figure 4-2. Geological and Grouped Hydrolithological Units Maps of Haromaya Woreda within Synoptic Boundary

II. Lineaments and Lineament Density

Lineaments were manually extracted with great care using DEM from (https://earthexplorer.usgs.gov/), hybrid morphometric maps, satellite images (Sentinel 2 from https://scihub.copernicus.eu/) and exisiting geological maps of the area. Usually, lineaments are presented in the form of lineament density. Lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. Accordingly, lineament densisty map of Haromaya woreda within the synoptic boundary was generated using an alogorithm in ArcGIS Spatial Analyist tool with a radius of about 1.5 km taking into consideration of intercepting all the identified lineaments, and maximum distance between the intersections and distribution of lineaments (Figure 4-3).

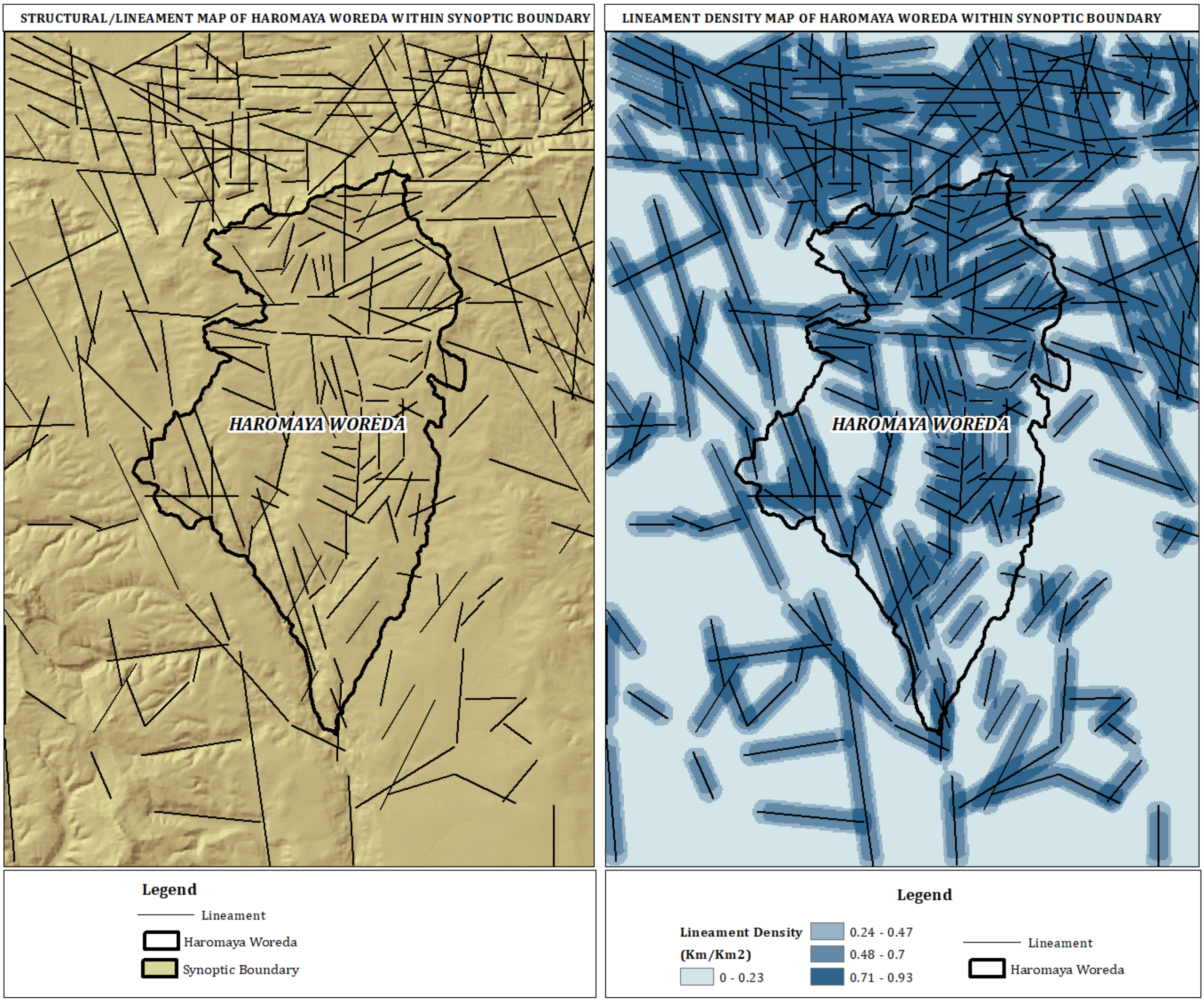

Figure 4-3. Geological Structure/Lineament and Lineament Density Maps of Haromaya Woreda within Synoptic Boundary

III. Recharge

The mean annual rainfall raster data set were obtained from open sources of CHIRPS satellite imageries of 10 years from 2011 to 2020 mean annual rainfall on geological survey of America (USGS) official website (https://chc.ucsb.edu/). The infiltration coefficients of geological units were obtained from Abay River Basin Integrated Resources Development Master Plan Study report (MoWR, 1999). According to the master plan study, the IC of various lithological units could be assigned based on the results obtained from recharge estimations made using an integrated approaches including base flow separation and estimation of proportion of annual rainfall amount that to be percolated to the subsurface based on correlation made between each lithological unit identified within the basin using a developed mathematical equation. Therefore, for the current study, the IC values were extracted from the basin study that have similar properties of lithological units found in the current study area and accordingly assigned to each lithological unit (Table 4-1).Then, the geological map converted to raster based on the assigned value of IC with cell size of 100m on ArcGIS platform. Finally, the raster maps of rainfall and IC of lithological units were multiplied using a raster calculation algorithm in ArcGIS in order to obtain spatial map of annual recharge amount for the Haromaya area.

Table 4-1 Assigned Infilitration Coefficent for Lithological Units (Correlated with Abay Master Plan Studies, MoWR, 1998) for Haromaya Synoptic area

Lithological Units (Study area)		Assigned Infiltration Coefficient (IC)	Lithological Units (Abay Basin)	
Symbol	**Description**		**Symbol**	**Description**
Qal2	Recent Quaternary Alluvium-	0.2	QAll	Alluvium
Qal1	Older Quaternary Alluvium-1	0.15	QAll	Alluvium
Qls	Lacustrine Sediments	0.15	QLAC	Lacustrine deposits
Qel	Quaternary Eluvium	0.05	QCOL	Colluvium
Tv4	Uppermost (Highland) Basalt	0.15	TASB	Ashangi Basalts
Tv3	Plateau Basalt	0.15	TASB	Ashangi Basalts
Tv1	Lower Basalt	0.1	TBNB	Blue Nile Basalts
Jh2	Upper Hamanilie Limestone	0.1	JANL	Antalo Limestone
Jh1	Lower Hamanilie Limestone	0.1	JANL	Antalo Limestone
Ka	Upper Sandstone	0.15	KAA2	Amba Aradam Sandstone (2)
Ja	Lower Sandstone	0.05	Ja	Adigrat Sandstone
Pgt2	Post-tectonic Granite	0.03	PGT2	Post tectonic granites
Pgt1	Syn-tectonic Granite	0.03	PGT1	Syntectonic granites
Pqfs	Quartz-Mica Schist	0.03	PUBL	undifferentiated Precambrian
Pugn	Undifferentiated Gneiss	0.03	PUBL	undifferentiated Precambrian

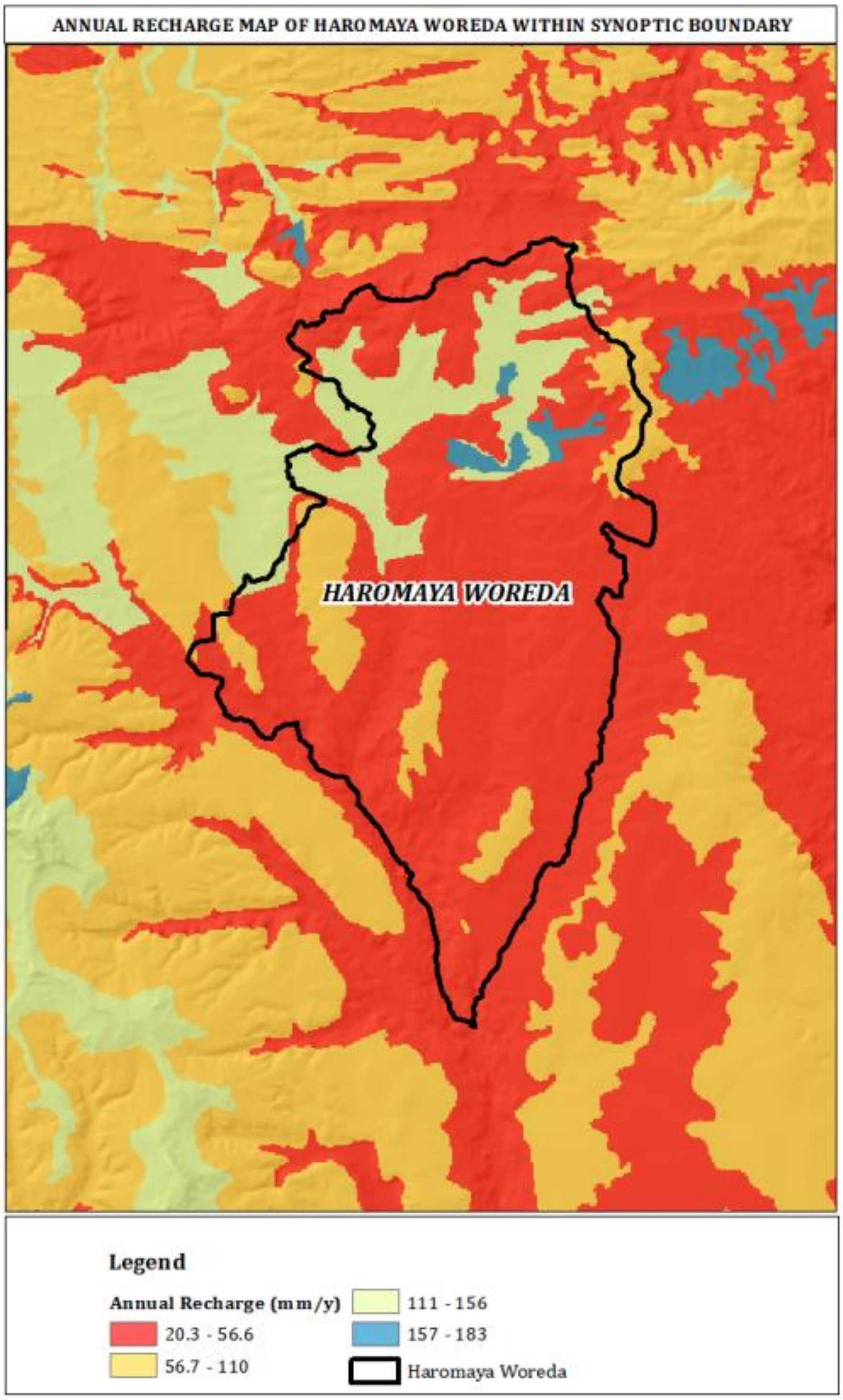

Figure 4-4. Recharge Map of Haromaya Woreda within Synoptic Boundary

IV. Topographic Wetness Index (TWI)

The Topographic wetness index, also known as the compound topographic index, is commonly used to quantify topographic control on hydrological processes. The index is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. The topographic wetness index (TWI) is a useful model to estimate where water will accumulate in an area with elevation differences (Sorensen, R; Zinko, U.; Seibert, J. (2006). Topographic wetness is a unitless quantity and it is represented by index with relative physical property. The topographic wetness index as a layer plays a significant role in line with other selected layers to delineate groundwater potential areas based on priority/ranking and weightage as per the layers' relative importance for groundwater enhancement/Potentiality. Accordingly, the TWI layer of Haromaya woreda within the synoptic area was prepared (Figure 4-5).

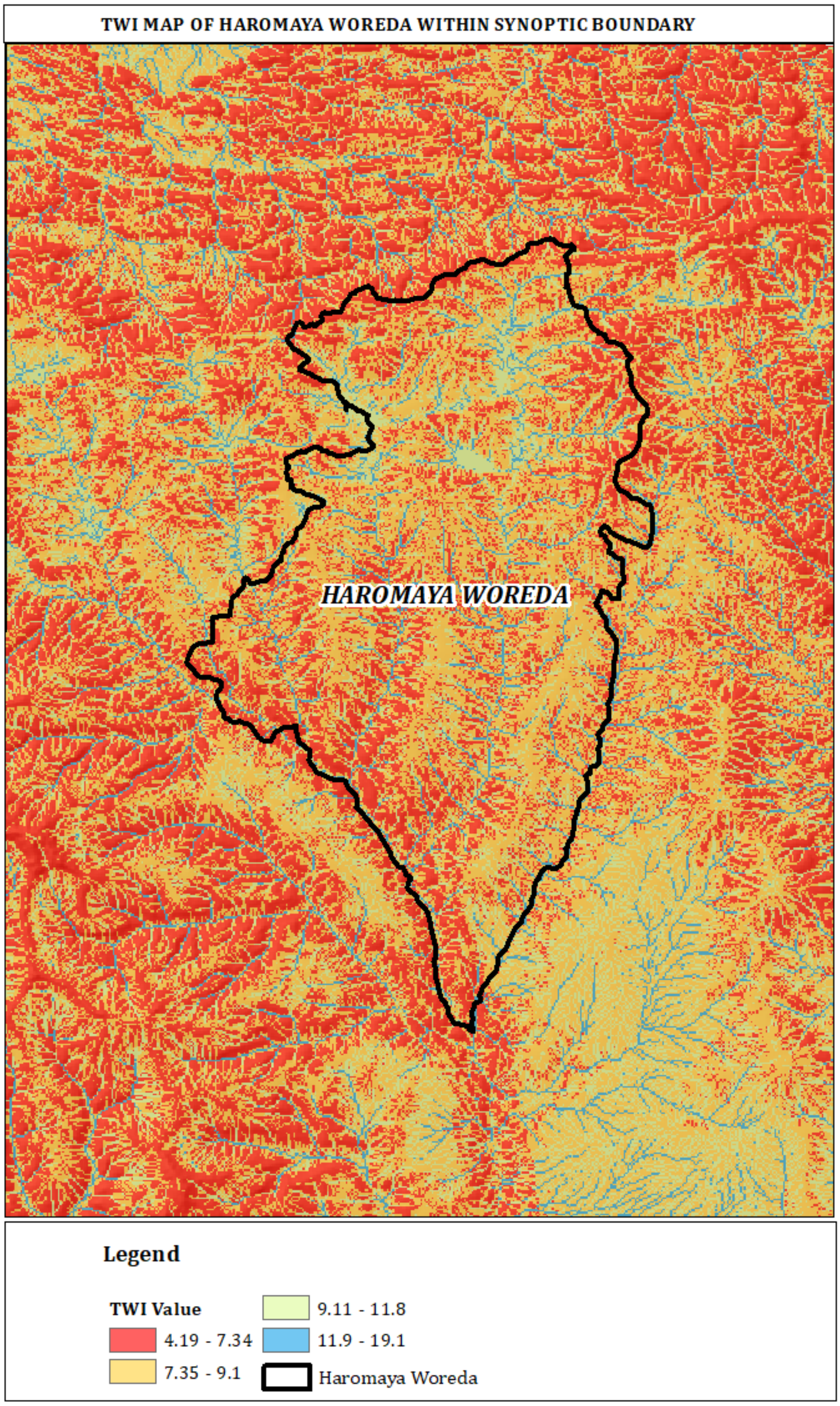

Figure 4-5. TWI Map of Haromaya Woreda within Synoptic Boundary

4.2.1.2. Map Layers within Boke Synoptic Area

In this synoptic area, the four thematic layers and maps such as geology, grouped hydrolithological units, lineament and lineament density, TWI, and recharge were prepared for Boke woreda in particular.

I. Geology

In preparation of the geological map of the target woreda, major lithological units, their spatial coverage and geomorphological condition of the Boke wereda within the synoptic area has been assessed from existing data and previous studies and geological map sheets (i.e., Bedessa Sheet (NC 37-16) & Ginnir Sheet (NB 37-4)) from the Geological Survey of Ethiopia (GSE, 1972 & 1974) and using sentnial 2 multispecgtral image for verfication and modification of the existing maps. This initial stage of the work encompasses extracting base map features, through the manipulations of topographic map in a GIS environment. The topographic map illustrates geographic references (Example, localities, names of rivers, road network and etc.) useful to mark widely distributed control points for accurate geo-referencing of previous geologic maps that is available in different scales. At local scale, the following geological units are exposed in Boke Woreda

- Mesozoic sediments that include - Lower and Upper Hamanilie limestone and upper Gabredarre limestone
- Unconsolidated Quaternary sediments that include, Eluvium and alluvium

At regional and local scale, Boke woreda in a rectangular synoptic view, the follwong geological units were identified:

Undifferentiated Gneiss (Pugn): This unit is represented by different types of gneisses, including migmatized quartzo-feldspathic gneiss, granitic gneiss, gabbroid rocks, lenses of meta-sedimentary rocks and different types of granites (Gebreyohannes et al, 1990). In some stream, the biotite gneiss is unconformablly, overlain by thin Adigrat Formation. The rock is light dark grey, fine to medium grained and strongly foliated. In weathered outcrops, it appears to be friable and buff colored. In places, it grades to augen gneiss consisting symmetric quartz and feldspar porphyroblasts. Locally, the gneiss is seen to be strongly migmatized and developed ptygmatic and vein type migmatite structures. Foliations in such migmattitic rocks are shallow dipping while lineations are sub-vertical. Association of concordant granite aplite, quartz veins and vein lets is common. The width of the quartz veins range between 10 and 50cm, and are normally boudined. Occasionally, the quartz veins seem to be sheared with quartzite appearance.

Low Grade Schists (Psc): These are strongly schistosed rocks and mainly represented by Biotite-muscovite-quartz schist with minor inter beds of quartz-muscovite schist, biotite-chlorite-muscovite-epidote-quartz schist and quartzite. The schsts are found to occur throughout the belt intruded by small bodies of meta-volcanics and gabbros. The dominant meta-sediment type: the biotite-muscovite-quartz schist is light olive green colored with boudined quartz veins. The quartz veins are concordant to the foliation with a maximum length not more than few meters, and in places show sugary texture.

Lower Sandstone (Ja): The Lower sandstone unit in the map area is the oldest and with the least distribution of outcrop sections exposed in the deep cut stream valeyes, only. It unconformably overlies on the Precambrian basement exposed in the central north and of the synoptic project area. In the map area, the total thickness of the formation is commonly measured between 100 and 120m. The Lower Sandstone in the map area is a non-fossil bearing sedimentary unit composed of conglomeratic sandstone, coarser to medium sandstone and mudstone beds, with rare development of fine sandstone. Coarser sediments are characterized by thick beds, whereas the fine sediments commonly show thin bedding and lamination. Cross beds are also common structures in the coarser sandstone facies. The sediments are dominantly red in color with minor light greybeds.

Upper Sandstone (Ka): The upper sandstone unit is exposed in southern part of the map area. This sandstone is assumed to be the continuation of the Ambaradom Formation of central Ethiopia. The Upper sandstone is stratgraphically below the Lower Hamanilie limestone formation and is underlain by Upper Gabredarre limestone. The sandstone is mainly fine grained, light gray to brownish gray, mostly horizontally stratified, but at places show inclined beds, probably due to deposition on sloppy surfaces. The rock is mostly thinly to medium bedded, horizontal, continuous, parallel and planar. The top part of the sandstone is interbedded with siltstone, shale and mudrocks. The siltstone is paper laminated, light grey, very fine grained and rests on the shale. The shale in turn rests on the mudrock, /claysone/. The shale is friable, loose, and grey and is ultrafine grained. The mudrock is also loose or slightly compacted brownish grey rock. Most part of the sandstone exposure is developed to secondary calcification, forming calcrete, caliche and calc-tufa. In the lowlands the sandstone is deeply weathered and altered to black cotton soil and also to reddish sandy soil. The upper sandstone is 100-meter-thick and at places the thickness diminishes. In most of the area the sandstone is quartzose sandstone with quartz enrichment and is mostly massive.

Lower Hamanlie Formation (Jh1): This member contains a succession of impure carbonate sediments lying directly on the Lower Sandstone with almost similar outcrop distribution to the later. The member has an estimated thickness of 60-80m consisting mainly of sandy limestone, fine sandstone and silty limestone.

Upper Sandstone (Ka): The upper sandstone unit is exposed in southern part of the map area. This sandstone is assumed to be the continuation of the Ambaradom Formation of central Ethiopia. The Upper sandstone is stratgraphically below the Lower Hamanilie limestone formation and is underlain by Upper Gabredarre limestone. The sandstone is mainly fine grained, light gray to brownish gray, mostly horizontally stratified, but at places show inclined beds, probably due to deposition on sloppy surfaces. The rock is mostly thinly to medium bedded, horizontal, continuous, parallel and planar. The top part of the sandstone is interbedded with siltstone, shale and mudrocks. The siltstone is paper laminated, light grey, very fine grained and rests on the shale. The shale in turn rests on the mudrock, /claysone/. The shale is friable, loose, and grey and is ultrafine grained. The mudrock is also loose or slightly compacted brownish grey rock. Most part of the sandstone exposure is developed to secondary calcification,

forming calcrete, caliche and calc-tufa. In the lowlands the sandstone is deeply weathered and altered to black cotton soil and also to reddish sandy soil. The upper sandstone is 100-meter-thick and at places the thickness diminishes. In most of the area the sandstone is quartzose sandstone with quartz enrichment and is mostly massive.

Upper Hamanlie Formation (Jh2): In the mapped area, the Upper Hamanlie Formation is typically fossil poor having two members termed as, (a) Lower Member (or Mixed carbonate-clastic sediments) and (b) Upper Member (coquina). Lower Member (Mixed carbonate-clastic Member) contains a succession of impure carbonate sediments lying directly on the Adigrat Sandstone. This member has an estimated thickness of 60-80m consisting mainly of sandy limestone, fine clastics and silty limestone. While, the Upper Member of Hamanlie encompasses coquina bearing limestone, upward thinning limestone, pellitic limestone and chert bearing grainstone.

Upper Gabredarre Formation (Jg2): It has a thickness not more than 1.5m, observed around Boke town at northwest extending to central and southeast around Wabe Shebele River. It covers about 664.65km^2 (19.8 %) of the geological map of Boke woreda. The upper Gabredarre Formation is generally a thin succession of carbonates (less than100m) with distinctly large and thick-shelled fossils of gastropods and bivalves. The formation comprises fossiliferous limestone, black limestone, sandy and silty limestone.

Abduya sandstone (Masst): This sandstone was first recognized on the mountains occurring north of Ginnir. Such sandstone, altitude stands on higher elevation above the Tertiary volcanic rocks. This sandstone was separated from the main upper sandstone, on the basis of marker bed, the limestone and diatomite occurring at the foot slope of Abduya mountain chain and Arada evaporite. The Abduya sandstone is light grey to white quartzose sandstone with thin bedding, which at places form rhythimic occurrence with arkosic sandstones. At places it also shows thick beds to massive. Arkosic sandstone is pinkish, fine to medium grained, hard and massive rock. The sandstone shows parallel and continuous beds of hard and compact rock. It is often interbedded with similar a lenticular bed which often pinches out. Some lenses are due to depositional slumping and turbidity current flows. The depositional environment is coastal, intertidal and also ranges to shelf.

Lower lava flows (Tv1): The lower basalt flows are mainly basalts, which are extensively layered, with minor pyroclasts at the top part, and bottom part (gravelly tufts). It is unconformably overlain by the middle lava flows. The contact with the underlying sandstone (Abduya sandstone) is also defined by unconformity (paleosoil of 2m thick). Where the sandstone is eroded, the basalt directly lies on the Gabredarre limestone. The Tv1 basalts are mainly aphanitic, (fine grained), hard and compact black massive rock. At places it shows columnar joint structures. There are also olivine phyric and pyroxene phyric basalts. At places secondary minerals (zeolite) are common, filling vesicles. Minor vesicular basalts also occur at places. The basalts are often deeply weathered to from thick soil. In some localities the basalt is mixed with scoria flow. Total approximate thickness of this unit exceeds 600 m.

Middle lava flows (Tv2): The Tv2 is cliff forming unit surrounding the plateau at southwestern part of the mapping area. The basalt is stratified, massive, hard and compact rock. The basalts at some places are intercalated with scoria flow. The middle basalt lies unconformable on the lower lava flows. The Tv2 is thin (100 to 120 m) covering limited geographic area. It represents fissural eruption of flood basalt flows, the source of which could be extensional tectonic fractures in central part of the country. The middle lava flows are dark grey, fine grained and mainly composed of mafic minerals. It is overlain sharply by plateau basalts in most of the map area. In some places the middle lava flows form characteristic columnar joints which are mainly vertical. The Tv2 exposure form rocky surfaces devoid of soil. The middle lava flow form three distinctive and erosion protective layers. The basalt is mostly fine grained, dark grey and at places columbary jointed.

Plateau basalts (Tv3): Plateau basalt forms plateau surfaces of limited southwestern mapping area. This basalt form high flat land. The plateau basalts are sharply separated from the underlying middle lava flows. It covers the most top part of the plateau, which is developed to thick fertile black cotton soil. The plateau basalt is characterized by basalt lava flows laterally grading to pyroclastic scoria flow. The basalt is fine grained and dark grey with dominant mafic mineral composition. The scoria flow is mixed with pieces of scoria rock fragments containing cobbles, gravels, and rarely boulders. This pyroclastic flow containing scoria fragments are cemented and hardend with finer basic lava.

Eluvial Deposit (Qel): This unit consists of residual soils, some travertine covers and loose sands and silts that widely developed on top of Mesozoic sediments. Residual soils are the dominant type developed on the flat areas of limestone. They are clayey, ranging in color from reddish brown to red. Rock fragments are rare, but calcretes. Travertines are also developed on the surfaces of cliff forming limestone outcrops.

Quaternary calcretes Qcal): The calcretes are secondary limestone forming small patchy areas in the lowlands of the southern map area. They have been developed mostly, on the upper sandstone exposure, and rarely on upper Gabredarre limestone. This calcrete is hard, compact and cemented concretions of carbonates, with rough surfaces. At places it develops to pure limestone bed rock with smooth surface. Mostly the calcrete represent recemented carbonate materials containing various rock fragments, but in most cases it is mainly limestone. The calcrete is light grey color with various grain sizes.

Alluvial Deposit (Qal): Recent sediments accumulated along the floor of large stream valleys are collectively mapped as alluvium sediments. They include talus and rock debris at the toe of the valley walls and silty soil over the flood plains. In the flanks of stream channels, silty soil is commonly observed to be laminated. The talus and rock debris are deposited mainly under the influence of gravity. They form irregular topographic relieves commonly at the mouth of small tributaries. The lateral extent of alluvial sediments is governed by the width of the valley.

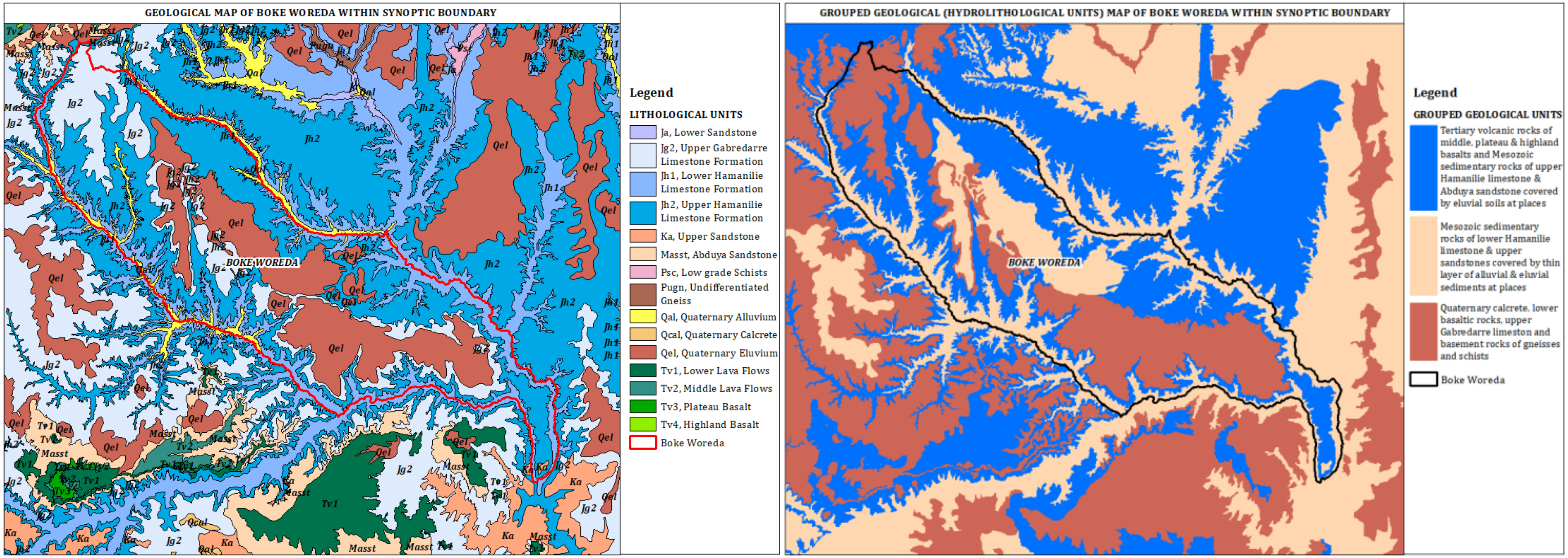

Figure 4-6. Geological and Grouped Hydrolithological Units Maps of Boke Woreda within Synoptic Boundary

II. Lineaments and Lineament Density

Lineaments are manually extracted with great care using DEM from (https://earthexplorer.usgs.gov/), hybrid morphometric maps, satellite images (Sentinel 2 from https://scihub.copernicus.eu/) and exisiting geological maps of the area.

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Four prominent orientation of lineaments identified are NW-SE, NE–SW, E – W and N–S trending lineaments.

Usually, lineaments are presented in the form of lineament density. Lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. Accordingly, lineament densisty map of Boke woreda within the synoptic boundary was generated using an alogorithm in ArcGIS Spatial Analyist tool with a radius of about 1.5 km taking into consideration of intercepting all the identified lineaments, and maximum distance between the intersections and distribution of lineaments (Figure 4-7).

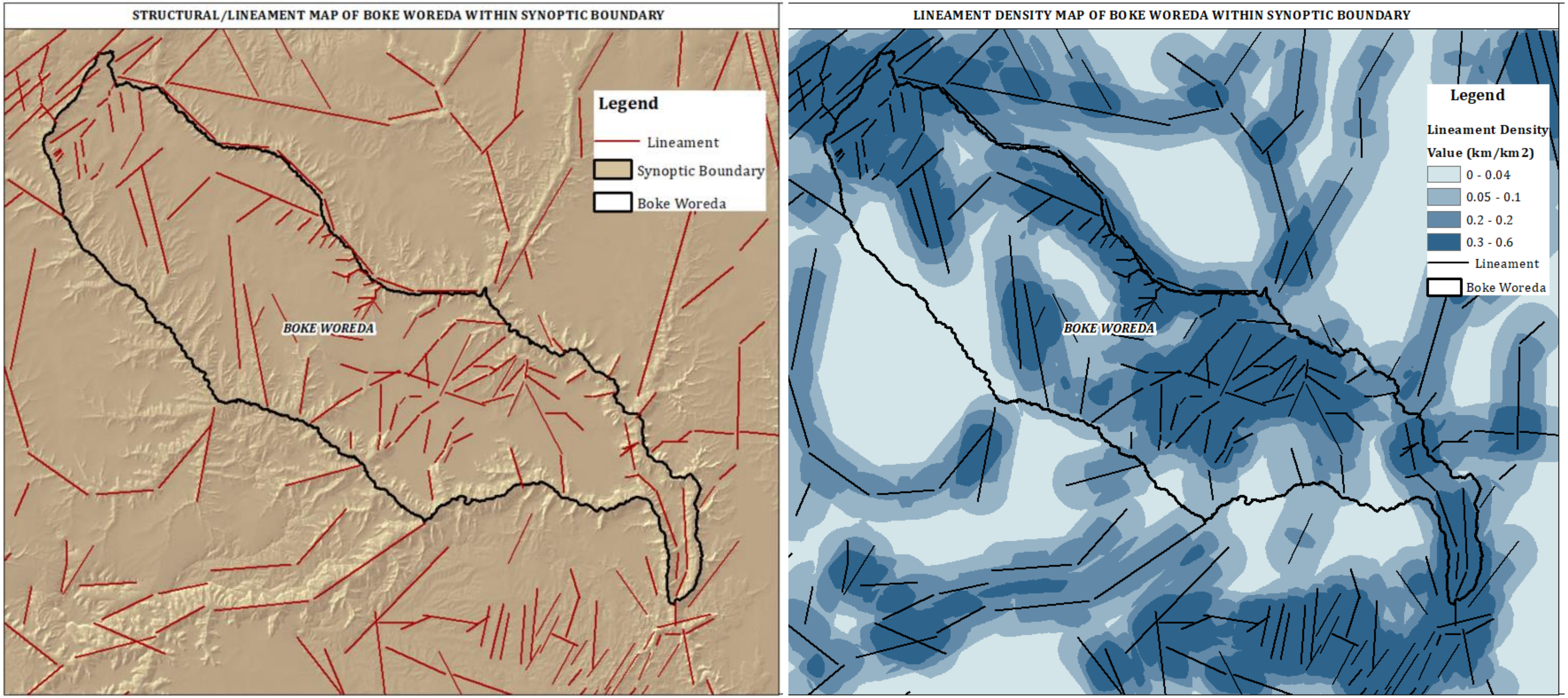

Figure 4-7. Geological Structure/Lineament and Lineament Density Maps of Boke Woreda within Synoptic Boundary

III. Recharge

The mean annual rainfall raster data set were obtained from open sources of CHIRPS satellite imageries of 10 years from 2011 to 2020 mean annual rainfall on geological survey of America (USGS) official website (https://chc.ucsb.edu/). The infiltration coefficients of geological units were obtained from Abay River Basin Integrated Resources Development Master Plan Study report (MoWR, 1999). According to the master plan study, the IC of various lithological units could be assigned based on the results obtained from recharge estimations made using an integrated approaches including base flow separation and estimation of proportion of annual rainfall amount that to be percolated to the subsurface based on correlation made between each lithological unit identified within the basin using a developed mathematical equation. Therefore, for the current study, the IC values were extracted from the basin study that have similar properties of lithological units found in the current study area and accordingly assigned to each lithological unit (Table 4-2). Then, the geological map converted to raster based on the assigned value of IC with cell size of 100m on ArcGIS platform. Finally, the raster maps of rainfall and IC of lithological units were multiplied using a raster calculation algorithm in ArcGIS in order to obtain spatial map of annual recharge amount for the project area (Figure 4-8).

Table 4-2 Assigned Infilitration Coefficent for Lithological Units (Correlated with Abay Master Plan Studies, MoWR, 1998) for Boke Synoptic area

Lithological Units (Study area)		**Assigned Infiltration Coefficient (IC)**	**Lithological Units (Abay Basin)**	
Symbol	**Description**		**Symbol**	**Description**
Qal	Recent Quaternary Alluvium	0.2	QAll	Alluvium
Qel	Quaternary Eluvium	0.15	QCOL	Colluvium
Tv4	Uppermost (Highland) Basalt	0.05	TASB	Ashangi Basalts
Tv3	Plateau Basalt	0.15	TASB	Ashangi Basalts
Tv2	Middle Basalt	0.15	TASB	Ashangi Basalts
Tv1	Lower Basalt	0.1	TBNB	Blue Nile Basalts
Masst	Abduya Sandstone	0.1	KAA2	Amba Aradam Sandstone (2)
Jg2	Upper Gabredarre Limestone	0.1	JANL	Antalo Limestone
Jh2	Upper Hamanilie Limestone	0.15	JANL	Antalo Limestone
Jh1	Lower Hamanilie Limestone	0.05	JANL	Antalo Limestone
Ka	Upper Sandstone	0.03	KAA2	Amba Aradam Sandstone (2)
Ja	Lower Sandstone	0.03	Ja	Adigrat Sandstone
Psc	Low Grade Schists	0.03	PUBL	Precambrian basement
Pugn	Undifferentiated Gneiss	0.03	PUBL	Precambrian basement

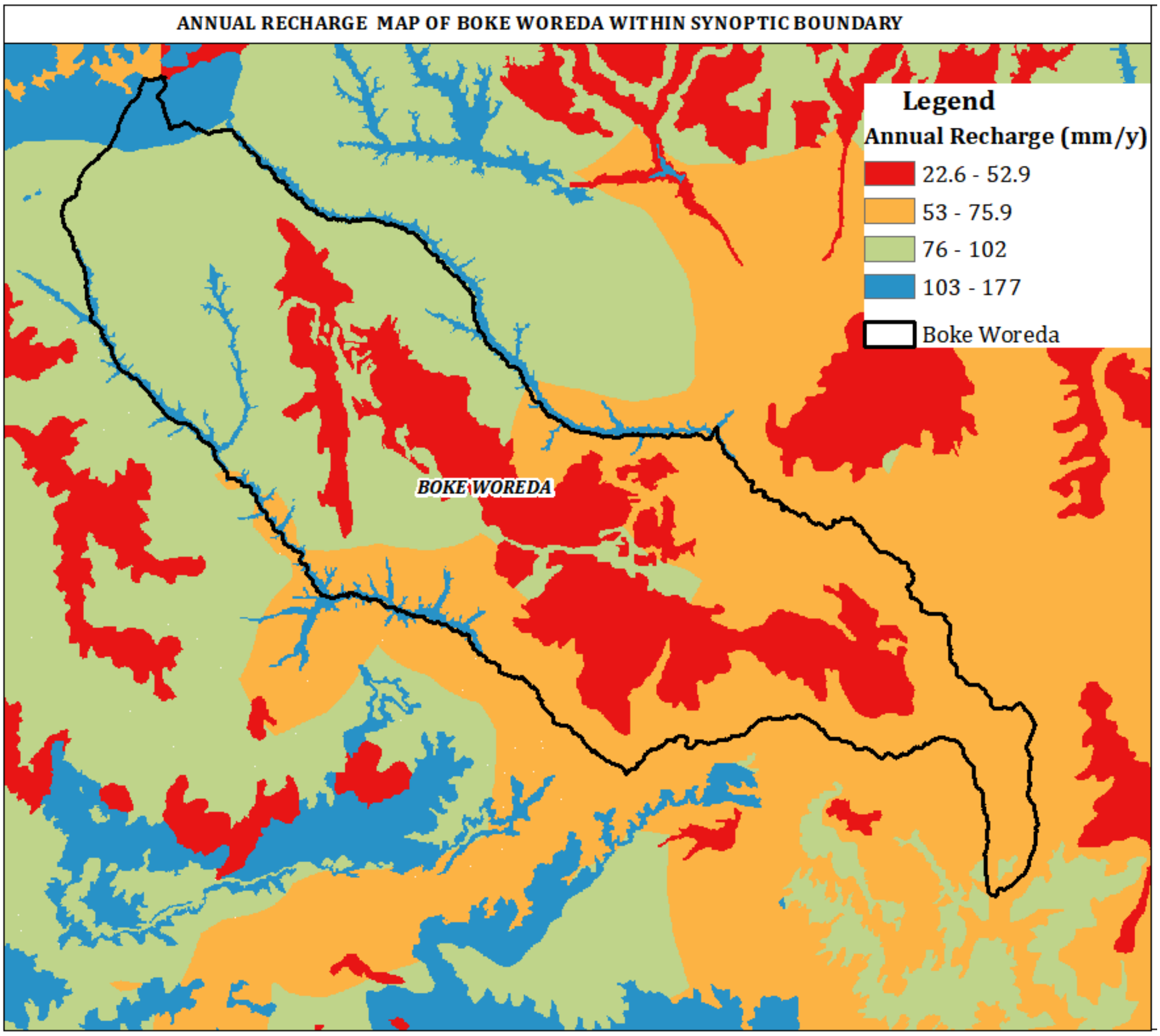

Figure 4-8. Recharge Map of Boke Woreda within Synoptic Boundary

IV. Topographic Wetness Index (TWI)

The Topographic wetness index, also known as the compound topographic index, is commonly used to quantify topographic control on hydrological processes. The index is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. The topographic wetness index (TWI) is a useful model to estimate where water will accumulate in an area with elevation differences (Sorensen, R; Zinko, U.; Seibert, J. (2006). Topographic wetness is a unitless quantity and it is represented by index with relative physical property. The topographic wetness index as a layer plays a significant role in line with other selected layers to delineate groundwater potential areas based on priority/ranking and weightage as per the layers' relative importance for groundwater enhancement/Potentiality. Accordingly, the TWI layer of Boke woreda within the synoptic area was prepared (Figure 4-9).

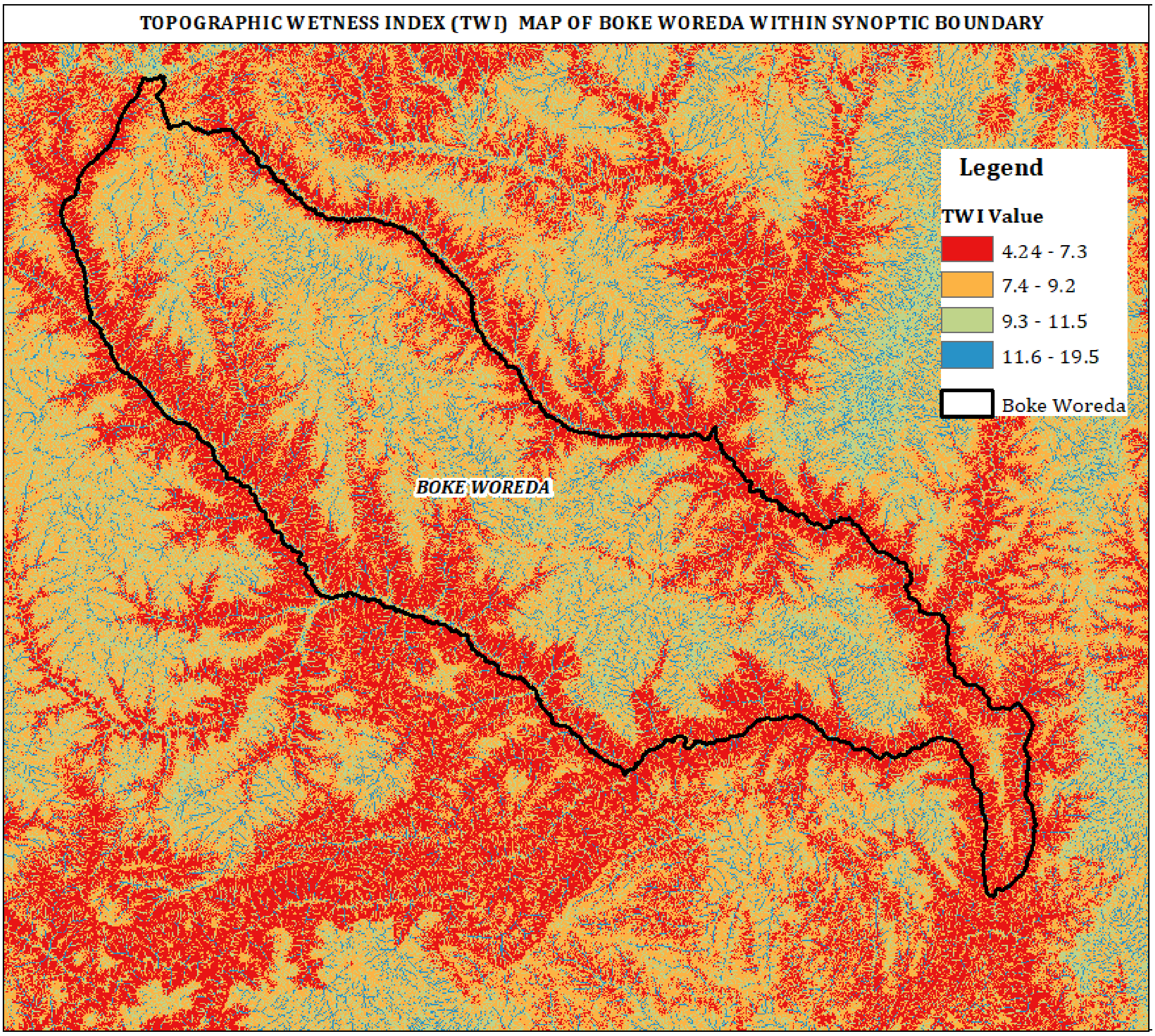

Figure 4-9. TWI Map of Boke Woreda within Synoptic Boundary

4.2.1.3. Map Layers with in Arsi-Bale Synoptic Area

The four main thematic layers and maps such as geology, grouped hydrolithological units, lineament and lineament density, TWI, and recharge were prepared for Arsi-Bale cluster synoptic rectangular area which comprises Agarfa, Gasera, Ginir, Robe, Seweyna, Sude and Tena woredas.

I. Geology

In preparation of the geological map of the target woredas within the rectangular Arsi-Bale synoptic area, major lithological units, their spatial coverage and geomorphological condition of the weredas has been assessed from existing data and previous studies and and geological map sheets (i.e., Nazret Sheet (NC 37-15), Asela Sheet (NB 37-3), Dodola Sheet (NB 37-7) & Ginnir Sheet (NB 37-4)) from the Geological Survey of Ethiopia (GSE, 1972 & 1974) and using sentnial 2 multispecgtral image for verfication and modification of the existing maps. This initial stage of the work encompasses extracting base map features, through the manipulations of topographic map in a GIS environment. The topographic map illustrates geographic references (Example, localities, names of rivers, road network and etc.) useful to mark widely distributed control points for accurate geo-referencing of previous geologic maps that is available in different scales. At local and regional scales, the follwong geological units were identified within the Arsi-Bale synoptic boundary:

Upper Hamanlie Formation (Jh2): In the geological map of Agarfa woreda, the Hamanlie Formation is commonly exposed along the valleys of streams, In the mapped area, the Upper Hamanlie Formation is typically fossil poor having two members termed as, (a) Lower Member (or Mixed carbonate-clastic sediments) and (b) Upper Member (coquina). Lower Member (Mixed carbonate-clastic Member) contains a succession of impure carbonate sediments lying directly on the Adigrat Sandstone. This member has an estimated thickness of 60-80m consisting mainly of sandy limestone, fine clastics and silty limestone. While, the Upper Member of Hamanlie encompasses coquina bearing limestone, upward thinning limestone, pellitic limestone and chert bearing grainstone.

Upper Gabredarre Formation (Jg2): The upper Gabredarre Formation is generally a thin succession of carbonates (less than100m) with distinctly large and thick-shelled fossils of gastropods and bivalves. The formation comprises fossiliferous limestone, black limestone, sandy and silty limestone.

Upper Sandstone (Ka): Upper sandstone is assumed to be the continuation of the Ambaradom Formation of central Ethiopia. The upper sandstone is stratgraphically is underlain by Gabredarre limestone. The sequential relation is best seen in the cuttings of Weyb River. The sandstone is mainly fine grained, light gray to brownish gray, mostly horizontally stratified, but at places show inclined beds, probably due to deposition on sloppy surfaces. The rock is mostly thinly to medium bedded, horizontal, continuous, parallel and planar. The top part of the sandstone is interbedded with siltstone, shale and mudrocks.

Upper Hamanilie Formation (Jh2): The upper limestone is mainly exposed in the valley cut of Wabe River. This unit is part of the southeastern Hamanlei limestone of Ethiopia. It is characterized by their grey to light grey color, thinly to medium bedded, planar, laminated, horizontal, continuous bed and fine to medium grain size. The limestones include calcarenite, calcilutite, calcisiltite with alternating thin beds of marl and lime-mudstone. There are also thin beds of siltstone and shale at the top part. These units are composed of grey to buff calcarenite and light grey calcilutite forming the lower part. Siltstone, fine grain sandstone, and shell layers occur at the top.

Cretaceous basalt (Mba): This basalt is dark grey, fine grained, massive and hard rock. This basalt flow, also show spots of scoraceous flows and generally lies on the upper sandstone.

Lower Hamanilie Formation (Jh1): The limestone is medium to coarse grained, light grey to white, dense, hard & compact rock. It shows cross-lamination to cross-bedding structures. This limestone mostly occurs below the Abduya sandstone. It is fossiliferous limestone, containing mega fossils of pelecypods, annelids and gastropods. Its composition is mainly calcite and shows light grey color and is medium to coarse grained rock. This limestone is 150 to 200 meters thick.

Arada (Cretaceouse) evaporite (Mev): This unit is overlain by anhydrite beds. The anhydrite is thinly bedded and is light greenish grey. The anhydrite is overlain by gypsum beds. The unit is mainly gypsum rock, which directly overlies the diatomite of lower limestone. The gypsum rock is mainly composed of gypsum mineral which is white, coarse grained and forms mostly massive, hard and compact rock. The claystone is grey, ultrafine and thinly bedded. At the higher stratigraphy comes again interbeds of gypsum and anhydrite layer. The gypsum is coarse grained, light grey and thin to thickly bedded. The anhydrite is thin to medium bedded and light greenish grey and is fine to medium grained.

Harbucha Sandstone (Mhsst): This unit is mainly exposed in the narrow, steep-sided, in high altitude, gently undulating areas adjacent to the gorge. The sandstone is light grey, sometimes variegated (light yellow, light brown, green to greenish grey and yellowish to whitish grey). It is fine- to coarse-grained, poorly to well sorted, with rounded to sub rounded grains. Quite often the rock is deeply weathered and loose. In general, the sandstone sequence fines upwards.

Abduya sandstone (Masst): The Abduya sandstone is light grey to white quartzose sandstone with thin bedding, which at places form rhythimic occurrence with arkosic sandstones. At places it also shows thick beds to massive. Arkosic sandstone is pinkish, fine to medium grained, hard and massive rock. The sandstone shows parallel and continuous beds of hard and compact rock. It is often interbedded with similar lenticular beds which often pinch out.

The lower lava flows (Tv1): The lower lava flows contains dominantly basalts, with minor amount of lower pyroclastic rocks. Between each lava layer, lateral facies of scoria flow occur. Several basalt layers form the lower lava flows. The basalts are commonly columnarly jointed and horizontally stratified and at places deeply weathered. Where weathering and alteration is intense secondary minerals such as zeolite and calcite are abundant. In some places the basalts are compact, hard and massive dark gray to black rocks.

The middle lava flows (Tv2): This unit is exposed in various localities lying above the Tv1 with distinct unconformity, marked by paleosoil. They are thin relative to lower lava flows, and these are also horizontally stratified relatively hard and compact dark grey basalts. These rocks are cliff forming on the plateau scarp north of Agarfa town and west of Sheneka plain. Compositionally, they are plagioclase phyric basalts which are at places interlayered with pyroclastic flow deposits. At places, the Tv2 is aphanitic dark grey basalts, but also occur as gray, coarse plagioclase phyric basalts. Most of these basalts are medium to coarse grained, massive, compact hard and fresh basalts. Zeolite and calcite are well developed along the cavity of the rock.

The plateau basalt Tv3 (1): These basalts form mostly the most top part of the plateau and hard resistant flat highland surface. But, at places, they form thinly layered medium to coarser basalts. The basalts are mainly aphanitic, dark grey, fine grained and very slightly weathered. The basalt includes, porphyritic plagioclase basalts, fine grained basalts, scoraceous vesicular basalts, pyroxene phyric basalts, olivine plagioclase phyric basalt. The basalts are rarely columnar and are mainly massive, dense and compact flows. At places, secondary minerals such as zeolites commonly fill the vesicles.

The upper pyroclasts (Tv3 (2)): The upper pyroclasts which are previously known as the Nazreth series cover vast plateau area. The thickness varies from place to place and the total thickness can reach up to 250 m. These pyroclasts include ignimbrites, ash-fall tuffs, gravelly ash, ash-fall deposits, volcanic breccias, & normal tuff. The upper pyroclasts outcrop, below the Termaber basalt, Chilalo basalt, Kaka basalt. At places the ignimbrite has well developed sanidine crystals and/or cavity like inclusions of secondary infillings that are partly decomposed. The common color is grey but it also has pinkish and grayish green varieties. The ignimbrite is usually below the tuff, ash-fall or ash-flow deposits.

The highland basalt flows (Tv4): Highland basalt forms mainly the highlands of Bale Mountain National Park extending to Mt. Shewiso. These are central eruptions and exposed on top of upper pyroclasts. These lava flows form large plateau areas and are younger fresh basalts. The basalts are separated with thin paleosoils. The basalts are fine grained and at places columnarly jointed. The highland basalts are correlated to the Termaber Formation and there are minor trachyte flows on top of the basalts. In the Bale Mountains National Park olivine-plagioclase phyric basalt, plagioclase phyric basalt, pyroxene-plagioclse phyric basalts are exposed.

Gobesa trachyte (Tv5): This is exposed mainly following the Galema mountain chains. This was probably originated prior to the major Pliocene trachyte flows. It is massive, fine to medium grained and often shows clear sanidine crystal.

Pliocene basalt flows (Tv6): The Pliocene basalts are exposed on the highland areas, restricted to the foot slopes of Mt. Shewiso in the area. The basalts are fresh, compact, massive, and dense, usually grey to dark grey in color. Compositionally, Tv6 contains plagioclase, olivine, and secondary minerals such as zeolite and calcite. The Pliocene basalt flows are immediately overlain by Plio-Pleistocene trachyte flows. They are younger post-rift flows.

Pliocene trachyte flows (TV7): These trachyte flows form the summit of Bale Mountain National Park. The Plio-Peistocene trachyte flows are younger post-rift central type flows. They are light grey, slightly weathered, fine to medium grained and locally porphyritic, showing sanidine phenocrysts.

Arba Gugu Basalts (N1g): This unit erupted from Arba Gugu shield volcano, is represented by successive lava flows up to 300 meters thick, made up mostly of porphyritic pyroxene and/or plagioclase basalts.

Quaternary Basalt Flows (Qv1): These basalts are exposed on the summit of Bale Mountains, also covering plateau of Bale regions, to the east of Agarfa and Senana State farm area in particular.They are relatively fresh, lessely decomposed rocky surface which are hard and compact, fine to medium grained and dark grey colored .The basalts are often vesicular but mainly form coarse grained basalts and rich in opaque minerals. The scoraciaceous olivine-phyric basalts are dark brown and grayish red in color. Locally it shows color band and slightly weathered. The Senana farm area is covered by relatively fresh, dark grey, vesicular plagioclase phyric and aphanitic basalt lava flows. At places it occupies lower topographic areas.

Scoria cones (Qv2): The scoria cones are younger central eruption. They are assumed to be Quaternary in age for both in the Main Ethiopian Rift and on the plateau. Separate hills in the Arsi Zone and also in the Bale Zone are formed of scoria falls, often showing slopping stratification in minor areas. Scoria cones show thin layering on the flanks of the vent. The scoria is rather loose or unconsolidated, but is gently stratified and forms cone. The material is composed of gravely fall deposit of scoria pieces, but also occurs as sandy or minor sizes which are either grey or pinkish to reddish in color.

Quaternary alluvial fan (Qaf): This type of flood deposit is thick decomposed soil forms the plain. In some areas the unit shows horizontally stratified silt sand layers of 1.5m thick. This occur interbedded with 20 m thick, horizontally layered sandy gravels. The gravels are pieces of limestone and sandstone removed from early formed rocks, during Quaternary. In most of the area the deposit is represented by massive thick brown soil.

Quaternary calcretes (Qcal): The calcretes are secondary limestone forming small patchy areas. They have been developed mostly, on the upper sandstone exposure, and rarely on lower limestone. This calcrete is hard, compact and cemented concretions of carbonates, with rough surfaces. At places it develops to pure limestone bed rock with smooth surface. Mostly the calcrete represent recemented carbonate materials containing various rock fragments, but in most cases, it is mainly limestone. The calcrete is light grey color with various grain sizes.

Quaternary alluvium 1 (Qal1): This type of river deposit is mostly exposed in the southeastern lowlands of the map area. It occurs in Hada and Hida Deno rivers and their minor tributaries. The Quaternary alluvium is heterogeneous deposits of silty sands, sandy gravels, and also decomposed soil. Most of the time, they cover wide distributaries channels and are relatively older Quaternary deposits. They represent mostly flood plains restricted to fossil river valleys. Recent river course cuts such deposits.

Quaternary alluvium 2 (Qal2): These are exposed also in the southeastern parts of the map mainly occurring along river valleys. There are also minor sediments occurring near the side of the river or beyond. They are relatively younger Quaternary deposits, containing soil mixed with sands and gravels.

Quaternary alluvium 3 (Qal3): Such deposits also occur towards the central southeastern parts of the map area. They represent present day river deposit or younger alluvial deposit mainly restricted to the valley floors. Quaternary alluvium-3 is heterogeneous deposit of different transported sediments Major geological units found within Arsi-Bale synoptic boundary is shown in Figure 4-10.

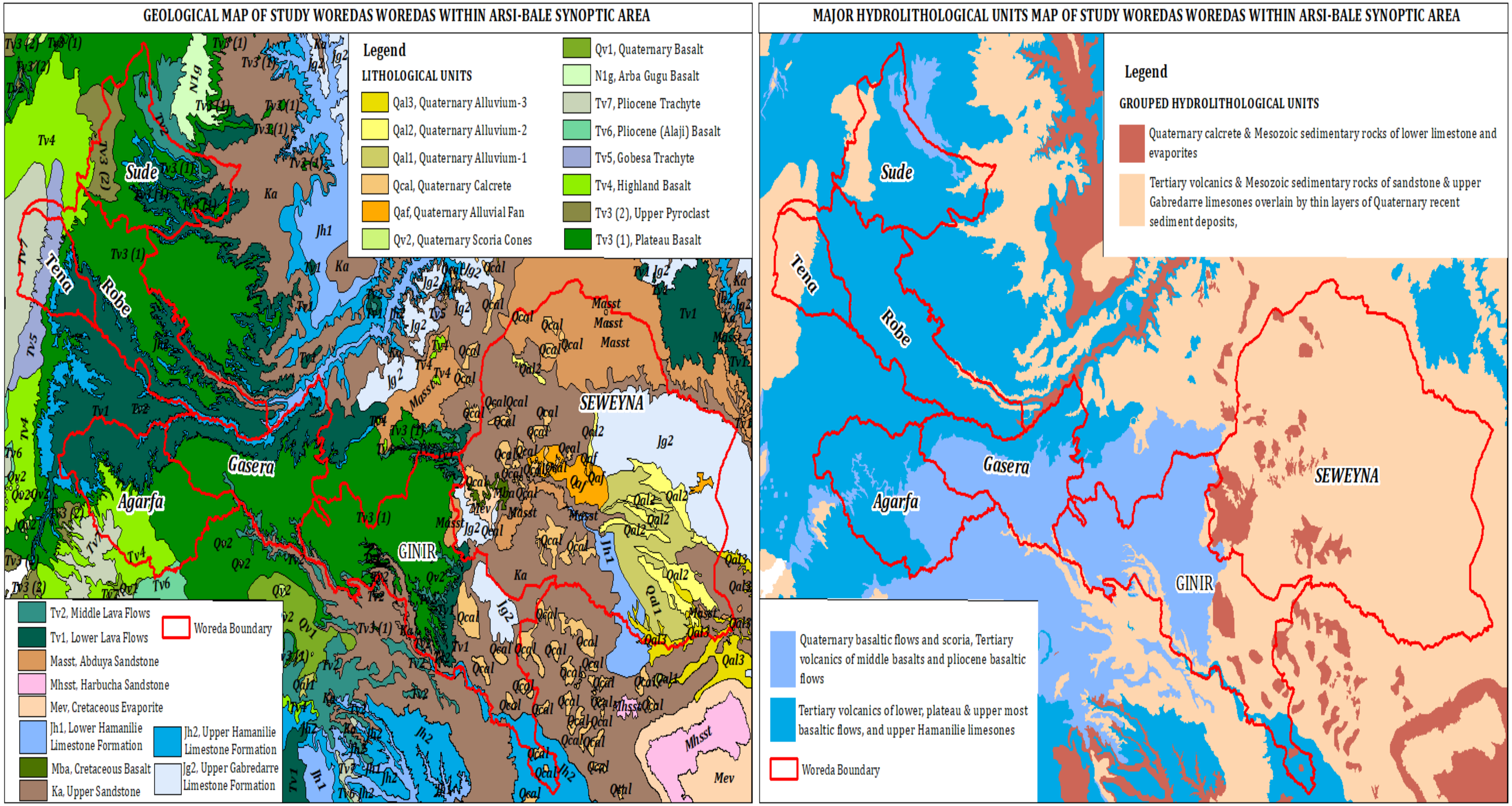

Figure 4-10. Geological and Grouped Hydrolithological Units Maps of Arsi-Bale Cluster Synoptic Area

II. Geological structures/Lineaments and Lineament Density

Lineaments are manually extracted with great care using DEM from (https://earthexplorer.usgs.gov/), hybrid morphometric maps, satellite images (Sentinel 2 from https://scihub.copernicus.eu/) and exisiting geological maps of the Arsi-Bale synoptic area.

The synoptic area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent orientation of lineaments identified are NW-SE and NE–SW trending lineaments.

Usually, lineaments are presented in the form of lineament density. Lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. Accordingly, lineament densisty map of Agarfa, Gasera, Ginir, Robe, Seweyna, Sude and Tena woredas within the Arsi-Bale synoptic boundary was generated using an alogorithm in ArcGIS Spatial Analyist tool with a radius of about 1.5 km taking into consideration of intercepting all the identified lineaments, and maximum distance between the intersections and distribution of lineaments (Figure 4-11).

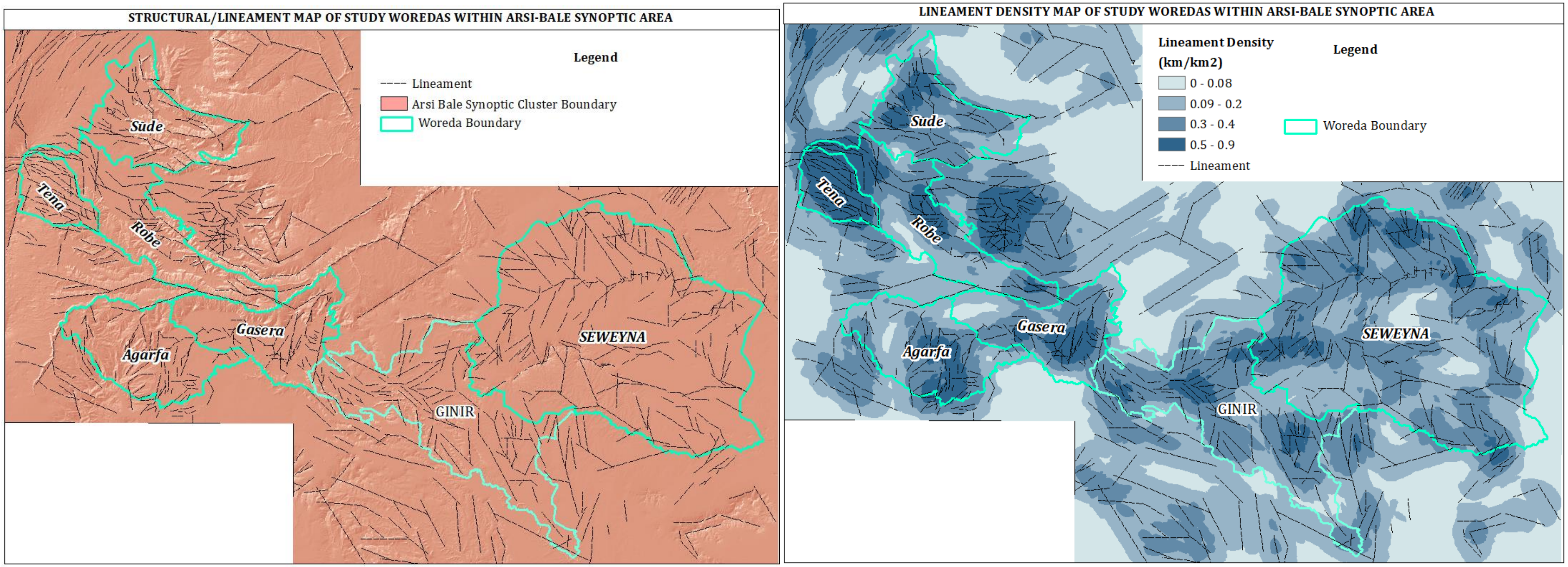

Figure 4-11. Geological Structure/Lineament and Lineament Density Maps of Arsi-Bale Cluster Synoptic Area

III. Recharge

The mean annual rainfall raster maps were obtained from open sources of CHIRPS satellite imageries of 10 years from 2011 to 2020 mean annual rainfall on geological survey of America (USGS) official website (https://chc.ucsb.edu/). The infiltration coefficients of geological units were obtained from Abay River Basin Integrated Resources Development Master Plan Study report (MoWR, 1999). According to the master plan study, the IC of various lithological units could be assigned based on the results obtained from recharge estimations made using an integrated approaches including base flow separation and estimation of proportion of annual rainfall amount that to be percolated to the subsurface based on correlation made between each lithological unit identified within the basin using a developed mathematical equation. Therefore, for the current study, the IC values were extracted from the basin study that have similar properties of lithological units found in the current study area and accordingly assigned to each lithological unit (Table 4-3). Then, the geological map converted to raster based on the assigned value of IC with cell size of 100m on ArcGIS platform. Finally, the raster maps of rainfall and IC of lithological units were multiplied using a raster calculation algorithm in ArcGIS in order to obtain spatial map of annual recharge amount for the project area (Figure 4-12).

Table 4-3. Assigned Infilitration Coefficent for Lithological Units (Correlated with Abay Master Plan Studies, MoWR, 1998) for Arsi-Bale synoptic area

Lithological Units (Study area)		**Assigned Infiltration Coefficient (IC)**	**Lithological Units (Abay Basin)**	
Symbol	**Description**		**Symbol**	**Description**
Qal1	Quaternary Alluvium-1	0.15	QAll	Alluvium
Qal2	Quaternary Alluvium-2	0.2	QAll	Alluvium
Qal2	Quaternary Alluvium-3	0.2	QAll	Alluvium
Ql	Lacustrine Sediment	0.15	QLAC	Lacustrine deposits
Qaf	Quaternary Alluvial Fan	0.2	QAll	Alluvium
Qv2	Quaternary Scoria Cones	0.2	QCB2	Basalts related to volcanic centres (2)
Qv1	Quaternary Basalt	0.15	QCB3	Basalt lava flows connected to volcanic centers (3)
N1g	Arba Gugu Basalt	0.1	TBNB	Blue Nile Basalts
Tv7	Pliocene Trachyte	0.1	QATB	AlkaliTrachyte, minor Basalt
Tv6	Pliocene (Alaji) Basalt	0.1	TBNB	Blue Nile Basalts
Tv5	Gobesa Trachyte	0.1	QATB	AlkaliTrachyte, minor Basalt
Tv4	Uppermost (Highland) Basalt	0.15	TASB	Ashangi Basalts
Tv3(2)	Upper Pyroclast	0.05	TAAB	Amba Aiba Basalts
Tv3(1)	Plateau Basalt	0.15	TASB	Ashangi Basalts
Tv2	Middle Lava Flows	0.15	TASB	Ashangi Basalts
Tv1	Lower Lava Flows	0.1	TBNB	Blue Nile Basalts
Masst	Abduya Sandstone	0.15	KAA2`	Amba Aradam Sandstone (2)
Jh1	Lower Hamanilie Limestone	0.1	JANL	Antalo Limestone
Mba	Cretaceous Basalt	0.1	TBNB	Blue Nile Basalts
Ka	Upper Sandstone	0.15	KAA2`	Amba Aradam Sandstone (2)
Jh2	Upper Hamanilie Limestone	0.1	JANL	Antalo Limestone
Jg2	Upper Gabredarre Limestone	0.1	JANL	Antalo Limestone

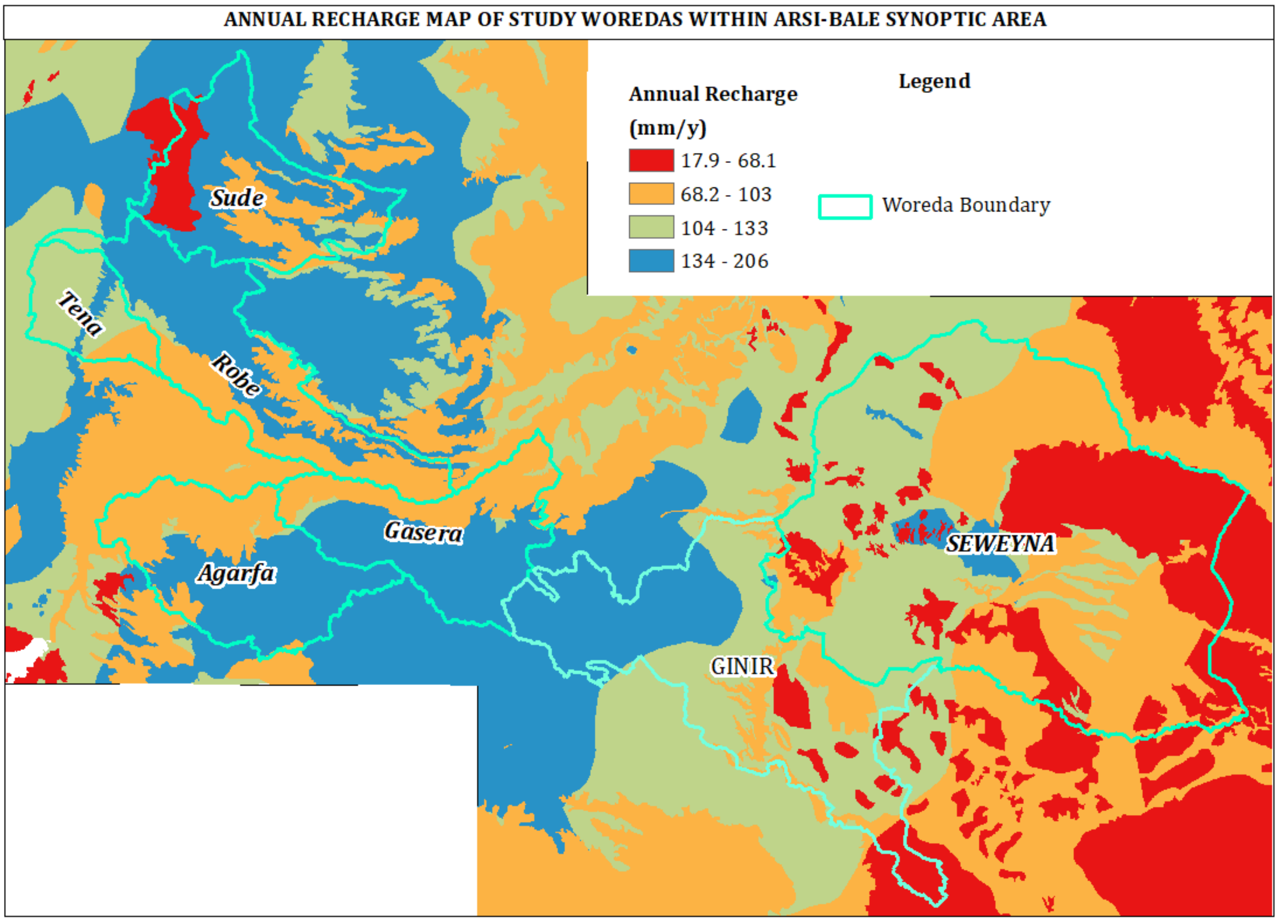

Figure 4-12. Recharge Map of Arsi-Bale Cluster Synoptic Area

IV. Topographic Wetness Index (TWI)

The Topographic wetness index, also known as the compound topographic index, is commonly used to quantify topographic control on hydrological processes. The index is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. The topographic wetness index (TWI) is a useful model to estimate where water will accumulate in an area with elevation differences (Sorensen, R; Zinko, U.; Seibert, J. (2006). Topographic wetness is a unitless quantity and it is represented by index with relative physical property. The topographic wetness index as a layer plays a significant role in line with other selected layers to delineate groundwater potential areas based on priority/ranking and weightage as per the layers' relative importance for groundwater enhancement/Potentiality. Accordingly, the TWI layer of Agarfa, Gasera, Ginir, Robe, Seweyna, Sude and Tena woredas within the Arsi-Bale synoptic area was prepared (Figure 4-13).

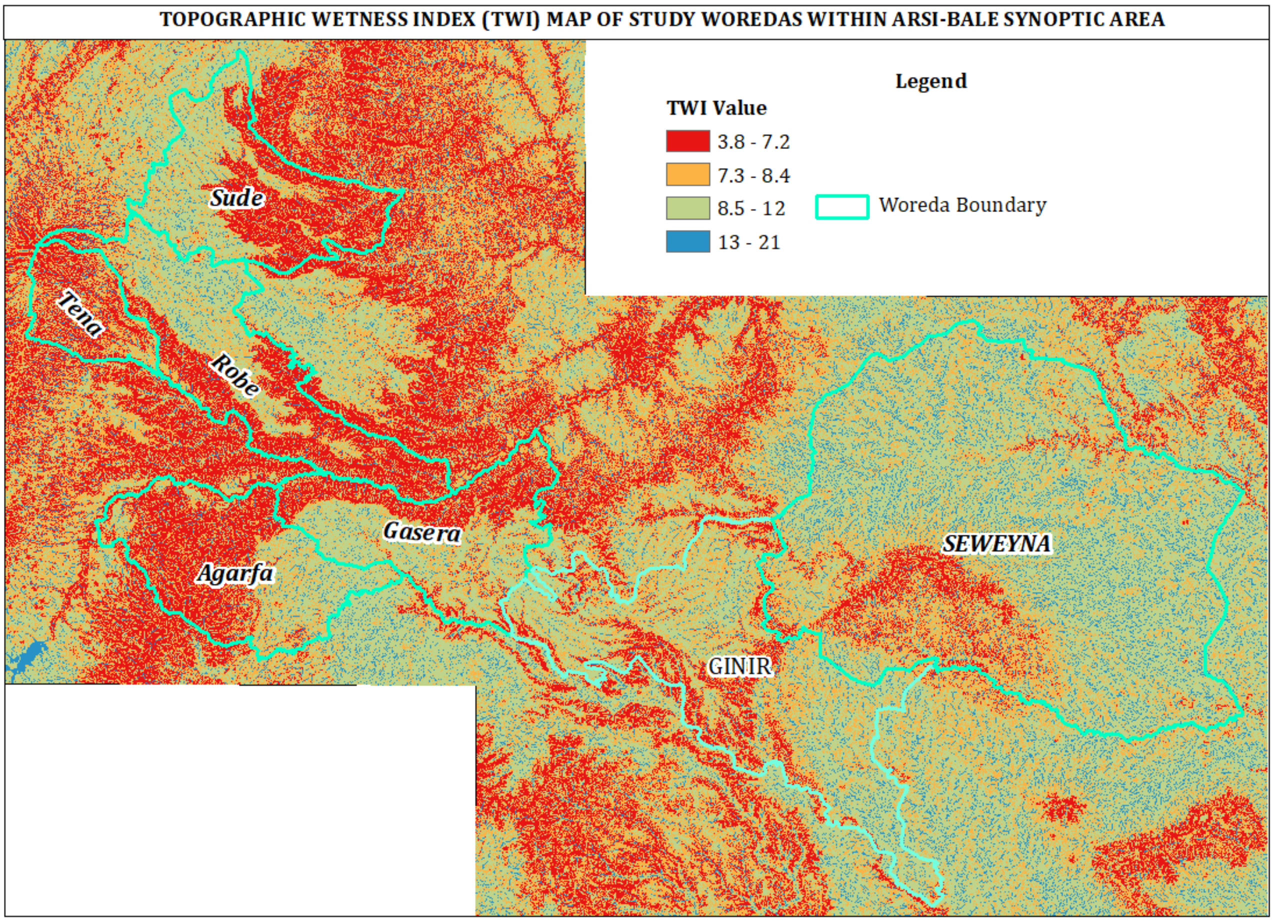

Figure 4-13. TWI Map of Arsi-Bale Cluster Synoptic Area

4.2.1.4. Map Layers with in Somali Synoptic Area

The four main thematic layers and maps such as geology, grouped hydrolithological units, lineament and lineament density, TWI, and recharge were prepared for Somali cluster synoptic rectangular area which comprises Adadle, Chereti, Elkere and Dolobay woredas.

I. Geology

In preparation of the geological map of the target woreda, major lithological units, their spatial coverage and geomorphological condition of the wereda has been assessed from existing data and previous studies and Geological mapsheets (i.e., Immi(NB-38-5), Kebridehar(NB-38-6), Elkerer(NB-38-9), Dolo(NB-38-13) and Kelafo(NB-38-10)) from the Geological Survey of Ethiopia (GSE, 1972 & 1974) and using sentnial 2 multispecgtral image for verfication and modification of the existing maps. This initial stage of the work encompasses extracting base map features, through the manipulations of topographic map in a GIS environment. The topographic map illustrates geographic references (Example, localities, names of rivers, road network and etc.) useful to mark widely distributed control points for accurate geo-referencing of previous geologic maps that is available in different scales. At regional scale, the following geological units are exposed in the synoptic cluster:

Tertiary basalt (Tba)

Basaltic peaks and ridge are mostly exposed in eastern areas of the map. It forms chain ridge of that extends northwest to southeast, and also form isolated hillocks. The total thickness of the Tertiary volcanic ranges 50 m to 250 m.

The basalt shows spheroidal weathering. The basalt show gray to dark color, and is fine to medium grained. It is slightly to moderately weathered, massive rocks which form hills, and is dissected by gulley and streams. The basalt includes olivine - plagioclase phyric, plagioclase –olivine phyric and aphanitic basalts. The basalt are often vesicular, amygdaloidal, and aphanites. The vesicular basalts are filled by calcite and chalcedony. Some vesicles are devoid of secondary minerals.

Fluvial sand silt (Stream channel deposit) (Qal)

These deposits occur mainly along the seasonal river channels found at eastern and northern parts of the study area.

The sediments are loose, poorly sorted and characterized by different broken rock fragments of gypsum, limestone and sandstone that range from silty-clayey to cobbles and often boulder size fragments.

Gravely sand silt (Alluvial fan deposit) (Qaf)

Thin eluvium cover is found on a limited flat land around northern areas of the map , frequently covering the gypsum and sandstone rocks. It is brown to reddish color and consists of silt to sand size particles. In rivers and stream cuts this deposit has a maximum thickness of about 5 m. Quaternary alluvial deposit occurs mainly along the seasonal river channels found at eastern and northern parts of the area. The sediments are loose, poorly sorted and characterized by different broken rock fragments of gypsum, limestone and sandstone that range from silty-clayey to cobbles and often boulder size fragments.

Gypsum, anhahydrite and potash intercalations with marl (Kg)

This evaporite covers extensive areas of the map which extends from southeast to northwest parts of the area. This lithological unit covers mostly flat land, but at places it forms hill and cliff particularly at eastern, southern and western regions of the area. It is mainly exposed by stream cut in areas of low topography.

Limestone locally cherty (Korahe_Belet Uen) (km)

This upper Korahe formation contains dominantly gypsum rock with minor shale, mudstone and lime mudstone and. Hill forming gypsum rock is mostly massive, horizontal, continuous and underlies the limestone. This formation is found on western and eastern part of the area.

Limestone with minor marl, micritic, bioclastic and oolitic (Upper Hamanlie Formation (Jh2)

This unit is mainly exposed in the extreme west boundary of the geological map of the area dissecting the Genale River. In many of its exposures, this limestone forms flat land and gentle slope topography. The limestone is mainly sandy limestone mostly light gray to yellowish, medium grained and slightly weathered rock. It shows bedding to laminations. The sandy limestone is hard, dense & compact rock.

Bottom section of the limestone succession is marked by sandy limestone grading upward to calcareous sandstone and calcareous siltstone.

Marly limestone, shaly mudstone and siltsone intercalations (Lower Korahe Formation (Kg1))

This unit is exposed at low land areas of central eastern parts of the geological map. The limestones are characterized by their light gray to yellow color, massive to medium bedded, planar, laminated, and horizontal, continuous beds and medium to coarse grain size. The limestones include calcarenite, calcirudite, marly limestone and rare sandy limestone outcrops. This unit is underlain by sandstone and overlain by anhydrite & gypsum.

Sandstone, siltstone intercalations with local limestone (KoraheAmbaradom) (Ka)

This formation is found on central part of the area. This unit is found intercalated with siltstone and hence named locally as Harbuch Sandstone.

Shale mudstone_limetone intercalations (Gabradarre)(Jg)

This formation is found on western part of the area. This unit is found intercalated with Sandstone and hence named locally as Harbuch Sandstone and is exposed central western parts of the map area. The maximum thickness measured in this unit is about 100 m. It is light grey, sometimes variegated (light yellow, light brown, green to greenish grey and yellowish to whitish grey). It is fine- to coarse-grained, poorly to well sorted, with rounded to sub rounded grains. Quite often the rock is deeply weathered and loose.

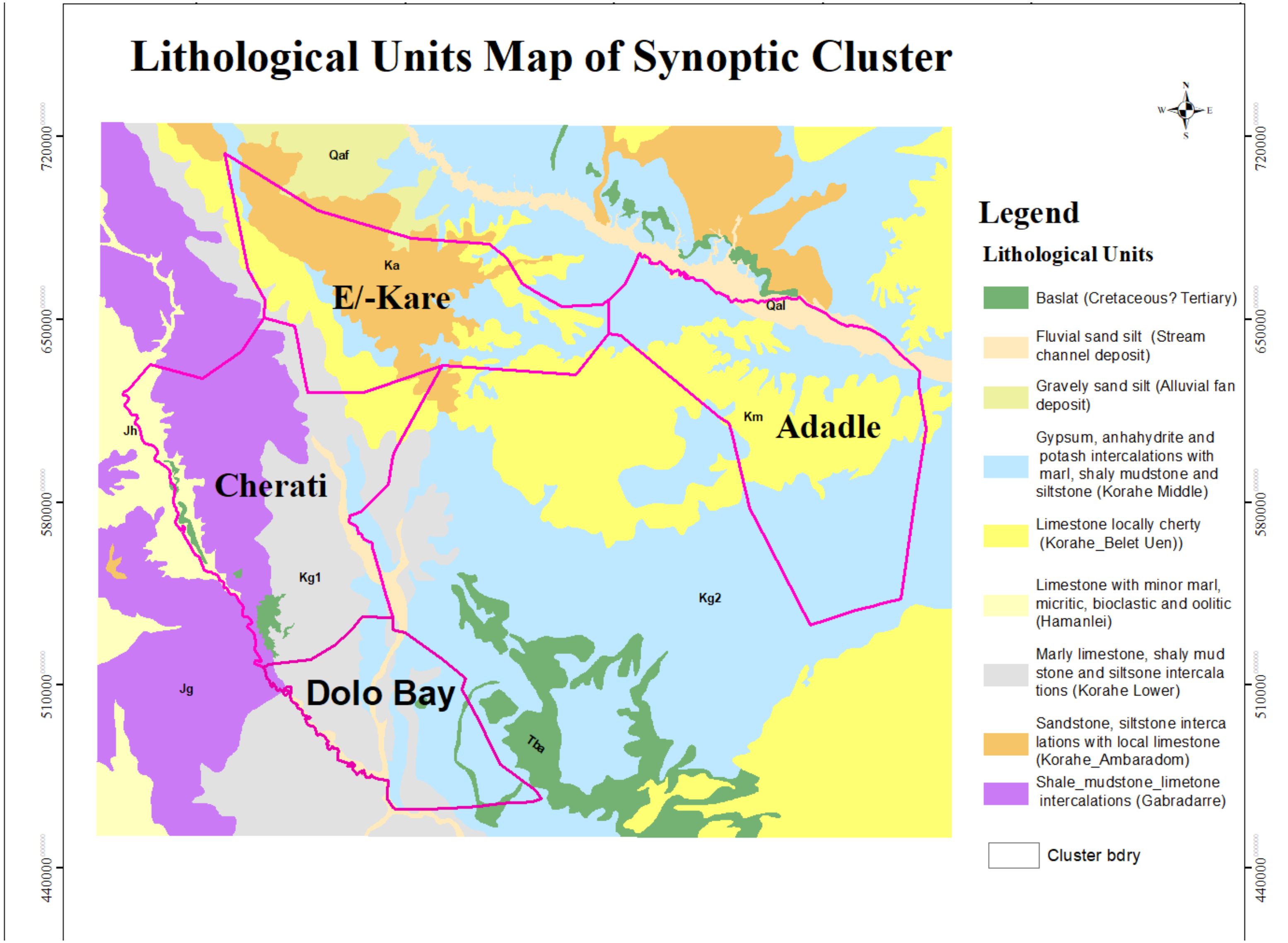

Figure 4-14 Geological Map of Somali Cluster Synoptic Area

II. Lineaments and Lineament Density

Lineaments are manually extracted with great care using DEM from (https://earthexplorer.usgs.gov/), hybrid morphometric maps, satellite images (Sentinel 2 from https://scihub.copernicus.eu/) and exisiting geological maps of the area.

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SE and N–S trending lineaments. Usually, lineaments are presented in the form of lineament density. Lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone.

For Adadleworeda, the lineament density varies from less than 0.26 km/km2 to 1.06 km/km^2 (Figure 4-15). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by mesozoic sediments associated with tertiary volcanics and quaternary sediments having relatively higher lineament density of 0.79 – 1.06 km/km2) compared with areas underlain by sedimentary rocks of lower Hamanilie limestone and lower sandstone with lower lineament densities of (<0.26 km/km2).

Thus, areas with higher lineament density are regarded as having good contribution for groundwater recharge and storage.

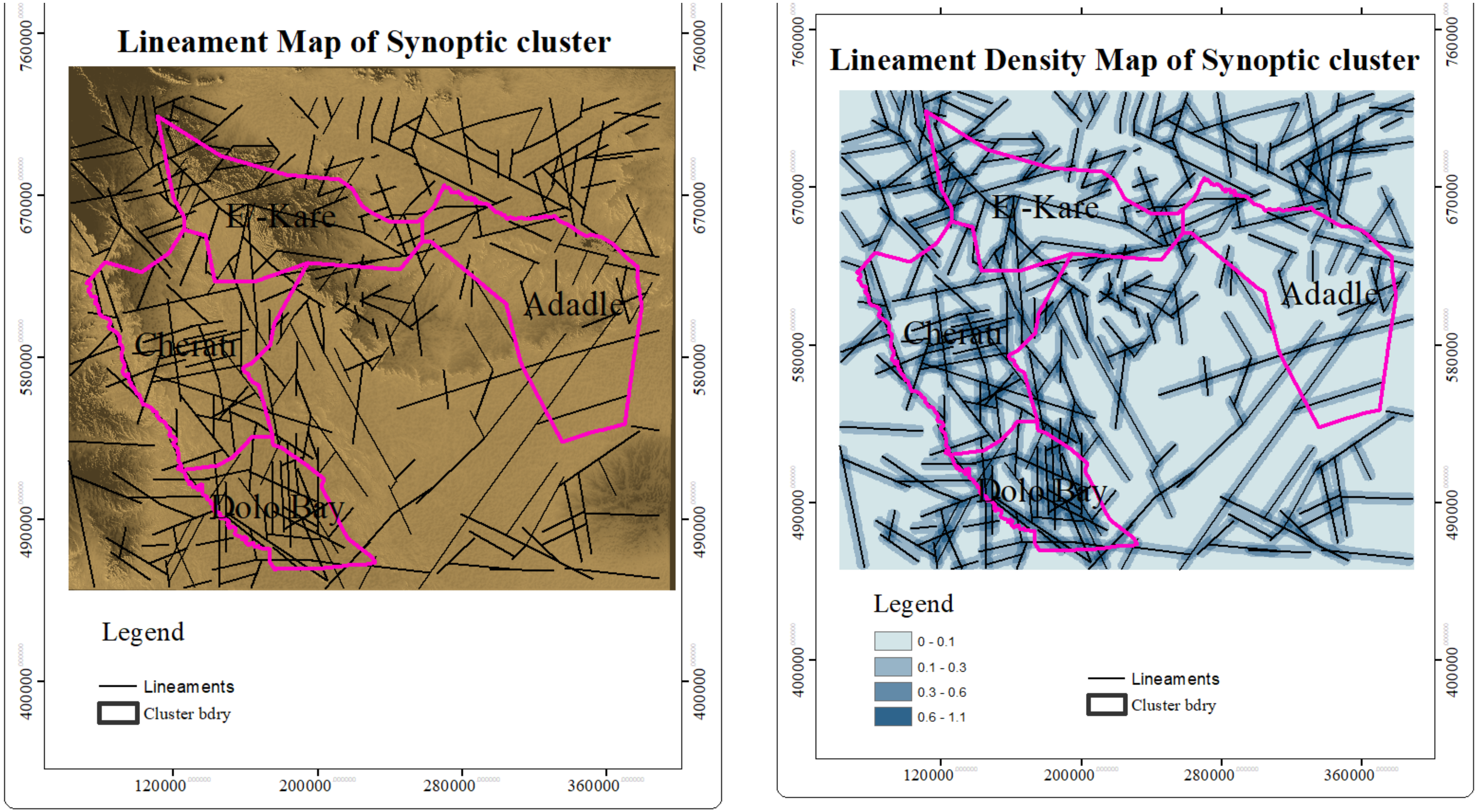

Figure 4-15 Geological Structure/Lineament and Lineament Density Maps of Somali Synoptic Area

III. Recharge

The mean annual rainfall raster data set were obtained from open sources of CHIRPS satellite imageries of 10 years from 2011 to 2020 mean annual rainfall on geological survey of America (USGS) official website (https://chc.ucsb.edu/). The infiltration coefficients of geological units were obtained from Abay River Basin Integrated Resources Development Master Plan Study report (MoWR, 1999). According to the master plan study, the IC of various lithological units could be assigned based on the results obtained from recharge estimations made using an integrated approaches including base flow separation and estimation of proportion of annual rainfall amount that to be percolated to the subsurface based on correlation made between each lithological unit identified within the basin using a developed mathematical equation. Therefore, for the current study, the IC values were extracted from the basin study that have similar properties of lithological units found in the current study area and accordingly assigned to each lithological unit (Table 4-4).Then, the geological map converted to raster based on the assigned value of IC with cell size of 100m on ArcGIS platform. Finally, the raster maps of rainfall and IC of lithological units were multiplied using a raster calculation algorithm in ArcGIS in order to obtain spatial map of annual recharge amount for the project area.

Table 4-4.Assigned InfilitrationCoefficent for Lithological Units (Correlated with Abay Master Plan Studies, MoWR, 1998) for Somali cluster area

Lithological Units (Study area)		Assigned Infiltration Coefficient (IC)	Lithological Units (Abay Basin)	
Symbol	**Description**		**Symbol**	**Description**
Qal1	Quaternary Alluvium-1	0.15	QAll	Alluvium
Qal2	Quaternary Alluvium-2	0.2	QAll	Alluvium
Qal2	Quaternary Alluvium-3	0.2	QAll	Alluvium
Ql	Lacustrine Sediment	0.15	QLAC	Lacustrine deposits
Qaf	Quaternary Alluvial Fan	0.2	QAll	Alluvium
Qv1	Quaternary Basalt	0.15	QCB3	Basalt lava flows connected to volcanic centers (3)
Tv1	Lower Lava Flows	0.1	TBNB	Blue Nile Basalts
Masst	Abduya Sandstone	0.15	KAA2`	AmbaAradam Sandstone (2)
Jh1	Lower Hamanilie Limestone	0.1	JANL	Antalo Limestone
Mba	Cretaceous Basalt	0.1	TBNB	Blue Nile Basalts
Ka	Upper Sandstone	0.15	KAA2`	AmbaAradam Sandstone (2)
Jh2	Upper Hamanilie Limestone	0.1	JANL	Antalo Limestone
Jg2	Upper Gabredarre Limestone	0.1	JANL	Antalo Limestone

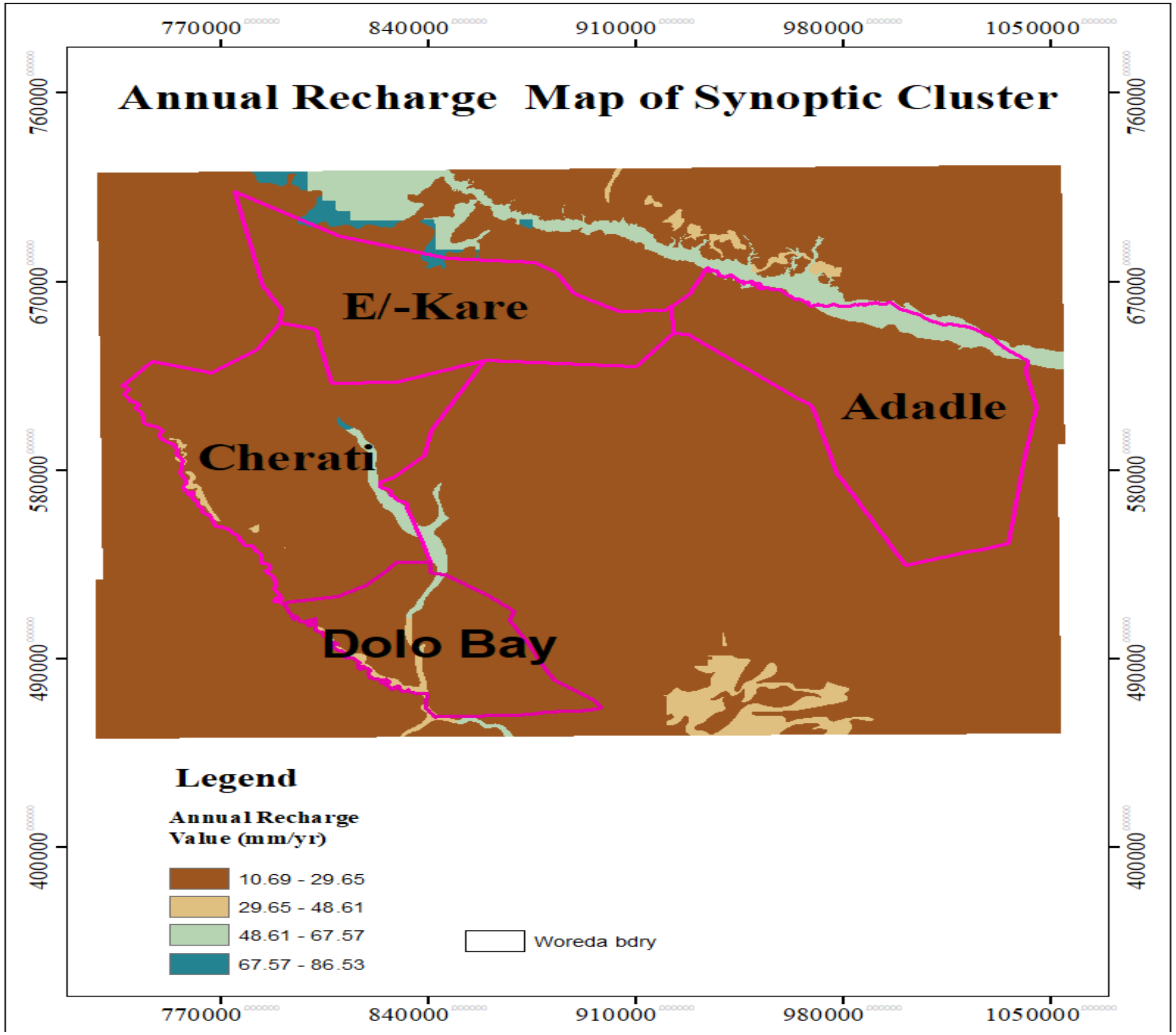

Figure 4-16 Annual Recharge Map of Adadle woreda within Synoptic Boundary

IV. Topographic Wetness Index (TWI)

The Topographic wetness index, also known as the compound topographic index, is commonly used to quantify topographic control on hydrological processes. The index is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. The topographic wetness index (TWI) is a useful model to estimate where water will accumulate in an area with elevation differences (Sorensen, R; Zinko, U.; Seibert, J. (2006). Topographic wetness is a unitless quantity and it is represented by index with relative physical property. The topographic wetness index as a layer plays a significant role in line with other selected layers to delineate groundwater potential areas based on priority/ranking and weightage as per the layers' relative importance for groundwater enhancement/Potentiality. Accordingly, the TWI layer of Dolobay, Cgereti, Adadle and Elkere woredas within the Somali synoptic area was prepared (Figure 4-17).

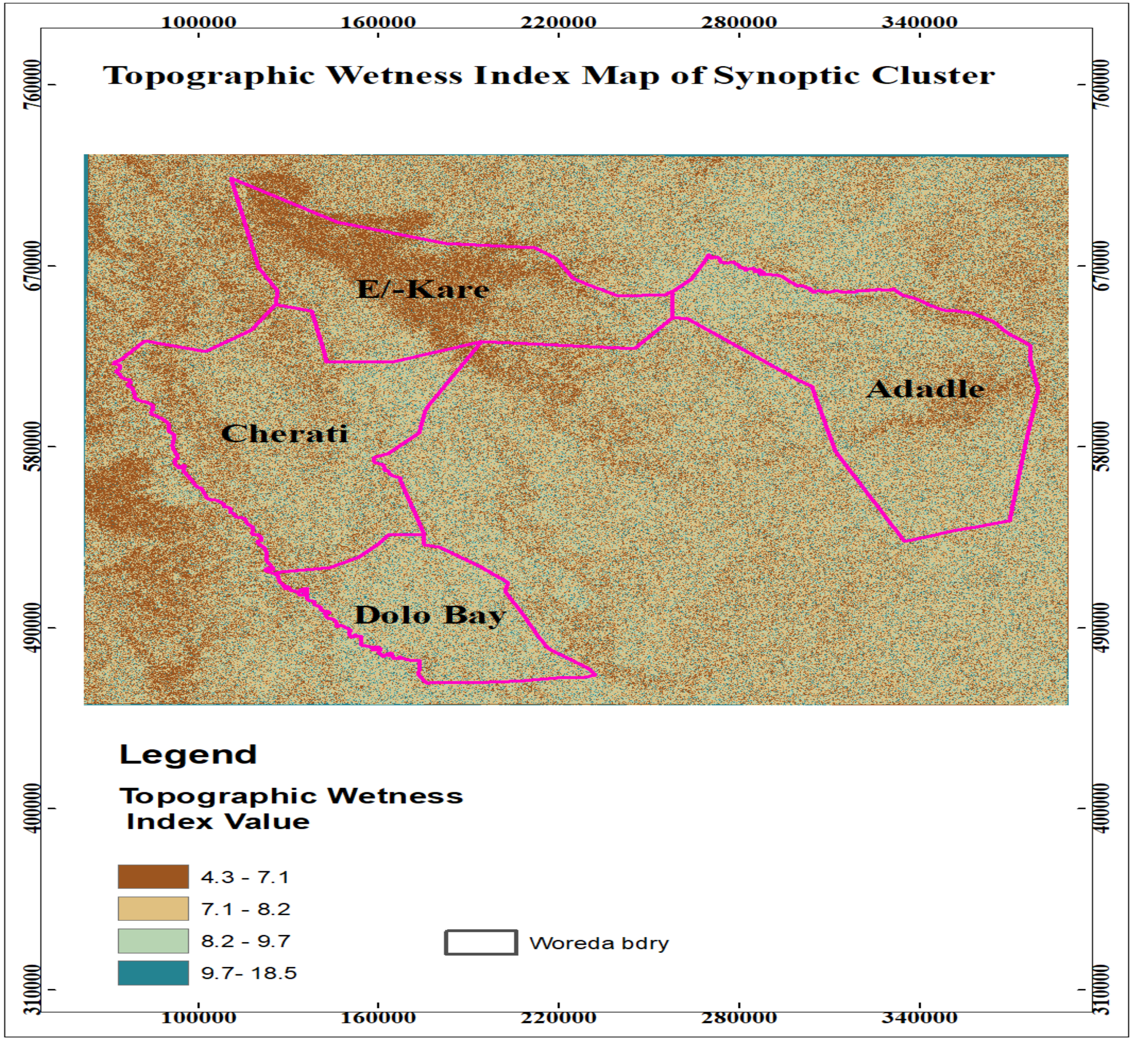

Figure 4-17. TWI Map of Somali Synoptic Boundary

4.2.1.5. Map Layers with in Dihun Synoptic Area

The four main thematic layers and maps such as geology, grouped hydrolithological units, lineament and lineament density, TWI, and recharge were prepared for Dihun Rectangular cluster synoptic area which comprises Dihun woreda.

I. Geology

In preparation of the geological map of the target woreda, major lithological units, their spatial coverage and geomorphological condition of the wereda has been assessed from existing data and previous studies and Geological map sheets (i.e., Immi (NB-38-5), and Dagamado (NB-38-1)) from the Geological Survey of Ethiopia and using sentnial 2 multispecgtral image for verfication and modification of the existing maps. This initial stage of the work encompasses extracting base map features, through the manipulations of topographic map in a GIS environment. The topographic map illustrates geographic references (Example, localities, names of rivers, road network and etc.) useful to mark widely distributed control points for accurate geo-referencing of previous geologic maps that is available in different scales. At regional scale, the following geological units are exposed in the synoptic cluster:

Gravely sand silt (Alluvial fan deposit) (Qaf)

Thin eluvium cover is found on a limited flat land around northern areas of the map , frequently covering the gypsum and sandstone rocks. It is brown to reddish color and consists of silt to sand size particles. In rivers and stream cuts this deposit has a maximum thickness of about 5 m. Quaternary alluvial deposit occurs mainly along the seasonal river channels found at eastern and northern parts of the area. The sediments are loose, poorly sorted and characterized by different broken rock fragments of gypsum, limestone and sandstone that range from silty-clayey to cobbles and often boulder size fragments.

Tertiary basalt (Tba)

Basaltic peaks and ridge are mostly exposed in eastern areas of the map. It forms chain ridge of that extends northwest to southeast, and also form isolated hillocks. The total thickness of the Tertiary volcanic ranges 50 m to 250 m.

The basalt shows spheroidal weathering. The basalt show gray to dark color, and is fine to medium grained. It is slightly to moderately weathered, massive rocks which form hills, and is dissected by gulley and streams. The basalt includes olivine - plagioclase phyric, plagioclase –olivine phyric and aphanitic basalts. The basalt are often vesicular, amygdaloidal, and aphanites. The vesicular basalts are filled by calcite and chalcedony. Some vesicles are devoid of secondary minerals.

Limestone locally cherty (Korahe_Belet Uen)(km)

This upper Korahe formation contains dominantly gypsum rock with minor shale, mudstone and lime mudstone and. Hill forming gypsum rock is mostly massive, horizontal, continuous and underlies the limestone. This formation is found on western and eastern part of the area.

Gypsum, anhahydrite and potash intercalations with marl (Kg)

This evaporite covers extensive areas of the map which extends from southeast to northwest parts of the area. This lithological unit covers mostly flat land, but at places it forms hill and cliff particularly at eastern, southern and western regions of the area. It is mainly exposed by stream cut in areas of low topography.

Sandstone, siltstone intercalations with local limestone (KoraheAmbaradom) (Ka)

This formation is found on central part of the area. This unit is found intercalated with siltstone and hence named locally as Harbuch Sandstone.

Shale mudstone_limetone intercalations (Gabradarre)(Jg)

This formation is found on western part of the area. This unit is found intercalated with Sandstone and hence named locally as Harbuch Sandstone and is exposed central western parts of the map area. The maximum thickness measured in this unit is about 100 m. It is light grey, sometimes variegated (light yellow, light brown, green to greenish grey and yellowish to whitish grey). It is fine- to coarse-grained, poorly to well sorted, with rounded to sub rounded grains. Quite often the rock is deeply weathered and loose.

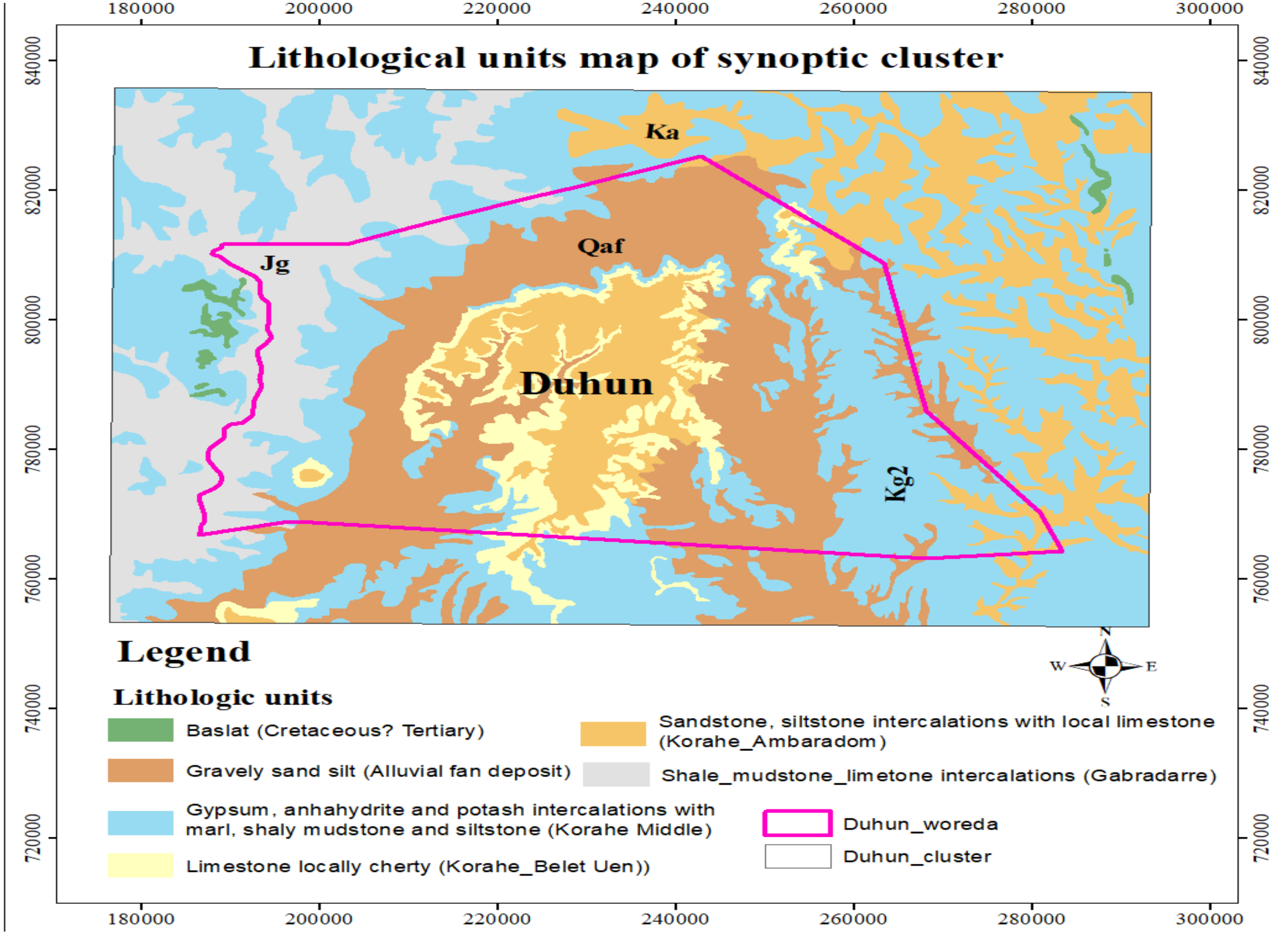

Figure 4-18.Geological Maps of Duhun woreda within Synoptic Boundary

II. Geological structures/Lineaments and Lineament Density

Lineaments are manually extracted with great care using DEM from (https://earthexplorer.usgs.gov/), hybrid morphometric maps, satellite images (Sentinel 2 from https://scihub.copernicus.eu/) and exisiting geological maps of the area.

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SE and N–S trending lineaments. Usually, lineaments are presented in the form of lineament density. Lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone.

For Dihun woreda, the lineament density varies from less than 0.21 km/km^2 to 0.87 km/km^2 (Figure 4-19). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by mesozoic sediments associated with sandstone andquaternary sediments having relatively higher lineament density of 0.65-0.87 km/km2) compared with areas underlain by sedimentary rocks of lower Hamanilie limestone and shale with lower lineament densities of (<0.21 km/km2).

Thus, areas with higher lineament density are regarded as having good contribution for groundwater recharge and storage.

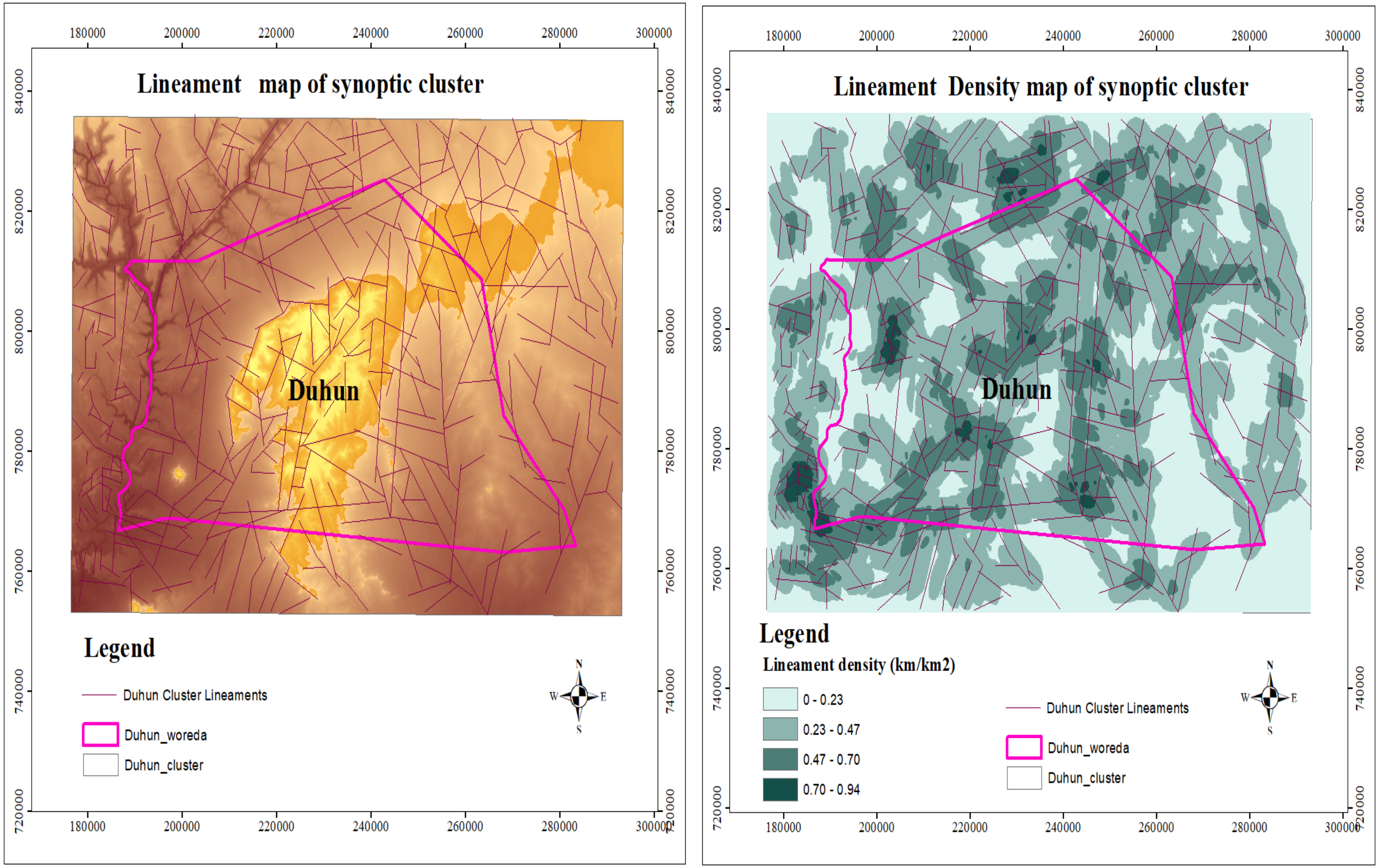

Figure 4-19.Geological Structure/Lineament Maps of Duhunworeda within Synoptic Boundary

III. Recharge

The mean annual rainfall raster data set were obtained from open sources of CHIRPS satellite imageries of 10 years from 2011 to 2020 mean annual rainfall on geological survey of America (USGS) official website (https://chc.ucsb.edu/). The infiltration coefficients of geological units were obtained from Abay River Basin Integrated Resources Development Master Plan Study report (MoWR, 1999). According to the master plan study, the IC of various lithological units could be assigned based on the results obtained from recharge estimations made using an integrated approaches including base flow separation and estimation of proportion of annual rainfall amount that to be percolated to the subsurface based on correlation made between each lithological unit identified within the basin using a developed mathematical equation. Therefore, for the current study, the IC values were extracted from the basin study that have similar properties of lithological units found in the current study area and accordingly assigned to each lithological unit (Table 4-5).Then, the geological map converted to raster based on the assigned value of IC with cell size of 100m on ArcGIS platform. Finally, the raster maps of rainfall and IC of lithological units were multiplied using a raster calculation algorithm in ArcGIS in order to obtain spatial map of annual recharge amount for the project area.

Table 4-5. Assigned InfilitrationCoefficent for Lithological Units (Adopted from Abay Master Plan Studies, MoWR, 1998) for Dihun Synoptic Area

Lithological Units (Study area)		Assigned Infiltration Coefficient (IC)	Lithological Units (Abay Basin)	
Symbol	**Description**		**Symbol**	**Description**
Qal1	Quaternary Alluvium-1	0.15	QAll	Alluvium
Qal2	Quaternary Alluvium-2	0.2	QAll	Alluvium
Qal2	Quaternary Alluvium-3	0.2	QAll	Alluvium
Ql	Lacustrine Sediment	0.15	QLAC	Lacustrine deposits
Qaf	Quaternary Alluvial Fan	0.2	QAll	Alluvium
Tv1	Lower Lava Flows	0.1	TBNB	Blue Nile Basalts
Masst	Abduya Sandstone	0.15	KAA2`	AmbaAradam Sandstone (2)
Jh1	Lower Hamanilie	0.1	JANL	Antalo Limestone
Mba	Cretaceous Basalt	0.1	TBNB	Blue Nile Basalts
Ka	Upper Sandstone	0.15	KAA2`	AmbaAradam Sandstone (2)
Jh2	Upper Hamanilie	0.1	JANL	Antalo Limestone
Jg2	Upper Gabredarre	0.1	JANL	Antalo Limestone

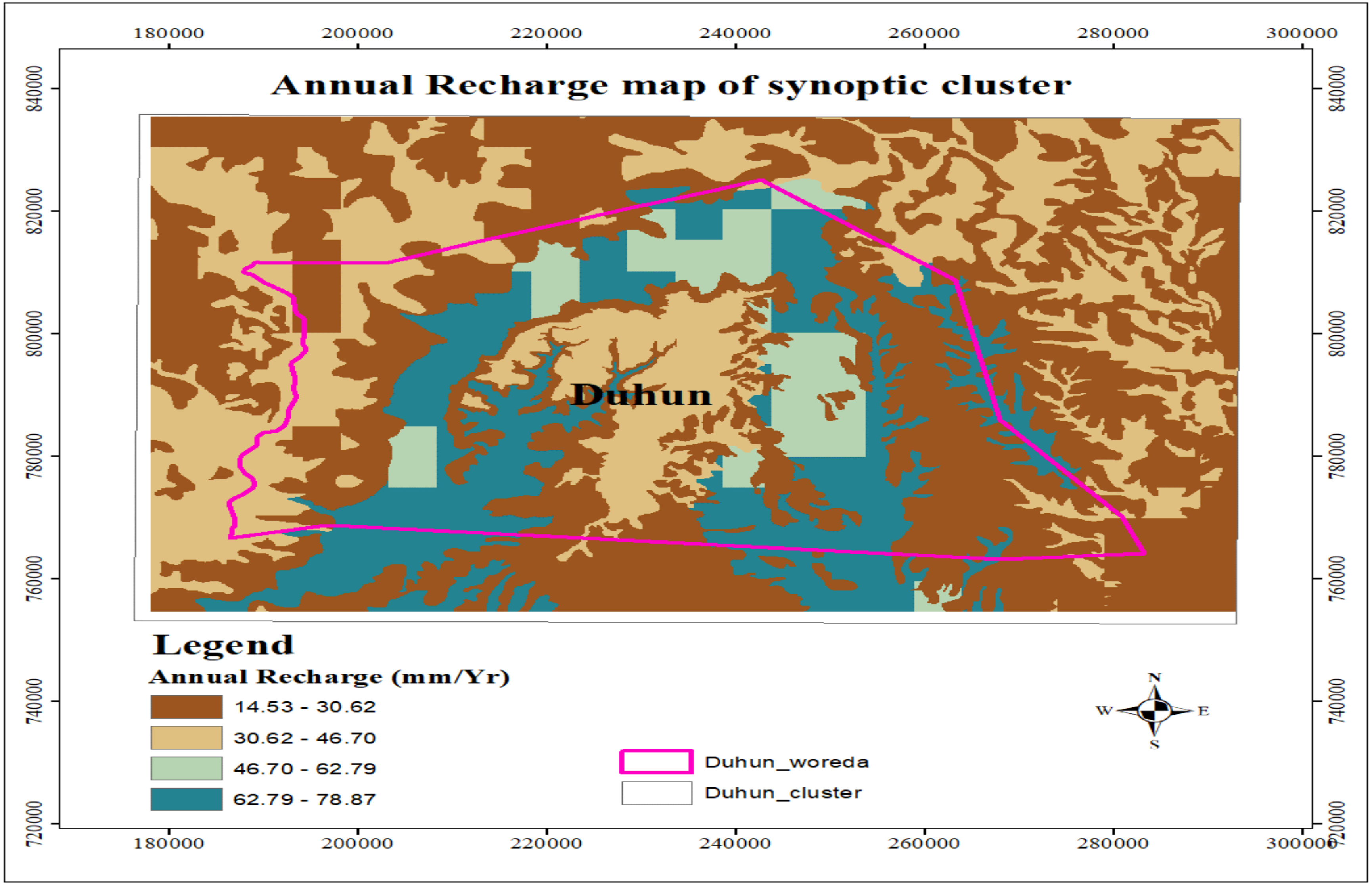

Figure 4-20.Annual Recharge Map of Duhun woreda within SynopticBoundary

IV. Topographic Wetness Index (TWI)

The Topographic wetness index, also known as the compound topographic index, is commonly used to quantify topographic control on hydrological processes. The index is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. The topographic wetness index (TWI) is a useful model to estimate where water will accumulate in an area with elevation differences (Sorensen, R; Zinko, U.; Seibert, J. (2006). Topographic wetness is a unitless quantity and it is represented by index with relative physical property. The topographic wetness index as a layer plays a significant role in line with other selected layers to delineate groundwater potential areas based on priority/ranking and weightage as per the layers' relative importance for groundwater enhancement/Potentiality. Accordingly, the TWI layer of Dihun woreda within the Somali synoptic area was prepared (Figure 4-21).

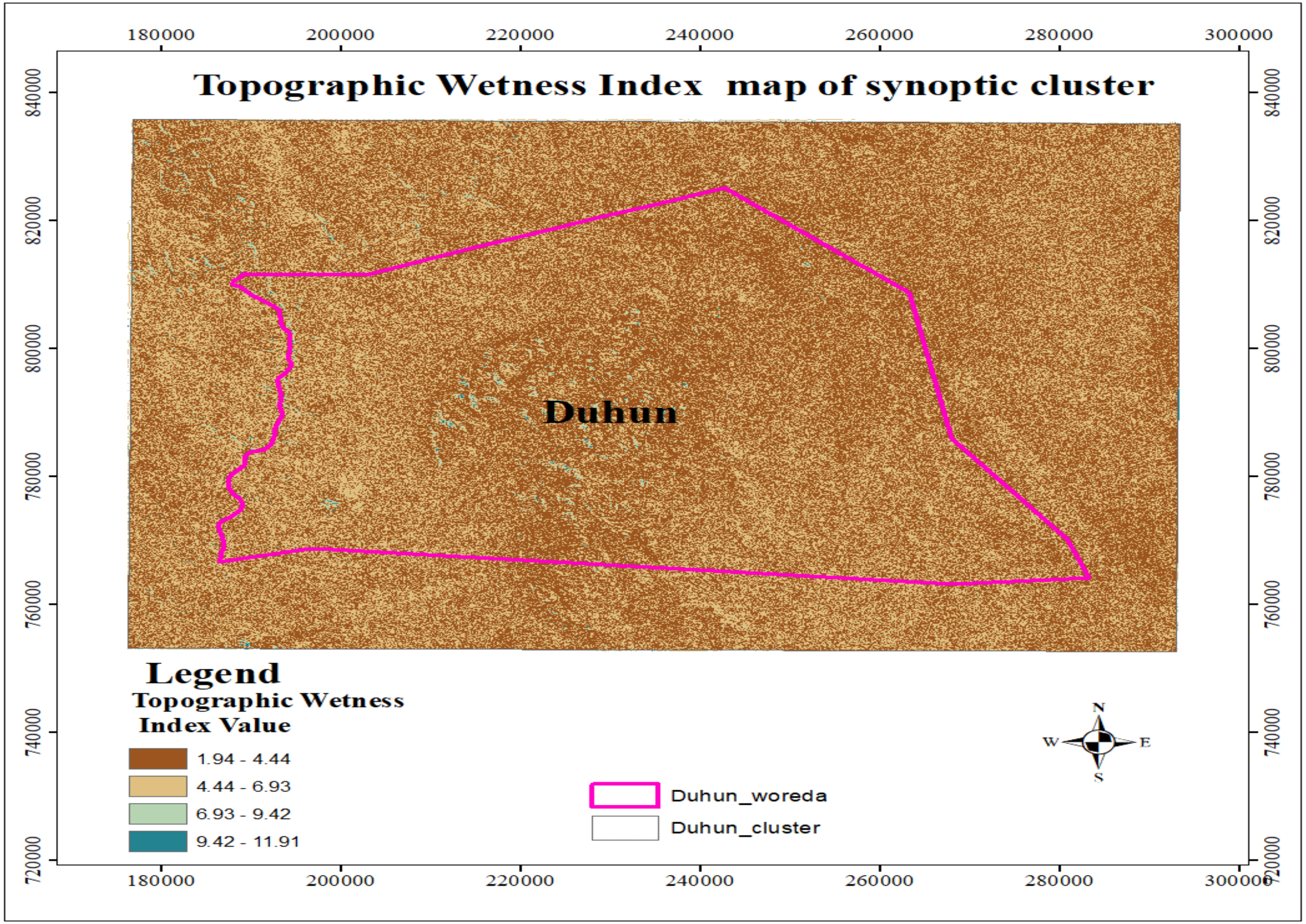

Figure 4-21. TWI Map of Elkere woreda within Synoptic Boundary

4.3. Analytical Hierarchy Process (AHP) and Weights Assignments

The analytic hierarchy approach (AHP) developed by Saaty (1980, 1986, 1992) was used in this study as a decision aiding method to finalize the weights assigned to different themes and their respective features used in deciphering groundwater potentiality. AHP is a simple mathematical matrix-based technique that allows users to assess the relative weight of multiple criteria in an intuitive manner. It allows efficient group decision-making, where group members can use their experience, values and knowledge to breakdown a problem into a hierarchy and solve it by AHP steps (Chowdhury et al. 2009). It also incorporates systematic checks on the consistency of judgments, which is one of the strongest points over the other multi-attribute value processes.

The weightage employed is in accordance with the respective importance of the map theme to groundwater occurrence following the approach of Saraf and Choudhary (1998), Rao and Jugran (2003), Prasad et al. (2008), Jha et al. (2010), Machiwal et al. (2011), Mukherjee et al. (2012) and Singh et al. (2013). The weights of the individual themes and their associated features were then normalized by the Saaty's AHP and the Eigen vector technique was used to reduce the subjectivity associated with the assigned weights (Table 4-6). The Consistency Index (CI) of the assigned weights was calculated following the procedure suggested by Saaty (1980, 1992) while the Consistency Ratio, which indicates the probability that the matrix ratings were randomly generated, was also computed using the values of Random Consistency Index (RI) which is the average value of CI for random matrices using the Saaty scale obtained by Forman (1983, 1990) based on the following relations:

Consistency Index = $(\lambda_{max} - n)/(n-1)$;

Consistency Ratio =CI/RI

Where n is the number of criteria or factors

It should be noted that the CR value should be less than 0.10 for consistent weights; otherwise, corresponding weights should be re-evaluated to avoid inconsistency (Saaty 1980, 1986, 1992).

The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). Furthermore, each of the thematic maps was then assigned weight in the range of 1–9 according to Saaty's scale of assignment (Table 4-6), which depicts the relative importance of the respective themes to groundwater availability.

Table 4-6 Saaty's scale for assignment of weights and its interpretation showing the pair-wise comparison process (Saaty 1980, 1986, 1992)

Less important				Equally important	More important			
Extremely	Very Strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very Strongly	Extremely
1/9	1/7	1/5	1/3	1	3	5	7	9

2, 4, 6 and 8 are intermediate values that denotes compromise

CHAPTER 5 GROUNDWATER POTENTIAL MAPPING

5.1. Haromaya Woreda

5.1.1. Weight Assignment

For this study woreda, the CR was estimated to be 0.04 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Haromaya woreda. The weights assigned to the themes are presented in Table 5-1). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-3. The normalized weights of different features of the four themes were obtained in the similar manner as presented in Table 5-3. The weights assigned to the respective thematic maps as presented in Table 5-3 indicate that geology was ranked the dominant factor with a normalized weight value of 0.39 while recharge is the least accounted factor with a normalized weight of 0.06 for groundwater occurrence in the study Haromaya woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Haromaya woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below. This technique is associated with the study of locations of geographic phenomena together with their spatial dimension and associated attributes (Prasad et al., 2008).

$$GWPZI = (GGwGGwi + LDwLDwi + TWIwTWIwi + GRwGRwi)$$

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Haromaya woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e. ‘very high’, ‘high’, ‘moderate’ and ‘low or poor’, in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-1 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Geology (GG)	9
Lineament density (LD)	7
Topographic Wetness Index (TWI)	5
Recharge (GR)	3

Table 5-2 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	GG	LD	TWI	GR	
GG	1	1	2	7	0.39
LD	1	1	2	5	0.36
TWI	1/2	1/2	1	3	0.19
GR	1/7	1/5	1/3	1	0.06

Table 5-3 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank	Area (km^2)	Area (%)
Geology/ Lithology, 'GG'	Quaternary deposits of alluvium & lacustrine sediments	Very good	4	0.54	0.39	87.0	15.7
	Mesozoic sedimentary rocks	Good	3	0.30		110.3	20.0
	Basement rocks	poor	1	0.16		355.6	64.3
Lineament Density,' LD' (Km/Km^2)	0 - 0.23	poor	1	0.11	0.36	-	-
	0.24 - 0.47	Moderate	2	0.15		-	-
	0.48 – 0.70	Good	3	0.28		-	-
	0.71 – 0.93	Very good	4	0.46		-	-
Topographic Wetness Index, 'TWI'	4.19 – 7.34	poor	1	0.11	0.19	-	-
	7.35 – 9.1	Moderate	2	0.15		-	-
	9.11 – 11.8	Good	3	0.28		-	-
	11.9 – 19.1	Very good	4	0.46		-	-
Recharge, 'GR' (mm/y)	23.3 - 27.7	poor	1	0.11	0.06	322.1	58.3
	27.8 - 47.1	Moderate	2	0.15		87.1	15.7
	47.2 - 94	Good	3	0.28		56.7	10.2
	94.1 - 183	Very good	4	0.46		87.1	15.8

5.1.2. Integration of Thematic Layers

The details of geology, lineament density, Topographic Wetness Index (TWI), and recharge together with their spatial distribution in target woreda are presented below:

I. Geology/Grouped Hydrolithological Units

In general, most parts of the Haromaya woreda are underlain by basement complexes of intrusive granitic and gneissic rocks. Quaternary deposits of alluvial and lacustrine sediments are mostly found central northern areas around Lake Haromaya, Lake Finkile and Lake Adele. Whereas, most sedimentary formation of limestone and sandstone rocks are outcropped at the central western and southern parts of the woreda.

However, the lithological units found in the woreda area are further classified into three major groups based on their significances to groundwater occurrence and productivity using borehole data on yield and transmissivity values in particular.

- Quaternary alluvium and lacustrine deposits (high productive with Qav. = 14.8 l/s)
- Mesozoic sedimentary rocks of lower Hamanilie limestone formation and lower sandstone rocks covered by thin eluvium soil at places (moderate productive with Qav = 4.8 l/s)
- Basement rocks of granitic and gneissic rocks overlain by thin eluvium soils at places (low productive with Qav = 2.6 l/s)

The crystalline basement rocks are the main lithologic framework of the Haromaya woreda which together covered a total area of about 355.6 km^2 or 64.3 % of the woreda area, quaternary recent sediments of alluvium and lacustrine covered about 87.0 km^2 (15.7 %), and Mesozoic sedimentary rocks of limestone and sandstone rocks all together covered about 110.3 km^2 or 20.0 % of the woreda area (Figure 5-1).

Usually, massive unfractured lithologic units in sedimentary and basement complex settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification and weathered overburden, and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the weathered regolith units, karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of poor productivity of basement rocks (0.16) \ moderate productivity of older alluvium deposits and sedimentary rocks (0.30) \ high productivity of alluvial/lacustrine sediments (0.54).

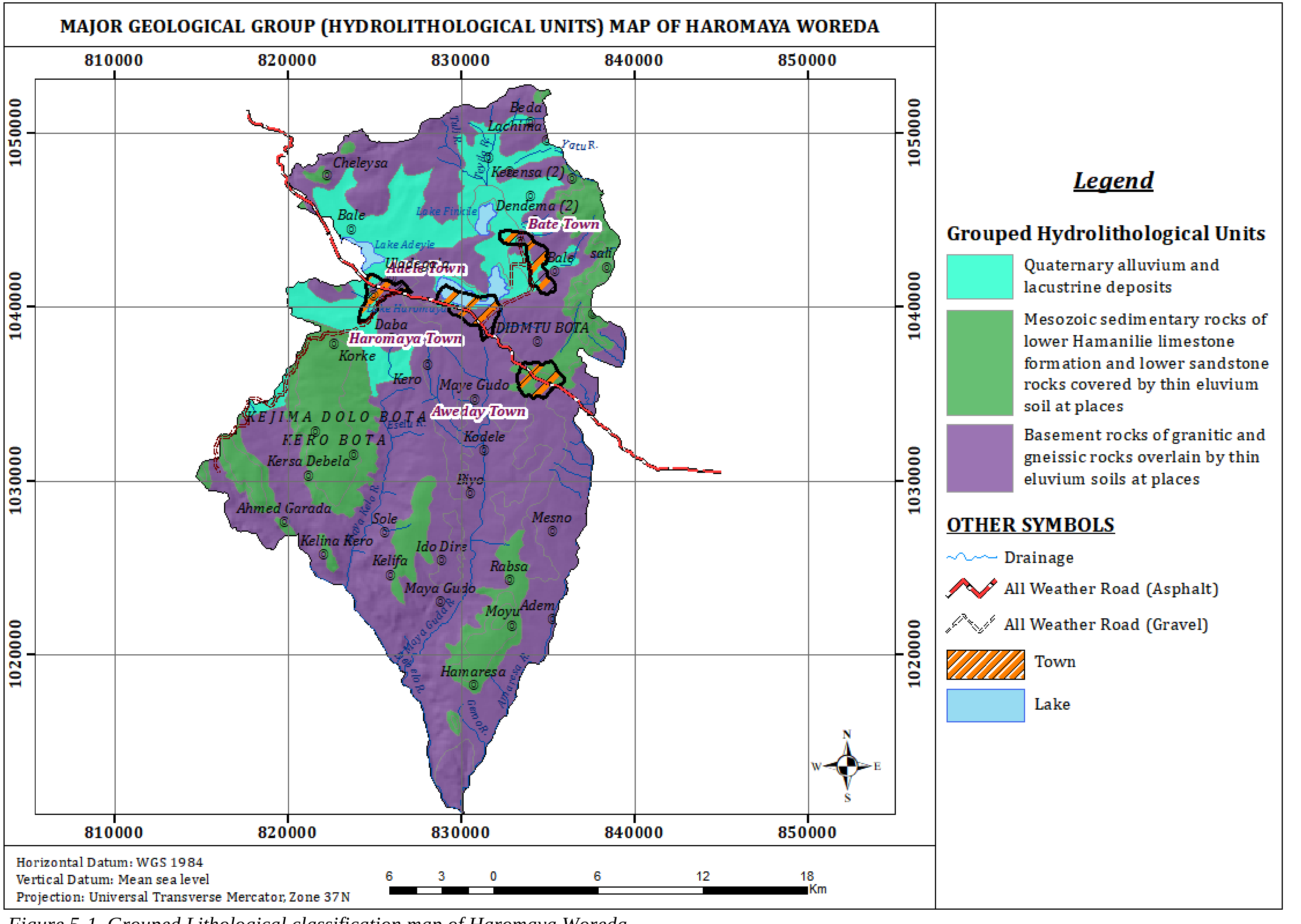

Figure 5-1. Grouped Lithological classification map of Haromaya Woreda

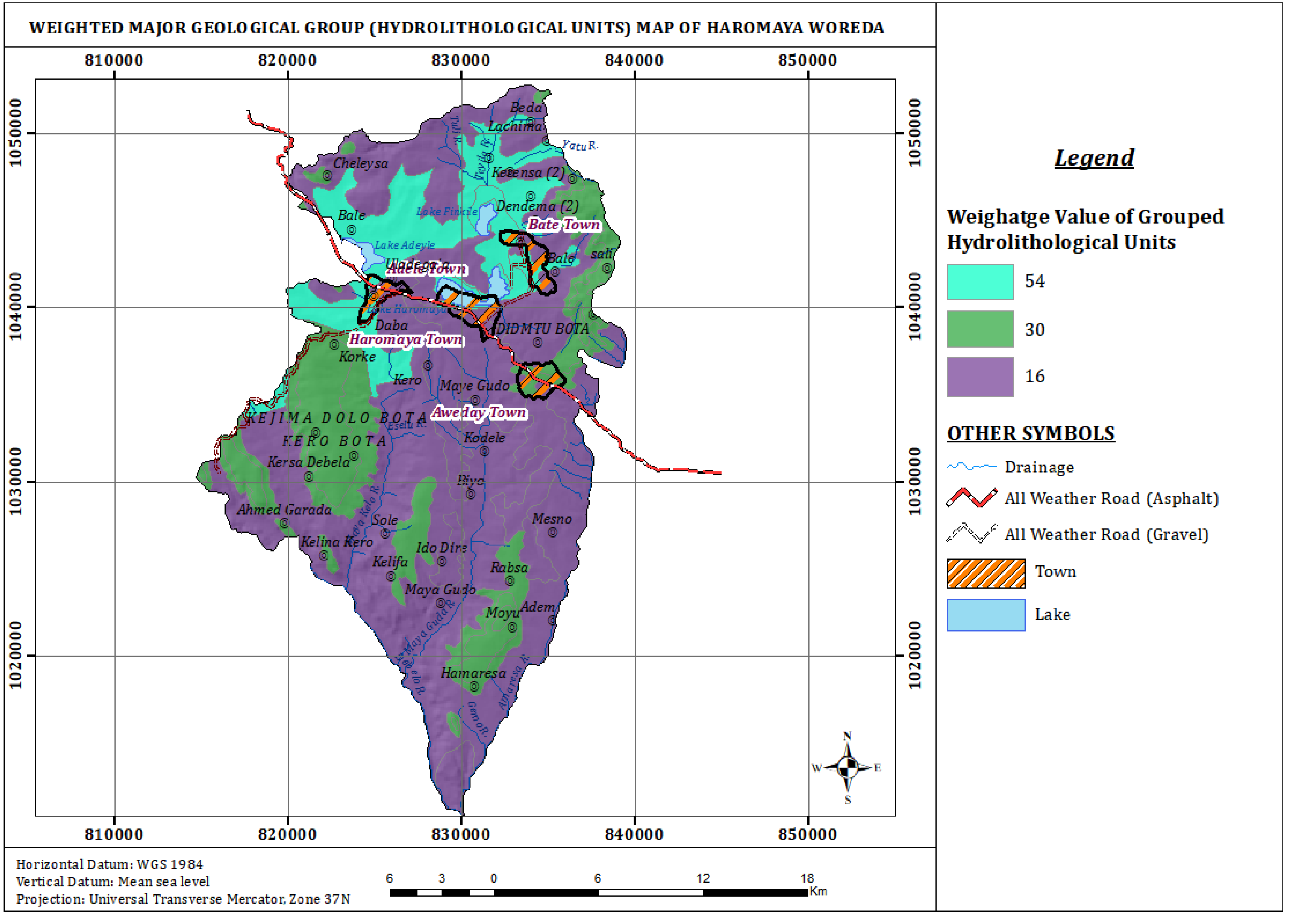

Figure 5-2. Weighted lithological classes' map of the Haromaya Woreda

II. Lineaments and lineament density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Three prominent directions identified are NW-SE, NE–SW and N–S trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.23 km/km2 to 0.93 km/km^2 (Figure 5-3). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by crystalline basement complex associated with quaternary sediments having relatively higher lineament density of 0.71 – 0.93 km/km^2) compared with areas underlain by sedimentary rocks of lower Hamanilie limestone and lower sandstone with lower lineament densities of (< 0.23 km/km^2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.46 was assigned to area with high density of lineaments, while a low weightage of 0.11 was assigned to areas with low lineament density (Figure 5-4).

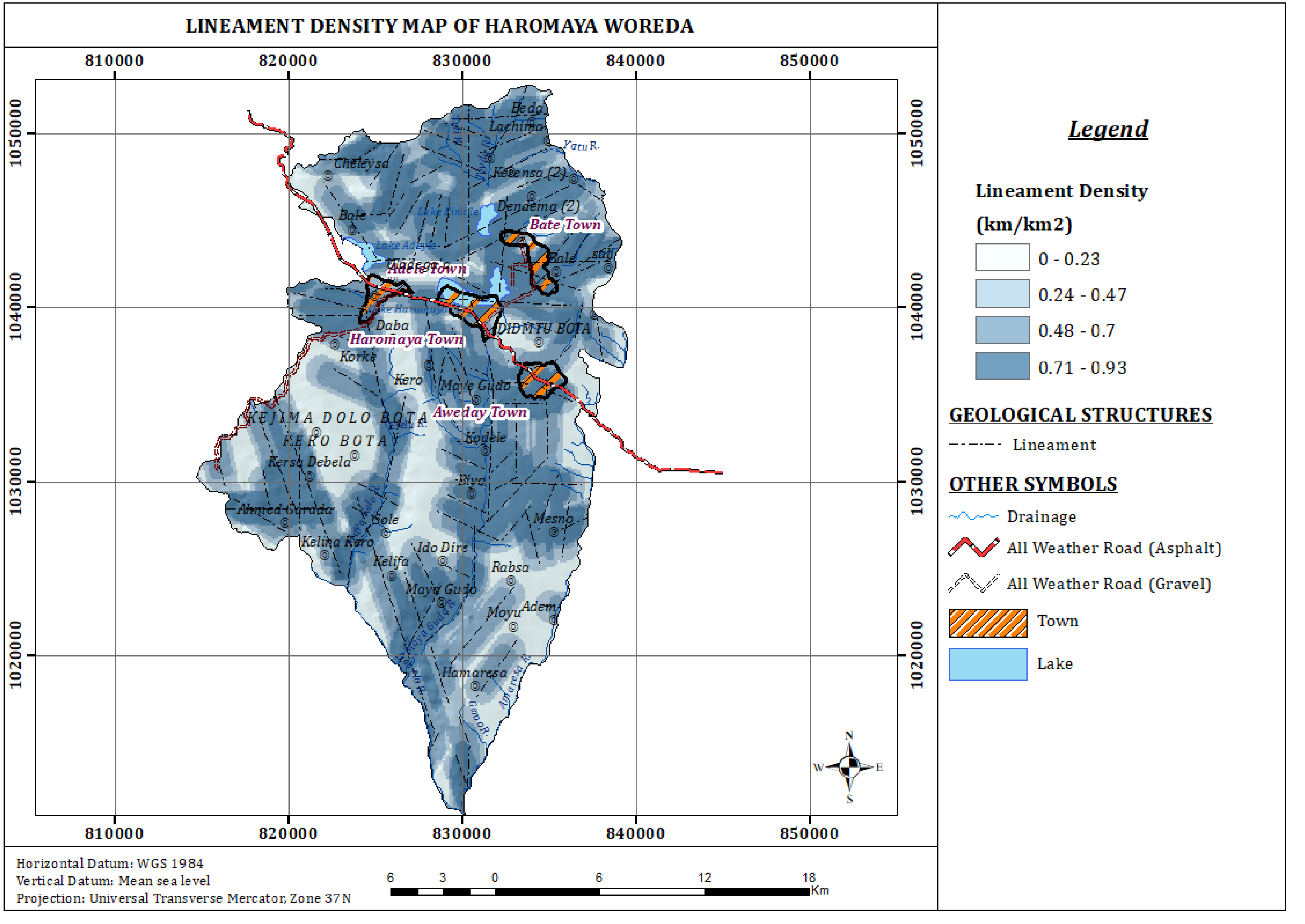

Figure 5-3. Lineament Density Map of Haromaya Woreda

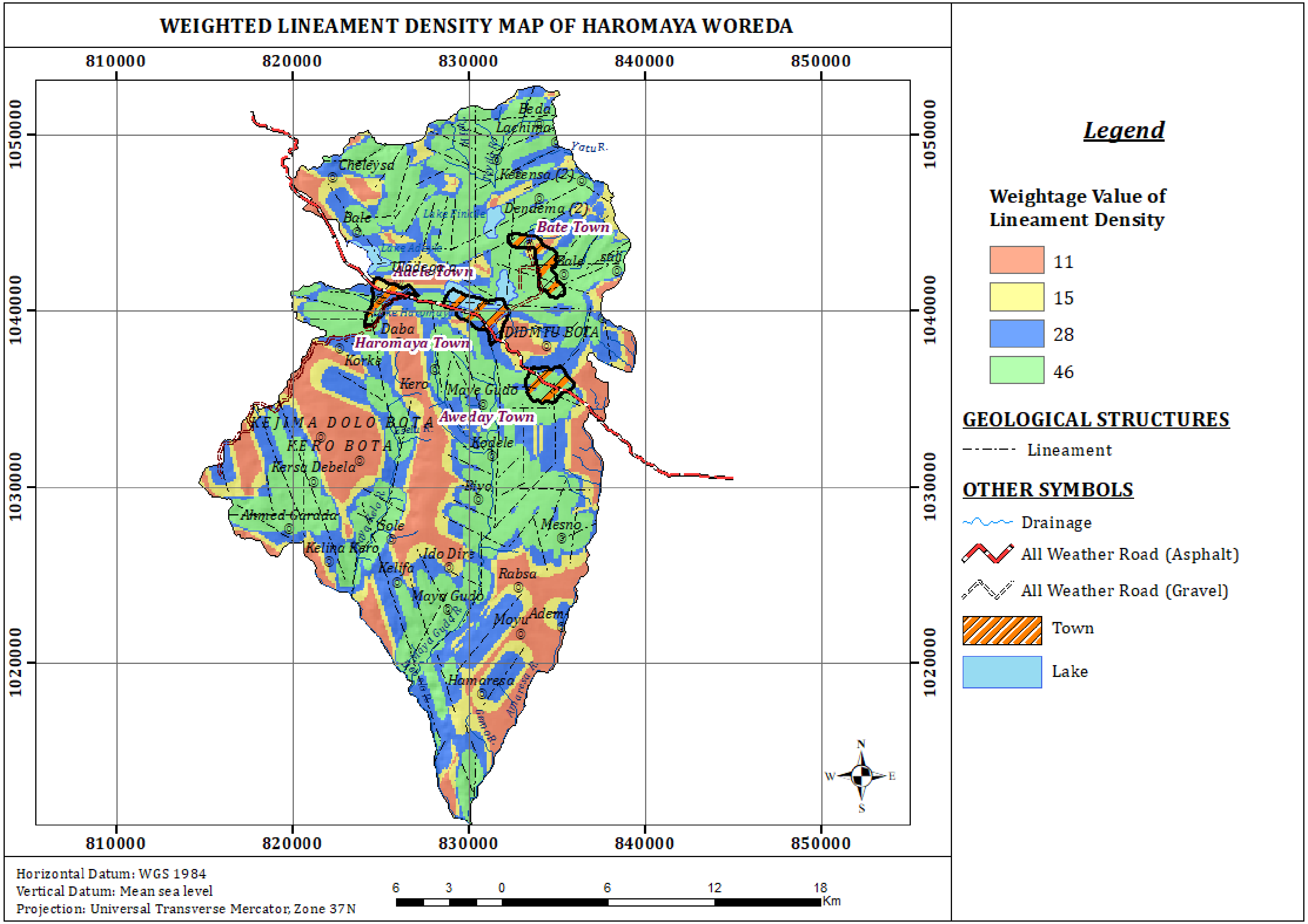

Figure 5-4. Weightage value of Lineament Density Map of Haromaya Woreda

III. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 4.2 and 19.1. A closer look at the classification revealed that most the high elevated areas and drainage systems with steep slopes have relatively lower TWI value while the low lying areas and drainage systems with gentle and flat slopes such as around Haromaya, Finkile and Adele lakes area in northern regions in particular have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.46) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.11).

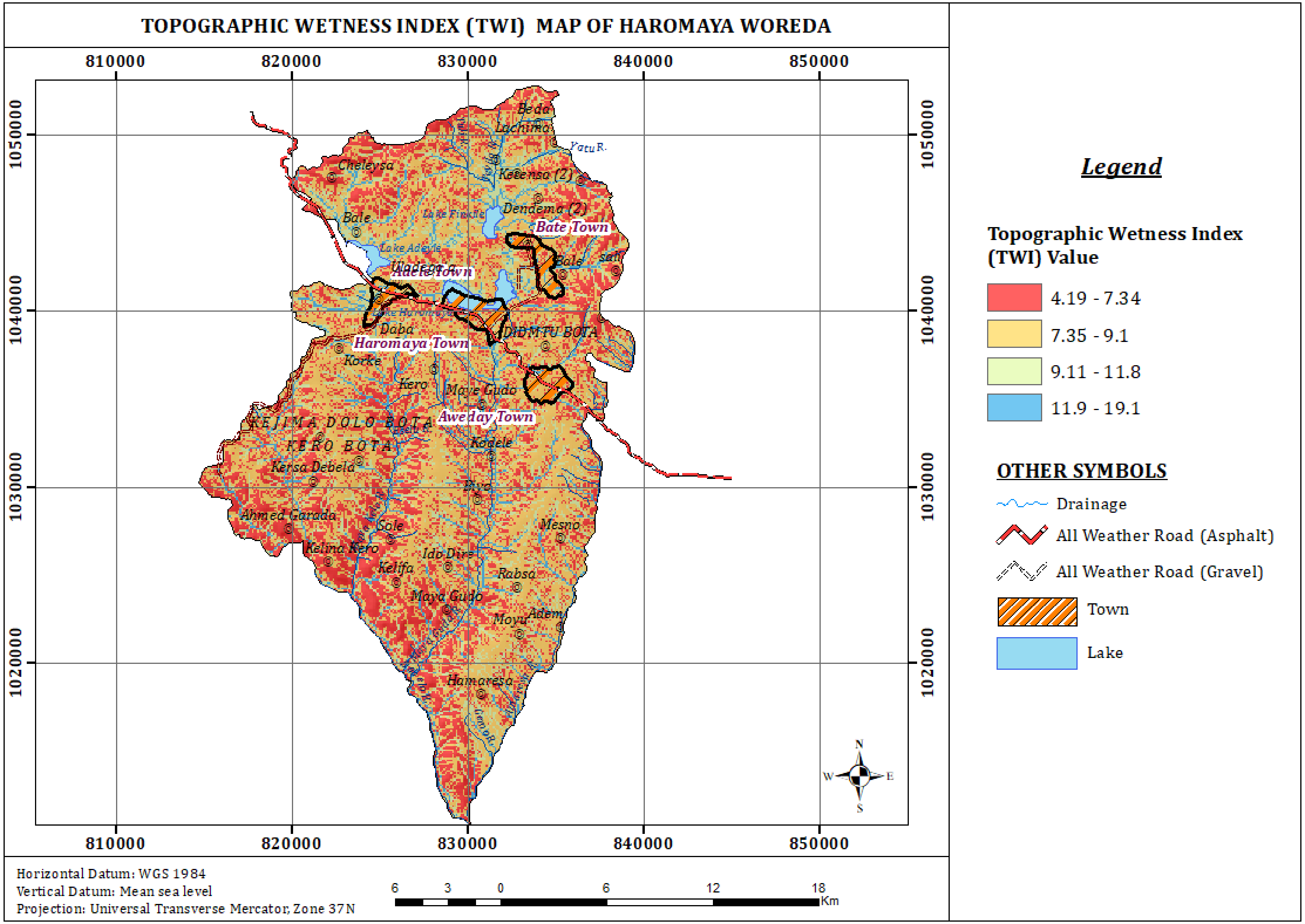

Figure 5-5. TWI Map of Haromaya Woreda

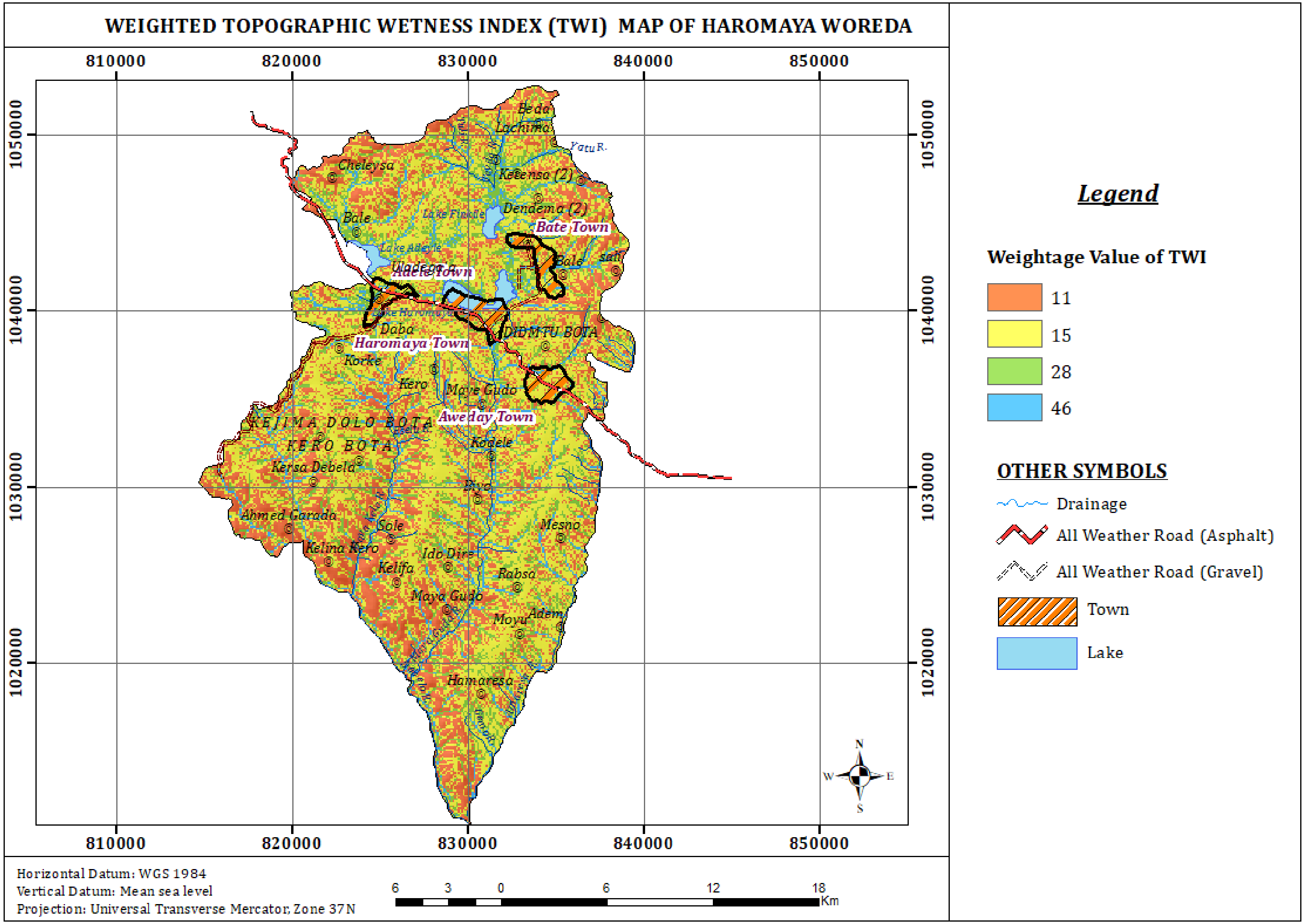

Figure 5-6. Weightage value of TWI Map of Haromaya Woreda

IV. Recharge

The spatial annual recharge rate distribution in the Haromaya woreda ranges from 23.3 to 183 mm/y suggesting groundwaters in most part of the woreda area underlain by basement complex receive low amount of recharge while areas underlain by sedimentary rocks and quaternary sediments have relatively higher recharge amount (Figure 5-7). Accordingly, areas with very high and high amount of recharge have weightage factor of 0.46 and 0.28, respectively signifying very good and good groundwater potential which covers about 87.1 km^2 (15.8 %) and 56.7 km^2 (10.2 %), respectively while areas with the moderate and lowest amount of recharge have weightage factor of 0.15 and 0.11, respectively suggesting moderate and poor groundwater potentiality and represent about 87.1 km^2 (15.7 %) and 322.1 km^2 (58.3 %), respectively. A closer look at the recharge thematic map revealed that most of the southern, central and eastern low-lying parts of the woreda have relatively lower recharge (< 30 mm/yr.). Generally, the study area is characterized with low mean annual recharge amount, whereas only limited areas at northwestern and central northern parts have very high mean annual recharge amount (> 94 mm/yr.).

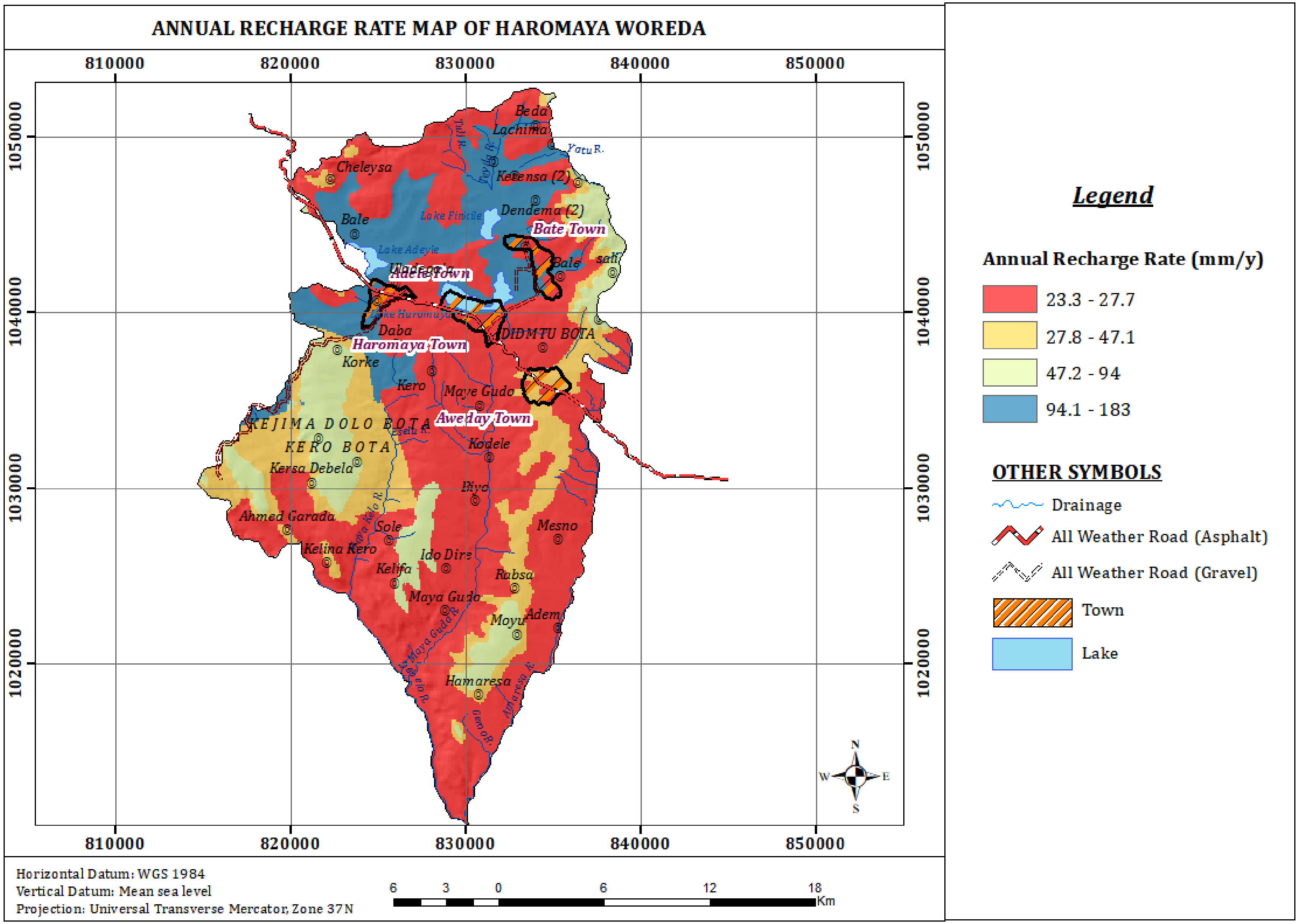

Figure 5-7. Annual Recharge Map of Haromaya Woreda

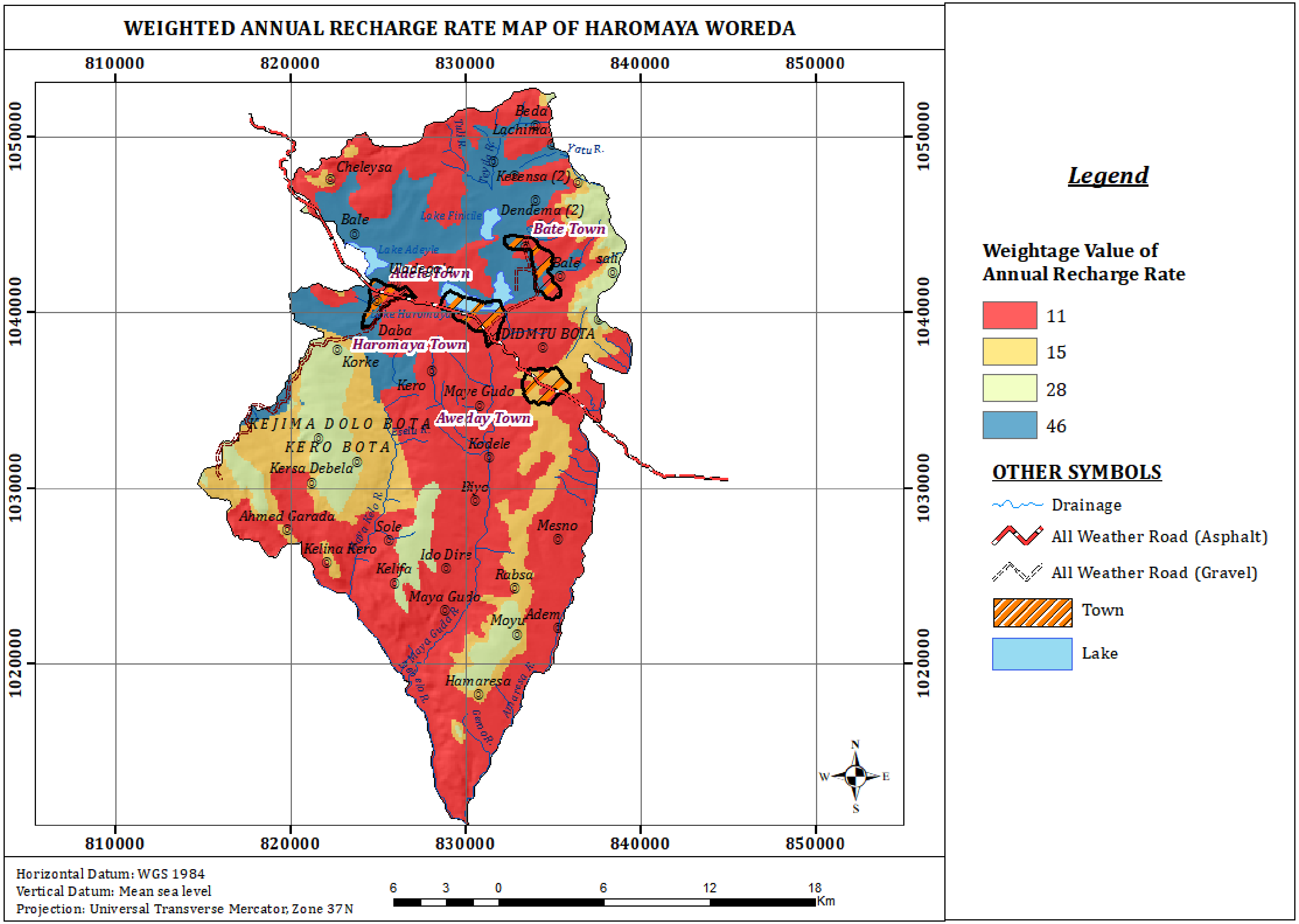

Figure 5-8. Weighted Annual Recharge classes' map of the Haromaya Woreda

5.1.3. Classification of Groundwater Potential Zones

The hydrogeological system of Haromaya woreda is comprised of four main lithological units as Quaternary deposits, Lower Hamanlie Limestone Formations, Lower Sandstone and Crystalline Rocks. At regional scale, Quaternary deposits form extensive and moderately productive aquifers. Within the domain of Haromaya woreda, theses, Quaternary deposits form aquifers with very high groundwater potential.

At regional scale, the Upper and Lower Hamanlie Limestone Formation and lower sandstone form extensive and high productive aquifers having high hydraulic conductivity. However, at local scale, within the domain of Haromaya woreda, due to the geomorphic setup, the Upper Hamanlie Limestone Formation and the underlying units do not form potential aquifer as revealed from existing borehole information.

Only the upper weathered and slightly fractured part of the crystalline basement rocks along lineamnets and faults have potential to store groundwater at shallow depth. Weathered and slightly fractured Crystaline basement rocks with overlying Quaternary deposit form major potential aquifer within the domain of Haromaya Woreda along lineament and fault lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-9). The potential groundwater zones (PGZ) of the Haromaya woreda revealed four distinct zones, namely low, moderate, high and very high zones whose distribution and extents are 223.0 km^2 (40.3 %), 210.6 km^2 (38.1 %), 55.2 km^2 (10 %) and 64.0 km^2 (11.6 %), respectively as presented in Table 5-4.

The potential map, as presented in Figure 5-9, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that most elevated areas around the central western, southeastern and central parts of the Haromaya Woreda generally have low potentials with area coverage of about 40.3 %, while limited areas at northern and northwestern regions generally exhibits high to very high potentials representing about 10 % and 11.6 % of the study area, respectively. The generally high to very high groundwater potentiality of the study area as reflected by 21.6 % coverage is a confirmation of generally moderate to high productive aquifers of alluvial and lacustrine deposits, whereas low groundwater potential areas have an indication of limited aquifers capabilities of basement complex terrain.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the geology and lineament density in addition to the topographic wetness index control. In addition, areas underlain by recent quaternary deposits especially in the northern sections of the study area which are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments and apparently deep fracturing and weathering have high and very high groundwater potential on the one hand. On the other hand, areas underlain by crystalline basement complexes in the majority of the woreda areas are characterized by small ridges and steep slopes, lower recharge and lineament densities, exhibit low groundwater potential while areas underlain by sedimentary rocks associated with sediments have medium potential. Moreover, low drainage densities and predominance of crystalline rock outcrops can be attributed to the observed low groundwater potentials at the most central and peripheries of the study area. However, predominance of recent sediments and sedimentary rock outcrops, high drainage density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential exhibited at northern and northwestern portions of the study area. Summary of the groundwater potential zones identified in the Haromaya woreda is presented in the table below (Table 5-4).

Table 5-4. Classification of groundwater potential zones and coverage areas alongside the respective yield and transmissivity categories

Woreda Name	GWP Zones	Area (km^2)	Area (%)	Major Aquifer Units	Borehole Yield Classification (l/s)		Transmissivity Classification (m^2/d)	
					Q (Range)	Mean 'Q'	T (Range)	Mean 'T'
Haromaya	Very High	64	11.6	Quaternary Sediments (Qal1, Qal2 & Qls)	8 - 22	13.9	106.1 – 336.9	202.3
	High	55.2	10.0	Older Alluvium (Qal1) & Sedimentary Rocks (Jh1 & Ja)	5 - 7	5.7	21.9 – 411.3	120.6
	Moderate	210.6	38.1	Basement rocks (Pgt1, Pgt2, & Pugn)	3.5 – 4.8	3.9	49.9 – 122.5	95.8
	Low	223	40.3	Basement rocks (Pgt1, Pgt2, & Pugn)	1.5 - 3	2.4	1.53 – 18.6	8.8

5.1.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) were collated for over 50 boreholes in and around the study woreda area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the study area vary from 8 to 22 lit/sec (av. 13.9 lit/sec) in very high potential zones and varying from 5 lit/sec to 7 lit/sec (av. 5.7 lit/sec) in high potential zones as compared with 3.5 lit/sec to 4.8 lit/sec (av. 3.9 lit/ sec) in the moderate and from 1.5 to 3 lit/sec (av. 2.4 lit/sec) in the low potential zones (Figure 5-9). As shown in the Figure 5-9, the occurrence of number of wells with yield of in the range 5- 7 lit/sec (high yield) and of > 8 lit/sec (very high yield) cut across mainly the quaternary deposits and sedimentary rocks. However, the less frequency of wells within basement rocks in the low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (3-5 lit/sec) categories are associated also with wells in the regolith deposits of weathered crystalline basement rocks. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks' unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such basement and sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

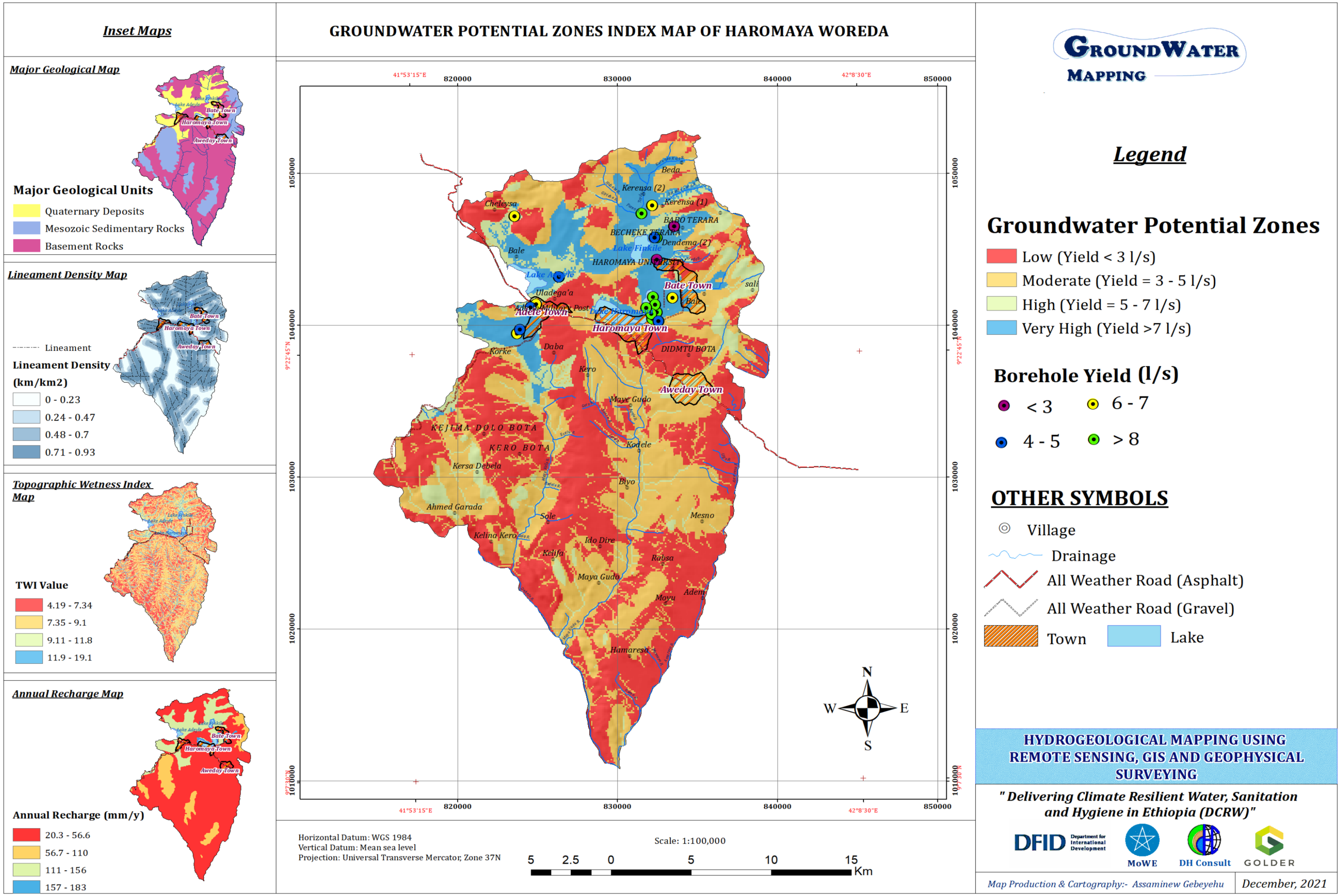

Figure 5-9. Groundwater Potential Zones Map of Haromaya Woreda

5.1.5. Population and Water Demand Projection of Haromaya Woreda

5.1.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-5 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P = Po\,(1 + r)^{n}$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Haromaya Woreda has been projected forward until 2036 using the growth rate of Oromia Regional State. The minimum and maximum population in the Woreda is 4,643 and 24,757 respectively. The total population of the Haromaya Woreda in 2036 is going to be 414,254.

5.1.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic purposes greatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO) & (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer’s life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24-hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-10 shows the distribution of water demand in each Kebeles of the Woreda. Kersa Qajima kebele water demand is the minimum with 417 M^3/day and maximum water demand is required for Ifa Haromaya Kebeles with 2224 M^3/day respectively. The overall water demand for the projected population in the Haromaya Woreda is 37,216 M^3/day.

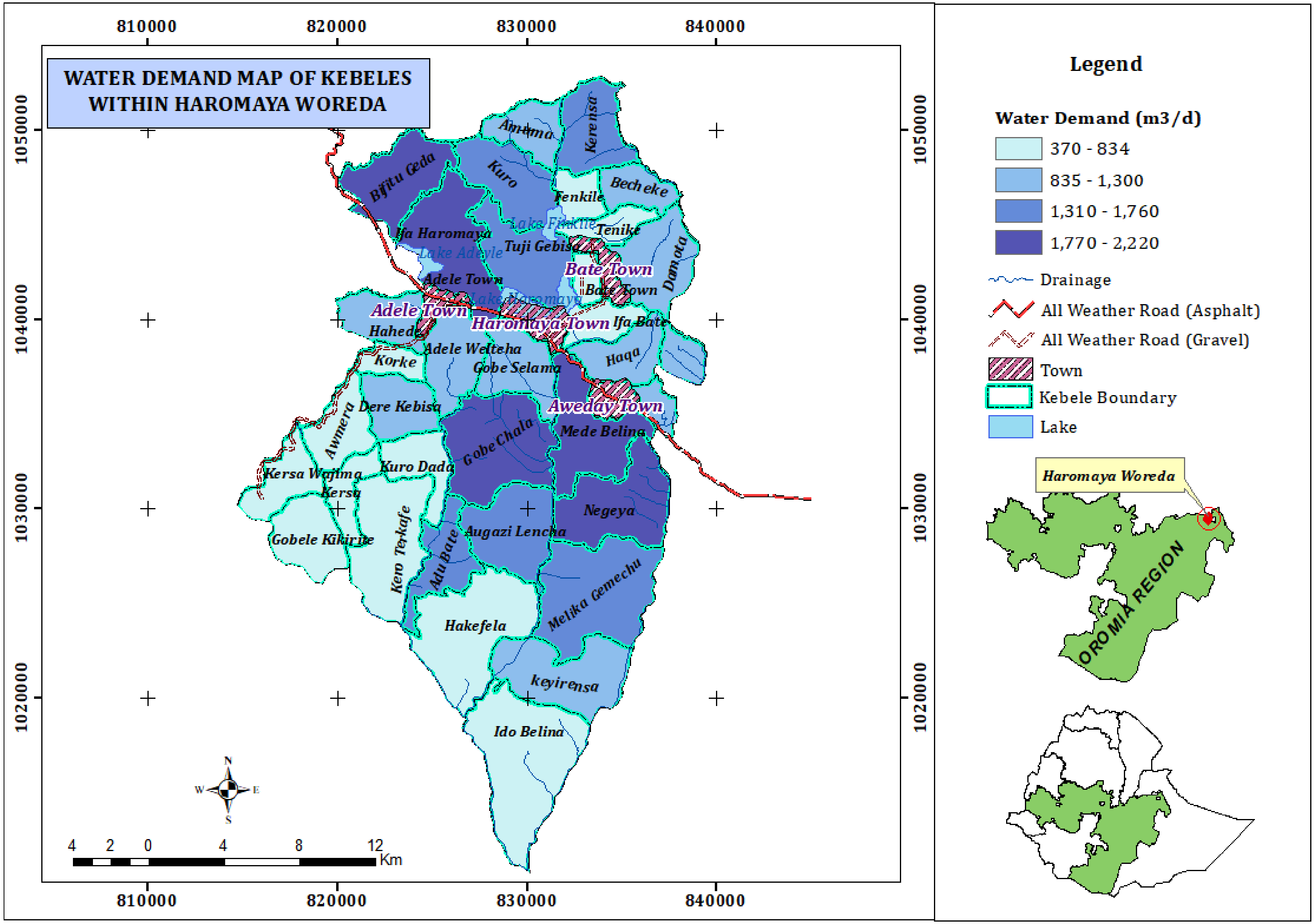

Figure 5-10:-Water Demand Map of Haromaya Woreda

5.1.6. Propsed Target Sites of Haromaya Woreda

Four target sites are identified and proposed within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficiaries and population density. With further discussion and consultation with stakeholders, two priority sites will be selected for further hydrogeological and geophysical investigations in phase III. The following are the four proposed sites (Figure 5-11):

Target Site-I:

This target site is located in the northern part of the woreda, around Lake Haromaya and Finkile. It is situated in the identified very high potential zones with expected optimum borehole discharge of about 10 l/s. This target site is mainly underlain by quaternary recent deposits of alluvial and lacustrine sediments.

Target Site-II:

This target site is located at northwestern part of the woreda, around Lake Adeyle. It is situated mainly in the identified high and very potential zones with expected optimum borehole discharge of about 5 l/s. This target site is mainly underlain by quaternary older deposits of alluvial sediments associated with granitic rocks and Mesozoic sedimentary rocks of lower sandstone and limestone.

Target Site-III:

This target site is located at central western part of the woreda, around Kersa Debela locality. It is situated mainly in the identified moderate potential zones with expected optimum borehole discharge of about 4 l/s. This target site is mainly underlain by Mesozoic sedimentary rocks of lower limestone associated with lower sandstone and granitic rocks.

Target Site-IV:

This target site is located at central eastern part of the woreda, around Kodele and Mesno localities. It is situated mainly in the identified moderate potential zones with expected optimum borehole discharge of about 3 l/s. This target site is mainly underlain by weathered regolith os granitic rocks associated with Mesozoic sedimentary rocks of lower limestone and lower sandstone.

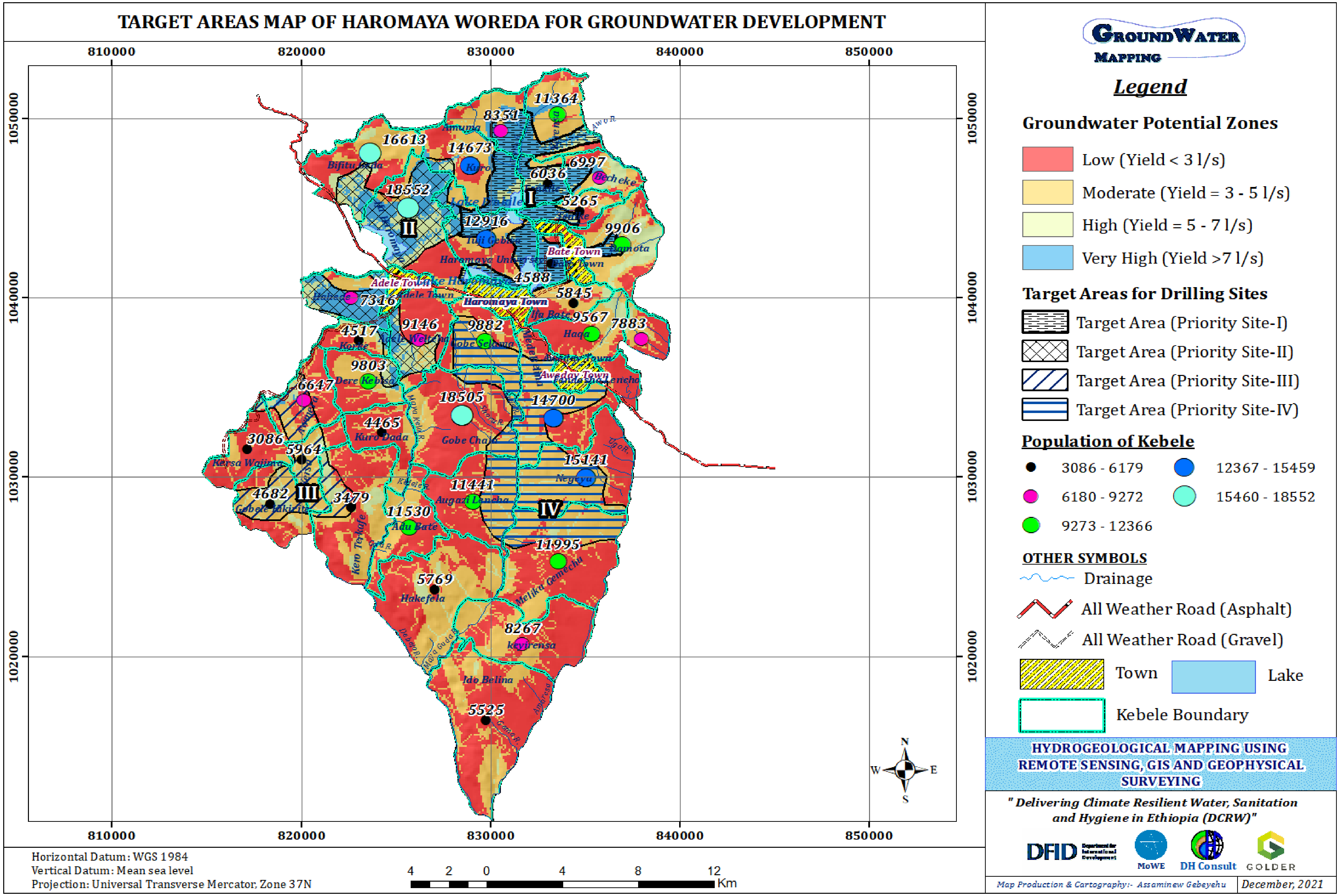

Figure 5-11:-Target Areas Map of Haromaya Woreda

5.2. Boke Woreda

5.2.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.024 which is far below the threshold consistency value of 0.10. Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Boke woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-6). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-7. The weights assigned to the respective thematic maps as presented in Table 5-8 indicate that geology was ranked the dominant factor with a normalized weight value of 0.43 while recharge is the least accounted factor with a normalized weight of 0.07 for groundwater occurrence in the study Boke woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Boke woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

GWPZI = (GGwGGwi + LDwLDwi + TWIwTWIwi + GRwGRwi)

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Boke woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e. 'very high', 'high', 'moderate' and 'low or poor', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-6 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Geology (GG)	9
Lineament density (LD)	8
Topographic Wetness Index (TWI)	7
Recharge (GR)	6

Table 5-7 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	GG	LD	TWI	GR	
GG	1	2	2	5	0.43
LD	1/2	1	2	5	0.31
TWI	1/2	1/2	1	3	0.19
GR	1/5	1/5	1/3	1	0.07

Table 5-8 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank
Geology/ Lithology, 'GG'	Mesozoic sedimentary rocks of upper Hamanilie limestone covered by eluvial soils at places.	Very good	4	0.54	0.43
	Mesozoic sedimentary rocks of low Hamanilie limestone & upper sandstones covered by thin layer of alluvium & eluvium depositsat places.	Good	3	0.30	
	Mesozoic sedimentary rocks of upper Gebredarre limestone	poor	2	0.16	
Lineament Density,' LD' (Km/Km^2)	0 - 0.04	poor	1	0.11	0.31
	0.05 - 0.11	Moderate	2	0.15	
	0.12 - 0.17	Good	3	0.28	
	0.18 - 0.57	Very good	4	0.46	
Topographic Wetness Index, 'TWI'	4.36 - 7.26	poor	1	0.11	0.19
	7.27 - 9.1	Moderate	2	0.15	
	9.11 - 11.4	Good	3	0.28	
	11.5 - 19.5	Very good	4	0.46	
Recharge, 'GR' (mm/y)	30.3 - 53	poor	1	0.11	0.07
	53.1 - 77.7	Moderate	2	0.15	
	77.8 - 99.9	Good	3	0.28	
	100 - 151	Very good	4	0.46	

5.2.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of geology, lineament density, Topographic Wetness Index (TWI), and recharge together with their spatial distribution in Boke woreda are presented below:

I. Geology/Grouped Hydrolithological Units

In general, most parts of the Boke woreda are underlain by Mesozoic sedimentary rocks of upper Hamanilie limestones. Whereas, sedimentary rocks of lower Gabredarre limestone formation overlain by thin layer of eluvial soil at places are outcropped mainly at northern parts of the woreda extending from southeastern parts through central region.

However, the lithological units found in the woreda area are further classified into three major groups based on their significances to groundwater occurrence and productivity using borehole data on yield and transmissivity analysis in particular.

- Mesozoic sedimentary rocks of upper Hamanilie limestone covered by eluvial soils at places. (High productive with Qav. = 13.3 l/s)
- Mesozoic sedimentary rocks of lower Hamanilie limestone & upper sandstones covered by thin layer of eluvium and alluvial deposits at places. (moderately productive with Qav = 4.8 l/s)
- Mesozoic sedimentary rocks of upper Gebredarre limestone (low productive with Qav = 2.5 l/s)

The upper Hamanilie limestone formation is the main lithologic framework of the Boke woreda while sedimentary rocks of lower Hamanilie limestones and upper sandstones overlain by thin layers of eluvial and alluvial sediments at places, and sedimentary rocks of upper Gabredarre limestone formation are also outcropped at limited areas exrtending from northwest to southeast through central regions of the woreda (Figure 5-12).

Usually, massive unfractured lithologic units in sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of poor productivity of upper Gabredarre limestone rocks (0.16)\ moderate productivity of recent alluvium deposits and sedimentary rocks of lower Hamanile limestones (0.30)\ high productivity of upper Hamanile limestone formation (0.54).

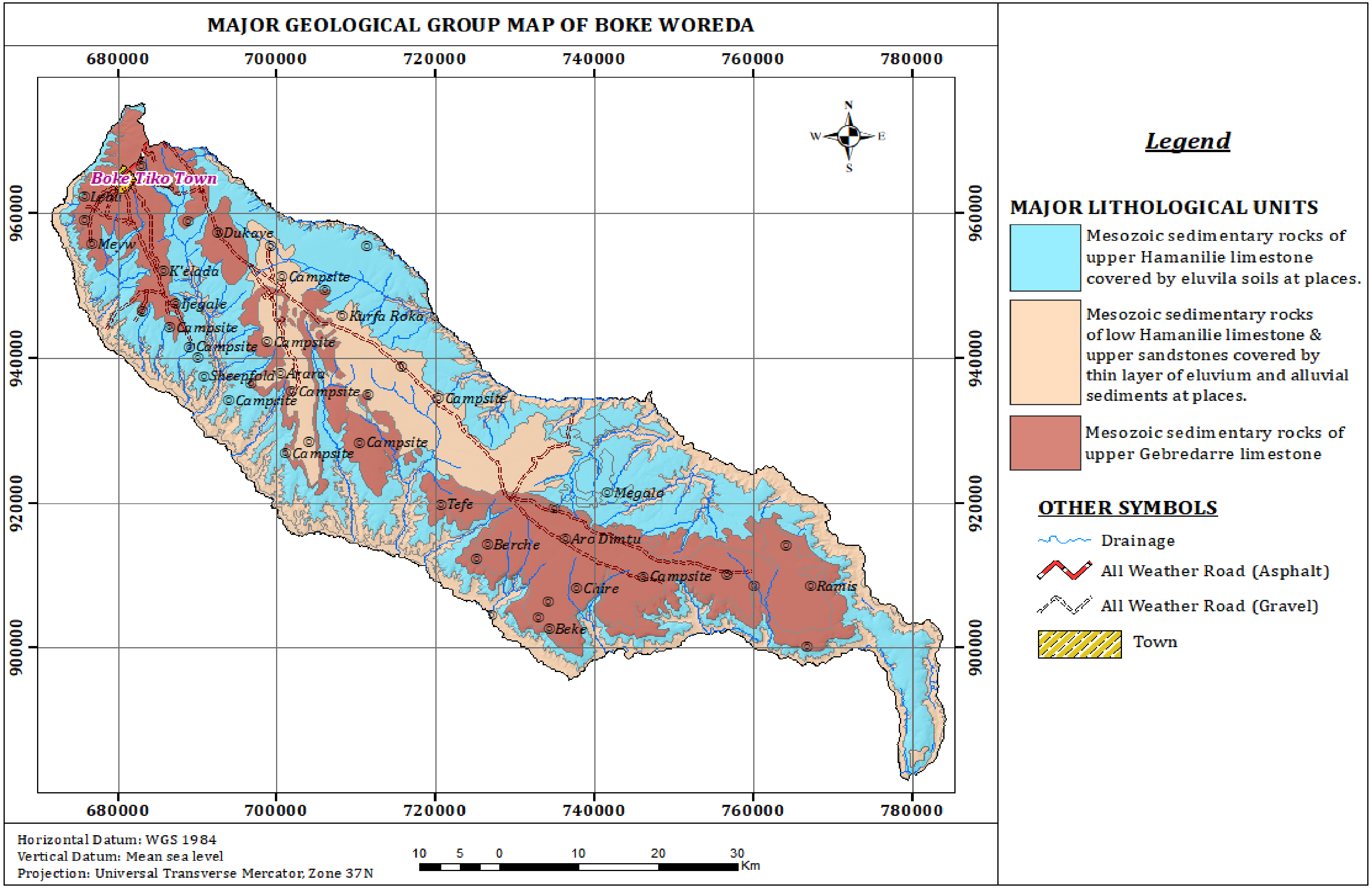

Figure 5-12. Grouped Lithological classification map of Boke Woreda

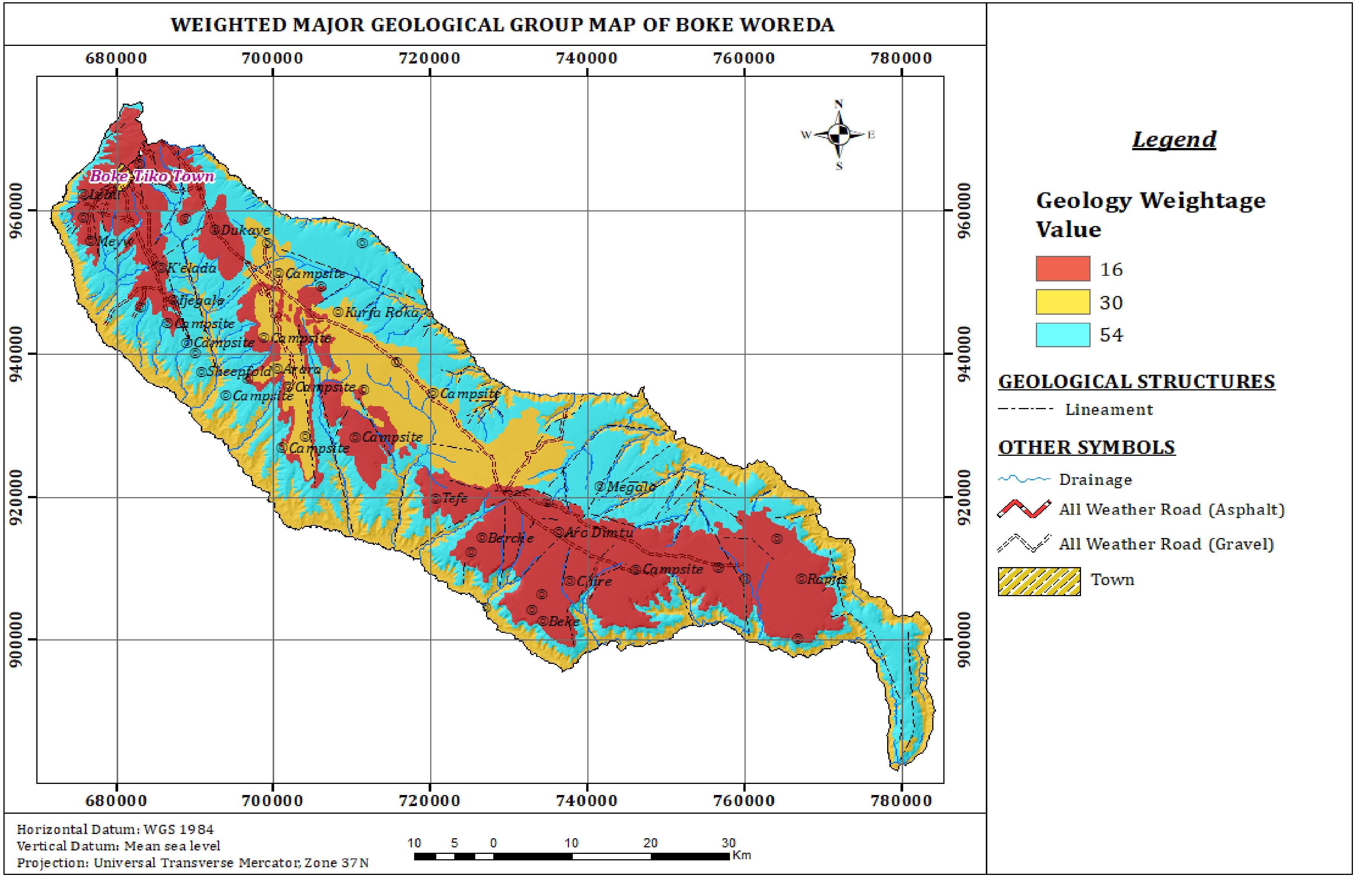

Figure 5-13. Weighted lithological classes' map of the Boke Woreda

II. Lineaments and Lineament Density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Three prominent directions identified are NW-SE, NE–SW, E-W and N–S trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.12 km/km^2 to 0.57 km/km^2 (Figure 5-14). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by upper limestone formations associated with quaternary sediments having relatively higher lineament density of 0.18 – 0.57 km/km^2) compared with areas underlain by sedimentary rocks of lower Hamanilie limestone with lower lineament densities of (< 0.04 km/km^2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.46 was assigned to area with high density of lineaments, while a low weightage of 0.11 was assigned to areas with low lineament density (Figure 5-15).

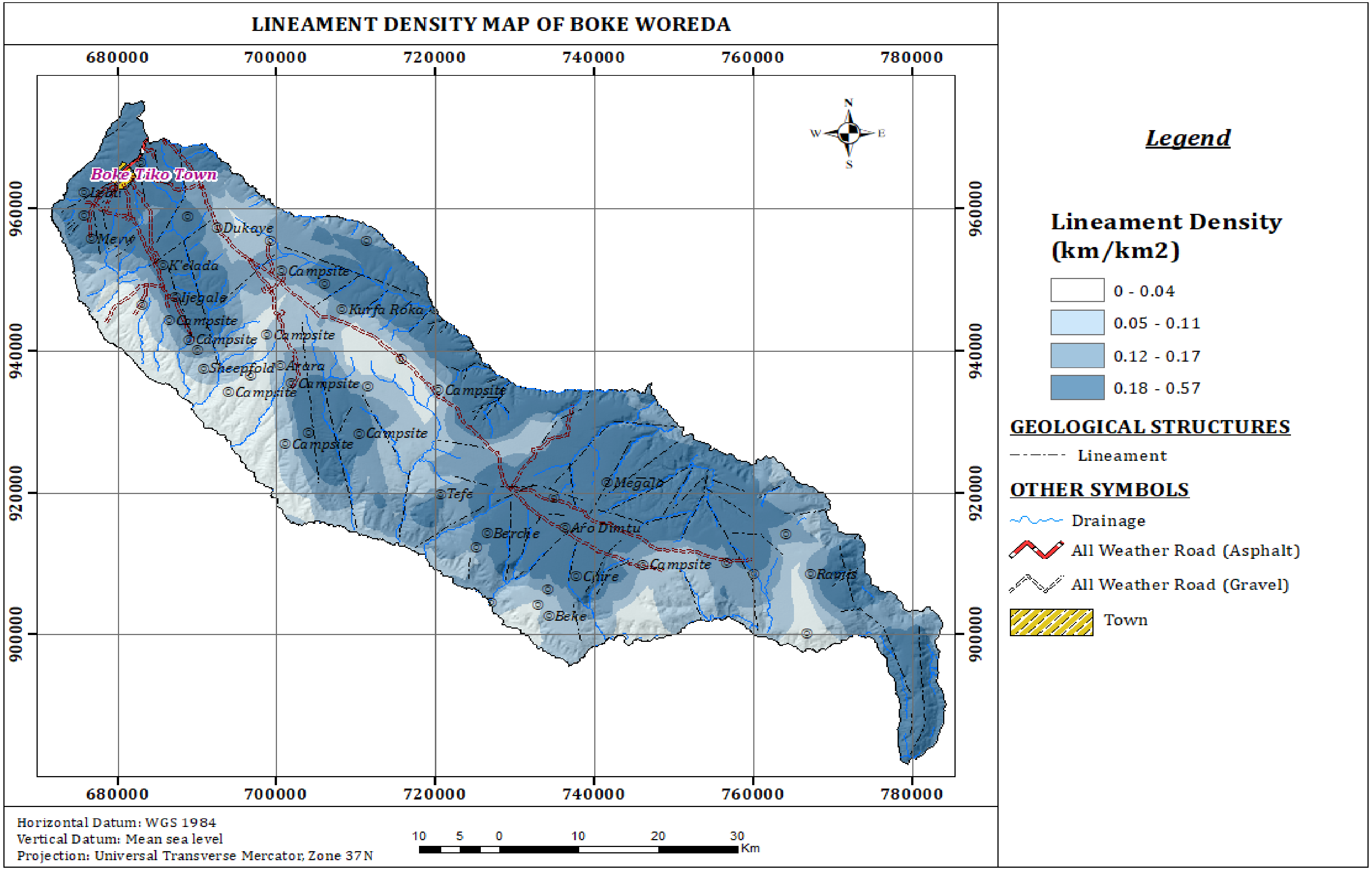

Figure 5-14. Lineament Density Map of Boke Woreda

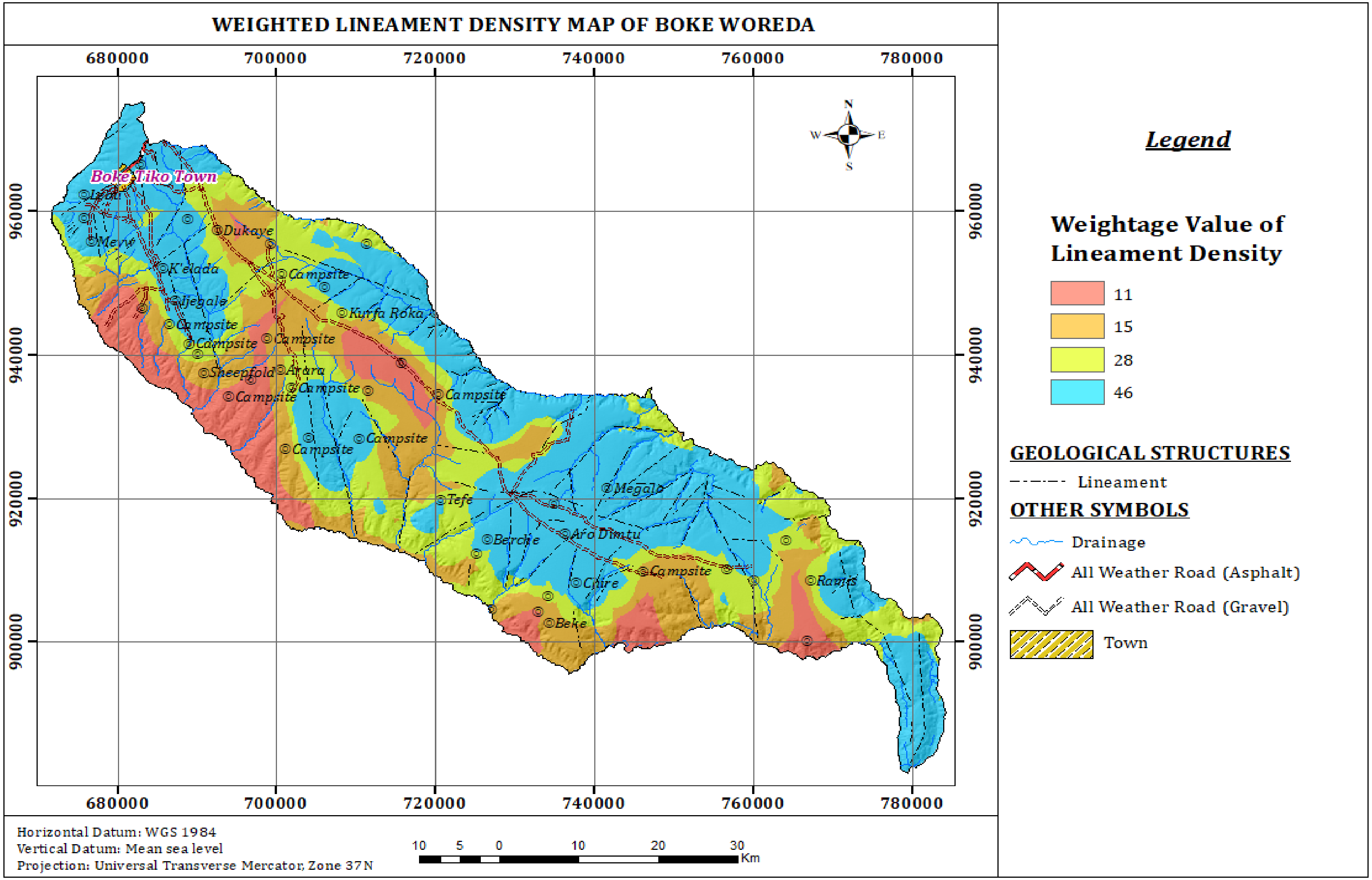

Figure 5-15. Weightage value of Lineament Density Map of Boke Woreda

III. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 4.36 and 19.5. A closer look at the classification revealed that most the high elevated areas and drainage systems with steep slopes have relatively lower TWI value while the low lying areas and drainage systems with gentle and flat slopes such as areas extending from northwest to southeast through central regions of the woreda in particular have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.46) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.11).

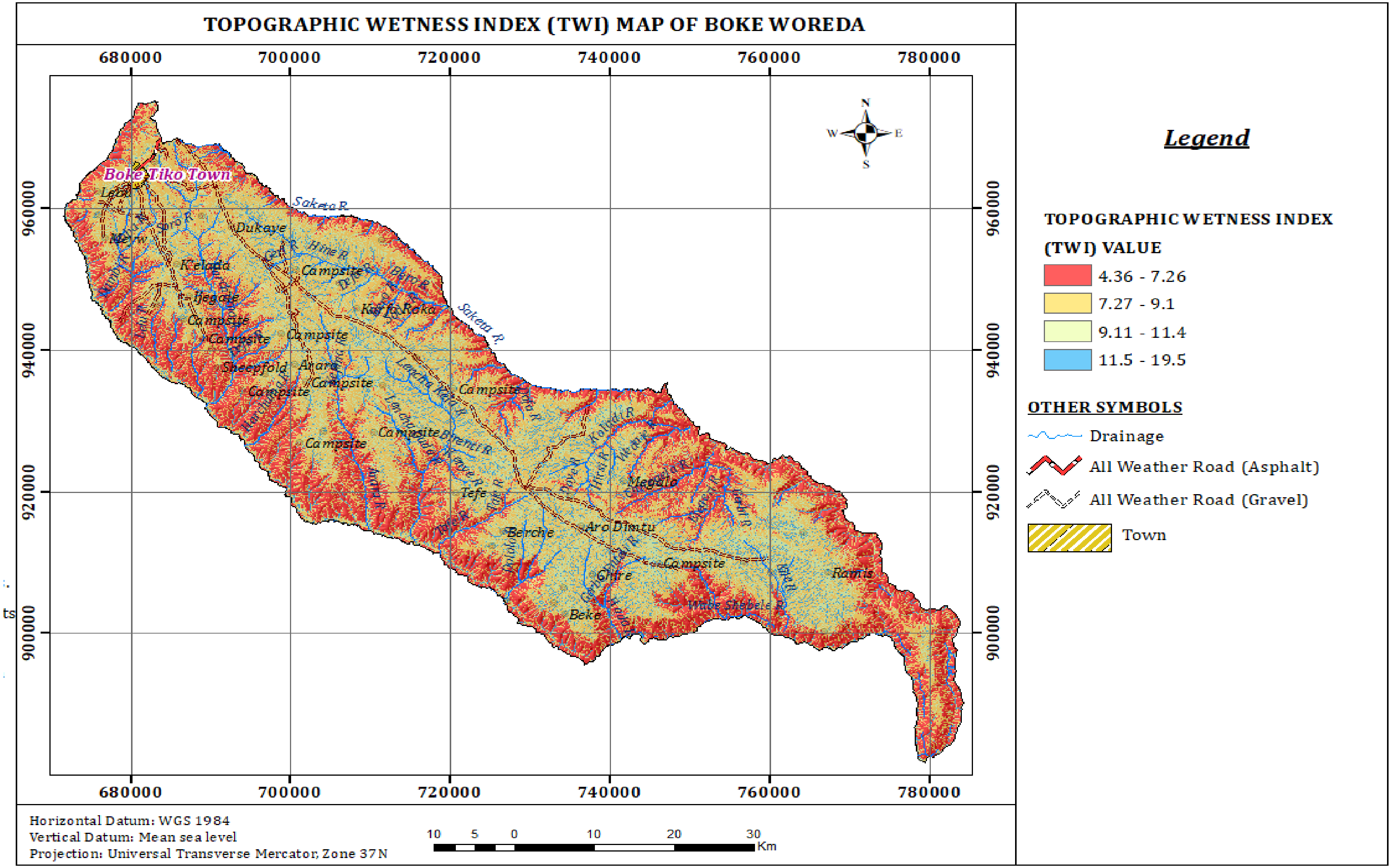

Figure 5-16. TWI Map of Boke Woreda

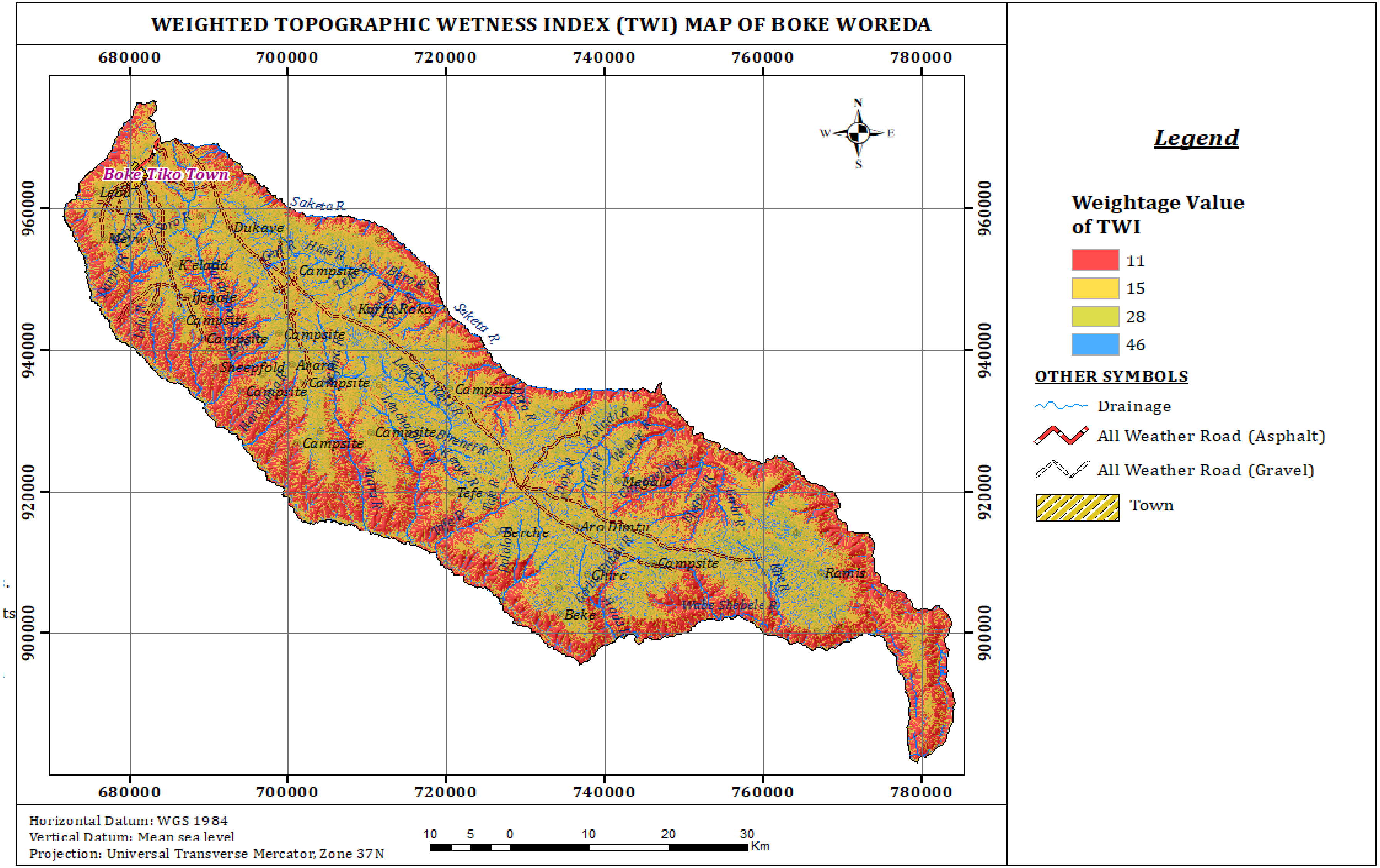

Figure 5-17. Weightage value of TWI Map of Boke Woreda

IV. Recharge

The spatial annual recharge rate distribution in the Boke woreda ranges from 30.3 to 151 mm/y suggesting groundwaters in most central part of the woreda area underlain by eluvial soil associated with upper Gabredarre limeston formation receive low amount of recharge while the most high elevated areas underlain by sedimentary rocks of upper Hamanile and Gabredarre limestone formations and quaternary sediments have relatively higher recharge amount (Figure 5-18). Accordingly, areas with very high and high amount of recharge have weightage factor of 0.46 and 0.28, respectively signifying very good and good groundwater potential while areas with the moderate and lowest amount of recharge have weightage factor of 0.15 and 0.11, respectively suggesting moderate and poor groundwater potentiality. A closer look at the recharge thematic map revealed that most of the central, central western, central eastern, and southeastern low-lying parts of the woreda have relatively lower recharge (< 78 mm/y). Generally, the study area is characterized with moderate to low to moderate mean annual recharge amount, whereas most of the central western parts have high to very high mean annual recharge amount (78 -151 mm/y).

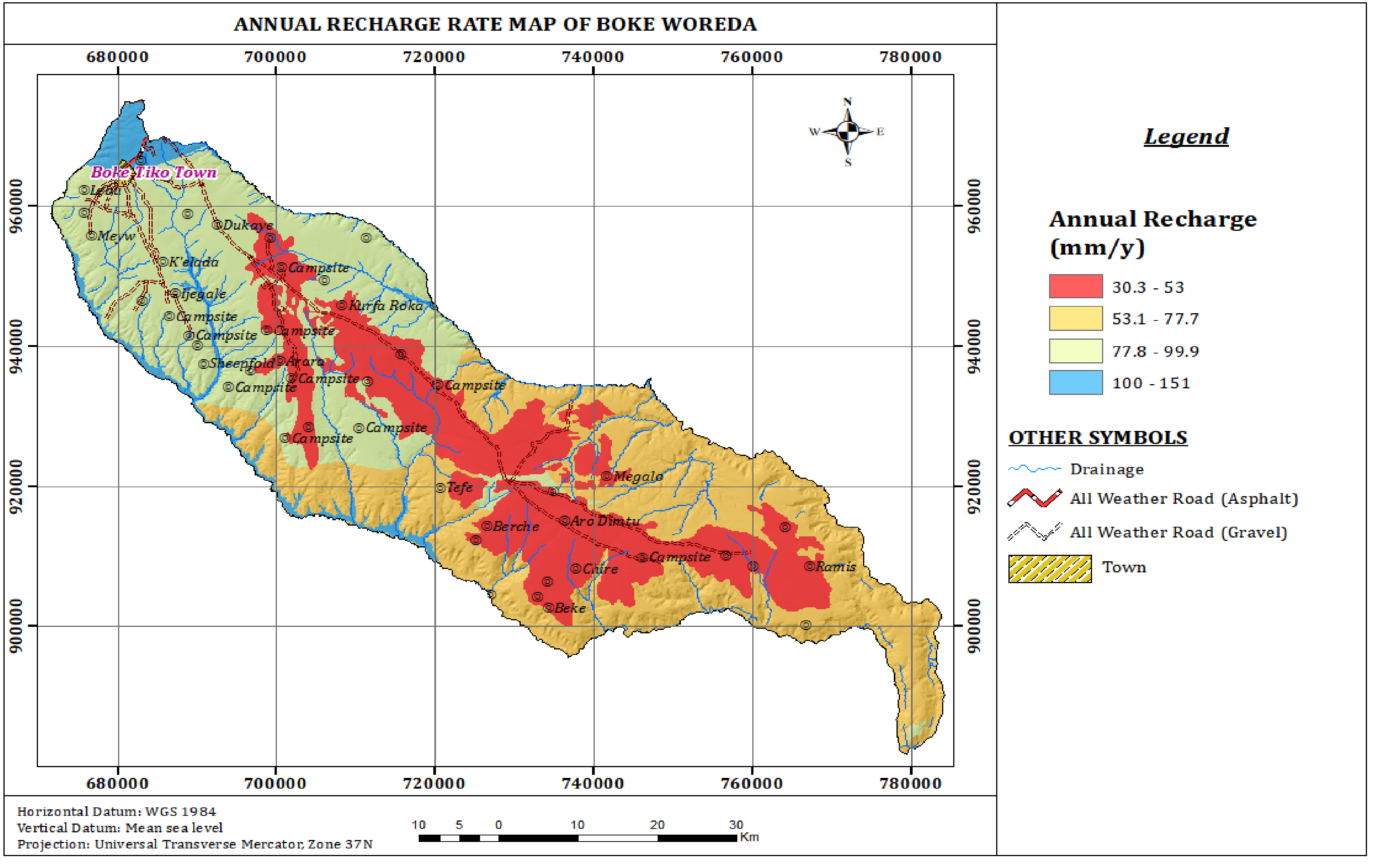

Figure 5-18. Annual Recharge Map of Boke Woreda

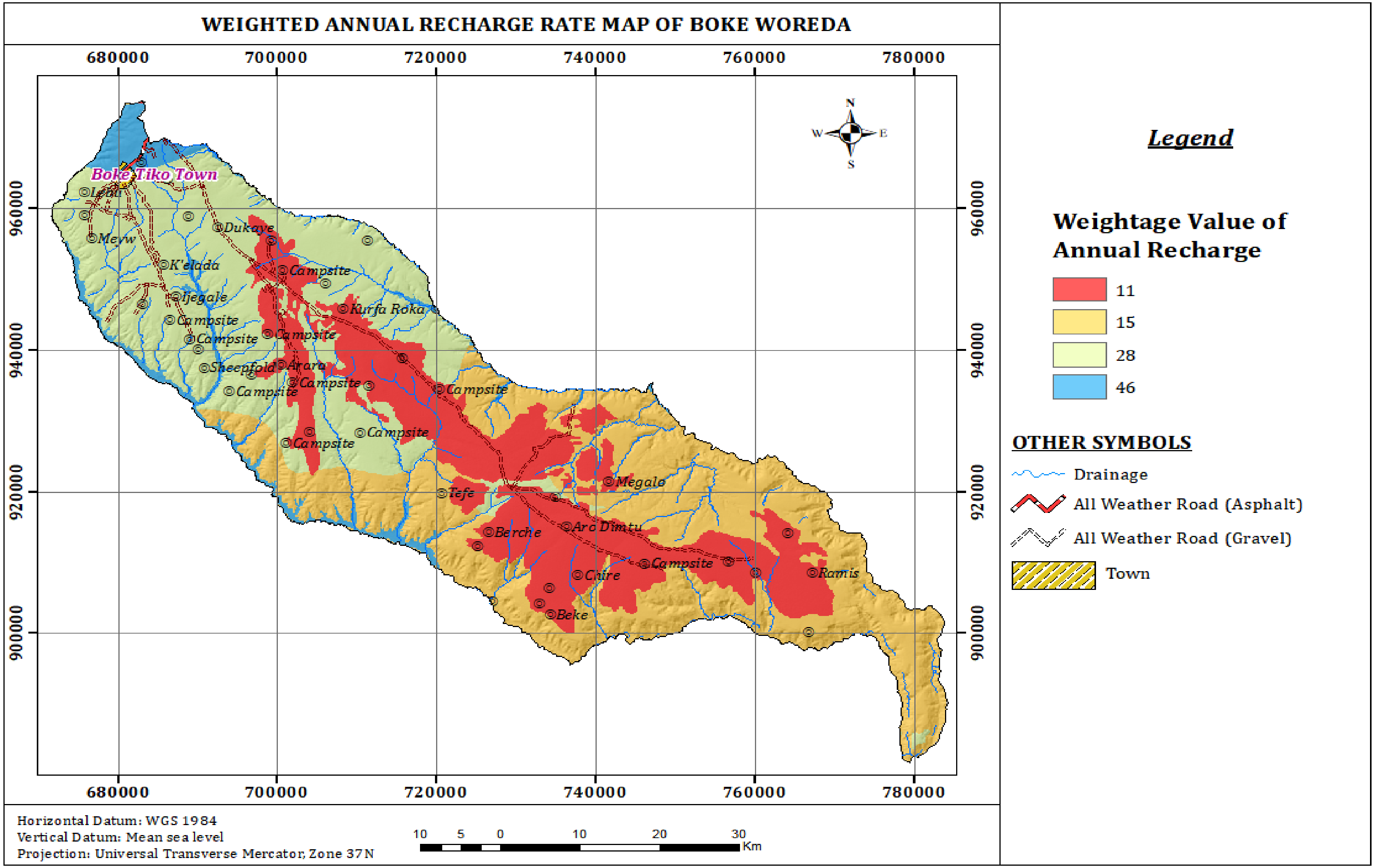

Figure 5-19. Weighted Annual Recharge classes' map of the Boke Woreda

5.2.3. Classification of Groundwater Potential Zones

The hydrogeological system of Boke woreda is comprised of three main lithological units as upper Gabredarre limestone formation, and upper Hamanlie and lower Hamanile limestone formations. At both regional scale and local scale within the domain of Boke woreda, upper Hamanilie limestone formation form extensive and high productive aquifers. Theses, limestone formations form aquifers with high groundwater potential as revealed from existing borehole information.

Only the upper weathered and slightly fractured and/or karistified part of the limestone rocks along lineamnets and faults have potential to store groundwater at shallow depth. Weathered and fractured/karstified fractured sedimentary rocks of limestone formations with overlying Quaternary deposit form major potential aquifer within the domain of Boke Woreda along lineament and fault lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-20). The potential groundwater zones (PGZ) of the Boke woreda revealed four distinct zones, namely low, moderate, high and very high zones as presented in Table 5-9.

The potential map, as presented in Figure 3-15, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that most elevated areas around the southeren peripheries and central parts of the Boke Woreda generally have low potentials, while most areas at central western, southeastern and western margins generally exhibits high to very high potentials. The generally high to very high groundwater potentiality of the study area is a confirmation of generally moderate to high productive aquifers of upper Hamanilie limestone formation; whereas low groundwater potential areas have an indication of limited aquifers capabilities of lower Gabredarre sedimentary terrain of limestone formation.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the geology and lineament density in addition to the topographic wetness index control. In addition, areas underlain by upper Hamanilie limestone formation especially in the central eastern sections of the study area are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments, and apparently deep fracturing and karstifcation system have high and very high groundwater potential on the one hand. On the other hand, areas underlain by upper Gabredarre limestone formations in the central, northwestern and western periphery of the woreda in particular are characterized by rugged and elevated topography with relatively teep slopes, and lower lineament densities, exhibit moderate to low groundwater potential while areas underlain by sedimentary rocks of lower Hamanilie limestone formation have medium potential. Moreover, low lineament densities and predominance of upper Gabradarre limestone formation intercalated with marls and shale outcrops can be attributed to the observed low groundwater potentials at the most central and peripheries of the study area. However, predominance of fractured and karstified sedimentary rocks of upper Hamanile limestone outcrops, high lineament density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential exhibited at most eastern portions of the study area. Summary of the groundwater potential zones identified in the Boke woreda is presented in the table below (Table 5-9).

Table 5-9. Classification of groundwater potential zones and coverage areas alongside the respective yield categories

Woreda Name	GWP Zones	Major Aquifer Units	Borehole Yield Classification (l/s)	
			Q (Range)	Mean 'Q'
Boke	Very High	Upper Hamanilie Limestone (Jh2)	5.6 - 30	11.3
	High	Upper & Lower Hamanilie Limestones (Jh2 & Jh1)	5 - 10	7.04
	Moderate	Upper Gabredarre Limestone (Jg2)	3.3 – 6.3	4.9
	Low	Upper Gabredarre Limestone (Jg2)	1.5 - 4	2.7

5.2.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) were collated for over 55 boreholes in and around the synoptic study area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the study area vary from 5.6 to 30 lit/sec (av. 11.3 lit/sec) in very high potential zones and varying from 5 lit/sec to 10 lit/sec (av. 7.04 lit/sec) in high potential zones as compared with 3.3 lit/sec to 6.3 lit/sec (av. 4.9 lit/ sec) in the moderate and from 1.5 to 4 lit/sec (av. 2.7 lit/sec) in the low potential zones (Figure 5-20). As shown in the Figure 5-20, the occurrence of number of wells with yield of in the range 5- 7 lit/sec (high yield) and of > 8 lit/sec (very high yield) cut across mainly the recent quaternary deposits and sedimentary rocks. However, the less frequency of wells within basement rocks in the low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (3-5 lit/sec) and high-yield (5 - 7 lit/sec) categories are associated also with wells in the Mesozoic sedimentary rocks and older alluvial deposits along river channel. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

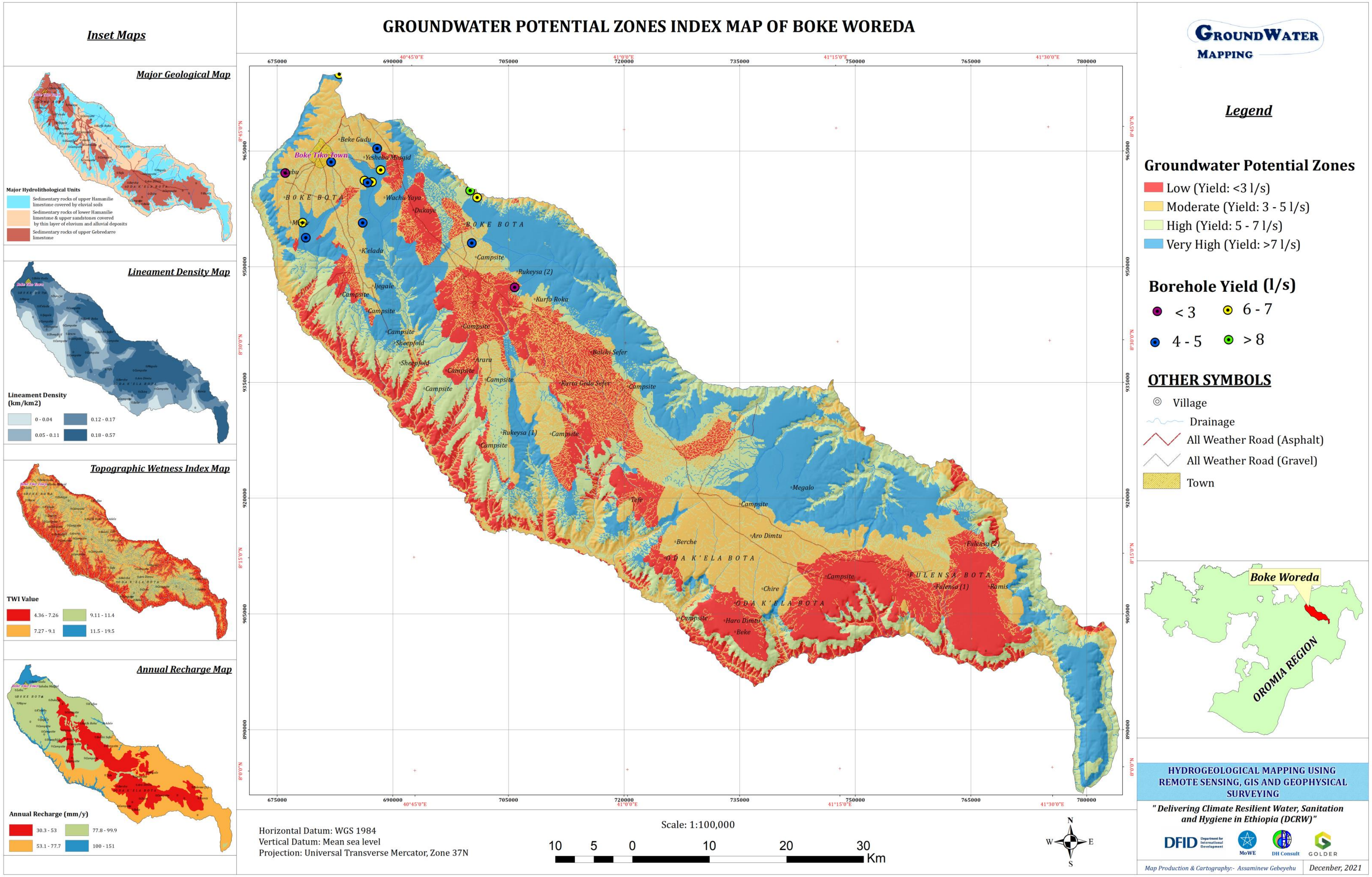

Figure 5-20. Groundwater Potential Zones Map of Boke Woreda

5.2.5. Projected Population and Water Demand

5.2.5.1. Population

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-10 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P = Po (1 + r)^{n}$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Boke Woreda has been projected forward until 2036 using the growth rate of Oromia Regional State. The minimum and maximum population in the Woreda is 701 and 18,015 respectively. The total population of the BokeWoreda in 2036 is going to be 270,801.

5.2.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic

purposes greatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO) & (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer's life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24 hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from 1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-21 shows the distribution of water demand in each Kebeles of the Woreda. Mada Jalala kebele water demand is the minimum with 63 M^3/day and maximum water demand is required for Tefe Kebeles with 1618 M^3/day respectively. The overall water demand for the projected population in the Boke Woreda is 24,327 M^3/day.

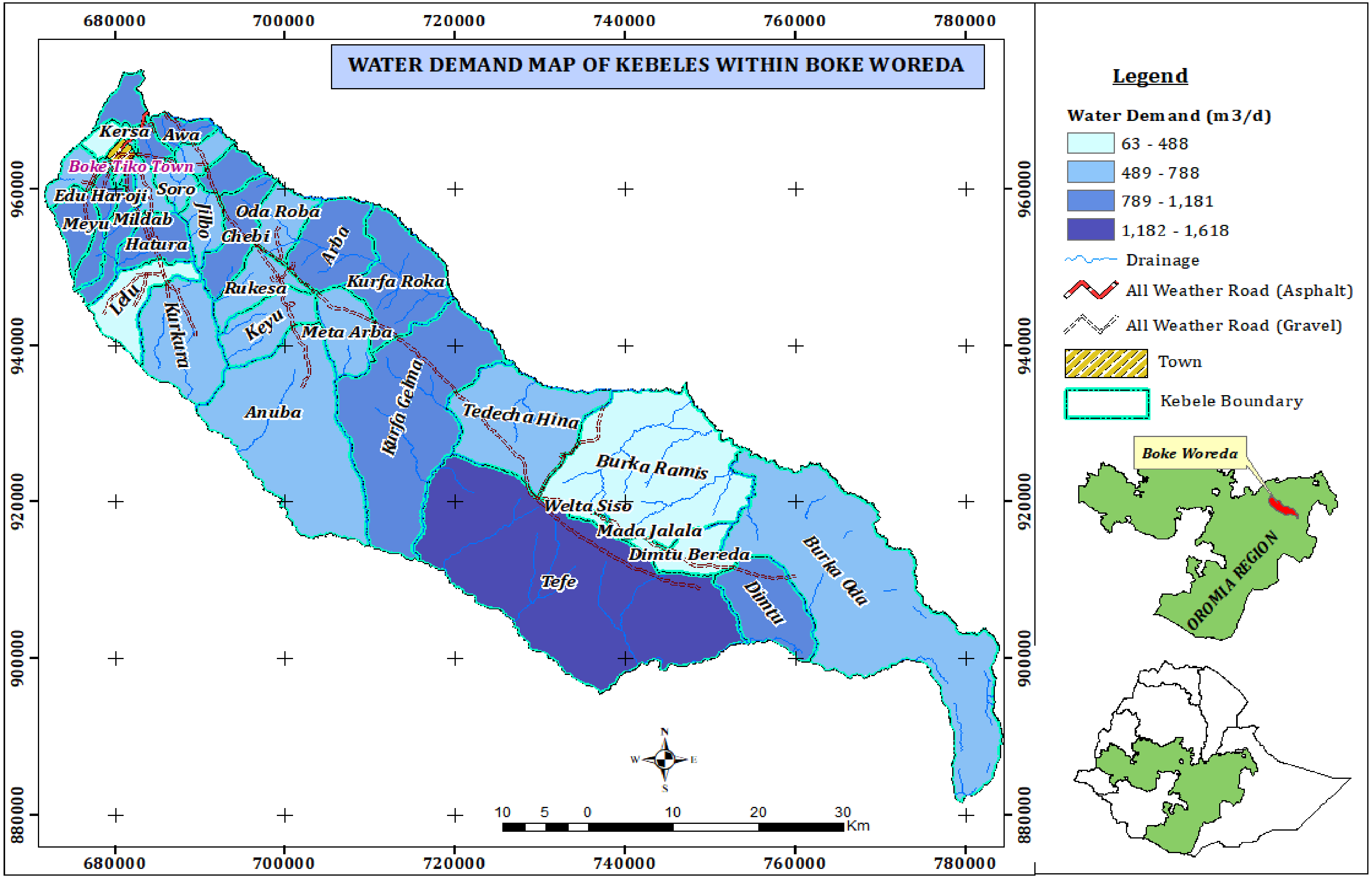

Figure 5-21:-Water Demand Map of Boke Woreda

5.2.6. Propsed Target Sites

Four target sites are identified and proposed within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficiaries and population density. With further discussion and consultation with stakeholders, two priority sites will be selected for further hydrogeological and geophysical investigations in phase III. The following are the four proposed sites:

Target Site-I:

This target site is located in the eastern part of the woreda, around Boke Bota Kufisa locality. It is situated in the identified very high and high potential zones with expected optimum borehole discharge of about 15 l/s. This target site is mainly underlain by Mesozoic sedimentary rocks of upper Hamanilie limestone formation.

Target Site-II:

This target site is located in the central northern part of the woreda, around south of Boke town. It is situated in the identified very high and high potential zones with expected optimum borehole discharge of about 6 l/s. This target site is mainly underlain by Mesozoic sedimentary rocks of upper Hamanilie limestone formation.

Target Site-III:

This target site is located in the northwestern part of the woreda, around southwest of Boke town. It is situated in the identified very high and high potential zones with expected optimum borehole discharge of about 5 l/s. This target site is mainly underlain by Mesozoic sedimentary rocks of upper Hamanilie limestone formation.

Target Site-IV:

This target site is located in the southeastern region of the woreda, around Megalo locality. It is situated in the identified very high and high potential zones with expected optimum borehole discharge of about 6 l/s. This target site is mainly underlain by Mesozoic sedimentary rocks of upper and lower Hamanilie limestone formations.

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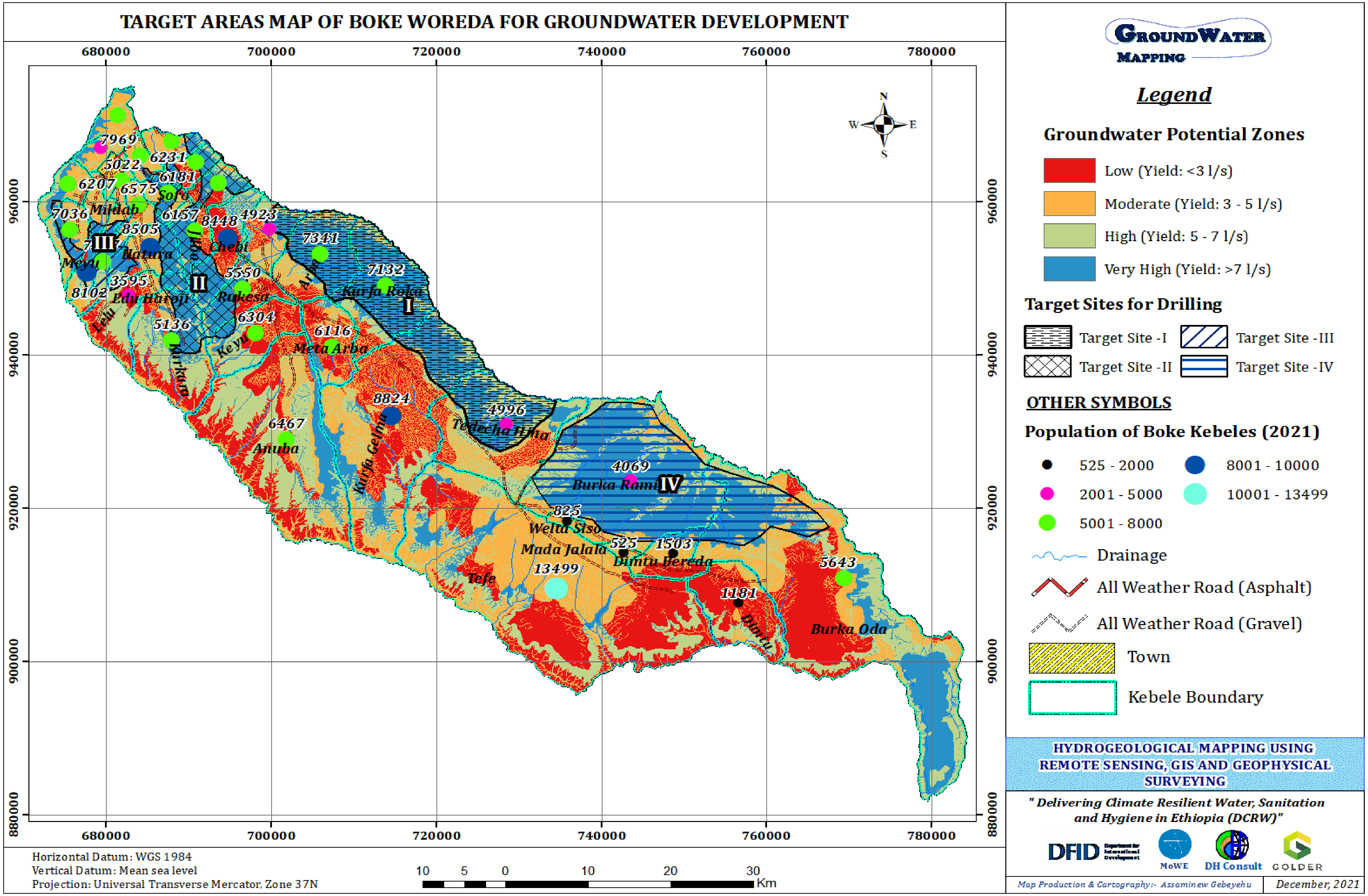

Figure 5-22:-Target Areas Map of Boke Woreda

5.3. Agarfa Woreda

5.3.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.05 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Agarfa woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-11). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-12. The weights assigned to the respective thematic maps as presented in Table 5-13 indicate that TWI was ranked the dominant factor with a normalized weight value of 0.41 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Agarfa woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Agarfa woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

GWPZI = (TWIwTWIwi + GGwGGwi + LDwLDwi + GRwGRwi)

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Agarfa woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e. 'very high', 'high', 'moderate' and 'low or poor', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-11 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Topographic Wetness Index (TWI)	9
Geology (GG)	8
Lineament density (LD)	7
Recharge (GR)	6

Table 5-12 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	TWI	GG	LD	GR	
TWI	1	1	3	5	0.41
GG	1	1	3	2	0.34
LD	1/3	1/3	1	2	0.15
GR	1/5	1/2	1/2	1	0.10

Table 5-13 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank
Topographic Wetness Index, 'TWI'	4.2 – 7.2	poor	1	0.11	0.41
	7.3 – 9.1	Moderate	2	0.15	
	9.2 - 11.6	Good	3	0.28	
	11.7 – 18.1	Very good	4	0.46	
Geology/ Lithology, 'GG'	Tertiary volcanics of lower and highland basaltic flows, and upper Hamanilie limesone Formation.	Very good	4	0.67	0.34
	Tertiary volcanics of plateau basalt and Alaji basalt	Good	3	0.33	
Lineament Density,' LD' (Km/Km^2)	0.01 - 0.14	poor	1	0.11	0.15
	0.15 - 0.26	Moderate	2	0.15	
	0.27 - 0.39	Good	3	0.28	
	0.45 - 0.51	Very good	4	0.46	
Recharge, 'GR' (mm/y)	77.2 - 88.3	poor	1	0.11	0.10
	88.4 - 103	Moderate	2	0.15	
	104 - 145	Good	3	0.28	
	146 - 158	Very good	4	0.46	

5.3.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of Topographic Wetness Index (TWI), geology, lineament density and recharge together with their spatial distribution in Agarfa woreda are presented below:

I. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 4.2 and 18.1. A closer look at the classification revealed that most the high elevated areas and drainage systems with steep slopes have relatively lower TWI value while the low lying areas and drainage systems with gentle and flat slopes such as areas in eastern regions of the woreda in particular have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.46) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.11).

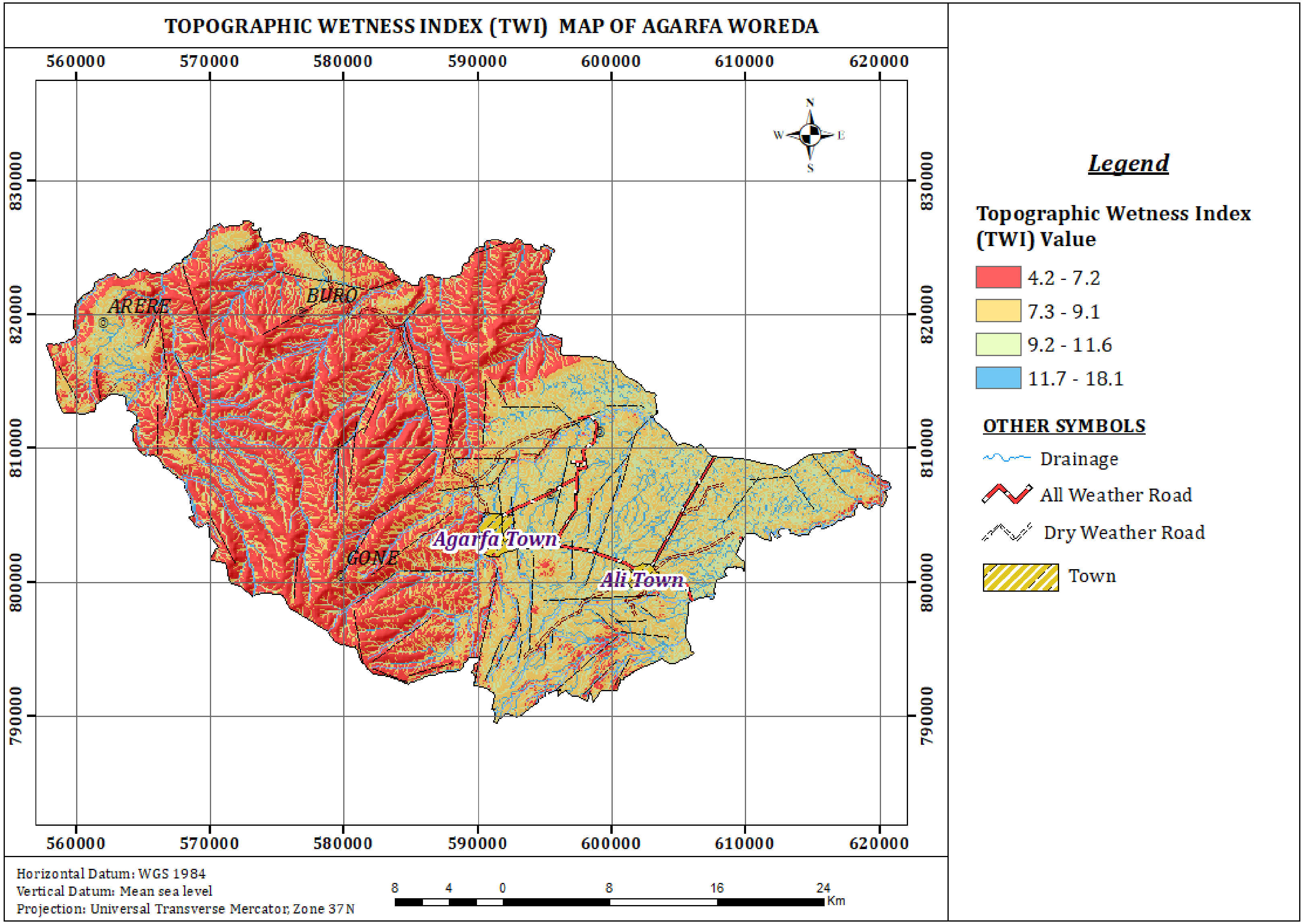

Figure 5-23. TWI Map of Agarfa Woreda

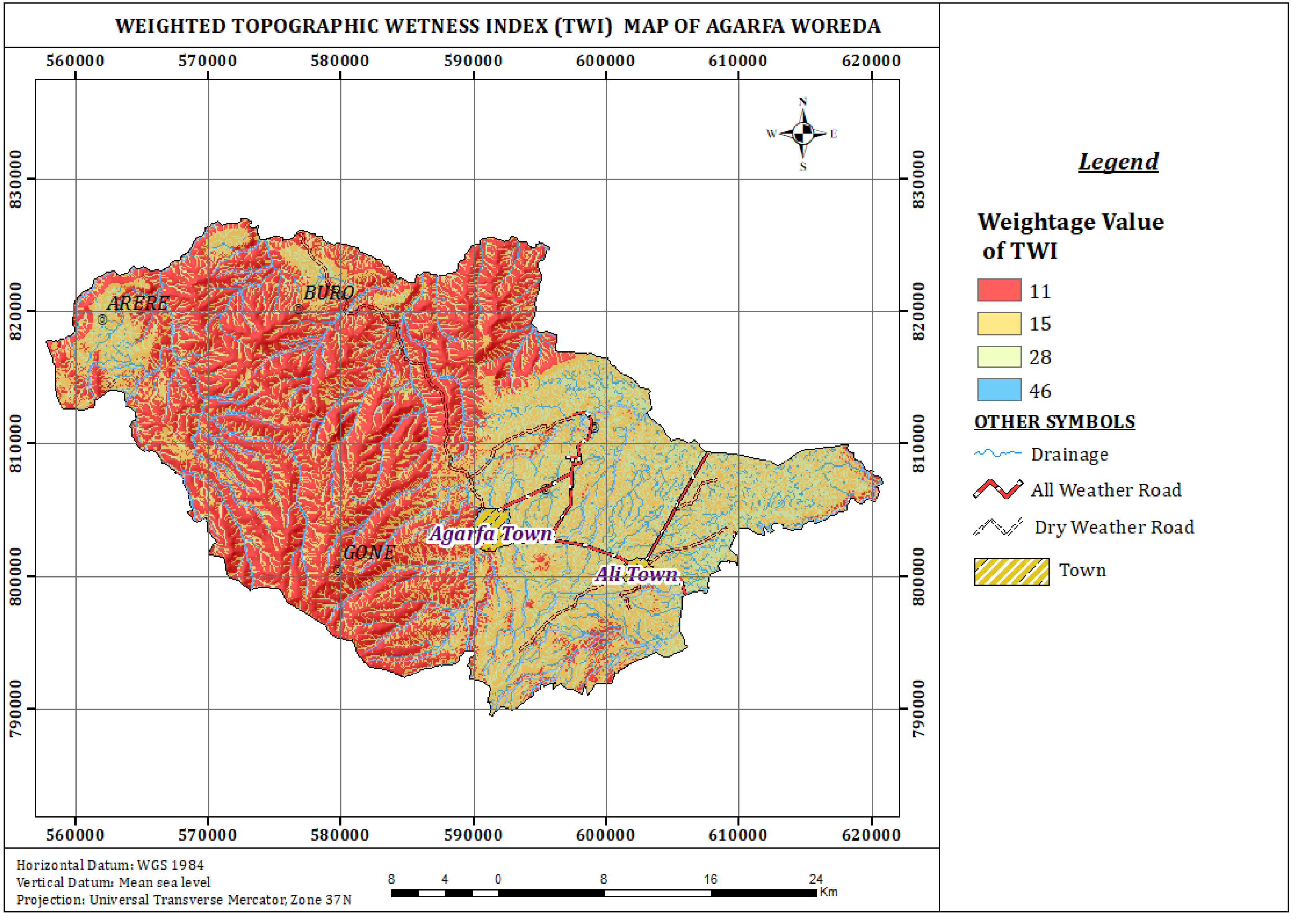

Figure 5-24. Weightage value of TWI Map of Agarfa Woreda

II. Geology/Grouped Hydrolithological Units

In general, most parts of the Agarfa woreda are underlain by Tertiary volcanic rocks of plateau, highland and lower basalts. Whereas, Mesozoic sedimentary rocks of upper Hamanile limestone formation are mainly outcropped at central western parts of the woreda.

However, the lithological units found in the woreda area are further classified into two major groups based on their significances to groundwater occurrence and productivity using borehole data on yield and transmissivity analysis in particular.

- Tertiary volcanics of lower and highland basaltic flows, and upper Hamanilie limesone Formation. (Very high productive with Qav. = 16 l/s)
- Tertiary volcanics of plateau basalt and Alaji basalt. (High productive with Qav = 11 l/s)

Tertiary volcanics of lower basalts, highland and plateau basalt are the main lithologic framework of the Agarfa woreda, and sedimentary rocks of upper Hamanilie limestone formation and volcanic rocks of Alaji basalt are also outcropped at limited areas of the woreda (Figure 5-25).

Usually, massive unfractured lithologic units in volcanic and sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification, weathering and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of high productivity of plateau basalt (0.33) \ very high productivity of Tertiary volcanics of lower and uppermost basaltic flows, and upper Hamanile limestone formation (0.67).

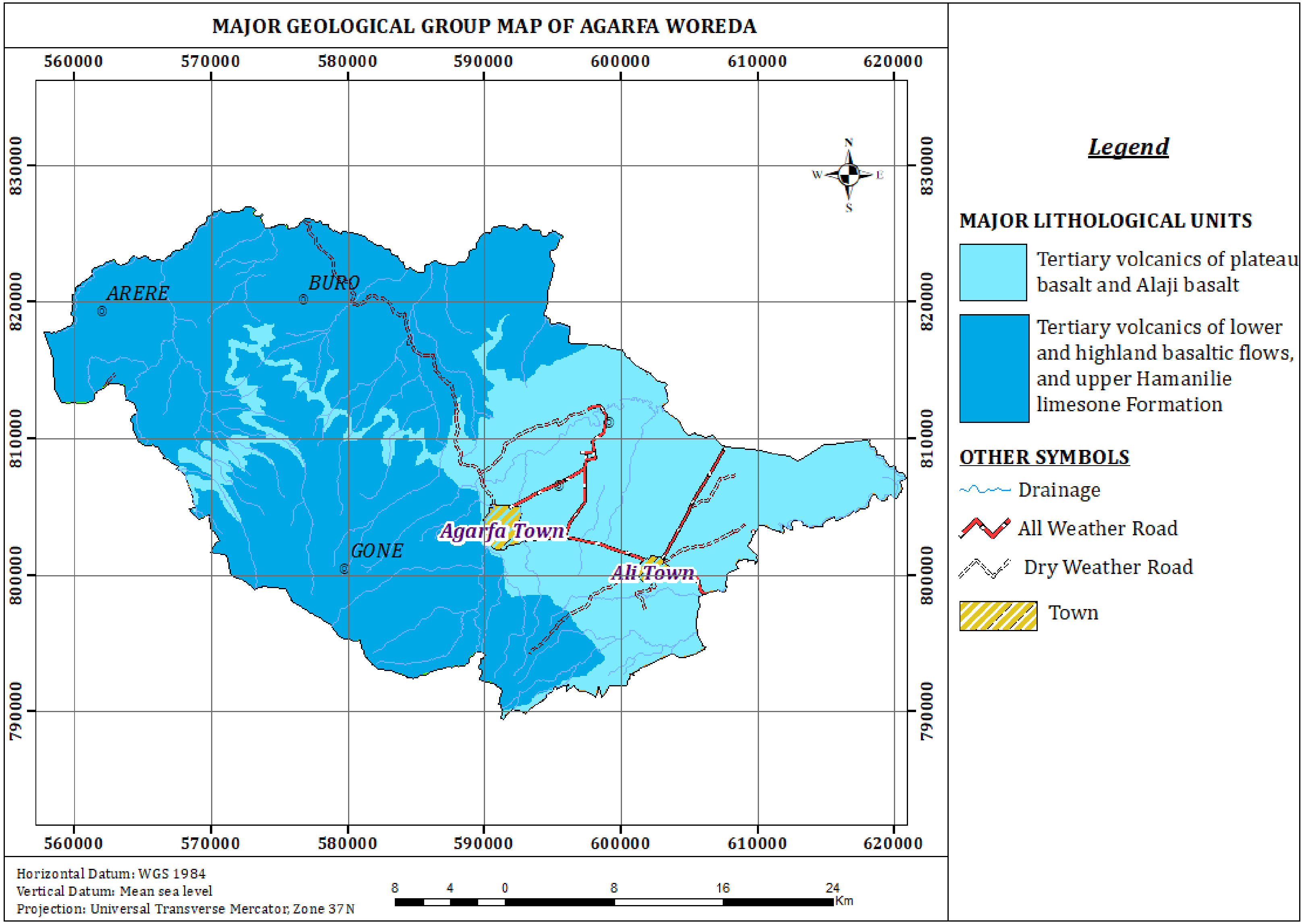

Figure 5-25. Grouped Lithological classification map of Agarfa Woreda

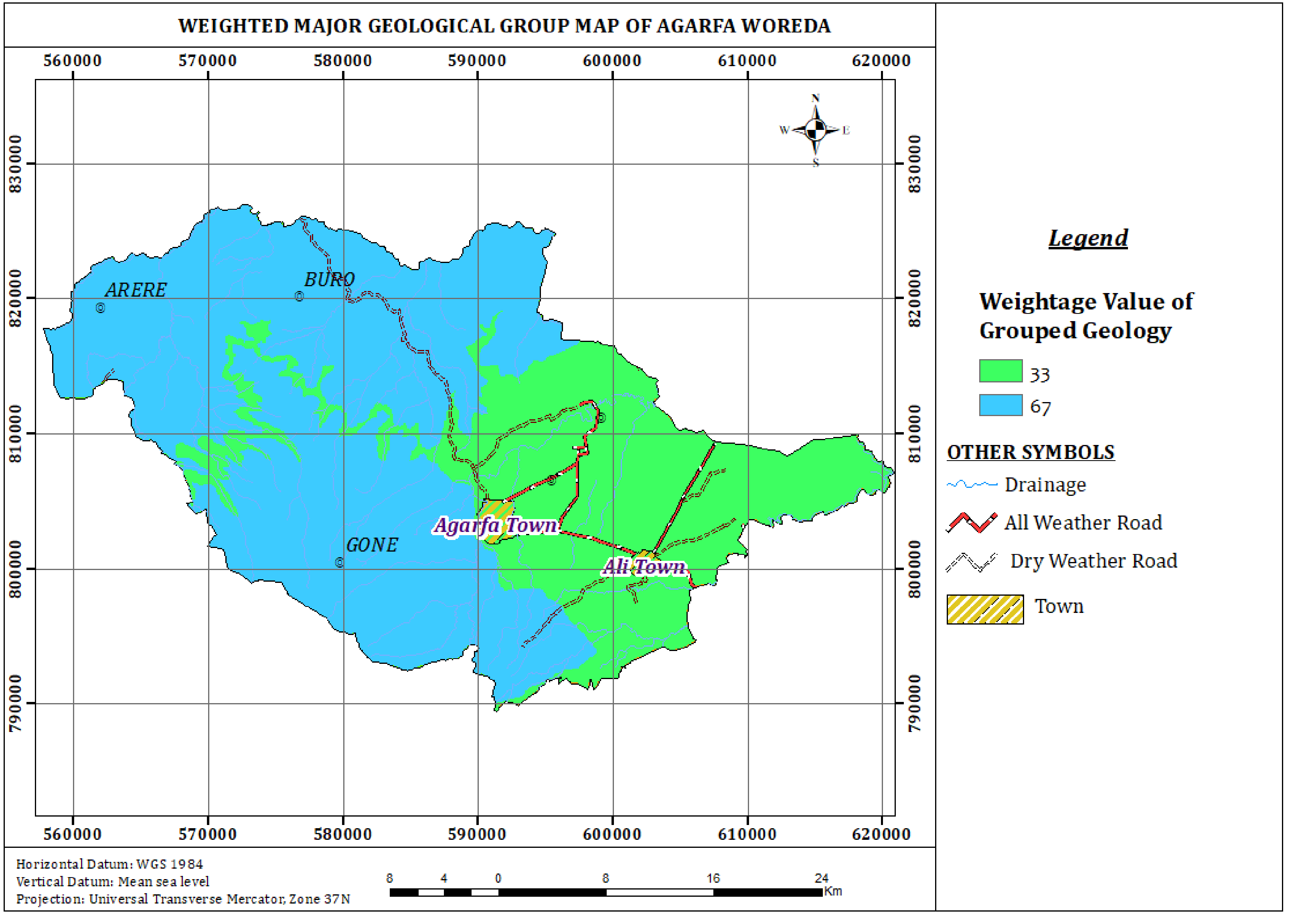

Figure 5-26. Weighted lithological classes' map of the Agarfa Woreda

III. Lineaments and Lineament Density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Three prominent directions identified are E-W, NW-SE and NE–SW trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.01 km/km^2 to 0.51 km/km^2 (Figure 5-27). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by Tertiary volcanics of plateau basalt having relatively higher lineament density of 0.45 - 0.51 km/km^2) compared with areas underlain by highland and lower basalts with lower lineament densities of (< 0.14 km/km^2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.46 was assigned to area with high density of lineaments, while a low weightage of 0.11 was assigned to areas with low lineament density (Figure 5.28).

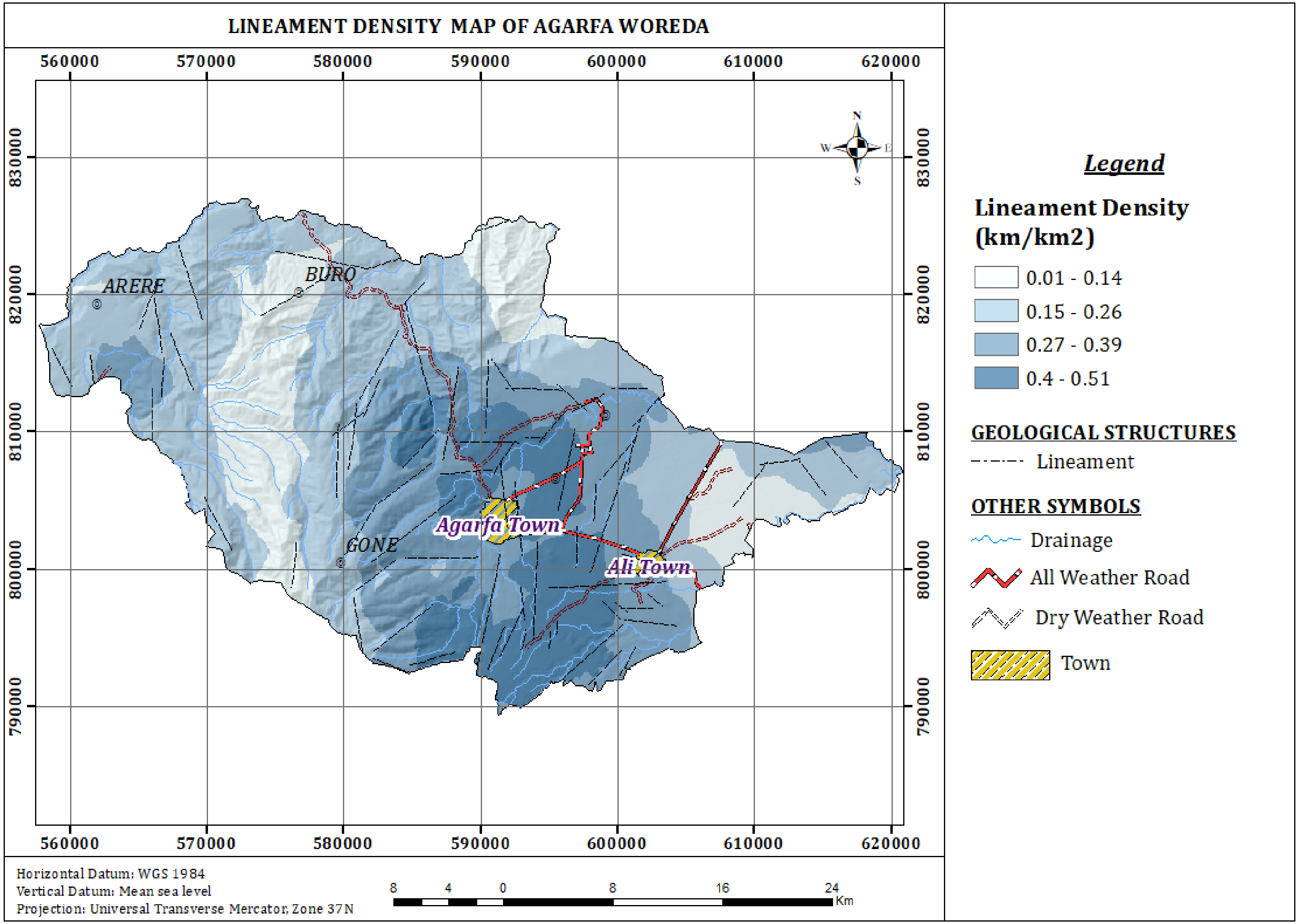

Figure 5-27. Lineament Density Map of Agarfa Woreda

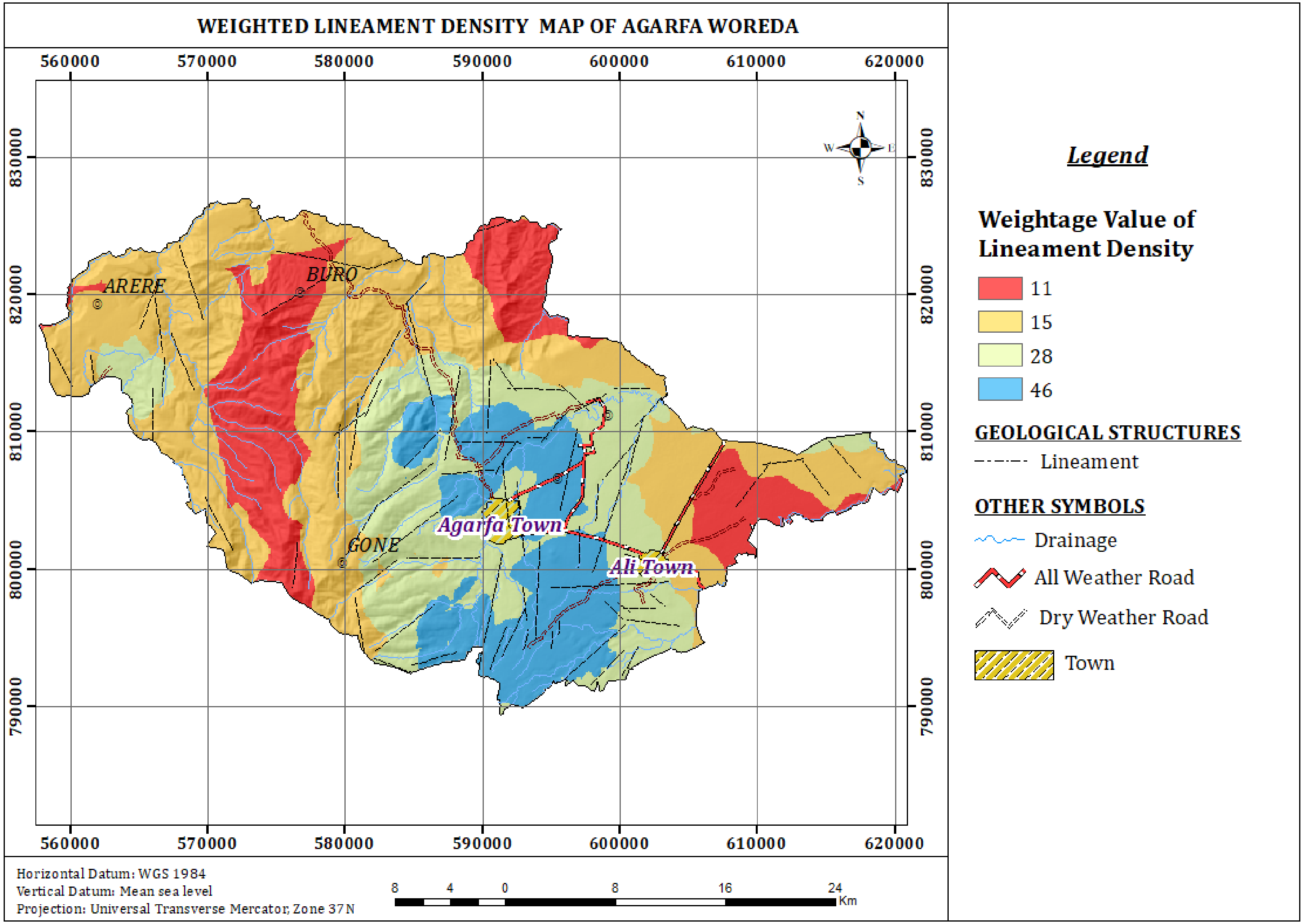

Figure 5-28. Weightage value of Lineament Density Map of Agarfa Woreda

IV. Recharge

The spatial annual recharge rate distribution in the Agarfa woreda ranges from 77.2 to 158 mm/y suggesting groundwaters in most central southern and eastern elevated regions of the woreda area underlain by Tertiary volcanics of highland and plateau basaltic flows receive high amount of recharge while the western low-lying areas underlain by Tertiary volcanics of lower basalt falls and upper Hamanilie limestone have relatively lower recharge amount due to very low infiltration rate of the lithological formation (Figure 5-29). Accordingly, areas with very high and high amount of recharge have weightage factor of 0.46 and 0.28, respectively signifying very good and good groundwater potential, respectively while areas with the mderate and lowest amount of recharge have weightage factor of 0.15 and 0.11, respectively, suggesting moderate and poor groundwater potentiality, respectively. Generally, the study area is characterized with high to very high mean annual recharge amount (> 104 mm/yr), whereas most of the western regions have moderate to low mean annual recharge amount (77-103 mm/yr).

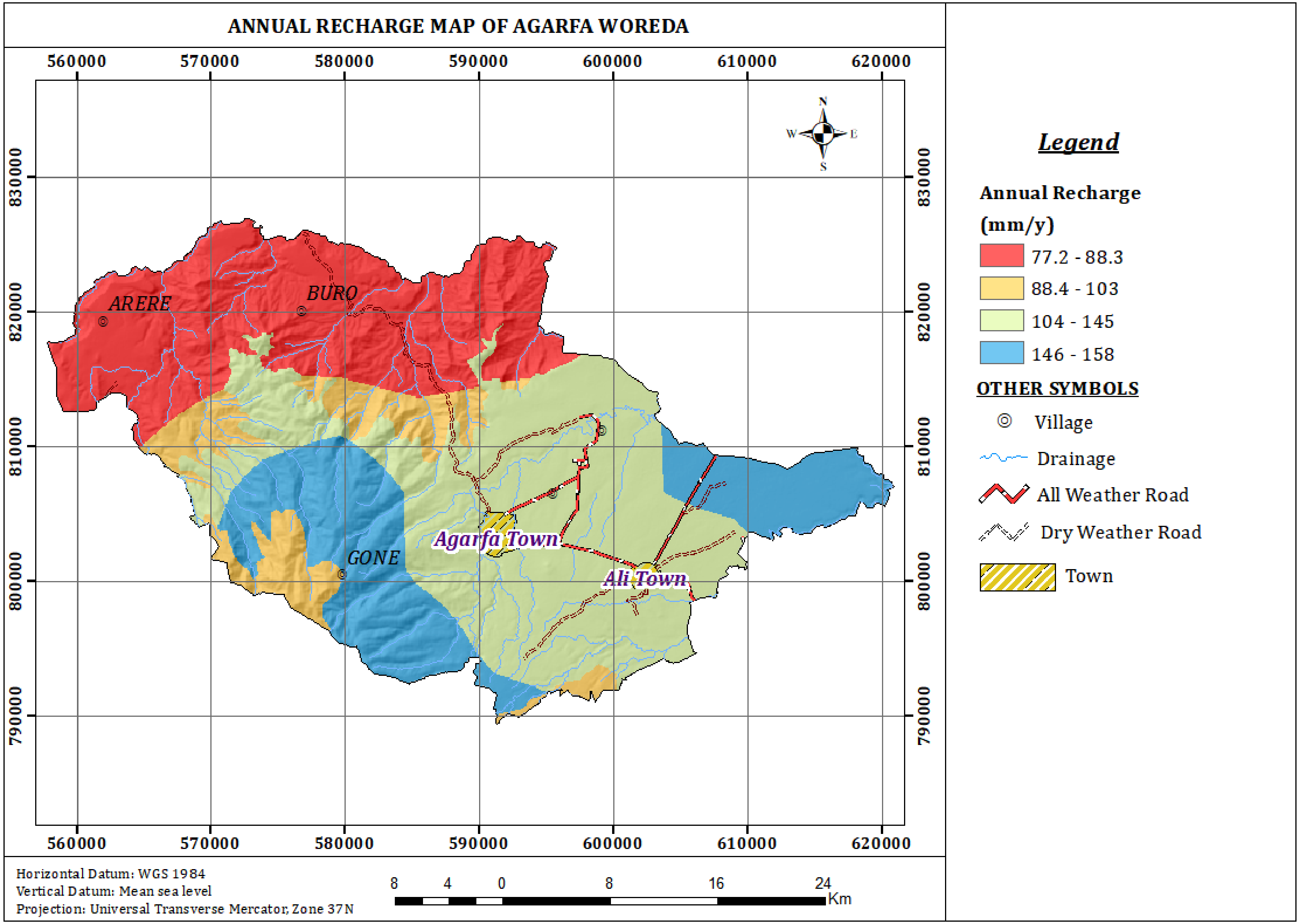

Figure 5-29. Annual Recharge Map of Agarfa Woreda

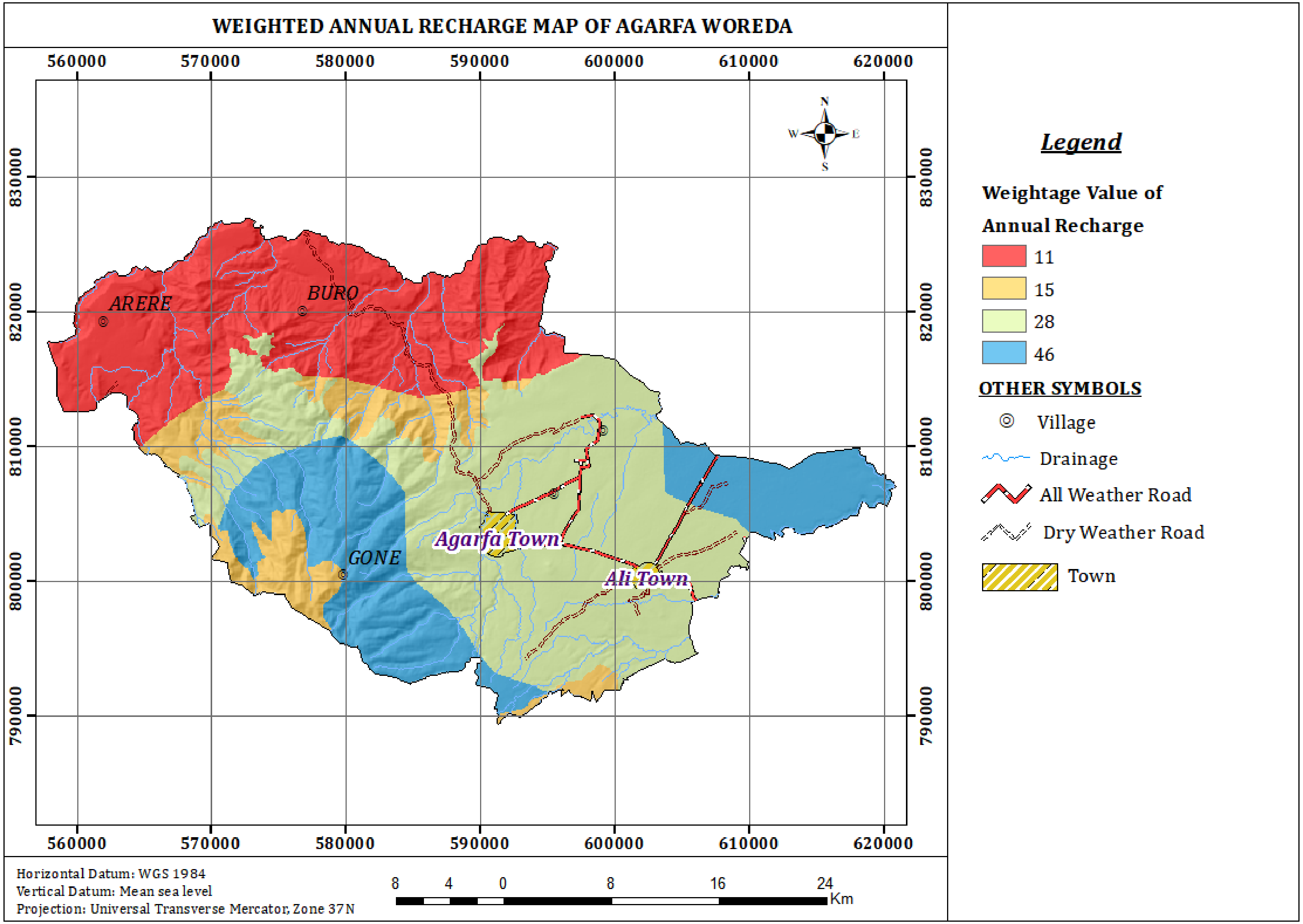

Figure 5-30. Weighted Annual Recharge classes' map of the Agarfa Woreda

5.3.3. Classification of Groundwater Potential Zones

The hydrogeological system of Agarfa woreda is comprised of three main lithological units as Tertiary volcanics of lower, plateau and highland basalts. At both regional scale and local scale within the domain of Agarfa woreda, lower and highland basalts form extensive and very high productive aquifers. Theses basaltic rocks form aquifers with very high groundwater potential as revealed from existing borehole information.

Only the upper weathered and slightly fractured part of the volcanic rocks along lineamnets and faults have potential to store groundwater at shallow depth. Weathered and fractured volcanic rocks of basaltic flows form major potential aquifer within the domain of Agarfa Woreda along lineament and fault lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-31). The potential groundwater zones (PGZ) of the Agarfa woreda revealed four distinct zones, namely low, moderate, high and very high zones, respectively as presented in Table 5-14.

The potential map, as presented in Figure 5-31, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that extreme part of nortwestern elevated areas, and southeastern and nortrhern and western peripheries of the woreda generally have low potentials, while most areas at central, southern, and eastern regions generally exhibits high to very high potentials. The generally high to very high groundwater potentiality of the study area is a confirmation of generally high productive aquifers of plateau and highland basalts, whereas low groundwater potential areas have an indication of limited aquifers capabilities of lower basalts.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the topographic wetness index and geology in addition to the lineament density and recharge control. In addition, areas underlain by plateau basalts especially in the central and central eastern sections of the study area are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments, and apparently deep fracturing system have high and very high groundwater potential on the one hand. On the other hand, areas underlain by lower basaltic rocks in the western and central northern regions of the woreda in particular are characterized by rugged and low-lying topography with relatively steep slopes, low recharge amount, and lower lineament densities, exhibit low groundwater potential while areas underlain by sedimentary rocks of upperr Hamanilie limestone formation and lower basaltic flows have moderate potential. Moreover, low lineament densities and predominance of steep slope topography can be attributed to the observed low groundwater potentials. However, predominance of fractured and weathered volcanic rocks of basaltic flows, high lineament density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential. Summary of the groundwater potential zones identified in the Agarfa woreda is presented in the table below (Table 5-14).

Table 5-14. Classification of groundwater potential zones and coverage areas alongside the respective yield categories

Woreda Name	GWP Zones	Major Aquifer Units	Borehole Yield Classification (l/s)	
			Q (Range)	Mean 'Q'
Agarfa	Very High	Highland basalt (Tv4) & Plateau basalt (Tv3(1))	7 - 32	13.6
	High	Highland basalt (Tv4)	7 - 10	8.5
	Moderate	lower basalt (Tv1)	3.4 – 10	6.7
	Low	lower basalt (Tv1)	1.5 - 8	4.8

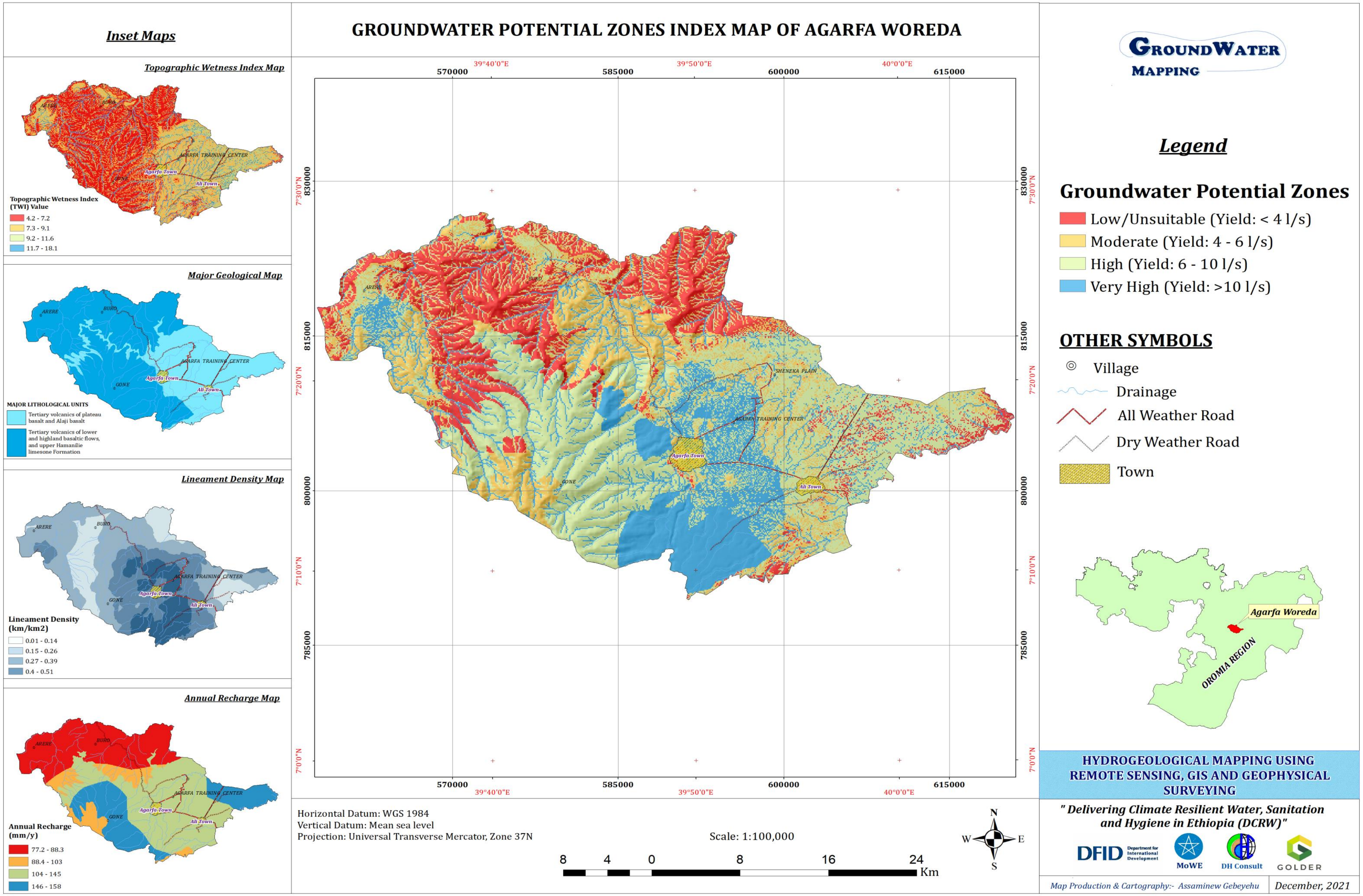

Figure 5-31. Groundwater Potential Zones Map of Agarfa Woreda

5.3.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) are were collated for over 50 boreholes found around the woreda within the synoptic cluster boundary area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the synoptic area vary from 7 to 32 lit/sec (av. 13.6 lit/sec) in very high potential zones and varying from 7 lit/sec to 10 lit/sec (av. 8.5 lit/sec) in high potential zones as compared with 3.4 lit/sec to 10 lit/sec (av. 6.7 lit/ sec) in the moderate and from 1.5 to 8 lit/sec (av. 4.8 lit/sec) in the low potential zones (Figure 5-32). As shown in the Figure 5-32, the occurrence of number of wells with yield of in the range 7 - 10 lit/sec (high yield) and of > 10 lit/sec (very high yield) cut across mainly the highland and plateau basaltic rocks. However, the less frequency of wells within lower basaltic rocks in the low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (3.4-10 lit/sec) category is associated also with wells in the fractured lower basaltic rocks. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

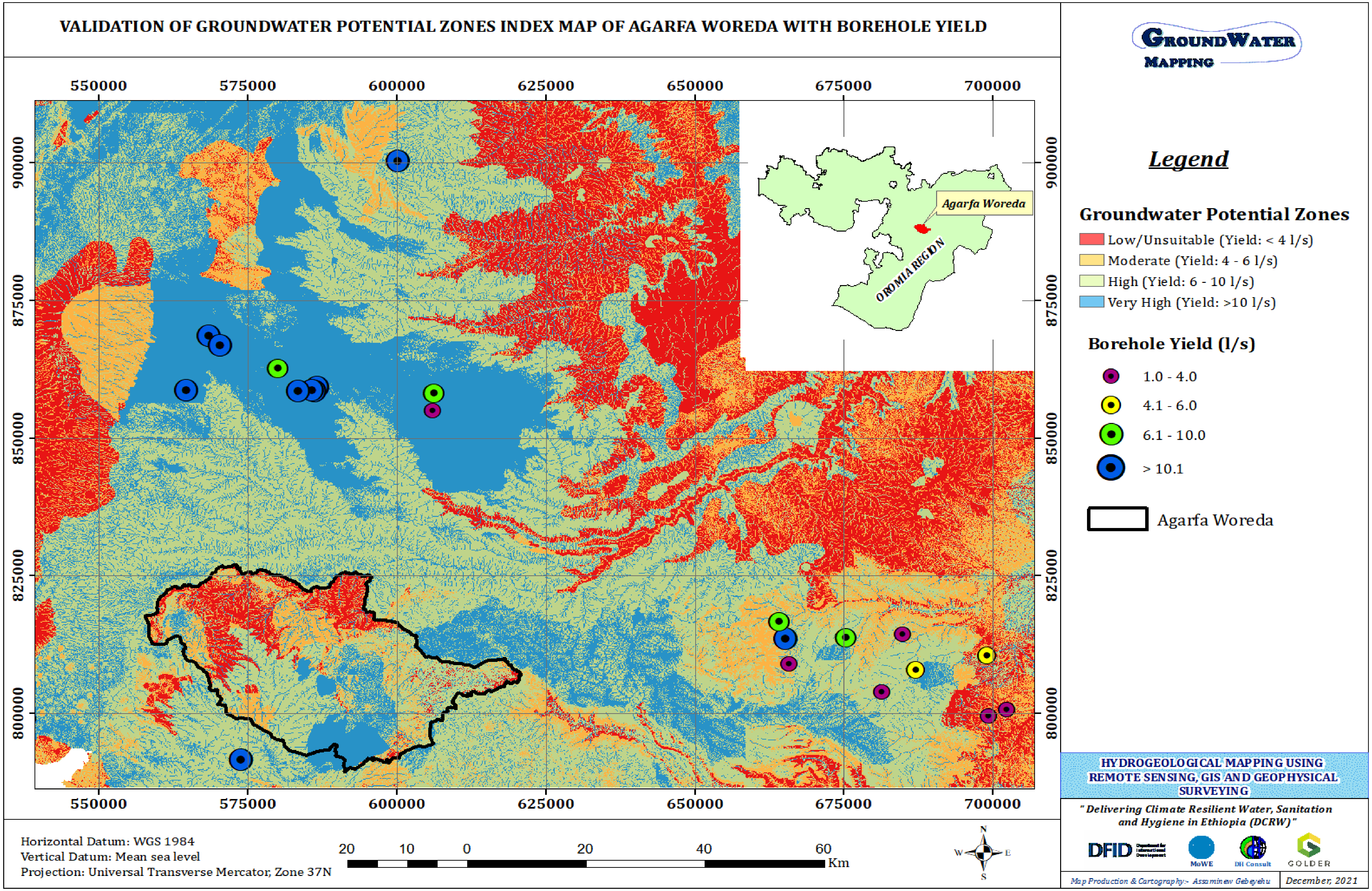

Figure 5-32 Validation of Groundwater Potential Zones Map of Agarfa Woreda within Arsi-Bale synoptic boundary

5.3.5. Projected Population and Water Demand of Agarfa

5.3.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-15 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P=Po\,(1 + r)^{n}$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Agarfa Woreda has been projected forward until 2036 using the growth rate of Oromia Regional State. The minimum and maximum population in the Woreda is 2,924 and 14,419 respectively. The total population of the AgarfaWoreda in 2036 is going to be 167,218.

5.3.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic purposes greatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO) & (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer's life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24 hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from 1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-33 shows the distribution of water demand in each Kebeles of the Woreda. Soba kebele water demand is the minimum with 263 M^3/day and maximum water demand is required for Weleti Wegerge Kebele with 1,301 M^3/day respectively. The overall water demand for the projected population in the Agarfa Woreda is 15,022 M^3/day.

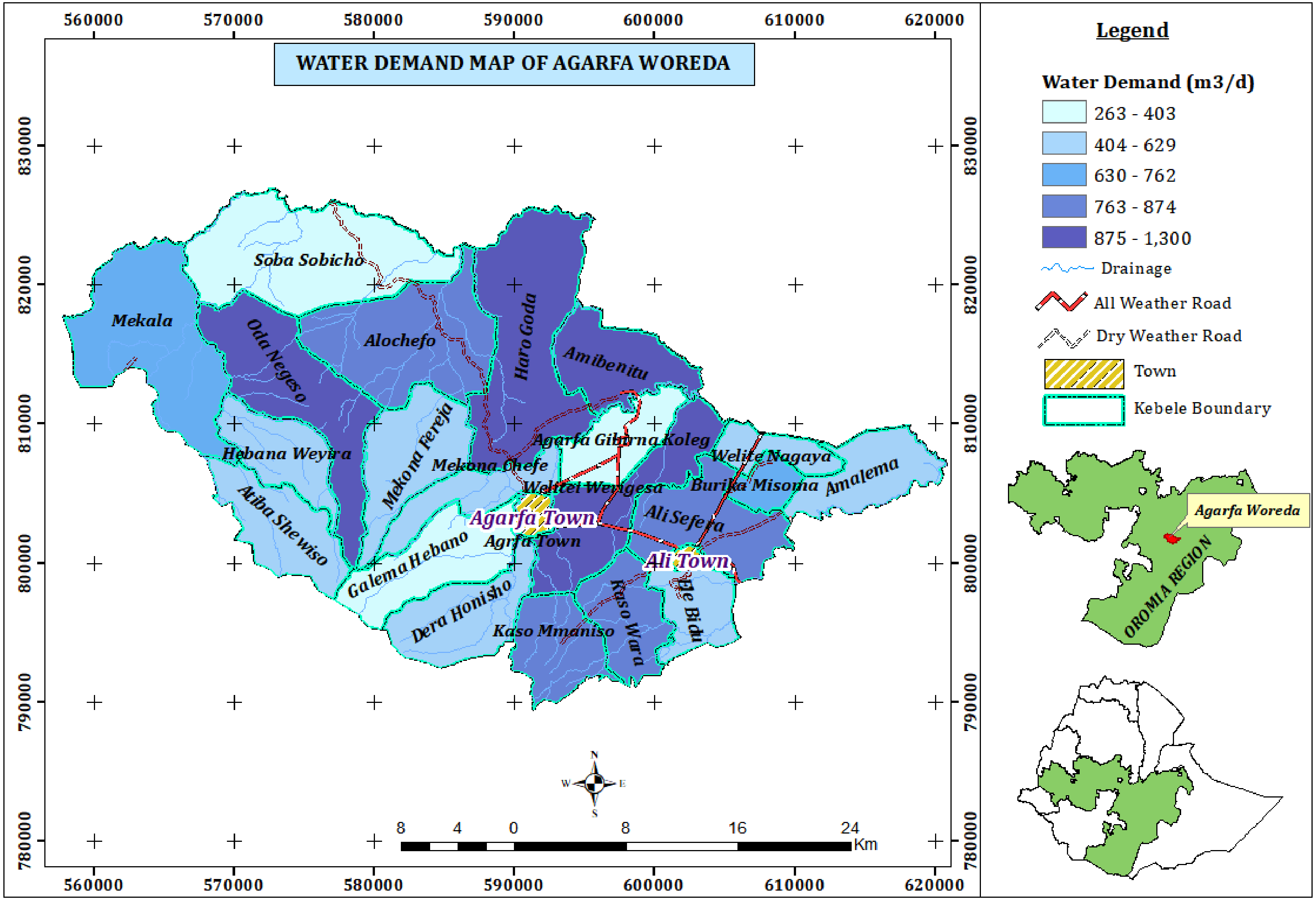

Figure 5-33:-Water Demand Map of Agarfa Woreda

5.3.6. Propsed Target Sites

Four target sites are identified and proposed within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficiaries and population density. With further discussion and consultation with stakeholders, two priority sites will be selected for further hydrogeological and geophysical investigations in phase III. The following are the four proposed sites:

Target Site-I:

This target site is located in the central eastern regions of the woreda, around Agarfa Town. It is situated in the identified very high potential zones with expected optimum borehole discharge of about 14 l/s. This target site is mainly underlain by highland and plateau basaltic rocks.

Target Site-II:

This target site is located in the eastern part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 11 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-III:

This target site is located in the central southern parts of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 16 l/s. This target site is mainly underlain by highland basaltic rocks.

Target Site-IV:

This target site is located in the western region of the woreda. It is situated in the identified high and very high potential zones with expected optimum borehole discharge of about 10 l/s. This target site is mainly underlain by lower basaltic rocks.

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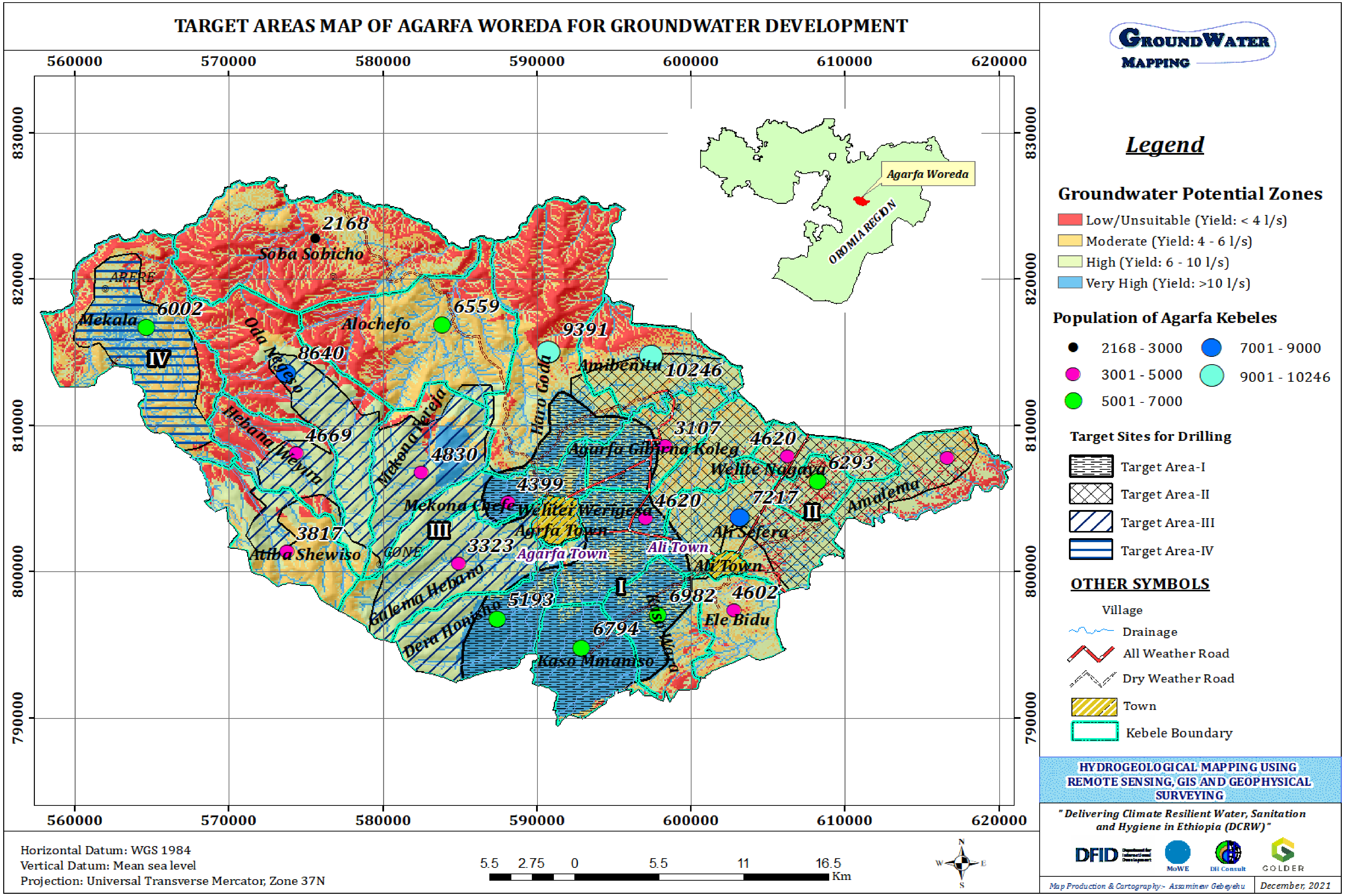

Figure 5-34:-Target Areas Map of Agarfa Woreda

5.4. Gasera Woreda

5.4.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.05 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Gasera woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-16. The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-17. The weights assigned to the respective thematic maps as presented in Table 5-18 indicate that TWI was ranked the dominant factor with a normalized weight value of 0.41 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Gasera woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Gasera woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

GWPZI = (TWIwTWIwi + GGwGGwi + LDwLDwi + GRwGRwi)

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Gasera woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e. 'very high', 'high', 'moderate' and 'low or poor', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-16 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Topographic Wetness Index (TWI)	9
Geology (GG)	8
Lineament density (LD)	7
Recharge (GR)	6

Table 5-17 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	TWI	GG	LD	GR	
TWI	1	1	3	5	0.41
GG	1	1	3	2	0.34
LD	1/3	1/3	1	2	0.15
GR	1/5	1/2	1/2	1	0.10

Table 5-18 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank
Topographic Wetness Index, 'TWI'	3.8 – 7.16	poor	1	0.11	0.41
	7.17 – 8.44	Moderate	2	0.15	
	8.45 - 11.8	Good	3	0.28	
	11.9 – 20.6	Very good	4	0.46	
Geology/ Lithology, 'GG'	Tertiary volcanics of lower basaltic flows and Mesozoic sedimentary rocks of upper Hamanilie limesone Formation.	Very good	4	0.11	0.34
	Tertiary volcanics of plateau basaltic rocks	Good	3	0.15	
	Mesozoic sedimentary rocks of upper sandstones	Moderate	2	0.28	
	Mesozoic sedimentary rocks of lower Hamanilie limestone Formation	poor	1	0.46	
Lineament Density,' LD' (Km/Km^2)	0 - 0.16	poor	1	0.11	0.15
	0.17 - 0.32	Moderate	2	0.15	
	0.33 - 0.48	Good	3	0.28	
	0.49 - 0.64	Very good	4	0.46	
Recharge, 'GR' (mm/y)	78.3 - 105.2	poor	1	0.11	0.10
	105.3 - 143.1	Moderate	2	0.15	
	143.2 - 155.8	Good	3	0.28	
	155.9 - 171.1	Very good	4	0.46	

5.4.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of Topographic Wetness Index (TWI), geology, lineament density and recharge together with their spatial distribution in Gasera woreda are presented below:

I. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 3.8 and 20.6. A closer look at the classification revealed that low elevated areas and drainage systems with steep slopes such as areas in northern peripheries of the woreda in particular have relatively lower TWI value while most of the high elevated areas and drainage systems with gentle and flat slopes have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.46) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.11).

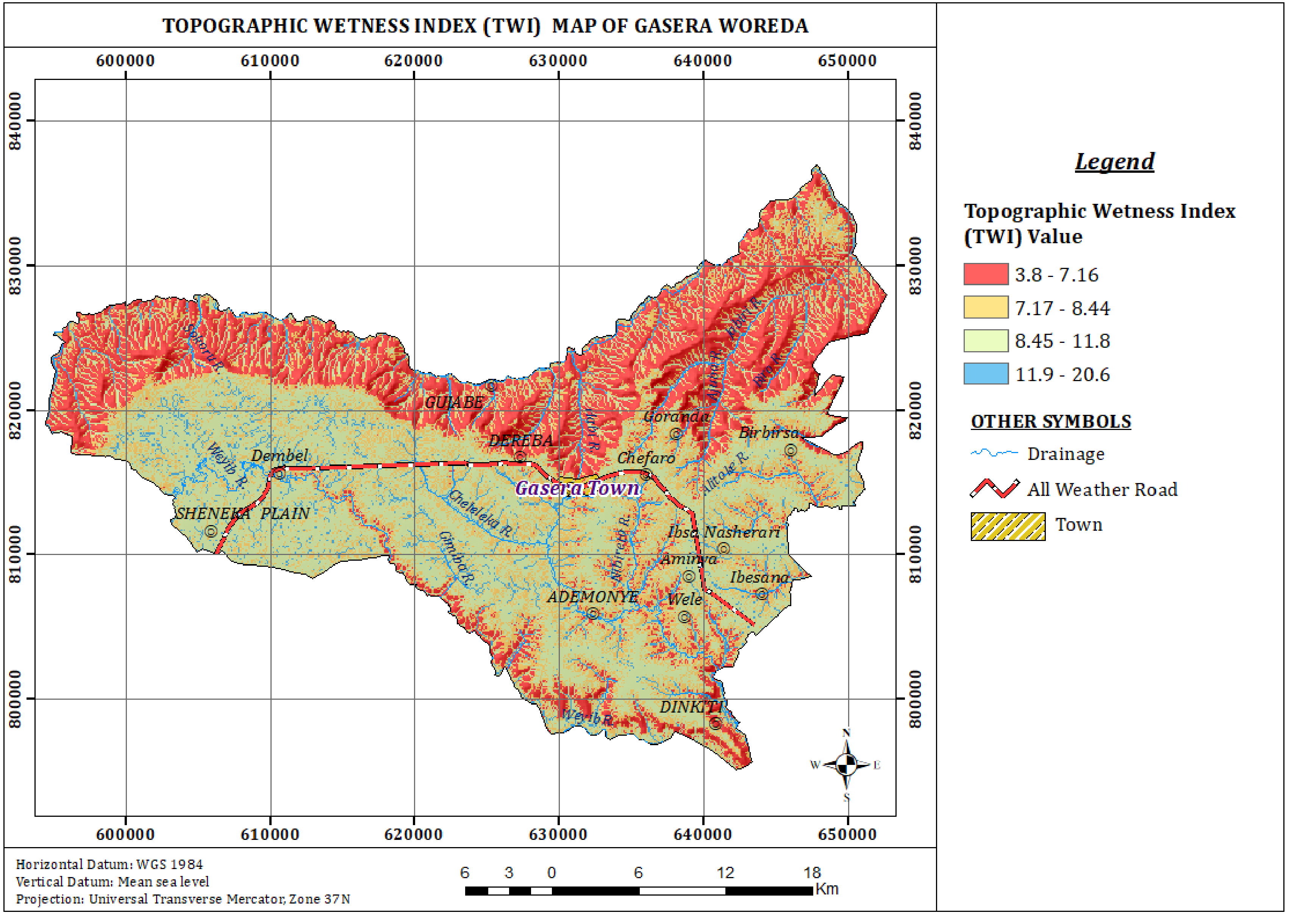

Figure 5-35. TWI Map of Gasera Woreda

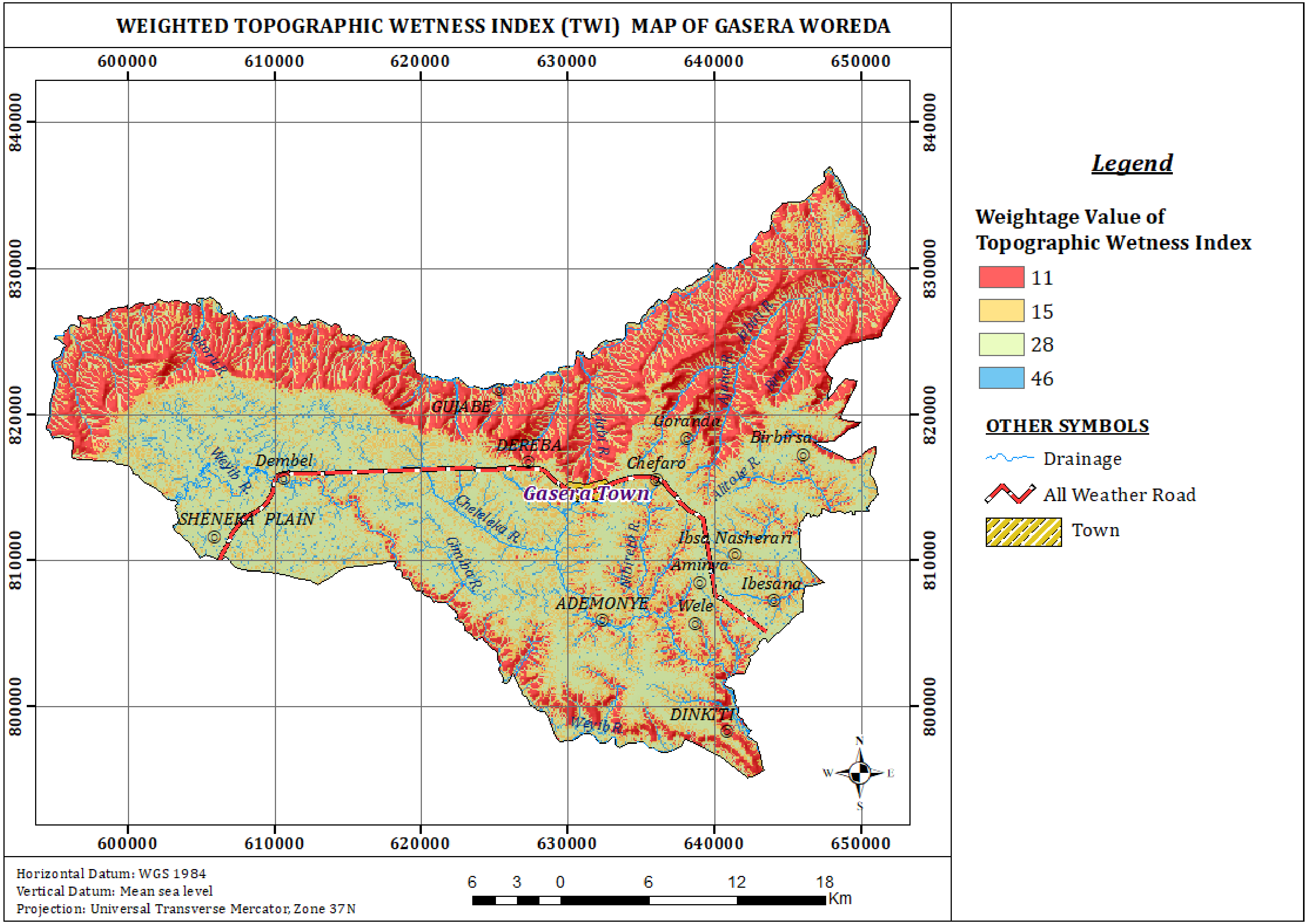

Figure 5-36 Weightage value of TWI Map of Gasera Woreda

II. Geology/Grouped Hydrolithological Units

In general, most parts of the Gasera woreda are underlain by Tertiary volcanic rocks of plateau and lower basalts. Whereas, Mesozoic sedimentary rocks of upper Hamanile limestone formation is mainly outcropped at northern peripheries of the woreda.

However, the lithological units found in the woreda area are further classified into four major groups based on their significances to groundwater occurrence and productivity using borehole data on yield and transmissivity analysis in particular.

- Tertiary volcanics of lower basaltic flows and Mesozoic sedimentary rocks of upper Hamanilie limesone Formation. (Very high productive with Qav. = 17 l/s)
- Tertiary volcanics of plateau basalt. (High productive with Qav = 11 l/s)
- Mesozoic sedimentary rocks of upper sandstones. (Moderately productive with Qav = 6 l/s)
- Mesozoic sedimentary rocks of lower Hamanilie limestone Formation. (Low productive with Qav = 4 l/s)

Tertiary volcanics of lower basalts and plateau basalts are the main lithologic framework of the Gasera woreda, and sedimentary rocks of upper & lower Hamanilie limestone formations and upper sandstone rocks are also outcropped at limited areas northern and eastern regions of the woreda (Figure 5-37).

Usually, massive unfractured lithologic units in volcanic and sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification, weathering and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of low productivity of lower limestone (0.11)\ moderate productivity of upper sandstone (0.15)\ high productivity of plateau basalt (0.28)\ very high productivity of Tertiary volcanics of lower basaltic flows, and upper Hamanile limestone formation (0.46).

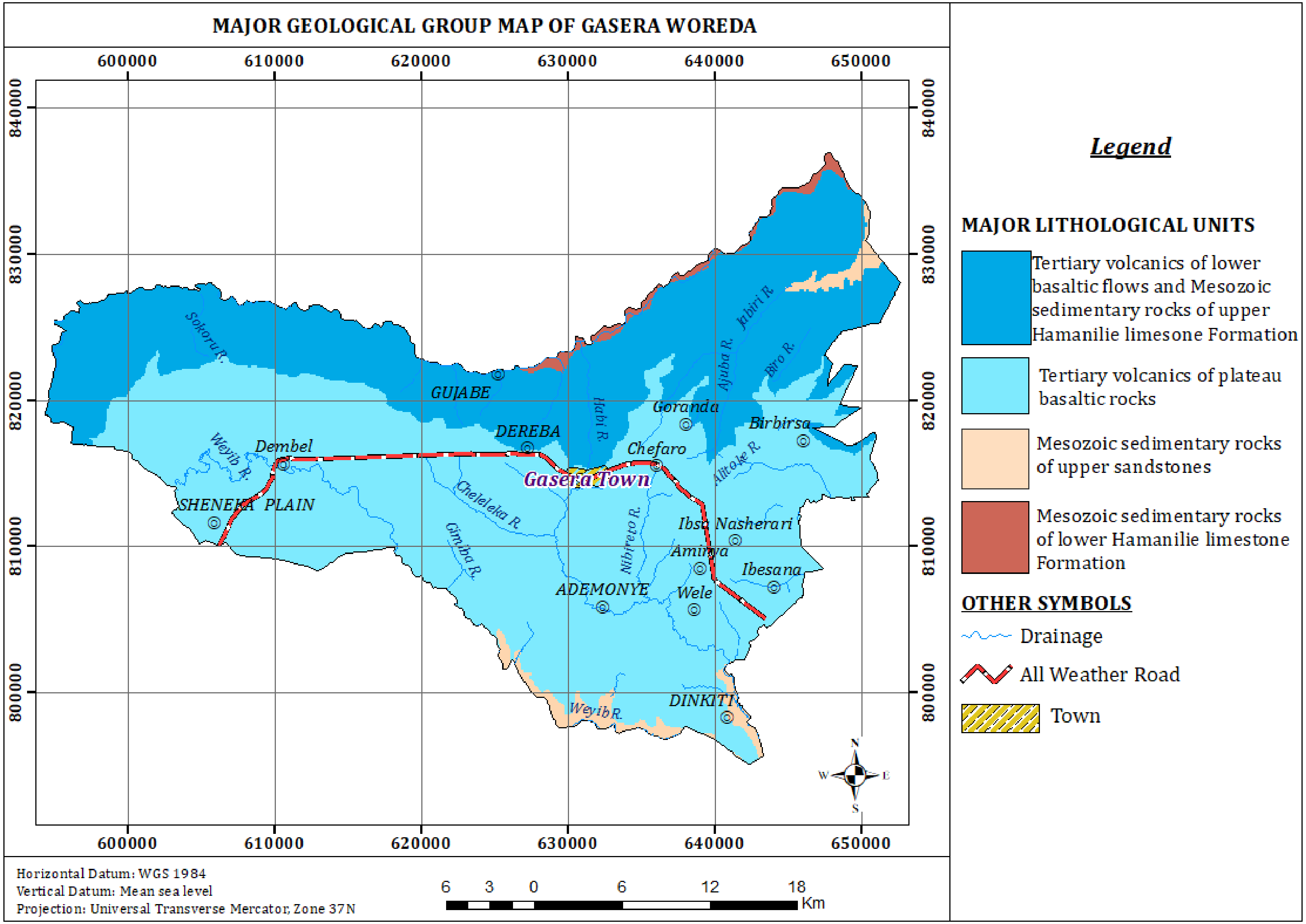

Figure 5-37. Grouped Lithological classification map of Gasera Woreda

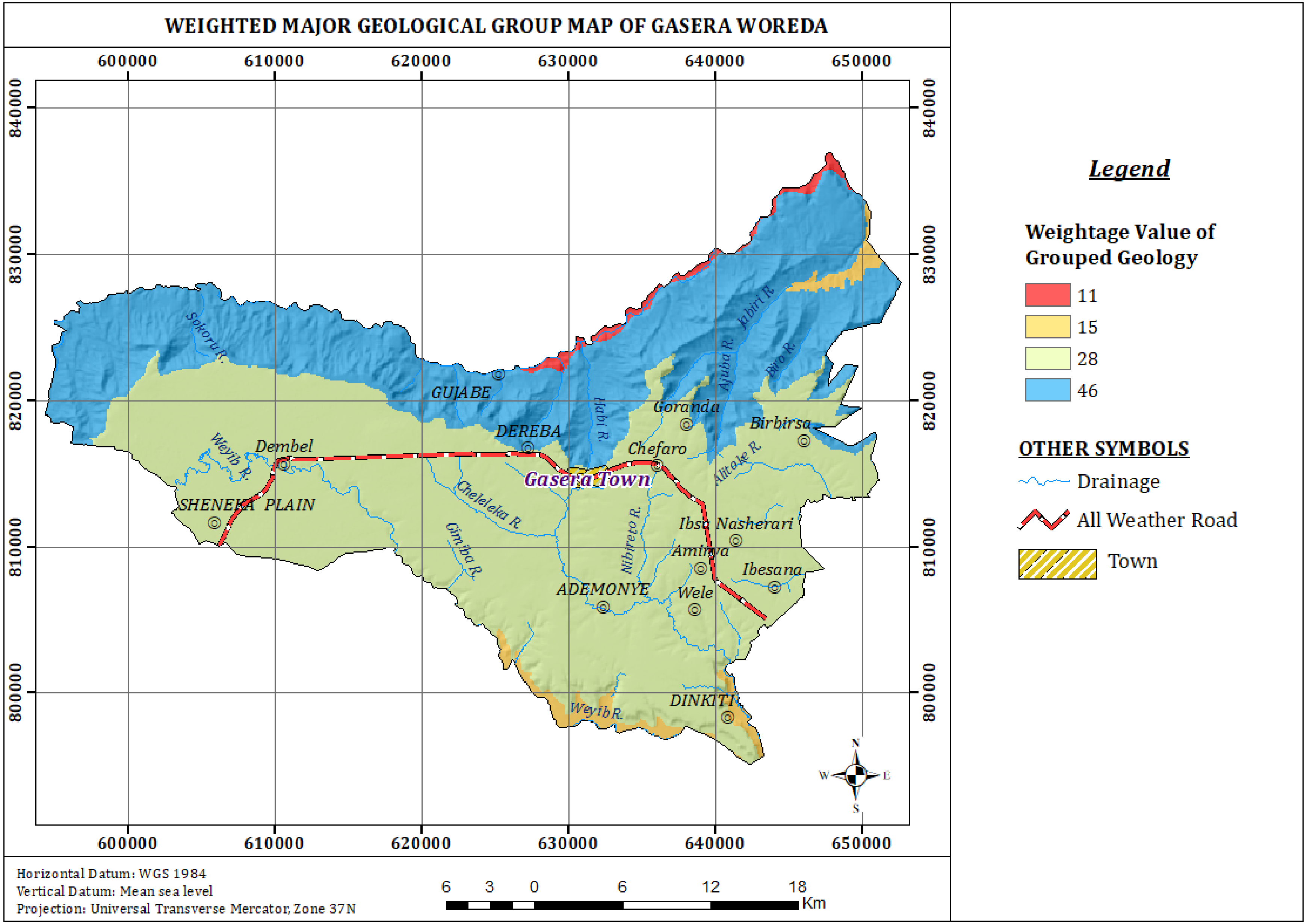

Figure 5-38. Weighted lithological classes' map of the Gasera Woreda

III. Lineaments and Lineament Density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Three prominent directions identified are NW-SE and NE–SW trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.16 km/km^2 to 0.64 km/km^2 (Figure 5-39). Though the lineaments are moderately widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by Tertiary volcanics of plateau basalt having relatively higher lineament density of 0.33 - 0.64 km/km^2) compared with areas underlain by upper & lower limestone, upper sandstone and lower basalts with lower lineament densities of (< 0.14 km/km^2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.46 was assigned to area with high density of lineaments, while a low weightage of 0.17 was assigned to areas with low lineament density (Figure 5-40).

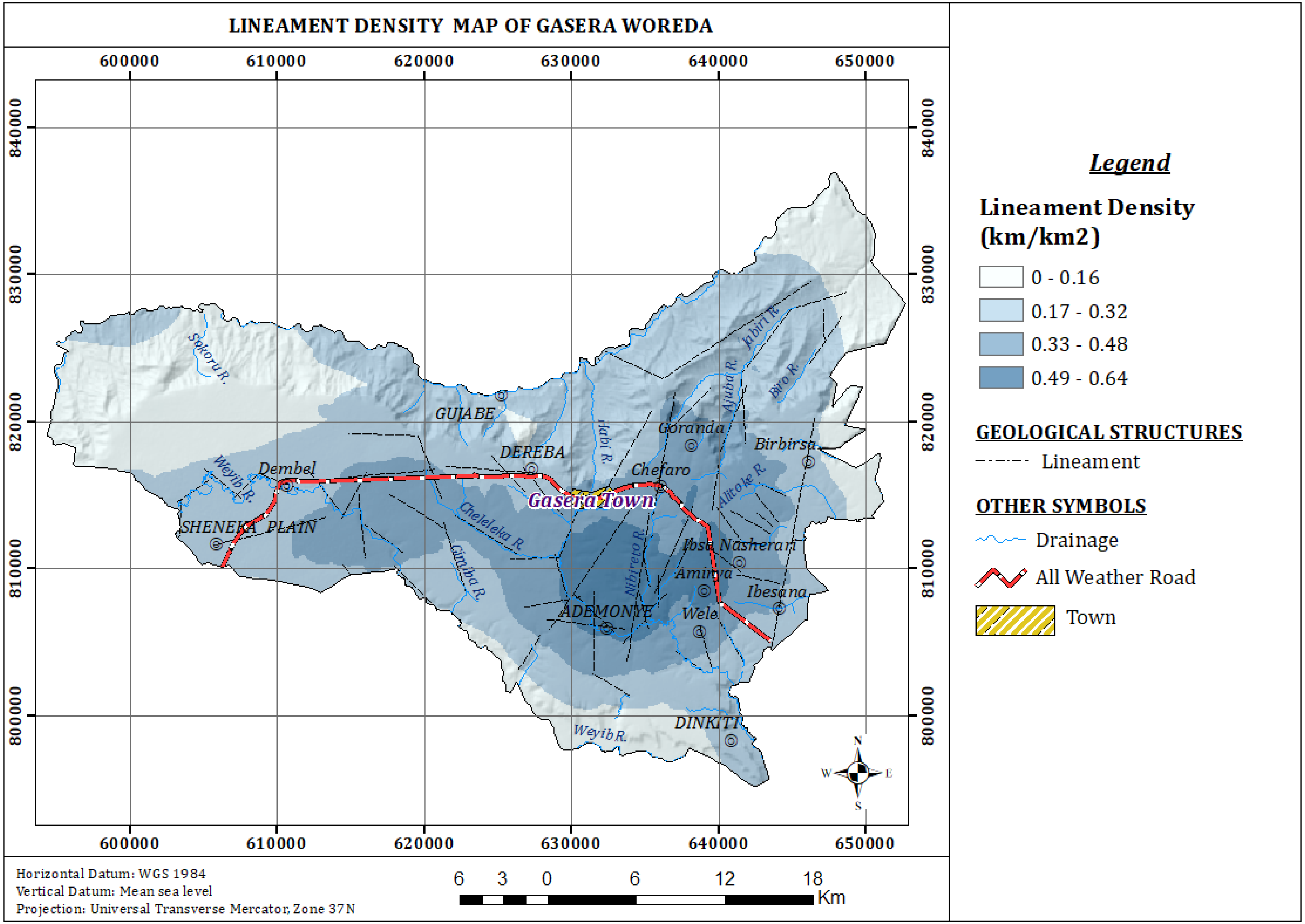

Figure 5-39. Lineament Density Map of Gasera Woreda

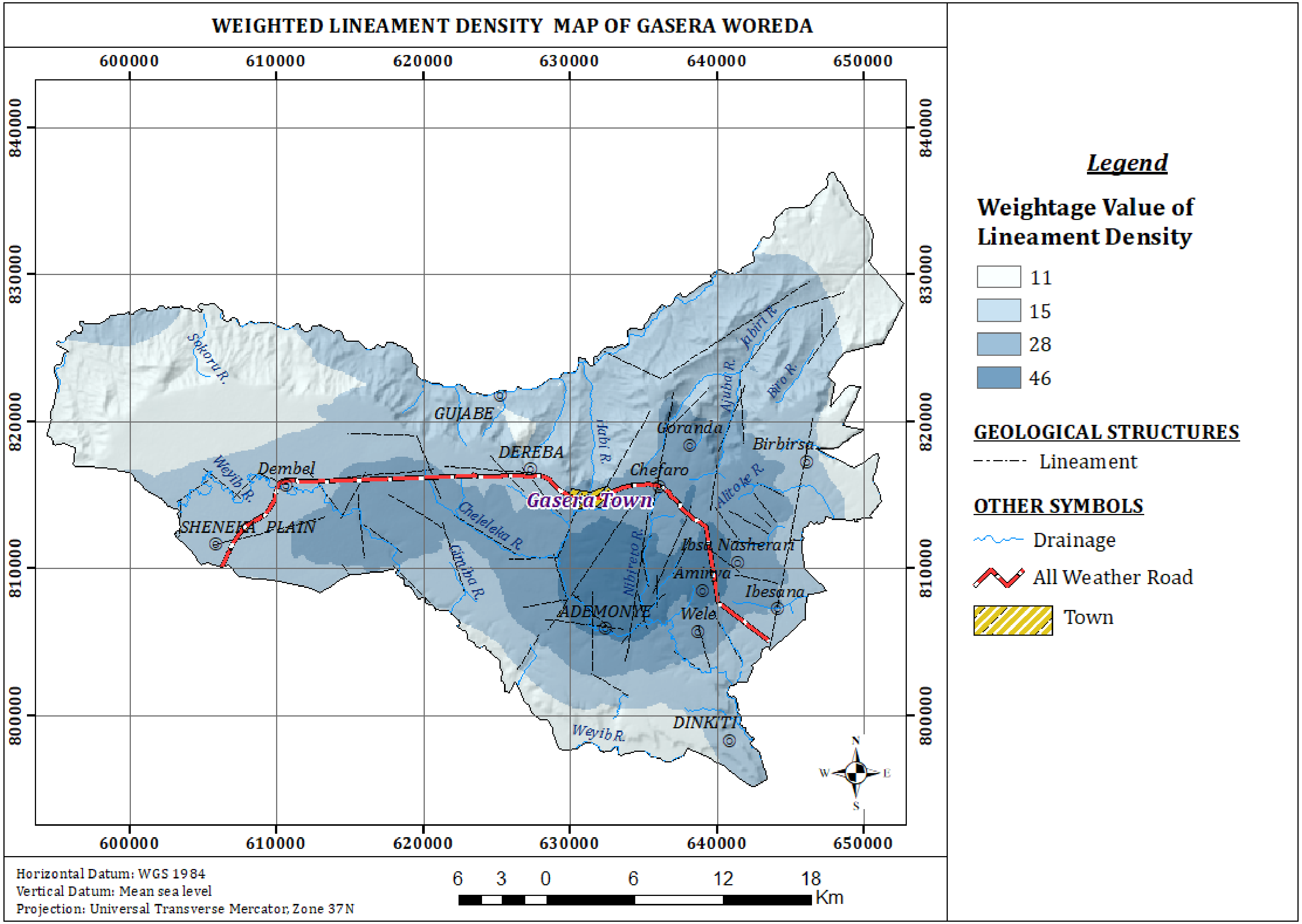

Figure 5-40. Weightage value of Lineament Density Map of Gasera Woreda

IV. Recharge

The spatial annual recharge rate distribution in the Gasera woreda ranges from 78.3 to 171.1 mm/y suggesting groundwaters in most central southern and eastern elevated regions of the woreda area underlain by Tertiary volcanics of plateu basaltic flows receive high amount of recharge while the northern low-lying areas underlain by Tertiary volcanics of lower basalt falls and upper Hamanilie limestone have relatively lower recharge amount due to very low infiltration rate of the lithological formation (Figure 5-41). Accordingly, areas with very high and high amount of recharge have weightage factor of 0.46 and 0.28, respectively signifying very good and good groundwater potential, respectively while areas with the mderate and lowest amount of recharge have weightage factor of 0.15 and 0.11, respectively, suggesting moderate and poor groundwater potentiality, respectively. Generally, the study area is characterized with high to very high mean annual recharge amount (> 143 mm/yr), whereas most of the northern peripheries have low mean annual recharge amount (< 105 mm/yr).

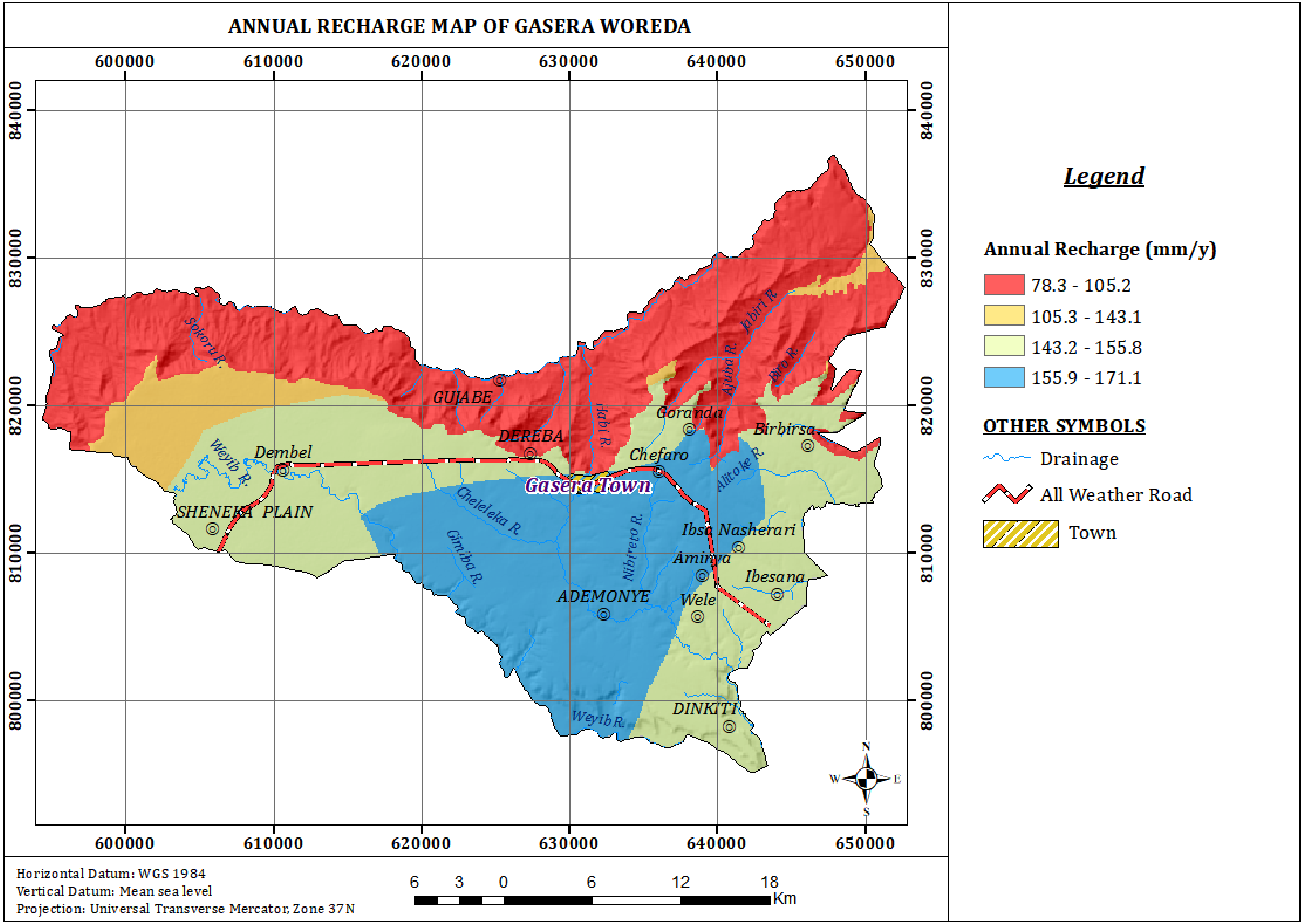

Figure 5-41. Annual Recharge Map of Gasera Woreda

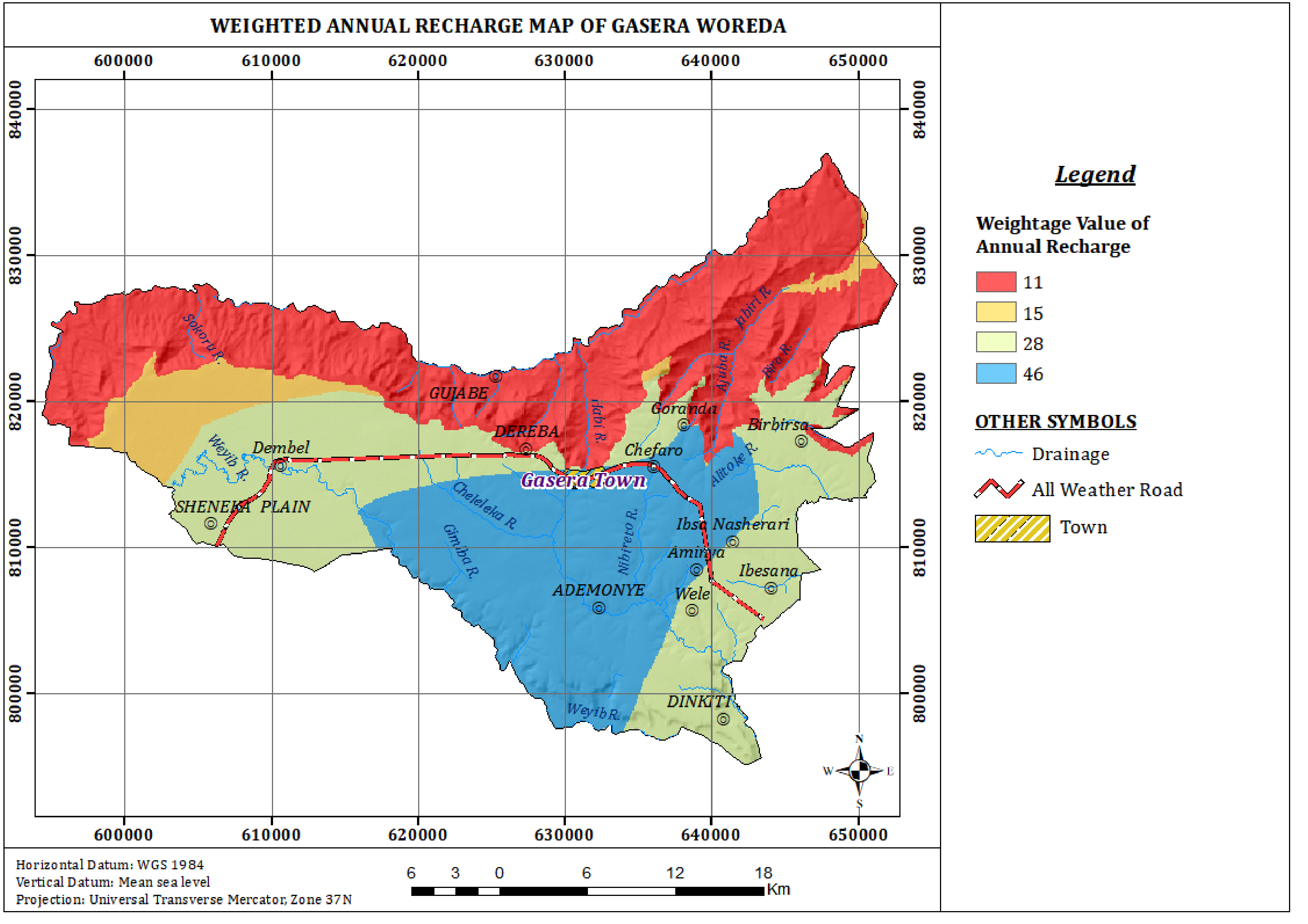

Figure 5-42. Weighted Annual Recharge classes' map of the Gasera Woreda

5.4.3. Classification of Groundwater Potential Zones

The hydrogeological system of Gasera woreda is comprised of two main lithological units as Tertiary volcanics of lower and plateau basalts. At both regional scale and local scale within the domain of Gasera woreda, lower and highland basalts form extensive and very high productive aquifers. Theses basaltic rocks form aquifers with very high groundwater potential as revealed from existing borehole information.

Only the upper weathered and slightly fractured part of the volcanic rocks along lineamnets and faults have potential to store groundwater at shallow depth. Weathered and fractured volcanic rocks of basaltic flows form major potential aquifer within the domain of Gasera Woreda along lineament and fault lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5.43). The potential groundwater zones (PGZ) of the Gasera woreda revealed four distinct zones, namely low, moderate, high and very high zones, respectively as presented in Table 5-19.

The potential map, as presented in Figure 5-43, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that northern, western, eastern and central southern peripheries of the woreda generally have low potentials, while most areas at central, central western and central eastern regions generally exhibits high to very high potentials, respectively. The generally high to very high groundwater potentiality of the study area is a confirmation of generally high productive aquifers of plateau basalts, whereas low groundwater potential areas have an indication of limited aquifers capabilities of lower basalts.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the topographic wetness index and geology in addition to the lineament density and recharge control. In addition, areas underlain by plateau basalts especially in the central and central eastern and western sections of the study area are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments, and apparently deep fracturing system have high and very high groundwater potential on the one hand. On the other hand, areas underlain by lower basaltic rocks in the northern regions of the woreda in particular are characterized by rugged and low-lying topography with relatively steep slopes, low recharge amount, and lower lineament densities, exhibit low groundwater potential while areas underlain by sedimentary rocks of upperr Hamanilie limestone formation and lower basaltic flows have moderate potential. Moreover, low lineament densities and predominance of steep slope topography can be attributed to the observed low groundwater potentials. However, predominance of fractured and weathered volcanic rocks of basaltic flows, high lineament density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential. Summary of the groundwater potential zones identified in the Gasera woreda is presented in the table below (Table 5-19).

Table 5-19. Classification of groundwater potential zones and coverage areas alongside the respective yield categories

Woreda Name	GWP Zones	Major Aquifer Units	Borehole Yield Classification (l/s)	
			Q (Range)	Mean 'Q'
Gasera	Very High	Plateau basalt (Tv3(1))	5.6 - 32	11
	High	Plateau basalt (Tv3(1))	3 - 15	6
	Moderate	lower basalt (Tv1) & upper limestone	3.4 – 10	7
	Low	lower basalt (Tv1), lower limestone & upper sandstone	1.5 - 8	5

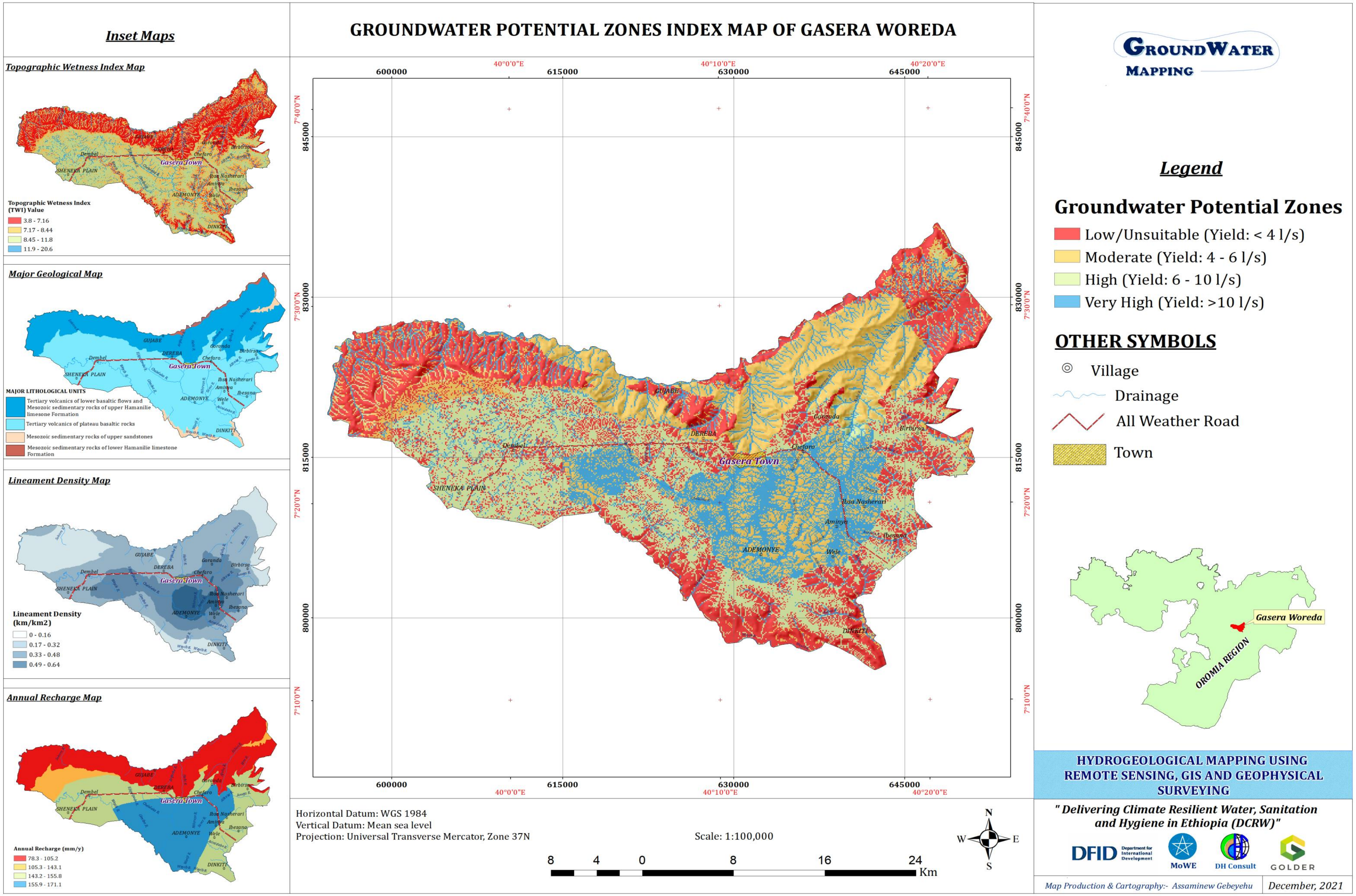

Figure 5-43. Groundwater Potential Zones Map of Gasera Woreda

5.4.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) are were collated for over 50 boreholes found around the woreda within the synoptic cluster boundary area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the synoptic area vary from 5.6 to 32 lit/sec (av. 11 lit/sec) in very high potential zones and varying from 3 lit/sec to 15 lit/sec (av. 6 lit/sec) in high potential zones as compared with 3.4 lit/sec to 10 lit/sec (av. 6.7 lit/ sec) in the moderate and from 1.5 to 8 lit/sec (av. 4.8 lit/sec) in the low potential zones (Figure 5-44). As shown in the Figure 5-44, the occurrence of number of wells with yield of in the range 7 - 10 lit/sec (high yield) and of > 10 lit/sec (very high yield) cut across mainly the plateau basaltic rocks. However, the less frequency of wells within lower basaltic rocks in the low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (3.4-10 lit/sec) category is associated also with wells in the fractured lower basaltic rocks and sedimentary rocks of lower limestone and upper sandstones. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

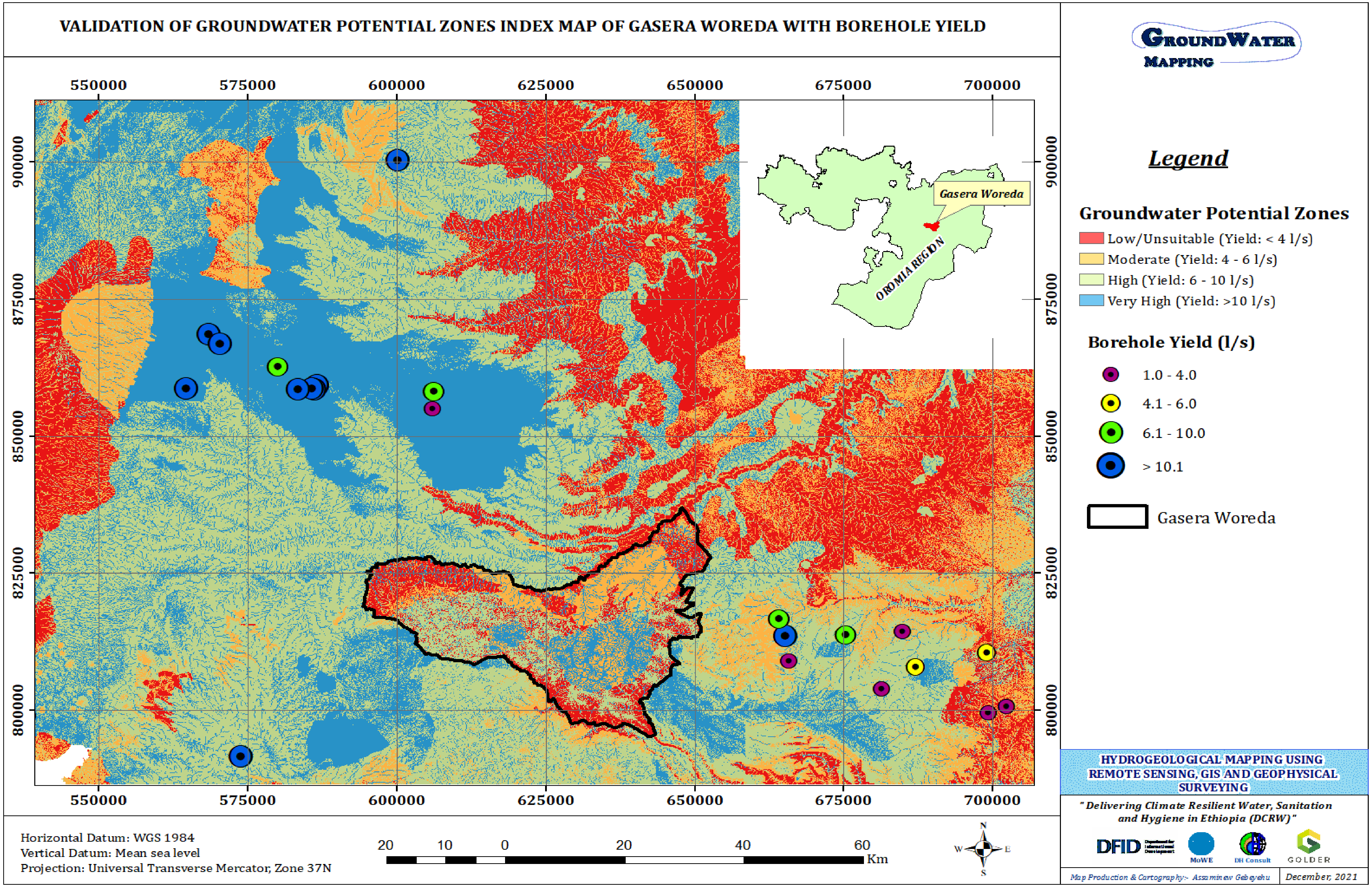

Figure 5-44. Validation of Groundwater Potential Zones Map of Gasera Woreda within Arsi-Bale synoptic boundary

5.4.5. Projected Population and Water Demand of Gasera

5.4.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-20 CSA Rural Population Growth Rates

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Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
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Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013
Geometric method forecasting formula

$$P = Po\,(1 + r)^{n}$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Gasera Woreda has been projected forward until 2036 using the growth rate of Oromia Regional State. The minimum and maximum population in the Woreda is 2,058 and 11,358 respectively. The total population of the Gasera Woreda in 2036 is going to be 138,818.

5.4.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic

purposes greatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
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- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
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After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
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N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer's life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24 hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from 1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-45 shows the distribution of water demand in each Kebeles of the Woreda. Wetechemo kebele water demand is the minimum with 185 M^3/day and maximum water demand is required for Awichache Birbirsa Kebele with 1,020 M^3/day respectively. The overall water demand for the projected population in the Gasra Woreda is 12,471M^3/day.

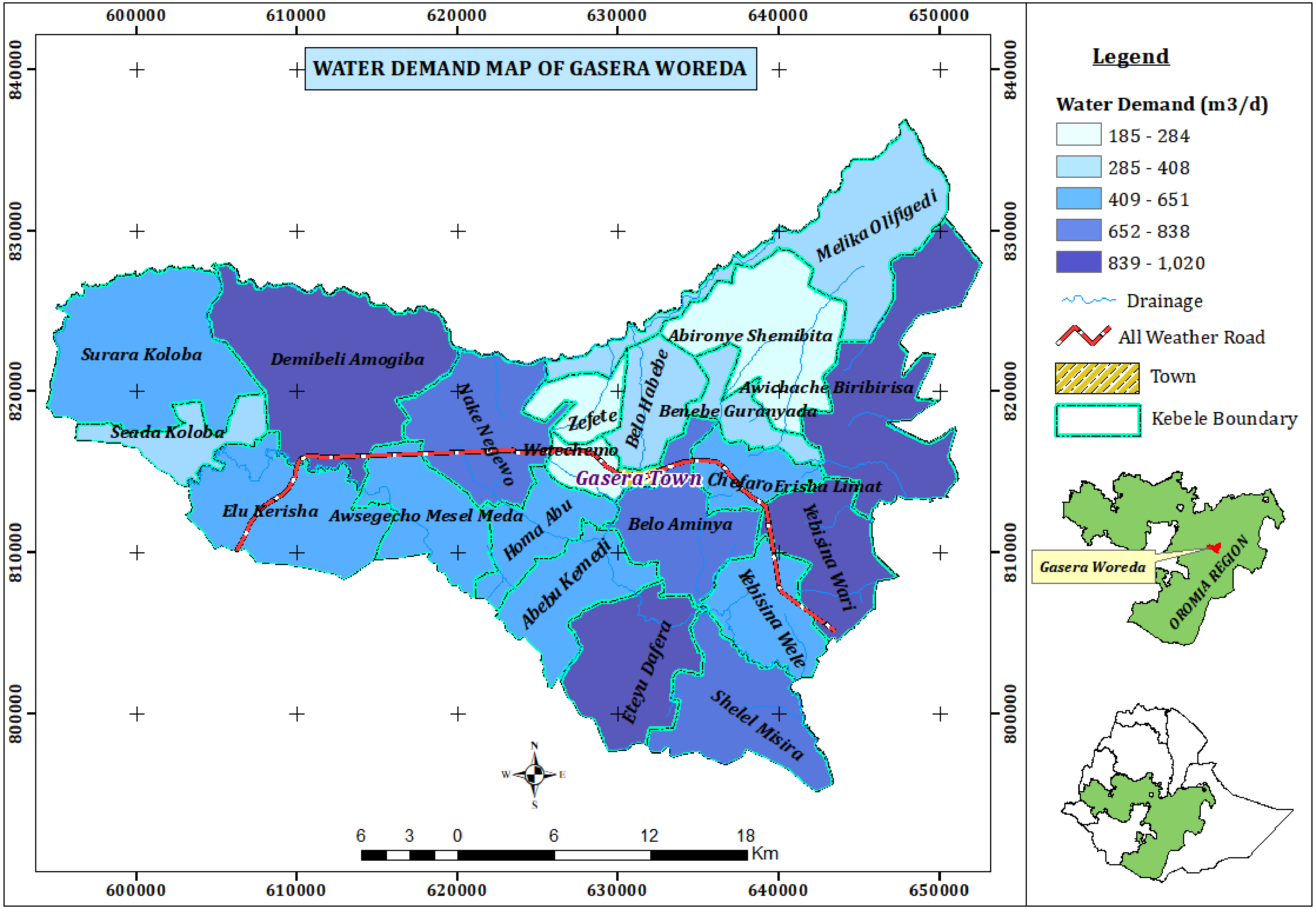

Figure 5-45:-Water Demand Map of Gasera Woreda

5.4.6. Propsed Target Sites of Gasera

Four target sites are identified and proposed within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficiaries and population density. With further discussion and consultation with stakeholders, two priority sites will be selected for further hydrogeological and geophysical investigations in phase III. The following are the four proposed sites:

Target Site-I:

This target site is located in the central eastern regions of the woreda, around south of Gasera Town. It is situated in the identified very high potential zones with expected optimum borehole discharge of about 11 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-II:

This target site is located in the central part of the woreda. It is situated in the identified high and very high potential zones with expected optimum borehole discharge of about 9 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-III:

This target site is located in the central eastern parts of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 6 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-IV:

This target site is located in the eastern region of the woreda. It is situated in the identified moderate potential zones with expected optimum borehole discharge of about 5 l/s. This target site is mainly underlain by lower basaltic rocks.

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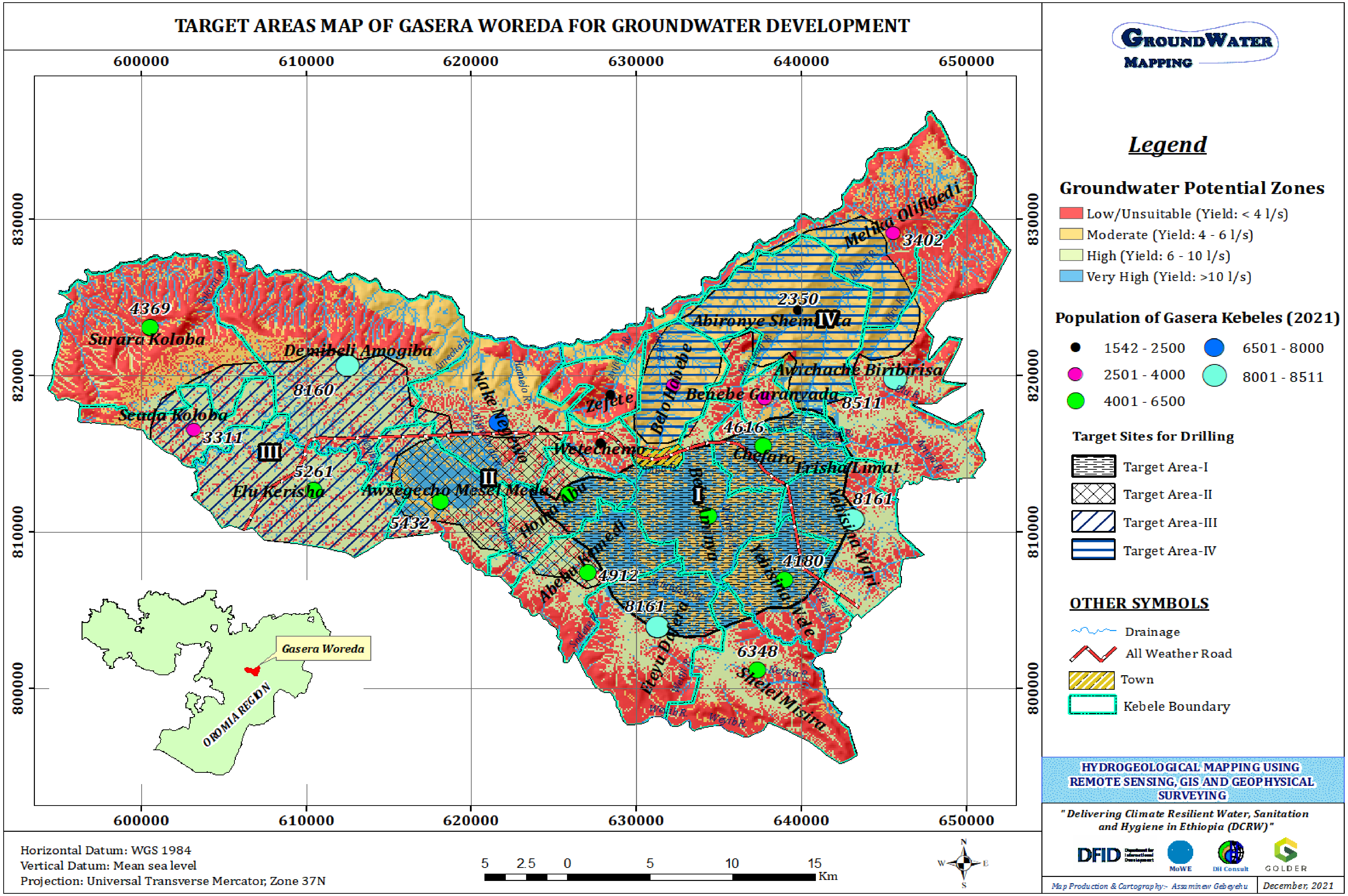

Figure 5-46:-Target Areas Map of Gasera Woreda

5.5. Ginir Woreda

5.5.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.05 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Ginir woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-21). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-22. The weights assigned to the respective thematic maps as presented in Table 5-23 indicate that TWI was ranked the dominant factor with a normalized weight value of 0.41 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Ginir woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Ginir woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

GWPZI = (TWIwTWIwi + GGwGGwi + LDwLDwi + GRwGRwi)

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Ginir woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e. 'very high', 'high', 'moderate' and 'low or poor', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-21 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Topographic Wetness Index (TWI)	9
Geology (GG)	8
Lineament density (LD)	7
Recharge (GR)	6

Table 5-22 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	TWI	GG	LD	GR	
TWI	1	1	3	5	0.41
GG	1	1	3	2	0.34
LD	1/3	1/3	1	2	0.15
GR	1/5	1/2	1/2	1	0.10

Table 5-23 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank
Topographic Wetness Index, 'TWI'	3.8 – 7.16	poor	1	0.11	0.41
	7.17 – 8.44	Moderate	2	0.15	
	8.45 - 11.8	Good	3	0.28	
	11.9 – 20.6	Very good	4	0.46	
Geology/ Lithology, 'GG'	Mesozoic sedimentary rocks of upper Hamanilie limesone Formation.	Very good	4	0.46	0.34
	Tertiary volcanics of lower, middle and plateau basaltic rocks	Good	3	0.28	
	Mesozoic sedimentary rocks of upper & Abduya sandstones and upper Gebredarre limestone Formation	Moderate	2	0.15	
	Quaternary Calcrete	poor	1	0.11	
Lineament Density,' LD' (Km/Km^2)	0 - 0.12	poor	1	0.11	0.15
	0.13 - 0.23	Moderate	2	0.15	
	0.24 - 0.35	Good	3	0.28	
	0.36 - 0.47	Very good	4	0.46	
Recharge, 'GR' (mm/y)	30.3 - 42.9	poor	1	0.11	0.10
	43 - 86.5	Moderate	2	0.15	
	86.6 - 124	Good	3	0.28	
	125 - 171	Very good	4	0.46	

5.5.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of Topographic Wetness Index (TWI), geology, lineament density and recharge together with their spatial distribution in Ginir woreda are presented below:

I. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 3.8 and 20.6. A closer look at the classification revealed that low elevated areas and drainage systems with steep slopes such as areas in southern peripheries of the woreda in particular have relatively lower TWI value while most of the high elevated and low-lying areas and drainage systems with gentle and flat slopes have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.46) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.11).

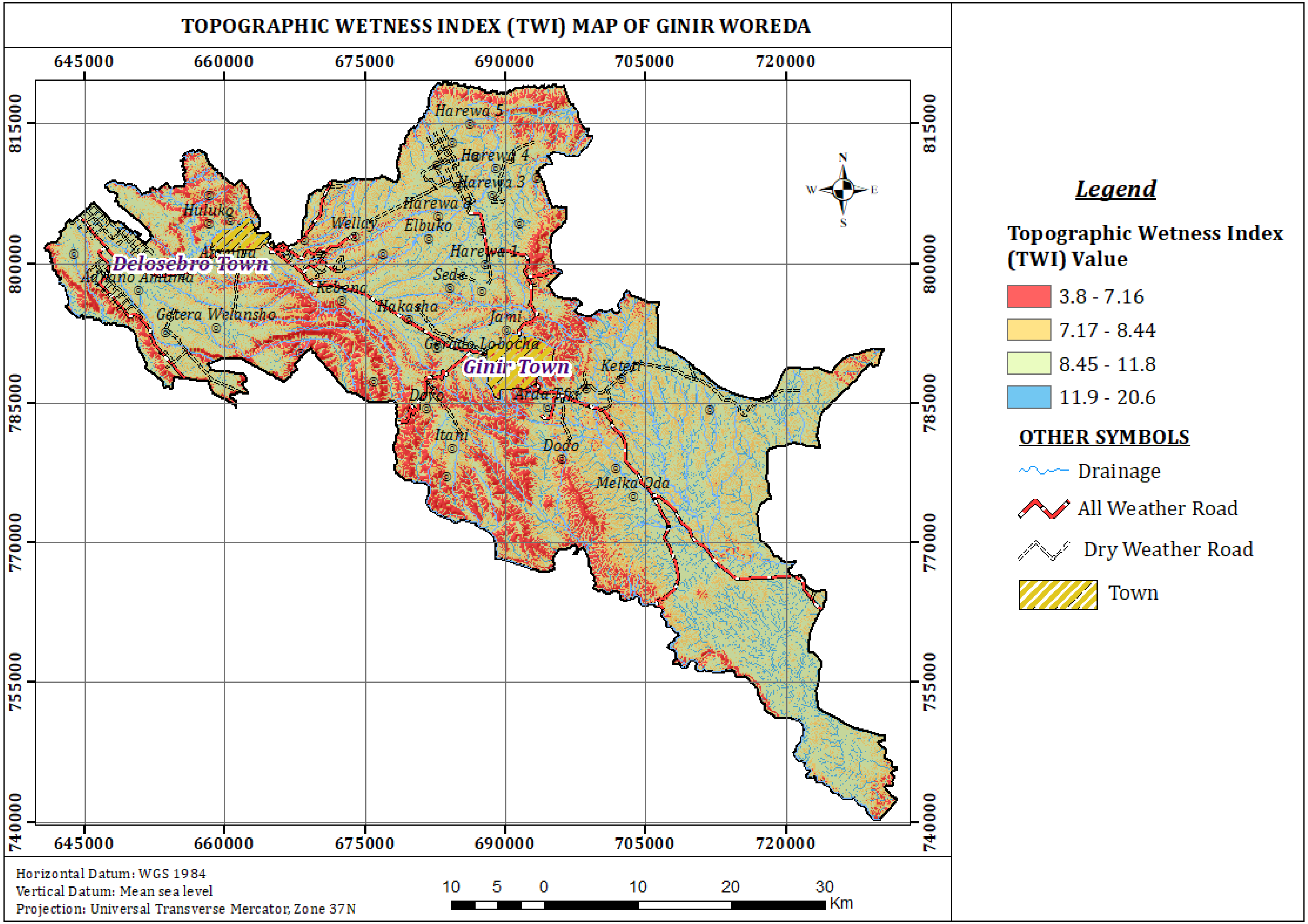

Figure 5-47. TWI Map of Ginir Woreda

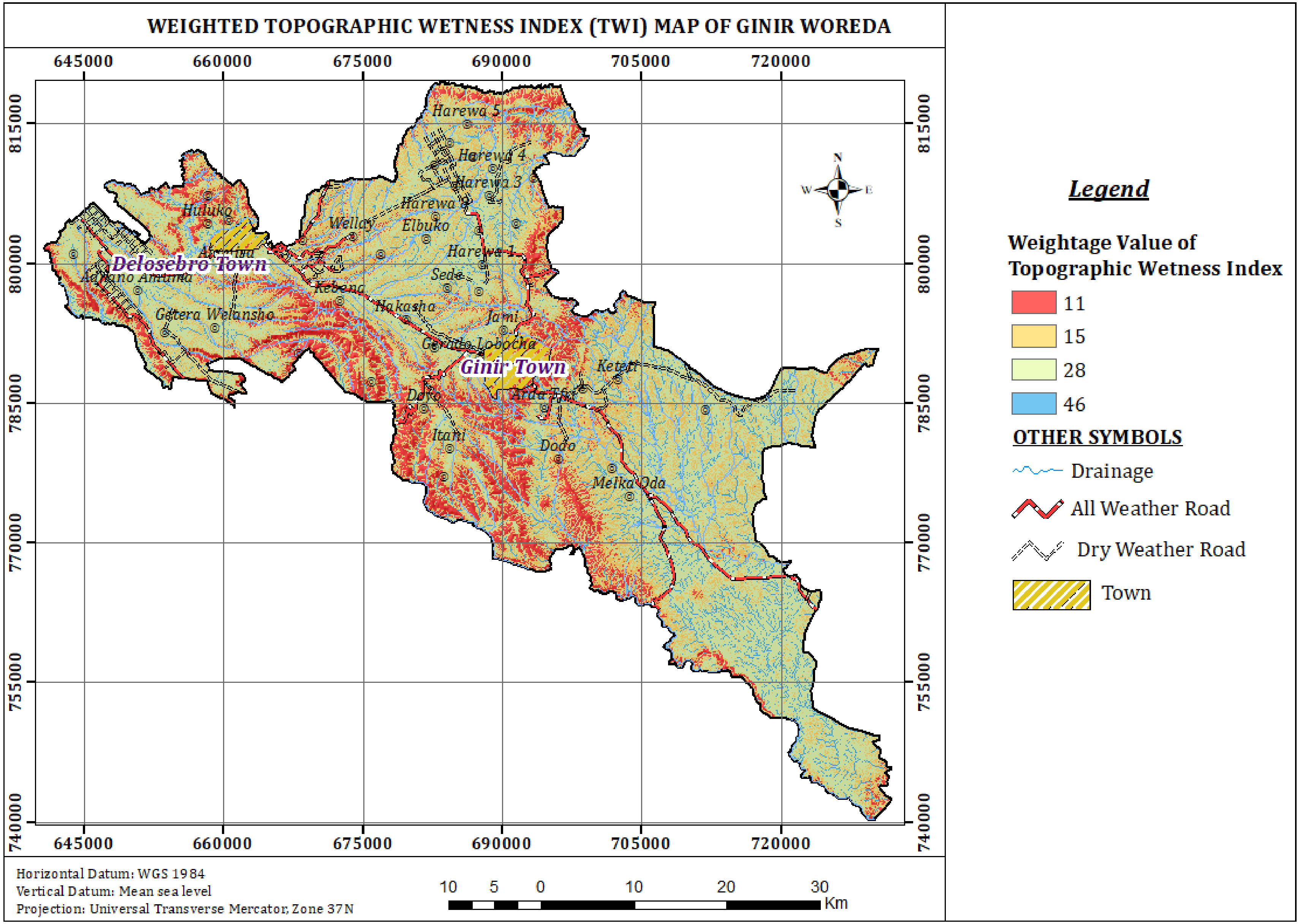

Figure 5-48. Weightage value of TWI Map of Ginir Woreda

II. Geology/Grouped Hydrolithology

In general, most parts of the Ginir woreda are underlain by Tertiary volcanic rocks of plateau and lower basalts, and Mesozoic sedimentary rocks of upper Hamanile limestone formation and upper sandstones. Whereas, quaternary calcrete, Abduya sandstone and upper Gabredarre limestone formation are also outcropped at places.

However, the lithological units found in the woreda area are further classified into four major groups based on their significances to groundwater occurrence and productivity using borehole data on yield and transmissivity analysis in particular.

- Mesozoic sedimentary rocks of upper Hamanilie limesone Formation. (Very high productive with Qav. = 12 l/s)
- Tertiary volcanics of lower, middle and plateau basaltic rocks. (High productive with Qav = 6.3 l/s)
- Mesozoic sedimentary rocks of upper & Abduya sandstones and upper Gebredarre limestone Formation. (Moderately productive with Qav = 4.3 l/s)
- Quaternary Calcrete. (Low productive with Qav = 3.3 l/s)

Tertiary volcanics of plateau basalts and Mesozoic sedimentary rocks of upper sandstone are the main lithologic framework of the Ginir woreda, and lower and middle basaltic rocks, sedimentary rocks of upper Hamanilie & upper Gabredarre limestone formations, Abduya sandstone and upper sandstone rocks, and quaternary calcrete are also outcropped at limited areas of central southeastern regions of the woreda (Figure 5-49).

Usually, massive unfractured lithologic units in volcanic and sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification, weathering and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of low productivity of Quaternary calcrete (0.11) \ moderate productivity of upper sandstone, Abduya sandstone & upper Gabredarre limestone (0.15) \ high productivity of lower, middle & plateau basalts (0.28) \ very high productivity of upper Hamanile limestone formation (0.46).

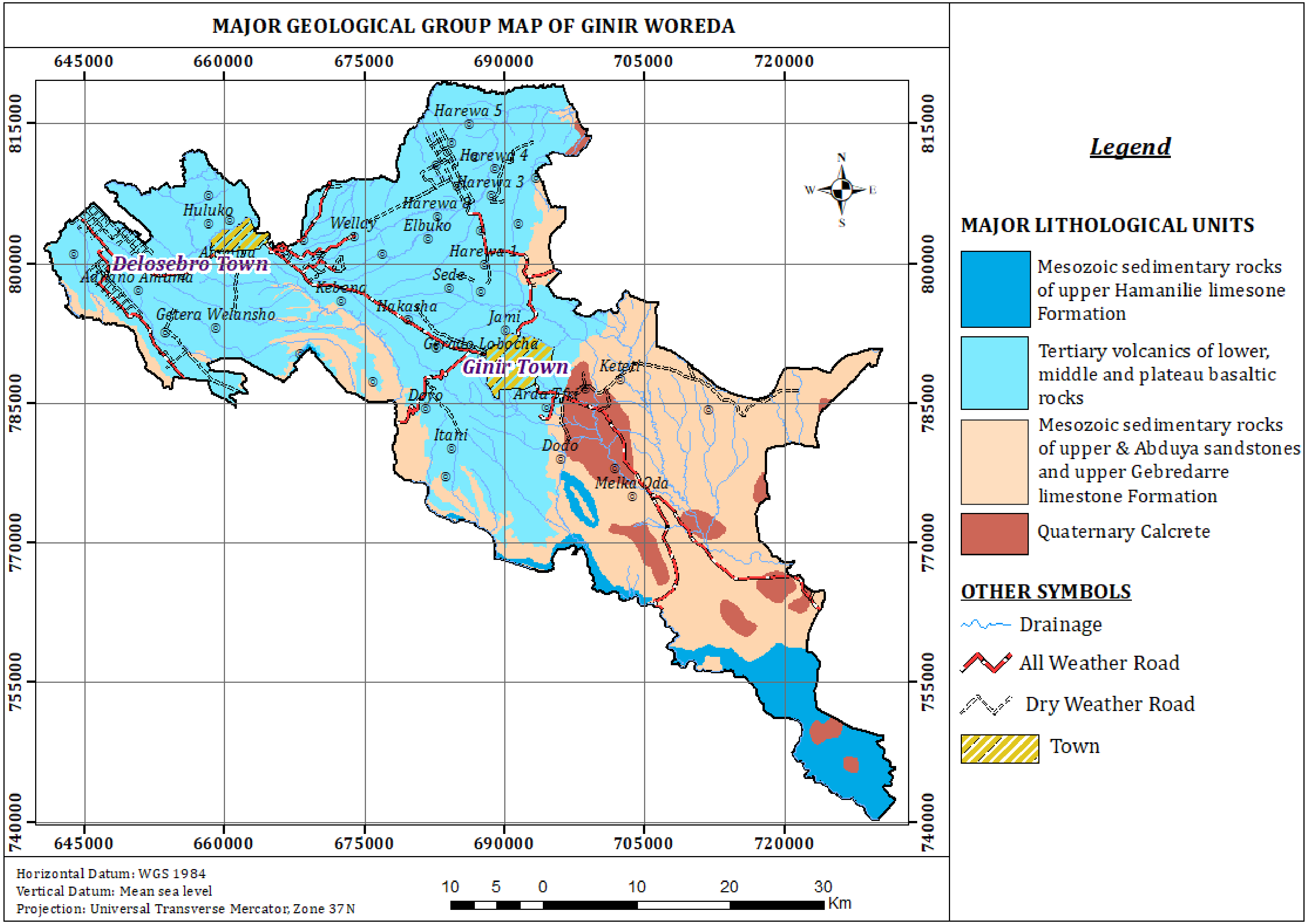

Figure 5-49. Grouped Lithological classification map of Ginir Woreda

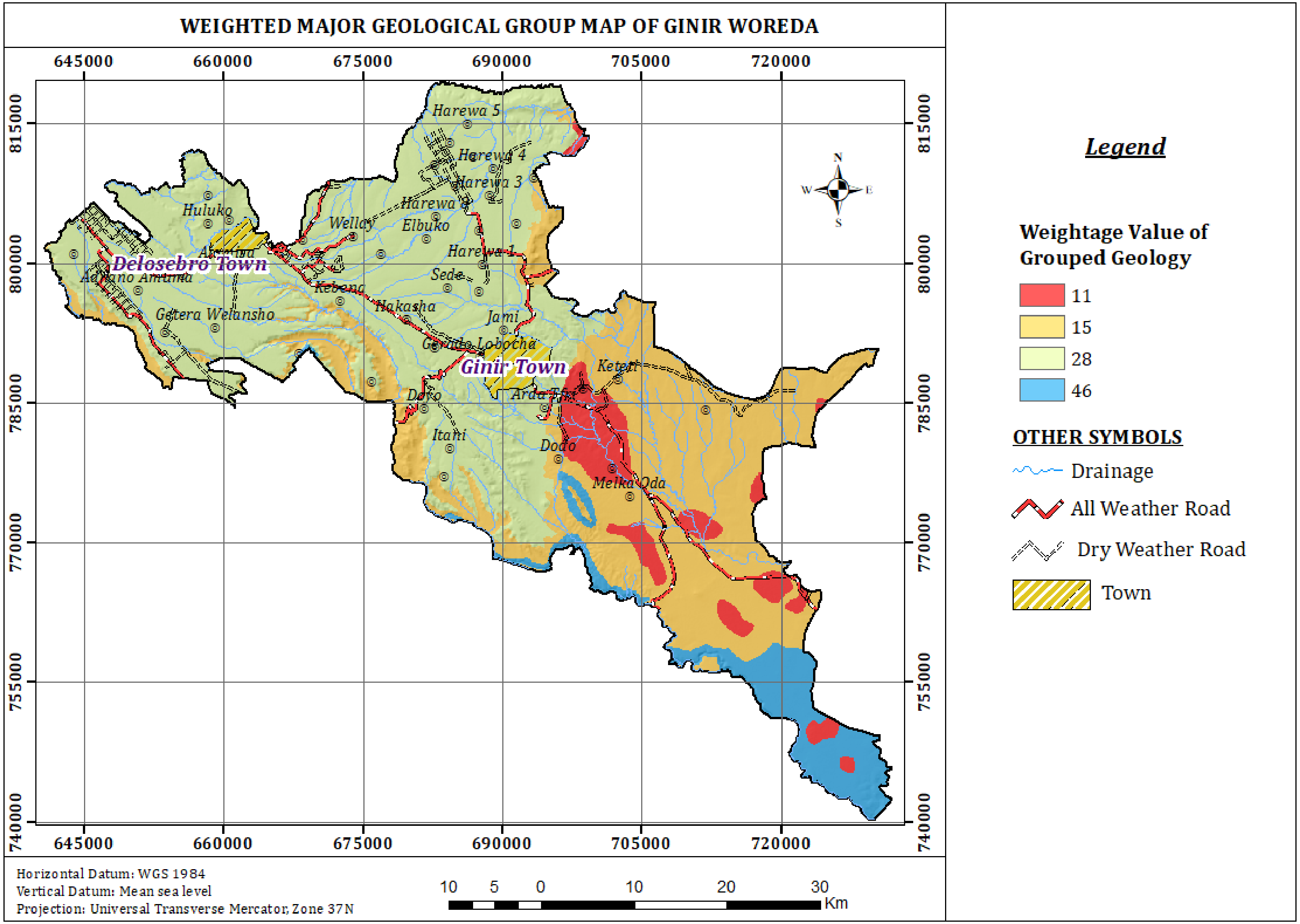

Figure 5-50. Weighted lithological classes' map of the Ginir Woreda

III. Lineaments and Lineament Density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SE and NE–SW trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from 0.24 km/km^2 to 0.47 km/km^2 (Figure 5-51). Though the lineaments are highly widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by Tertiary volcanics of plateau basalt. Upper Hamanilie limestone and upper sandstone having relatively higher lineament density of 0.24 km/km^2 to 0.47 km/km^2) compared with areas underlain by upper Gabredare limestone and lower basalt with lower lineament densities of (< 0.23 km/km^2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.46 was assigned to area with high density of lineaments, while a low weightage of 0.17 was assigned to areas with low lineament density (Figure 5-52).

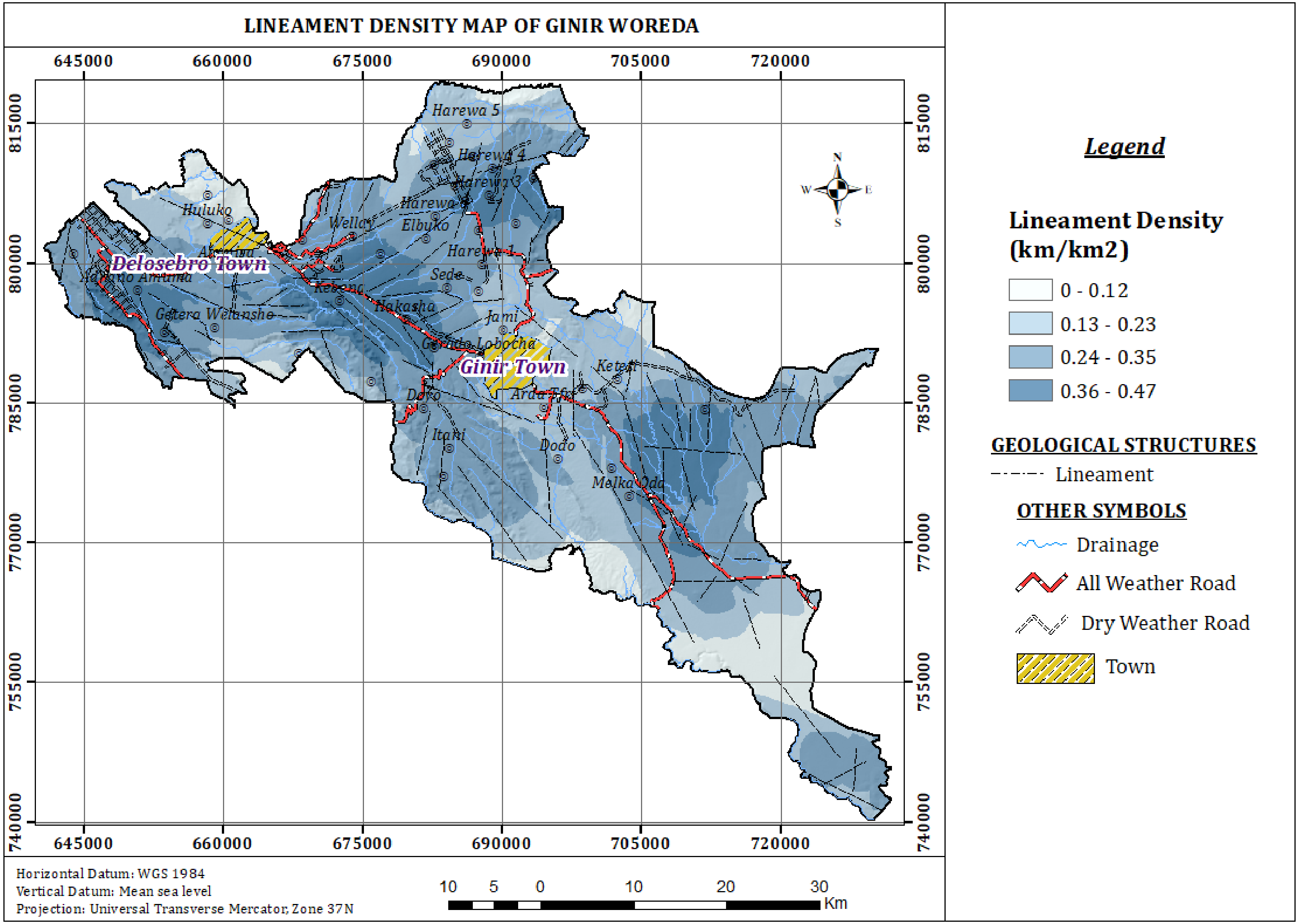

Figure 5-51. Lineament Density Map of Ginir Woreda

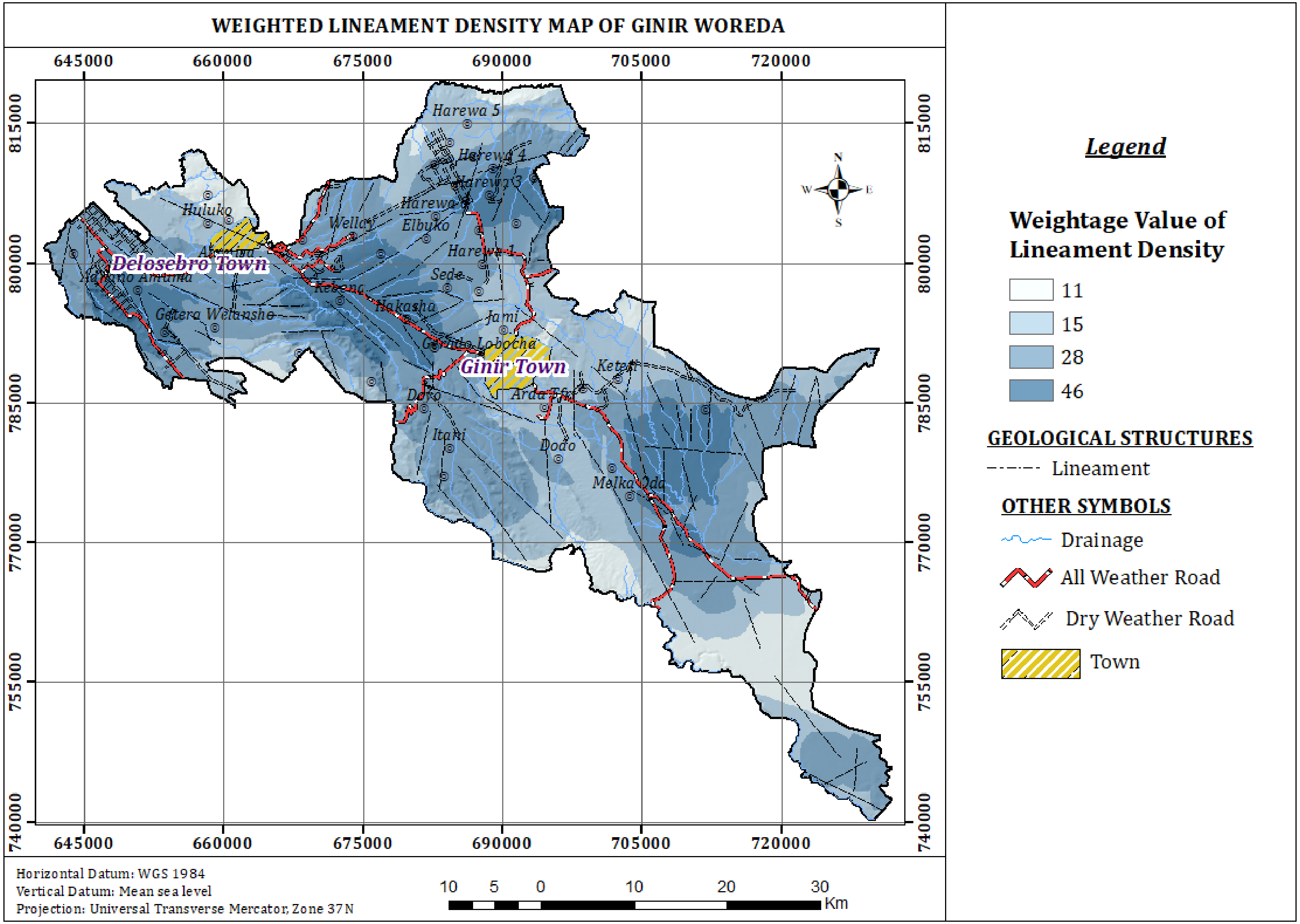

Figure 5-52. Weightage value of Lineament Density Map of Ginir Woreda

IV. Recharge

The spatial annual recharge rate distribution in the Ginir woreda ranges from 30.3 to 171 mm/y suggesting groundwaters in most central western elevated regions of the woreda area underlain by Tertiary volcanics of plateu basaltic flows receive high amount of recharge while the central and southeastern low-lying limited regions underlain by Tertiary volcanics of lower basalt, upper Gabredarre limestone and quaternary calcrete have relatively lower recharge amount due to very low infiltration rate of the lithological formation (Figure 5-53). Accordingly, areas with very high and high amount of recharge have weightage factor of 0.46 and 0.28, respectively signifying very good and good groundwater potential, respectively while areas with the moderate and lowest amount of recharge have weightage factor of 0.15 and 0.11, respectively, suggesting moderate and poor groundwater potentiality, respectively. Generally, the study area is characterized with high to very high mean annual recharge amount (> 87 mm/yr), whereas some of the central, central northern and southeastern areas of the woreda have moderate to low mean annual recharge amount (87-171 mm/yr).

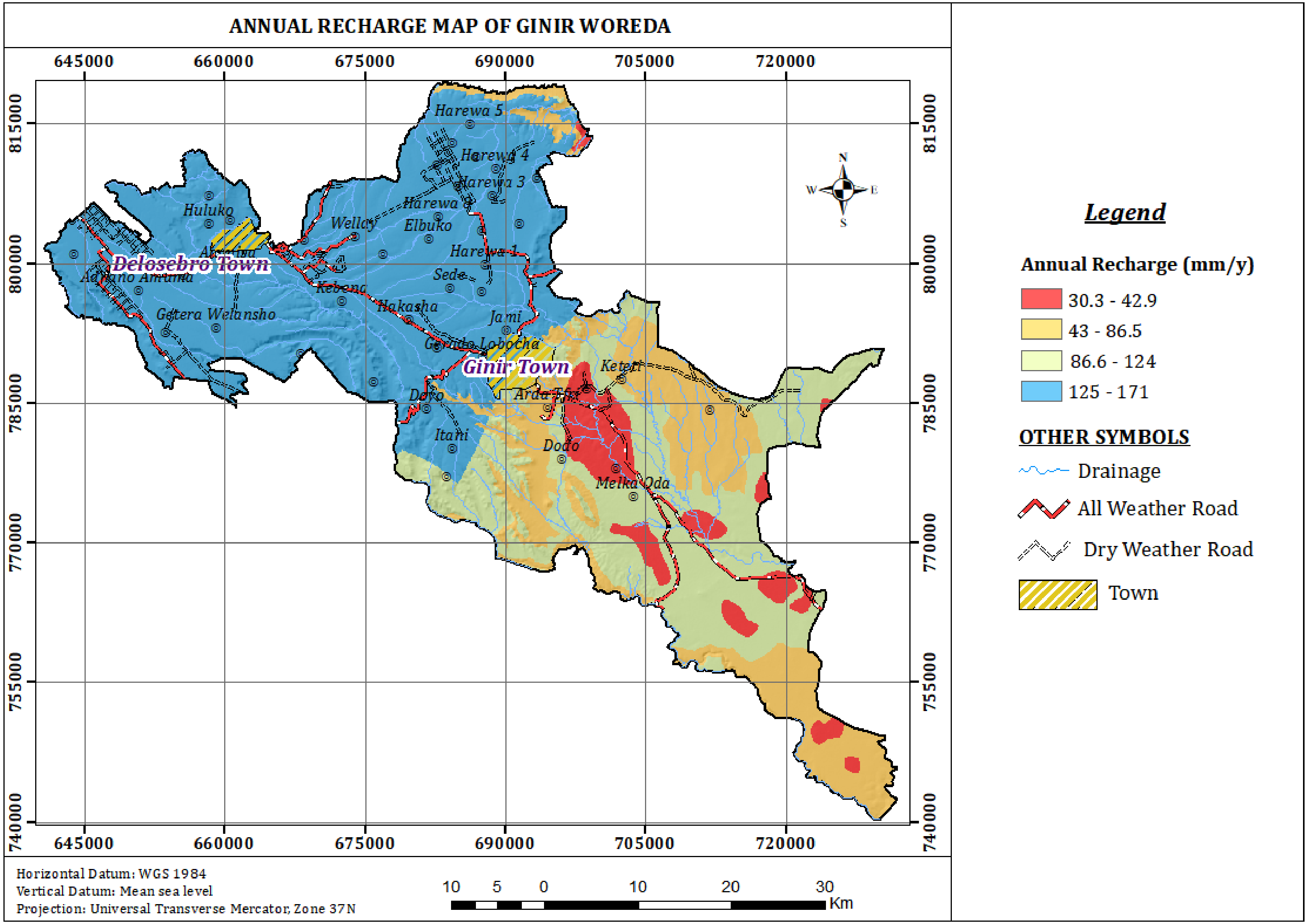

Figure 5-53. Annual Recharge Map of Ginir Woreda

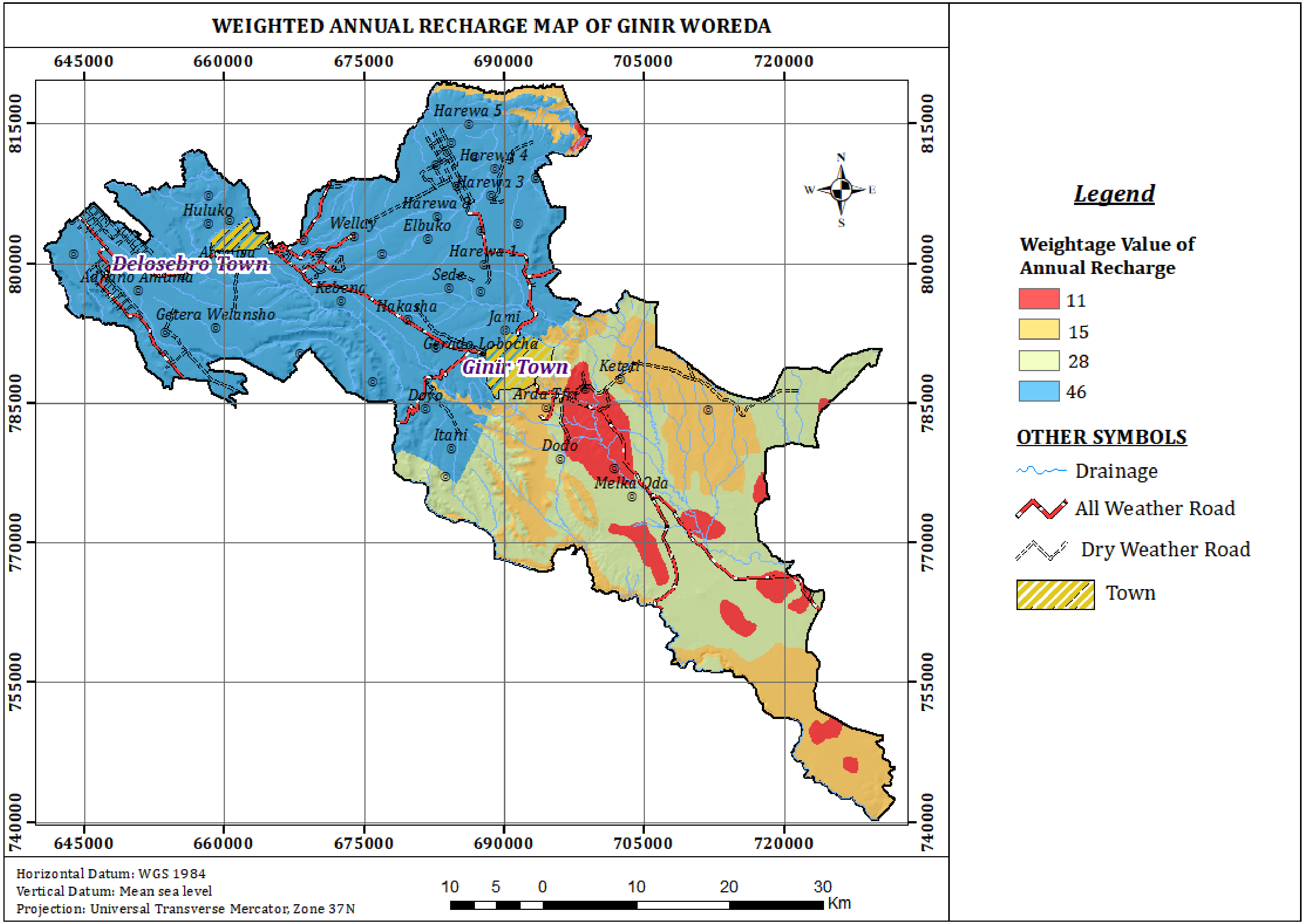

Figure 5-54. Weighted Annual Recharge classes' map of the Ginir Woreda

5.5.3. Classification of Groundwater Potential Zones

The hydrogeological system of Ginir woreda is comprised of two main lithological units as Tertiary volcanics of plateau basalts and upper sandstones. At both regional scale and local scale within the domain of Ginir woreda, plateau basalts form extensive and high to very high productive aquifers. This basaltic rock forms aquifers with very high groundwater potential as revealed from existing borehole information. Apart from this, upper Hamanilie limestone formation at limited southestern region forms also a very high groundwater potential.

Only the upper weathered and slightly fractured part of the volcanic and sedimentary rocks along lineamnets and faults have potential to store groundwater at shallow depth. Weathered and fractured volcanic rocks of plateau basaltic rocks form major potential aquifer within the domain of Ginir Woreda along lineament and fault lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-55). The potential groundwater zones (PGZ) of the Ginir woreda revealed four distinct zones, namely low, moderate, high and very high zones, respectively as presented in Table 5-24.

The potential map, as presented in Figure 5-55, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that central southeastern and central southern peripherial region of the woreda generally have low potentials, while most elevated areas at central, central western and southwestern regions generally exhibits high to very high potentials, respectively. The generally high to very high groundwater potentiality of the study area is a confirmation of generally high productive aquifers of plateau basalts and upper Hamanilie limestone, whereas low groundwater potential areas have an indication of limited aquifers capabilities of lower basalts, upper Gabredarre limestone and upper sandstone.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the topographic wetness index and geology in addition to the lineament density and recharge control. In addition, areas underlain by plateau basalts especially in the central and central western sections of the study area are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments, and apparently deep fracturing system have high and very high groundwater potential on the one hand. On the other hand, areas underlain by upper sandstone and upper Gabredarre limestone rocks in the central southeastern regions of the woreda in particular are characterized by rugged and low-lying topography with relatively steep slopes, low recharge amount, and lower lineament densities, exhibit low groundwater potential. Moreover, low lineament densities and predominance of steep slope topography can be attributed to the observed low groundwater potentials. However, predominance of fractured and weathered volcanic rocks of plateau basaltic flows and upper Hamanilie limestone, high lineament density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential. Summary of the groundwater potential zones identified in the Ginir woreda is presented in the table below (Table 5-24).

Table 5-24. Classification of groundwater potential zones and coverage areas alongside the respective yield categories

Woreda Name	GWP Zones	Major Aquifer Units	Borehole Yield Classification (l/s)	
			Q (Range)	Mean 'Q'
Ginir	Very High	Plateau basalt (Tv3(1)) & upper Hamanilie limestone (Jh2)	5.6 – 15.3	10
	High	Plateau basalt (Tv3(1)) and upper sandstone (Ka)	2.5 - 8	5
	Moderate	lower basalt (Tv1) , middle basalt (Tv2) & upper sandstone (Ka)	2 – 5.9	4
	Low	upper sandstone (Ka) & upper Gabredarre limestone (Jg2)	2.5 – 4.9	3.7

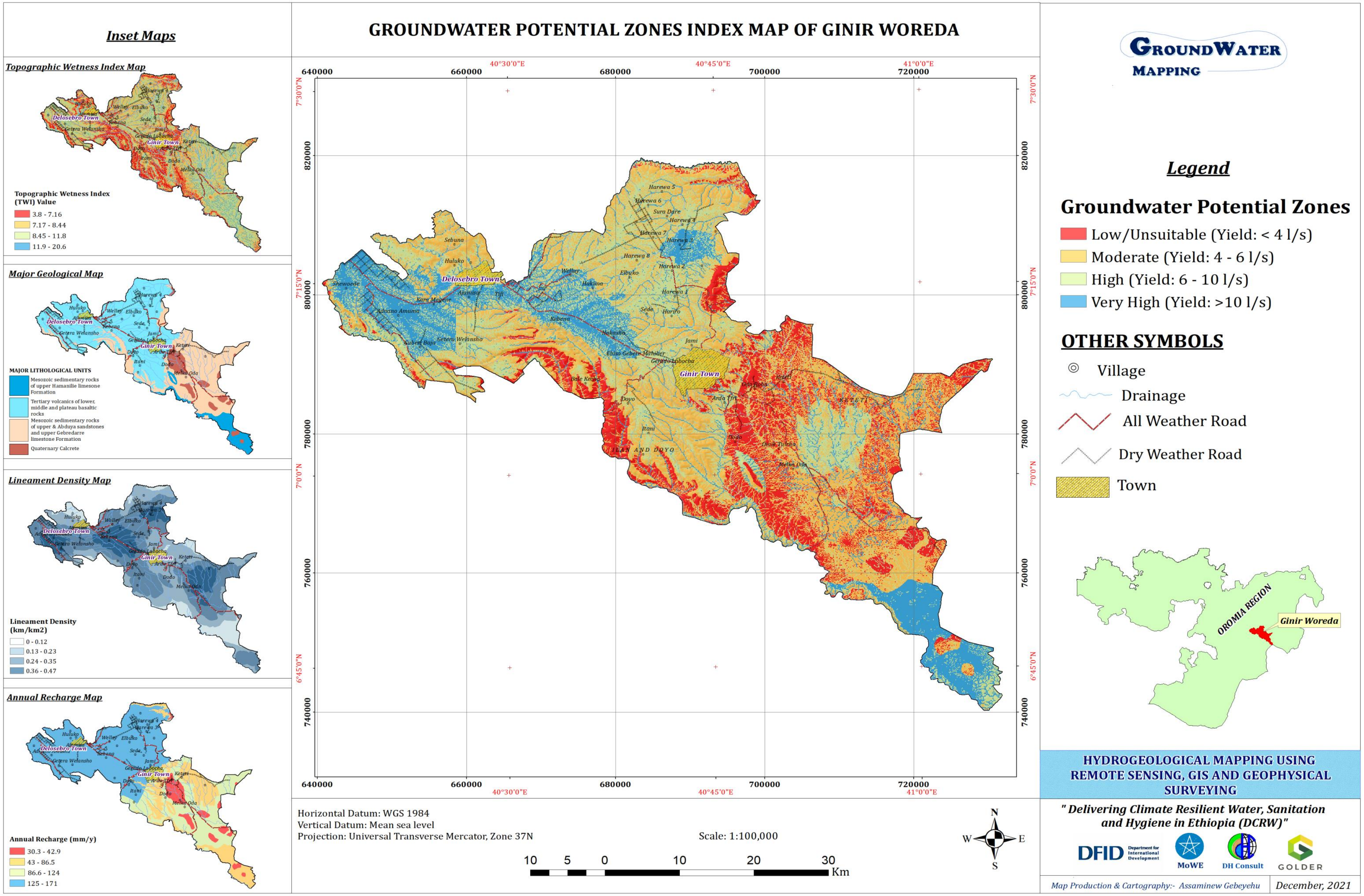

Figure 5-55. Groundwater Potential Zones Map of Ginir Woreda

5.5.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) are were collated for over 50 boreholes found around the woreda within the synoptic cluster boundary area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the synoptic area vary from 5.6 – 15.3 lit/sec (av. 10 lit/sec) in very high potential zones and varying from 2.5 lit/sec to 8 lit/sec (av. 5 lit/sec) in high potential zones as compared with 2 lit/sec to 5.9 lit/sec (av. 4 lit/ sec) in the moderate and from 2.5 to 4.9 lit/sec (av. 3.7 lit/sec) in the low potential zones (Figure 5-56). As shown in the Figure 5-56, the occurrence of number of wells with yield of in the range 2.5 - 8 lit/sec (high yield) and of > 6 lit/sec (very high yield) cut across mainly the plateau basaltic rocks and upper sandstone and limestone formations. However, the less frequency of wells within lower Gabredarre limestone formation in the low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (2.5-4.9 lit/sec) category is associated also with wells in the fractured lower and middle basaltic rocks and sedimentary rocks of upper sandstones. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

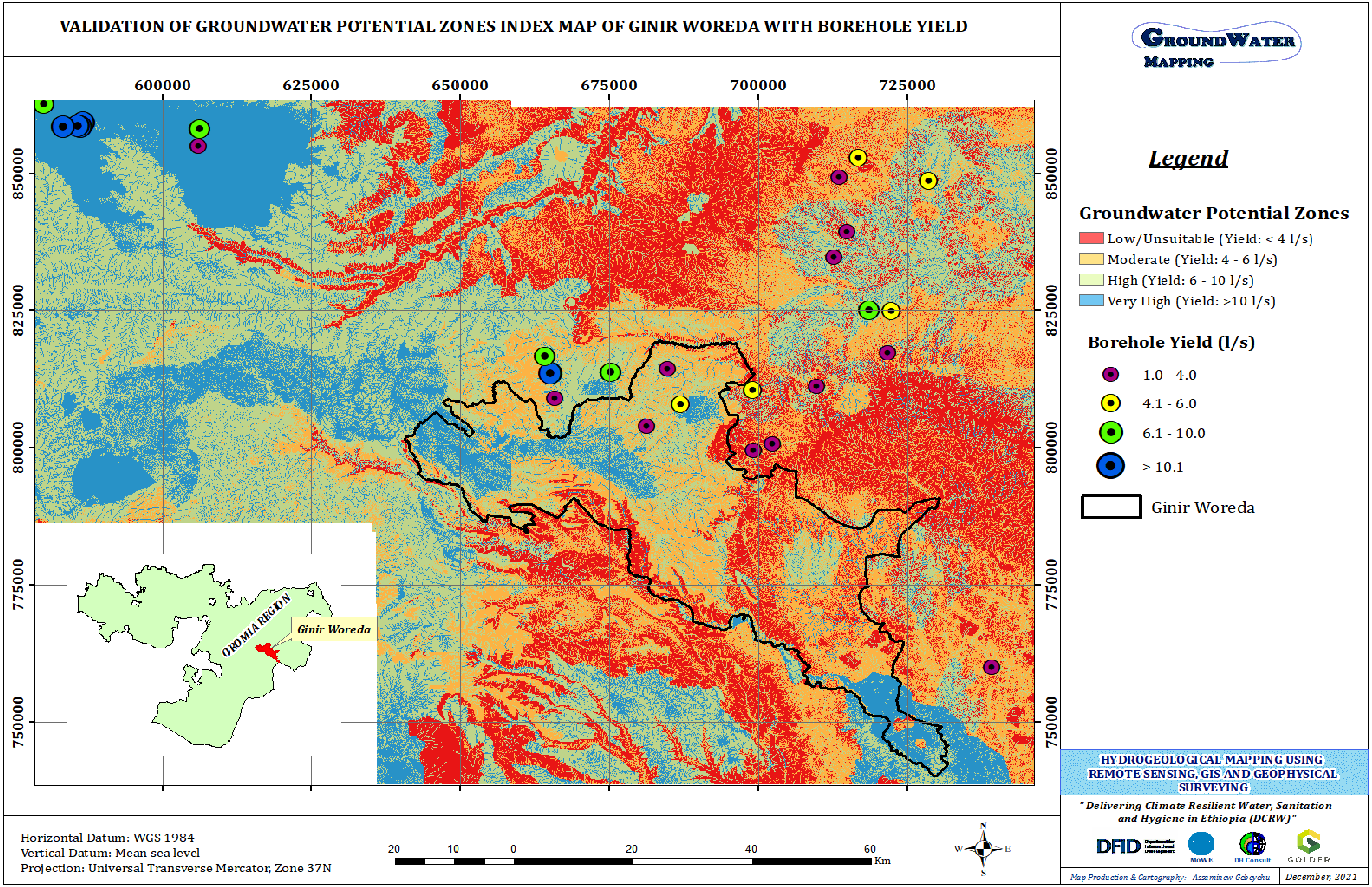

Figure 5-56. Validation of Groundwater Potential Zones Map of Ginir Woreda within Arsi-Bale synoptic boundary

5.5.5. Projected Population and Water Demand of Ginir

5.5.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-25 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013
Geometric method forecasting formula

$$P = Po\,(1 + r)^{n}$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Ginir Woreda has been projected forward until 2036 using the growth rate of Oromia Regional State. The minimum and maximum population in the Woreda is 4 and 17,289 respectively. The total population of the Ginir Woreda in 2036 is going to be 223,635.

5.5.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic

purposes greatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO) & (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer’s life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24 hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from 1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-57 shows the distribution of water demand in each Kebeles of the Woreda. Mehammed Ali kebele water demand is the minimum with 0.4 M^3/day and maximum water demand is required for Karadano Kebele with 1,553 M^3/day respectively. The overall water demand for the projected population in the Ginir Woreda is 20,094 M^3/day.

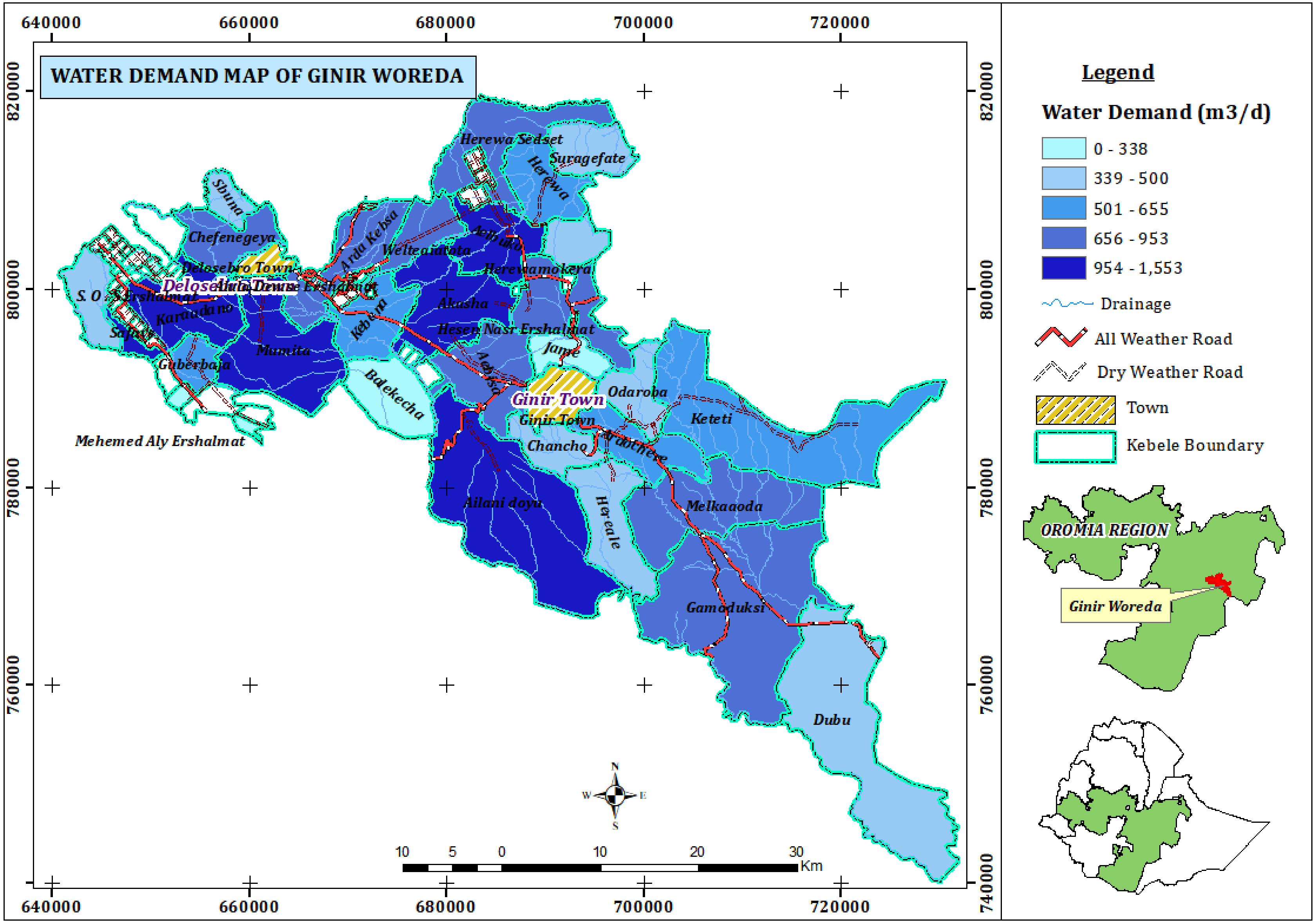

Figure 5-57:-Water Demand Map of Ginir Woreda

5.5.6. Propsed Target Sites of Ginir

Four target sites are identified and proposed within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficiaries and population density. With further discussion and consultation with stakeholders, two priority sites will be selected for further hydrogeological and geophysical investigations in phase III. The following are the four proposed sites:

Target Site-I:

This target site is located in the southwestern regions of the woreda. It is situated in the identified very high potential zones with expected optimum borehole discharge of about 8 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-II:

This target site is located in the northwester part of the woreda. It is situated in the identified high and very high potential zones with expected optimum borehole discharge of about 5 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-III:

This target site is located in the central eastern parts of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 3 l/s. This target site is mainly underlain by upper Gabredarre limestone and upper sandstone rocks.

Target Site-IV:

This target site is located in the southeastern region of the woreda. It is situated in the identified very high potential zones with expected optimum borehole discharge of about 8 l/s. This target site is mainly underlain by upper Hamanilie limestone rocks.

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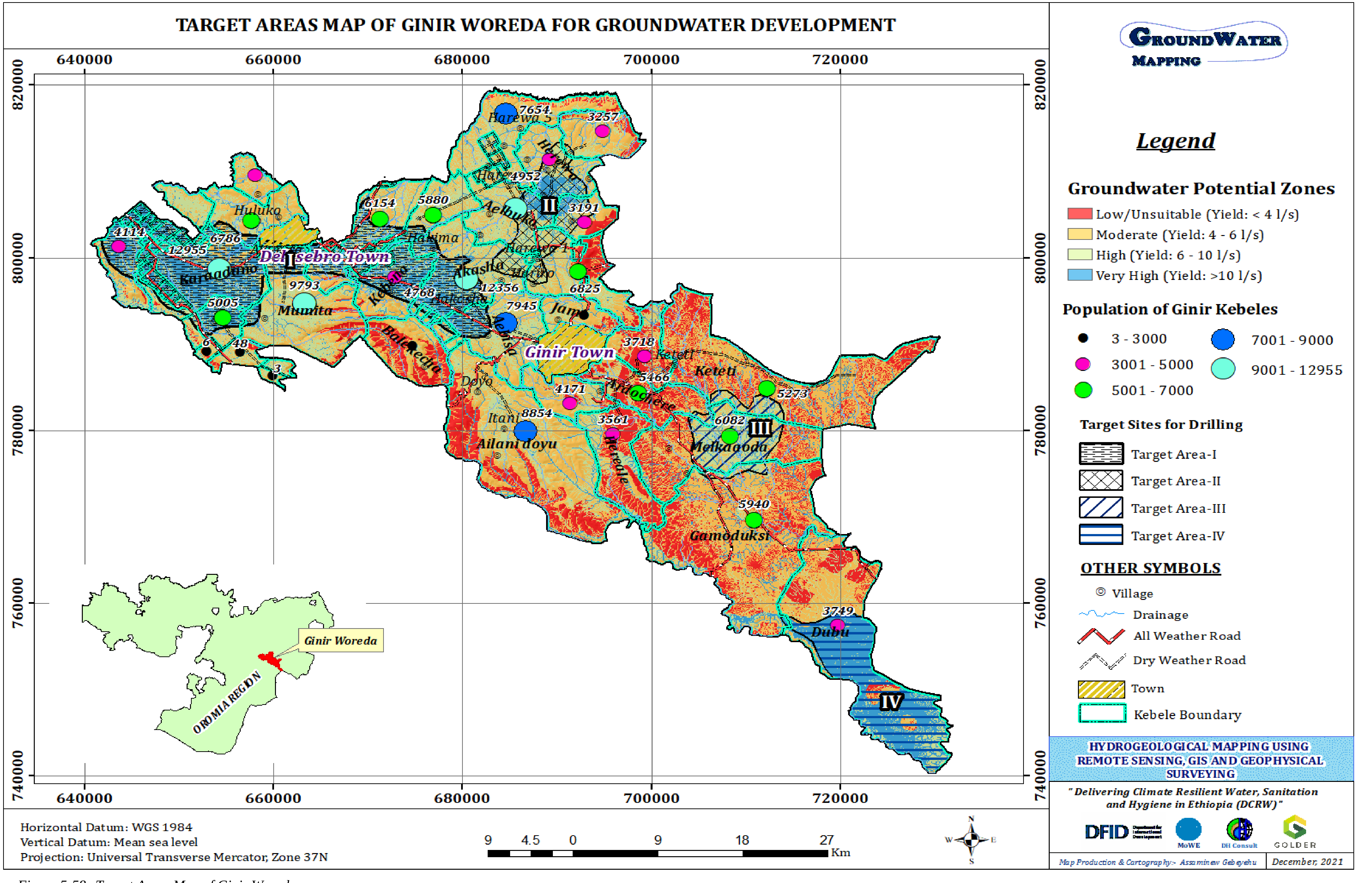

Figure 5-58:-Target Areas Map of Ginir Woreda

5.6. Robe Woreda

5.6.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.05 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Robe woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-26). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-27. The weights assigned to the respective thematic maps as presented in Table 5-28 indicate that TWI was ranked the dominant factor with a normalized weight value of 0.41 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Robe woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Robe woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

GWPZI = (TWIwTWIwi + GGwGGwi + LDwLDwi + GRwGRwi)

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Robe woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e. 'very high', 'high', 'moderate' and 'low or poor', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-26 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Topographic Wetness Index (TWI)	9
Geology (GG)	8
Lineament density (LD)	7
Recharge (GR)	6

Table 5-27 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	**Theme**				**Normalized weight**
	TWI	GG	LD	GR	
TWI	1	1	3	5	0.41
GG	1	1	3	2	0.34
LD	1/3	1/3	1	2	0.15
GR	1/5	1/2	1/2	1	0.10

Table 5-28 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank
Topographic Wetness Index, 'TWI'	3.8 – 7.16	poor	1	0.11	0.41
	7.17 – 8.44	Moderate	2	0.15	
	8.45 - 11.8	Good	3	0.28	
	11.9 – 20.6	Very good	4	0.46	
Geology/ Lithology, 'GG'	Tertiary volcanics of lower, plateau & highland basaltic flows, and upper Hamanilie limesones.	Very good	4	0.54	0.34
	Tertiary volcanics of trachytes & Mesozoic sedimentary rocks of upper sandstone	Moderate	3	0.30	
	Mesozoic sedimentary rocks of lower Hamanilie limesones.	Poor	2	0.16	
Lineament Density,' LD' (Km/Km^2)	0 - 0.08	poor	1	0.11	0.15
	0.09 - 0.2	Moderate	2	0.15	
	0.3 - 0.4	Good	3	0.28	
	0.5 - 0.9	Very good	4	0.46	
Recharge, 'GR' (mm/y)	84.6 - 99.1	poor	1	0.11	0.10
	99.2 - 121	Moderate	2	0.15	
	122 - 152	Good	3	0.28	
	153 - 162	Very good	4	0.46	

5.6.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of Topographic Wetness Index (TWI), geology, lineament density and recharge together with their spatial distribution in Robe woreda are presented below:

I. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 3.8 and 20.6 (Figure 5-59). A closer look at the classification revealed that most the high elevated areas and drainage systems with steep slopes have relatively lower TWI value while the low lying areas and drainage systems with gentle and flat slopes such as areas extending from central to western regions of the woreda in particular have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.46) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.11) as shown in Figure 5-60.

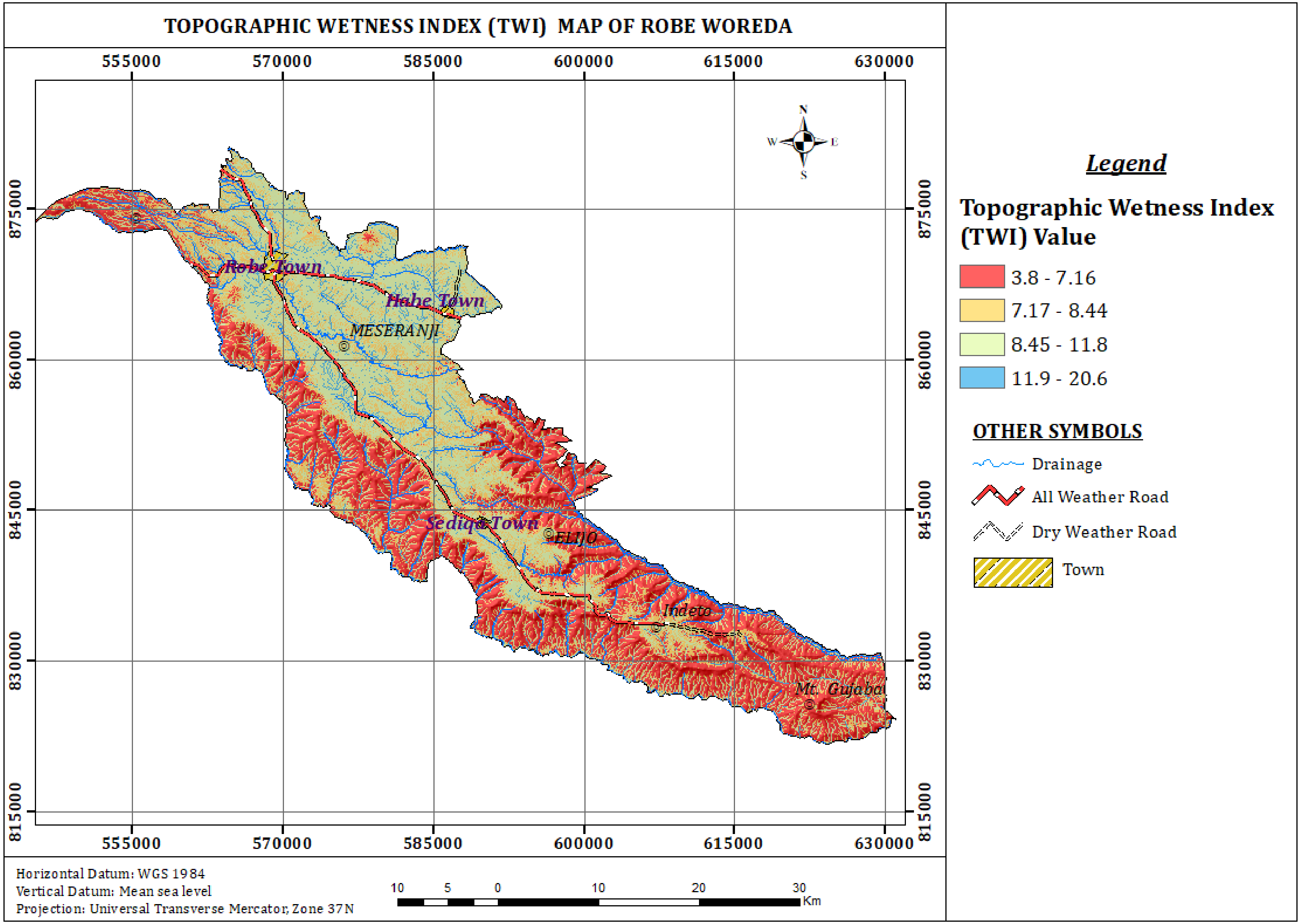

Figure 5-59. TWI Map of Robe Woreda

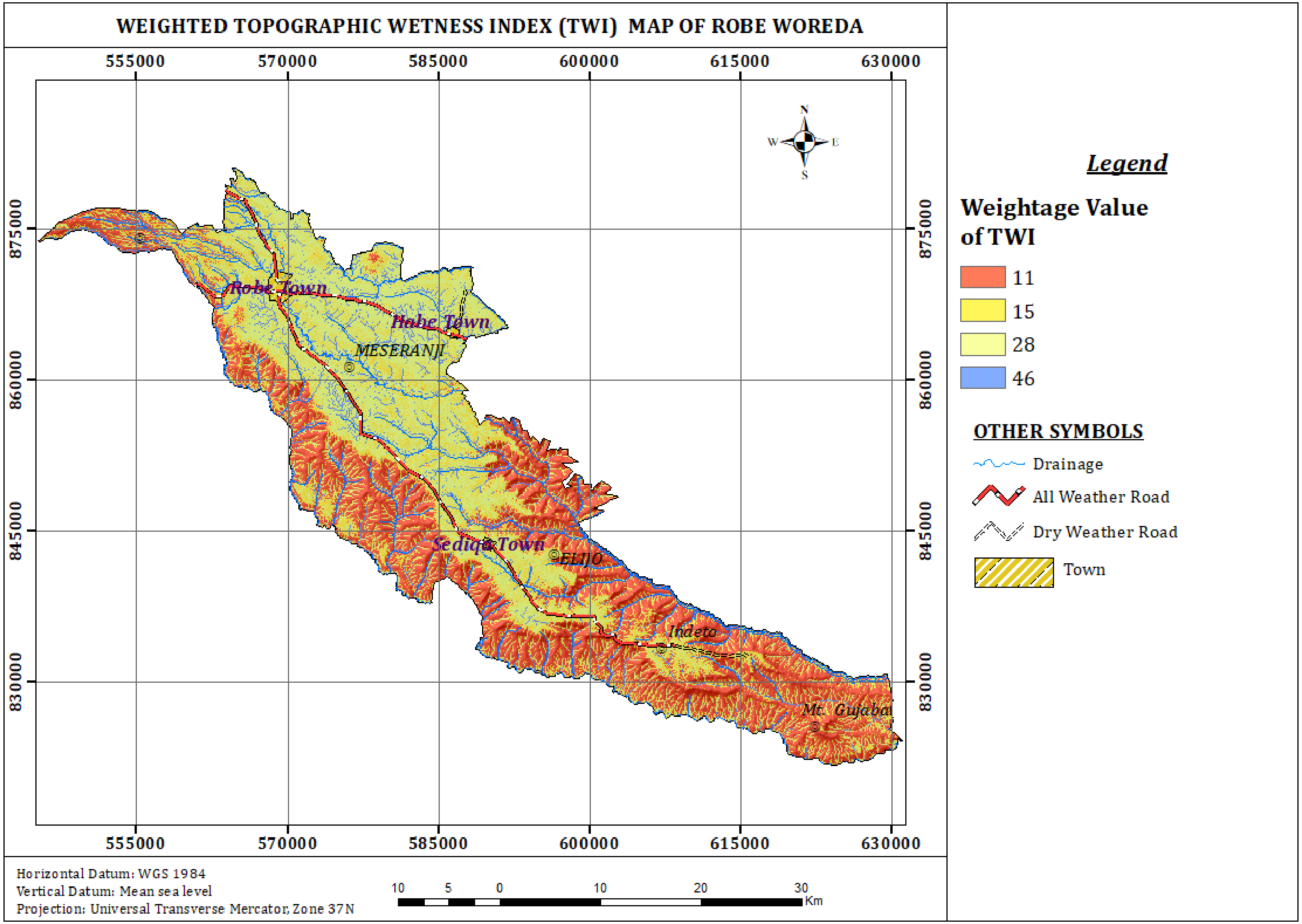

Figure 5-60. Weightage value of TWI Map of Robe Woreda

II. Geology/Grouped Hydrolithology

In general, most parts of the Robe woreda are underlain by Tertiary volcanic rocks of plateau and lower basalts. Whereas, Mesozoic sedimentary rocks of upper Hamanile limestone formation and upper sandstones are mainly outcropped at central, western and eastern peripheries of the woreda while Tertiary volcanics of trachytes and upper most basalt are outcropped at limited areas of northwestern extreme parts of the woreda.

However, the lithological units found in the woreda area are further classified into three major groups based on their significances to groundwater occurrence and productivity using borehole data on yield and transmissivity analysis in particular.

- Tertiary volcanics of lower, plateau & highland basaltic flows, and upper Hamanilie limesone Formation. (Very high productive with Qav. = 15 l/s)
- Tertiary volcanics of trachytes & Mesozoic sedimentary rocks of upper sandstone. (Moderately productive with Qav = 5.5 l/s)
- Mesozoic sedimentary rocks of lower Hamanilie limesones (Low productive with Qav = 3.8 l/s)

Tertiary volcanics of lower basalts and plateau basalt are the main lithologic framework of the Robe woreda, and sedimentary rocks of upper Hamanilie limestone formation and upper sandstone, volcanic rocks of trachytes and highland basalt are also outcropped at limited areas of the woreda (Figure 5-61).

Usually, massive unfractured lithologic units in volcanic and sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification, weathering and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of low productivity of lower Hamanilie limestone (0.16)\ moderate productivity of trachytes and upper sandstone (0.30)\ very high productivity of Tertiary volcanics of lower,plateau and uppermost basaltic flows, and upper Hamanile limestone formation (0.54) as shown in Figure 5-62.

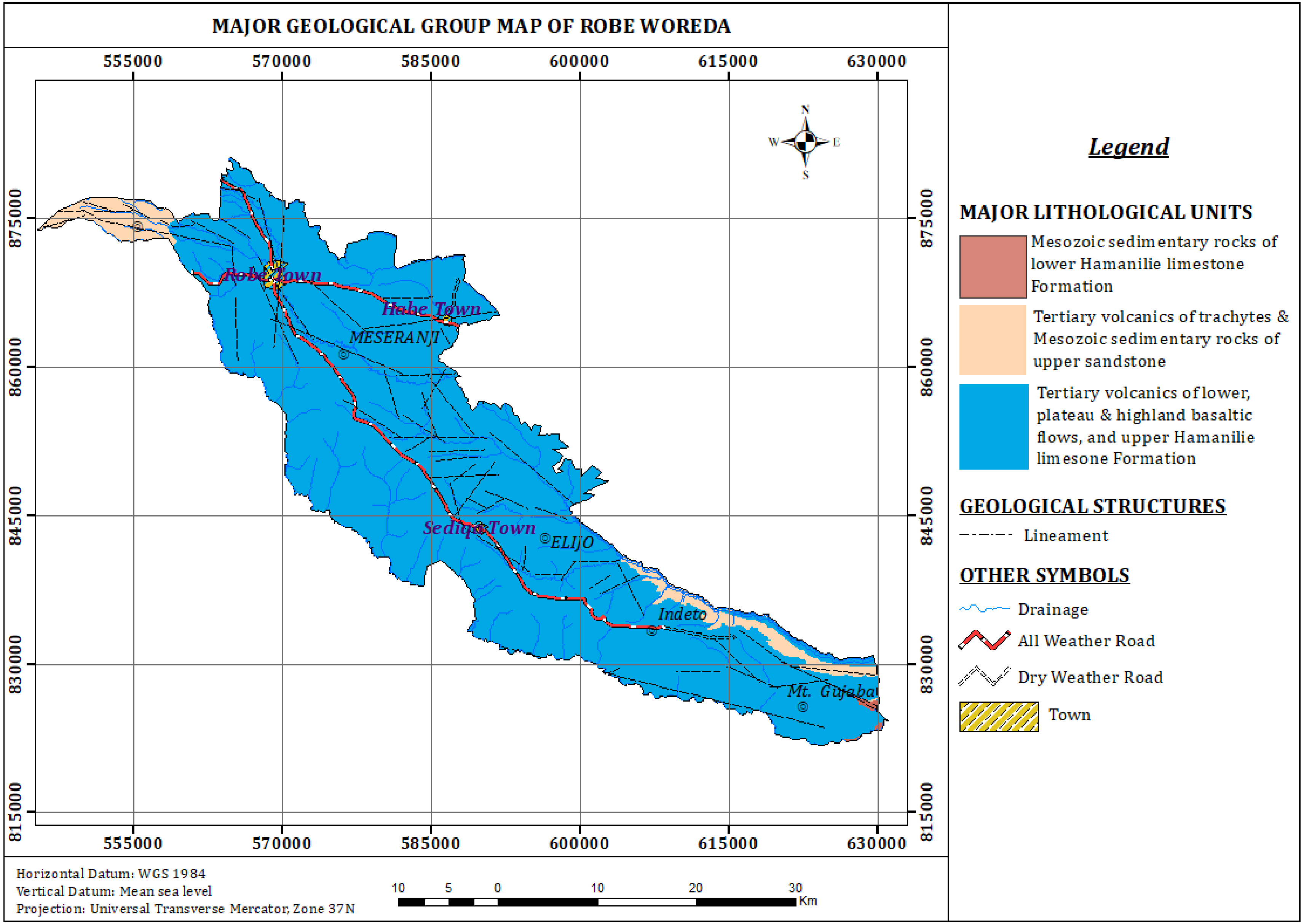

Figure 5-61. Grouped Lithological classification map of Robe Woreda

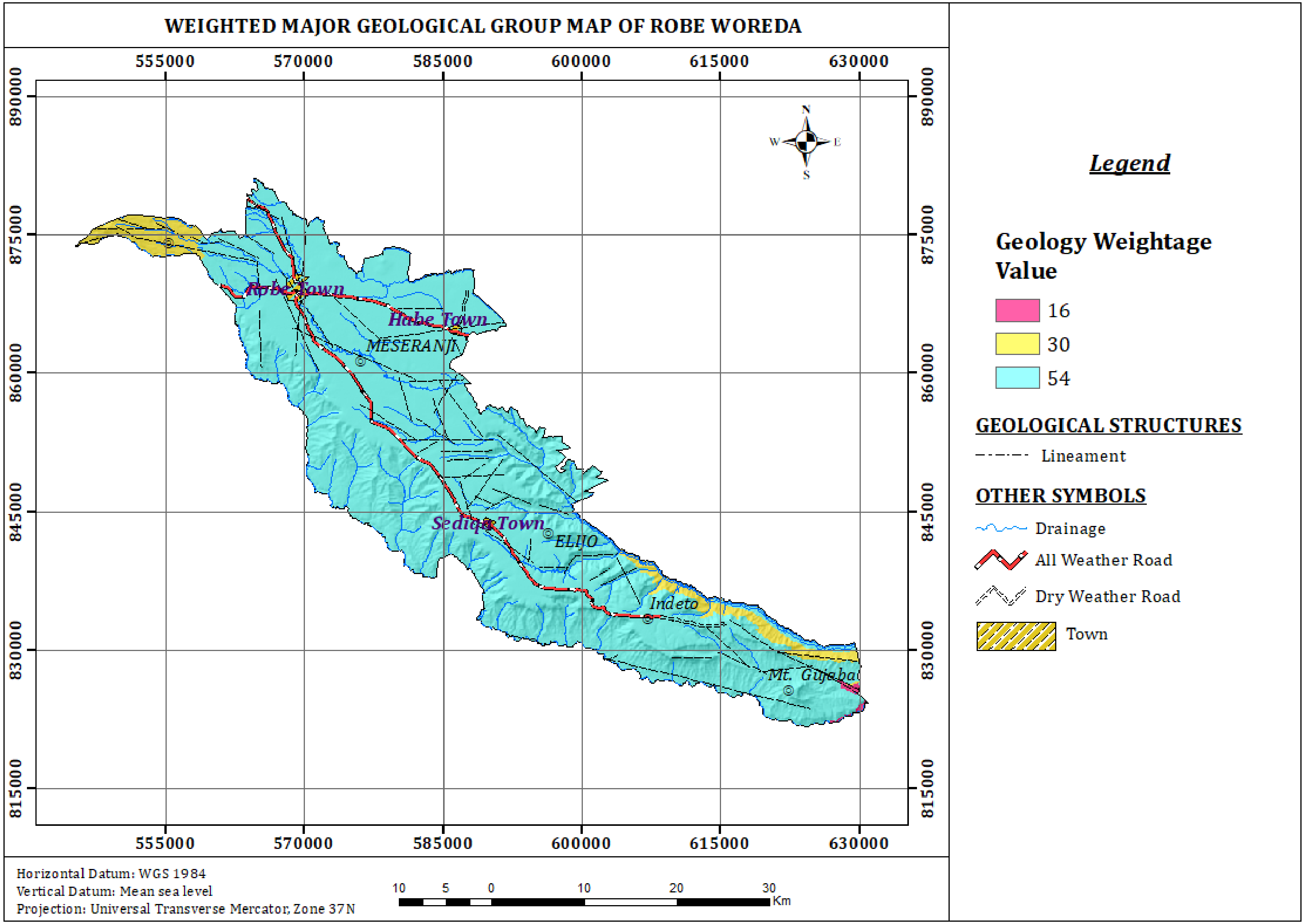

Figure 5-62. Weighted lithological classes' map of the Robe Woreda

III. Lineaments and Lineament Density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SE and NE–SW trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.08 km/km^2 to 0.9 km/km^2 (Figure 5-63). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by Tertiary volcanics of plateau basalt having relatively higher lineament density of 0.5 – 0.9 km/km^2) compared with areas underlain by sedimentary rocks of upper limestone and lower basalts with lower lineament densities of (< 0.3 km/km^2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.46 was assigned to area with high density of lineaments, while a low weightage of 0.11 was assigned to areas with low lineament density (Figure 5-64).

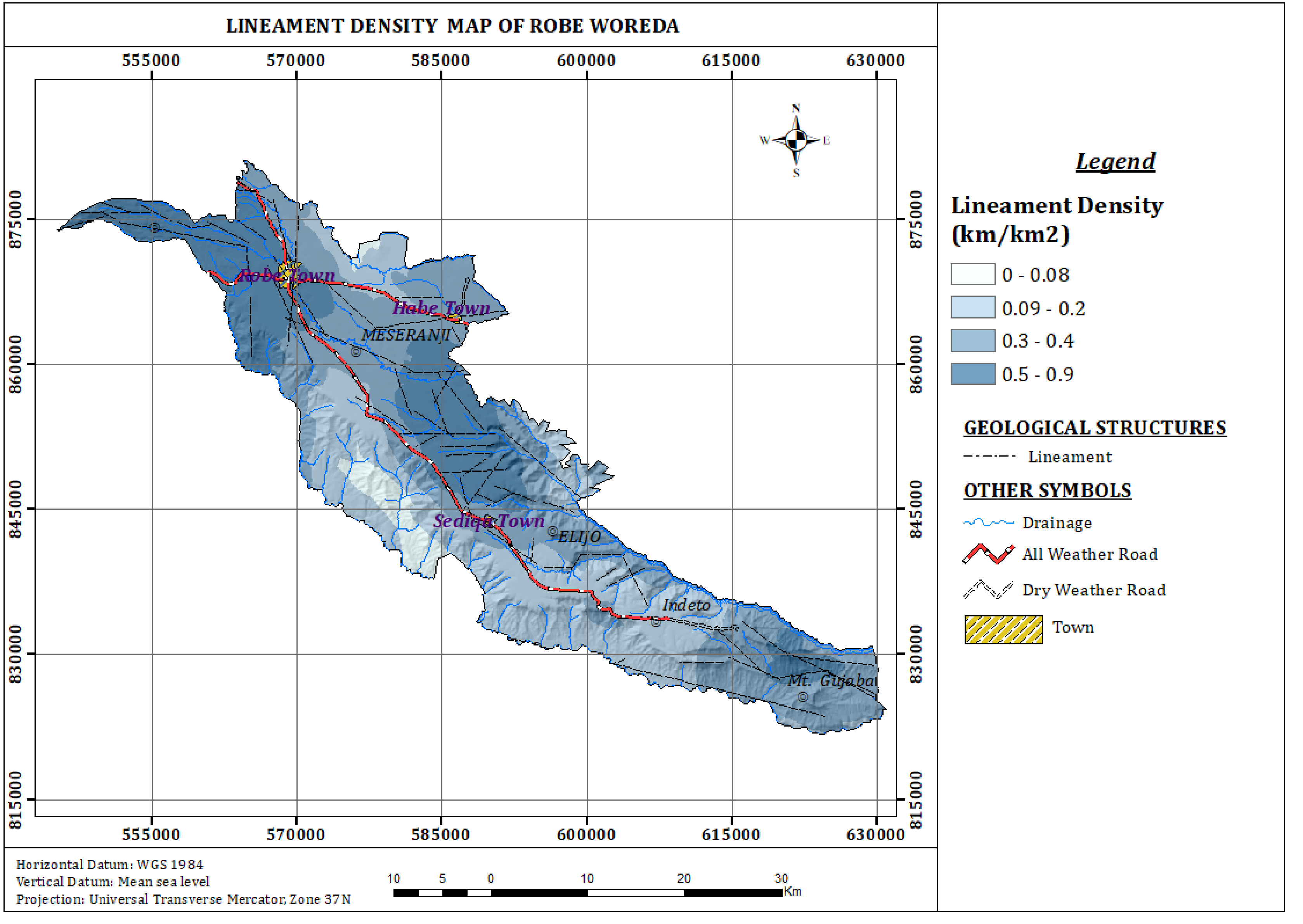

Figure 5-63. Lineament Density Map of Robe Woreda

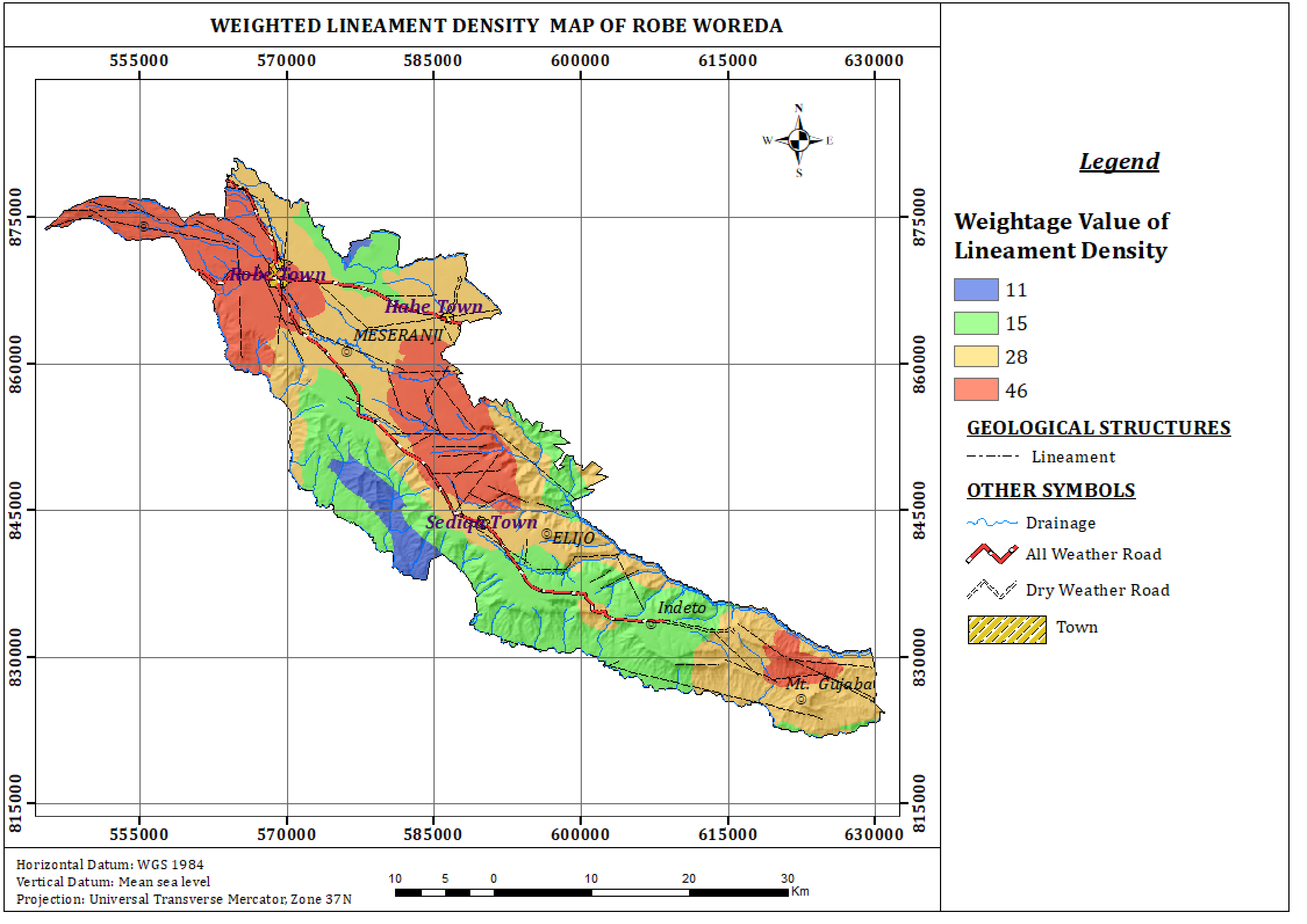

Figure 5-64. Weightage value of Lineament Density Map of Robe Woreda

IV. Recharge

The spatial annual recharge rate distribution in the Robe woreda ranges from 84.6 to 162 mm/y suggesting groundwaters in most northwester elevated regions of the woreda area underlain by Tertiary volcanics of plateu basaltic flows receive high amount of recharge while the central southern and northern, and southeastern low-lying peripherial areas underlain by Tertiary volcanics of lower basalt falls and upper Hamanilie limestone have relatively lower recharge amount due to very low infiltration rate of the lithological formation (Figure 5-65). Accordingly, areas with very high and high amount of recharge have weightage factor of 0.46 and 0.28, respectively signifying very good and good groundwater potential, respectively while areas with the moderate and lowest amount of recharge have weightage factor of 0.15 and 0.11, respectively, suggesting moderate and poor groundwater potentiality, respectively. Generally, the study area is characterized with high to very high mean annual recharge amount (> 122 mm/yr), whereas some of the northern and southern peripheries have moderate to low mean annual recharge amount (85-121 mm/yr).

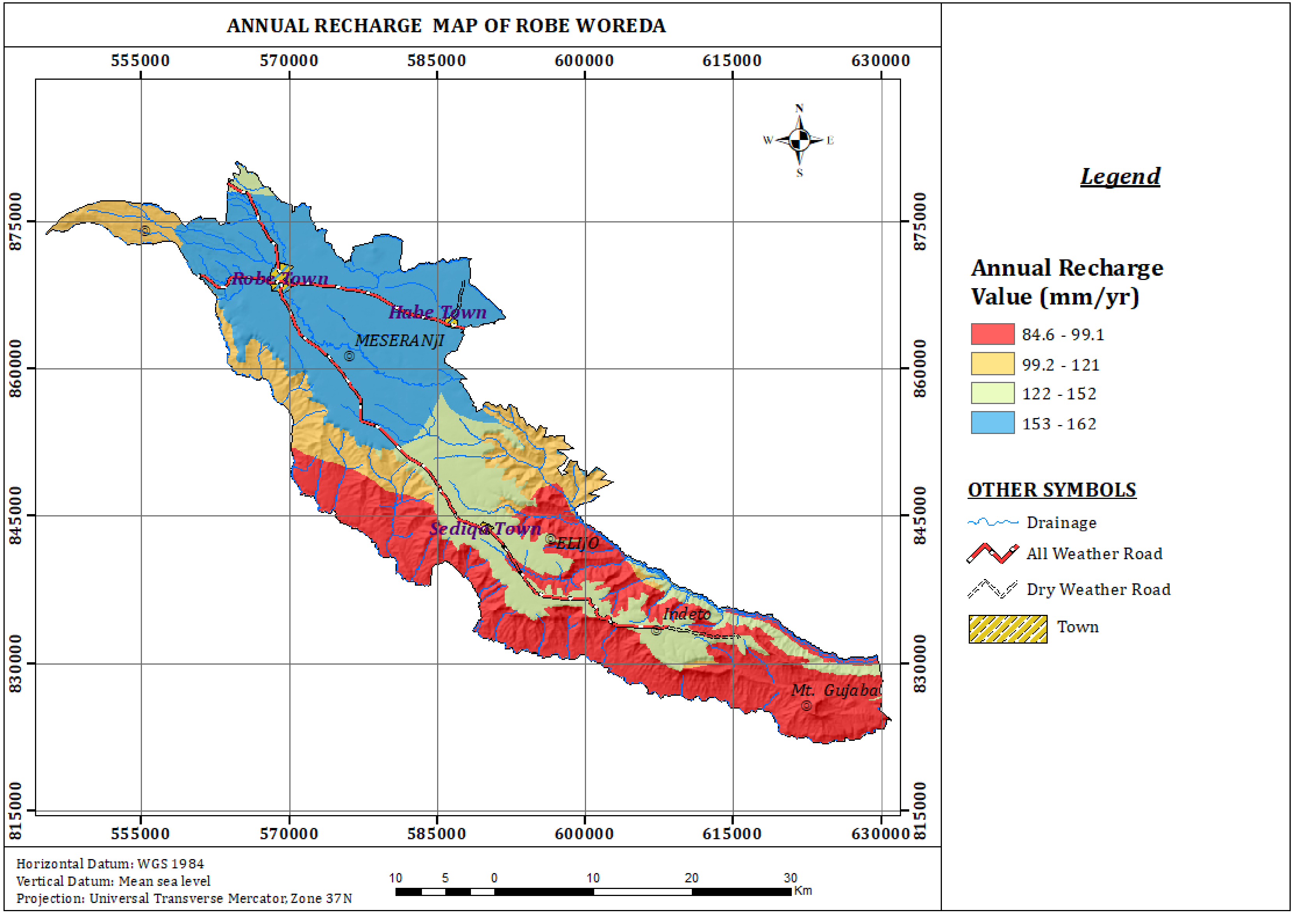

Figure 5-65. Annual Recharge Map of Robe Woreda

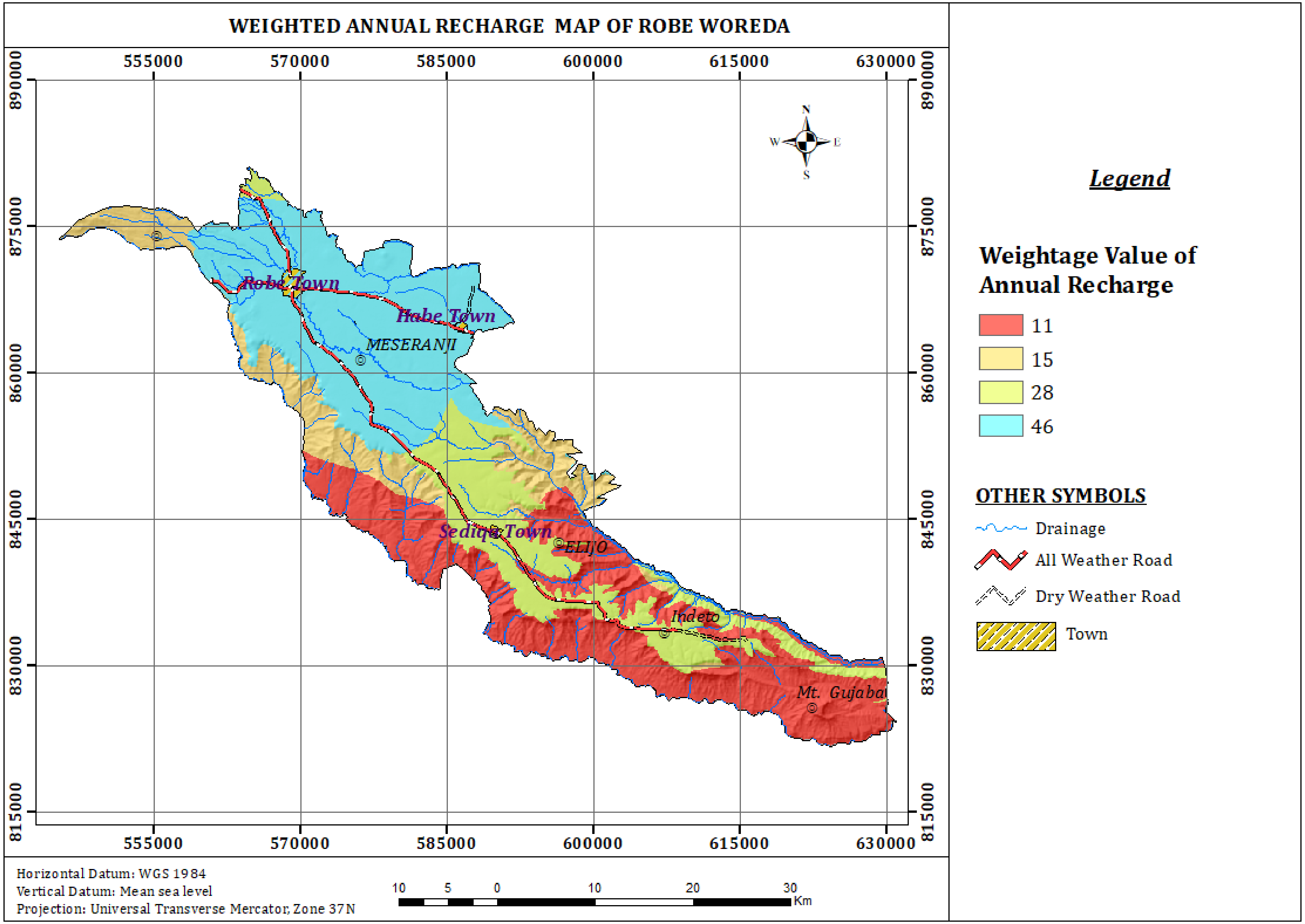

Figure 5-66. Weighted Annual Recharge classes' map of the Robe Woreda

5.6.3. Classification of Groundwater Potential Zones

The hydrogeological system of Robe woreda is comprised of three main lithological units as Tertiary volcanics, upper sandstone and upper Hamanlie limestone formations. At both regional scale and local scale within the domain of Robe woreda, plateau basalts form extensive and very high productive aquifers. Theses basaltic rocks form aquifers with very high groundwater potential as revealed from existing borehole information.

Only the upper weathered and slightly fractured part of the volcanic rocks along lineamnets and faults have potential to store groundwater at shallow depth. Weathered and fractured volcanic rocks of basaltic flows form major potential aquifer within the domain of Robe Woreda along lineament and fault lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-67). The potential groundwater zones (PGZ) of the Robe woreda revealed four distinct zones, namely low, moderate, high and very high zones, respectively as presented in Table 5-29.

The potential map, as presented in Figure 5-67, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that extreme part of nortwestern elevated areas, and southeastern and norteastern peripheries the woreda generally have low potentials, while most areas at central, central eastern, northwestern regions generally exhibits high to very high potentials, respectively. The generally high to very high groundwater potentiality of the study area is a confirmation of generally high productive aquifers of plateau basalts, whereas low groundwater potential areas have an indication of limited aquifers capabilities of trachytes, lower basalts and upper sandstone formation.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the topographic wetness index and geology in addition to the lineament density and recharge control. In addition, areas underlain by plateau basalts especially in the central and central western sections of the study area are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments, and apparently deep fracturing system have high and very high groundwater potential on the one hand. On the other hand, areas underlain by lower basalt and upper sandstone formations in the northeastern and southwestern peripheries of the woreda in particular are characterized by rugged and low-lying topography with relatively steep slopes, low recharge amount, and lower lineament densities, exhibit low groundwater potential while areas underlain by sedimentary rocks of upperr Hamanilie limestone formation and lower basaltic flows have moderate potential. Moreover, low lineament densities and predominance of steep slope topography can be attributed to the observed low groundwater potentials. However, predominance of fractured and weathered volcanic rocks of basaltic flows, high lineament density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential. Summary of the groundwater potential zones identified in the Robe woreda is presented in the table below (Table 5-29).

Table 5-29. Classification of groundwater potential zones and coverage areas alongside the respective yield categories

Woreda Name	**GWP Zones**	**Major Aquifer Units**	**Borehole Yield Classification (l/s)**	
			Q (Range)	**Mean 'Q'**
Robe	Very High	Plateau basalt (Tv3(1))	10 - 32	23.7
	High	Plateau basalt (Tv3(1))	7 - 30	18.5
	Moderate	lower basalt (Tv1)	3.4 – 10	6.7
	Low	Trachytes (Tv5 & Tv7) and lower basalt (Tv1)	1.5 - 8	4.8

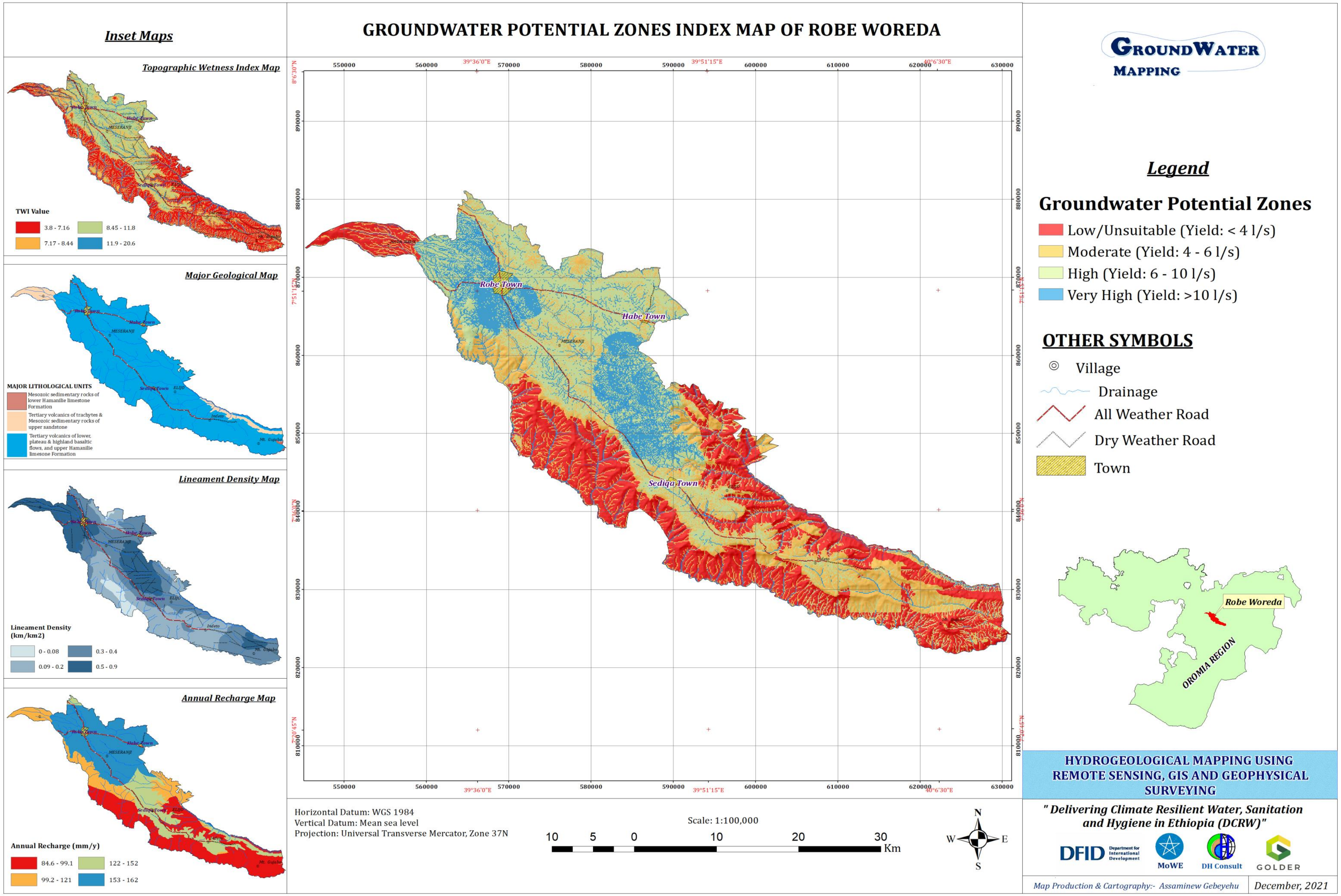

Figure 5-67. Groundwater Potential Zones Map of Robe Woreda

5.6.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) are were collated for over 50 boreholes found around the woreda within the synoptic cluster boundary area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the synoptic area vary from 10 to 32 lit/sec (av. 23.7 lit/sec) in very high potential zones and varying from 7 lit/sec to 30 lit/sec (av. 18.5 lit/sec) in high potential zones as compared with 3.4 lit/sec to 10 lit/sec (av. 6.7 lit/ sec) in the moderate and from 1.5 to 8 lit/sec (av. 4.8 lit/sec) in the low potential zones (Figure 5-68). As shown in the Figure 5-68, the occurrence of number of wells with yield of in the range 7 - 30 lit/sec (high yield) and of > 10 lit/sec (very high yield) cut across mainly the plateau basaltic rocks. However, the less frequency of wells within lower basalt and trachytic rocks in the low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (3.4-10 lit/sec) category is associated also with wells in the fractured lower basaltic rocks. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

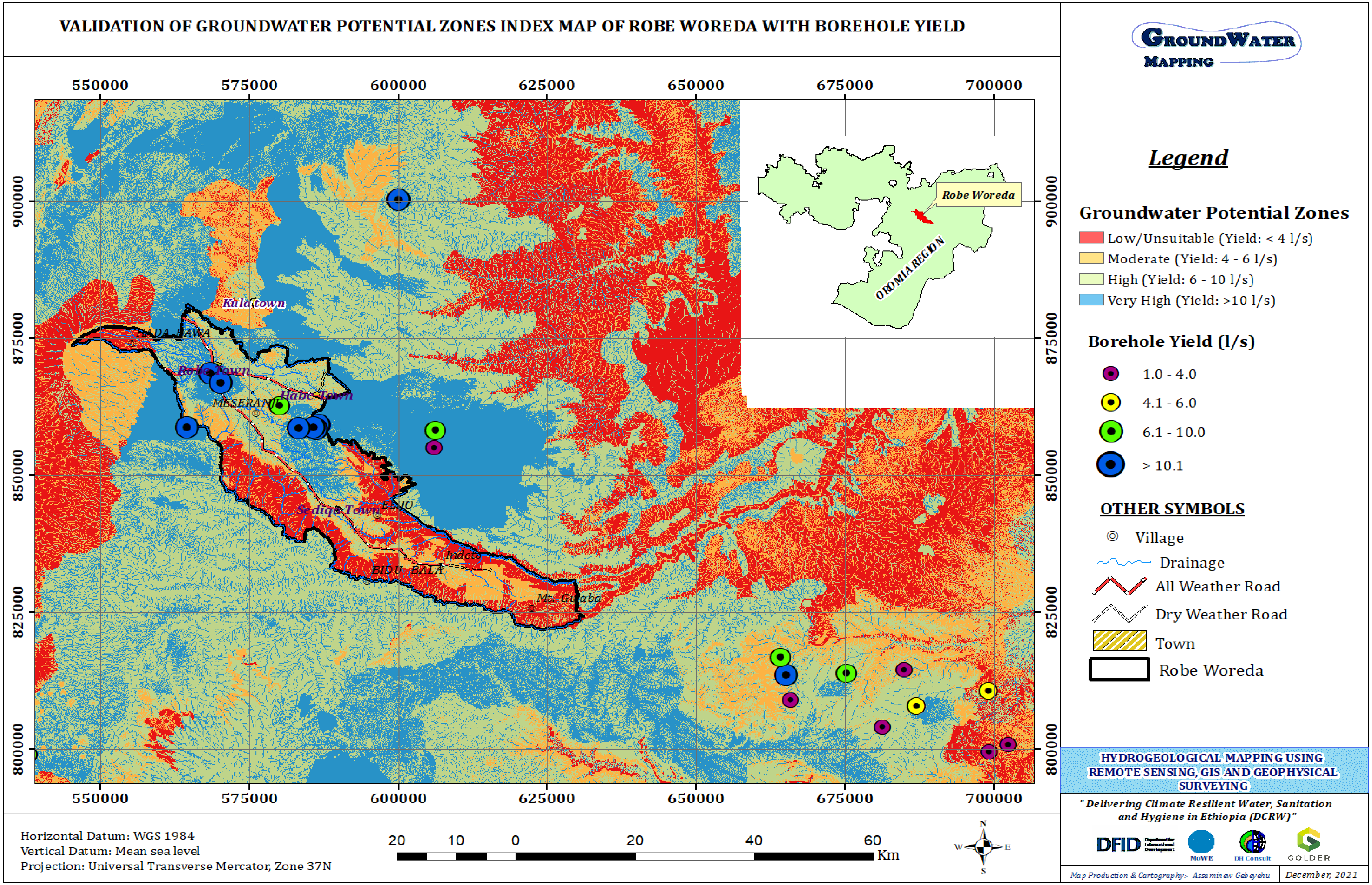

Figure 5-68. Validation of Groundwater Potential Zones Map of Robe Woreda within Arsi-Bale synoptic boundary

5.6.5. Projected Population and Water Demand of Robe

5.6.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-30 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013
Geometric method forecasting formula

$P = Po (1 + r)^n$

Where
P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Robe Woreda has been projected forward until 2036 using the growth rate of Oromia Regional State. The minimum and maximum population in the Woreda is 4,795 and 15,192 respectively. The total population of the Robe Woreda in 2036 is going to be 270,932.

5.6.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic purposes greatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO) & (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer's life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24-hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from 1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-69 shows the distribution of water demand in each Kebeles of the Woreda. Sadiqua Atuche kebele water demand is the minimum with 431 M^3/day and maximum water demand is required for Sebro Chefa Kebele with 1,365 M^3/day respectively. The overall water demand for the projected population in the Robe Woreda is 24,341M^3/day.

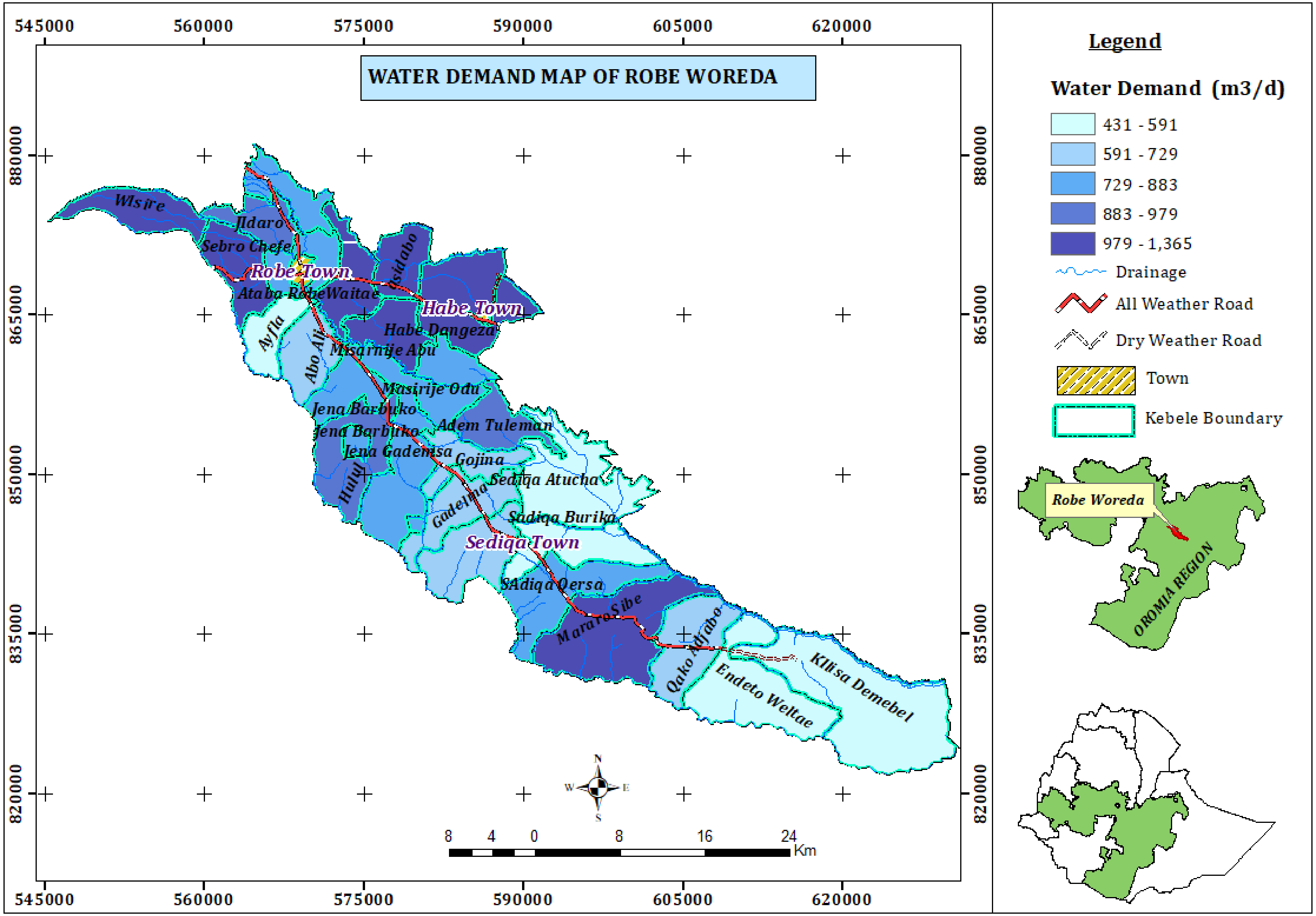

Figure 5-69:-Water Demand Map of Robe Woreda

5.6.6. Propsed Target Sites of Robe

Four target sites are identified and proposed within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficiaries and population density (Figure 5-70). With further discussion and consultation with stakeholders, two priority sites will be selected for further hydrogeological and geophysical investigations in phase III. The following are the four proposed sites:

Target Site-I:

This target site is located in the northwestern regions of the woreda. It is situated in the identified very high potential zones with expected optimum borehole discharge of about 14 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-II:

This target site is located in the central northern part of the woreda. It is situated in the identified very high potential zones with expected optimum borehole discharge of about 24 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-III:

This target site is located in the central southeastern parts of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 12 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-IV:

This target site is located in the northwestern region of the woreda. It is situated in the identified high and very high potential zones with expected optimum borehole discharge of about 7 l/s. This target site is mainly underlain by plateau basaltic rocks.

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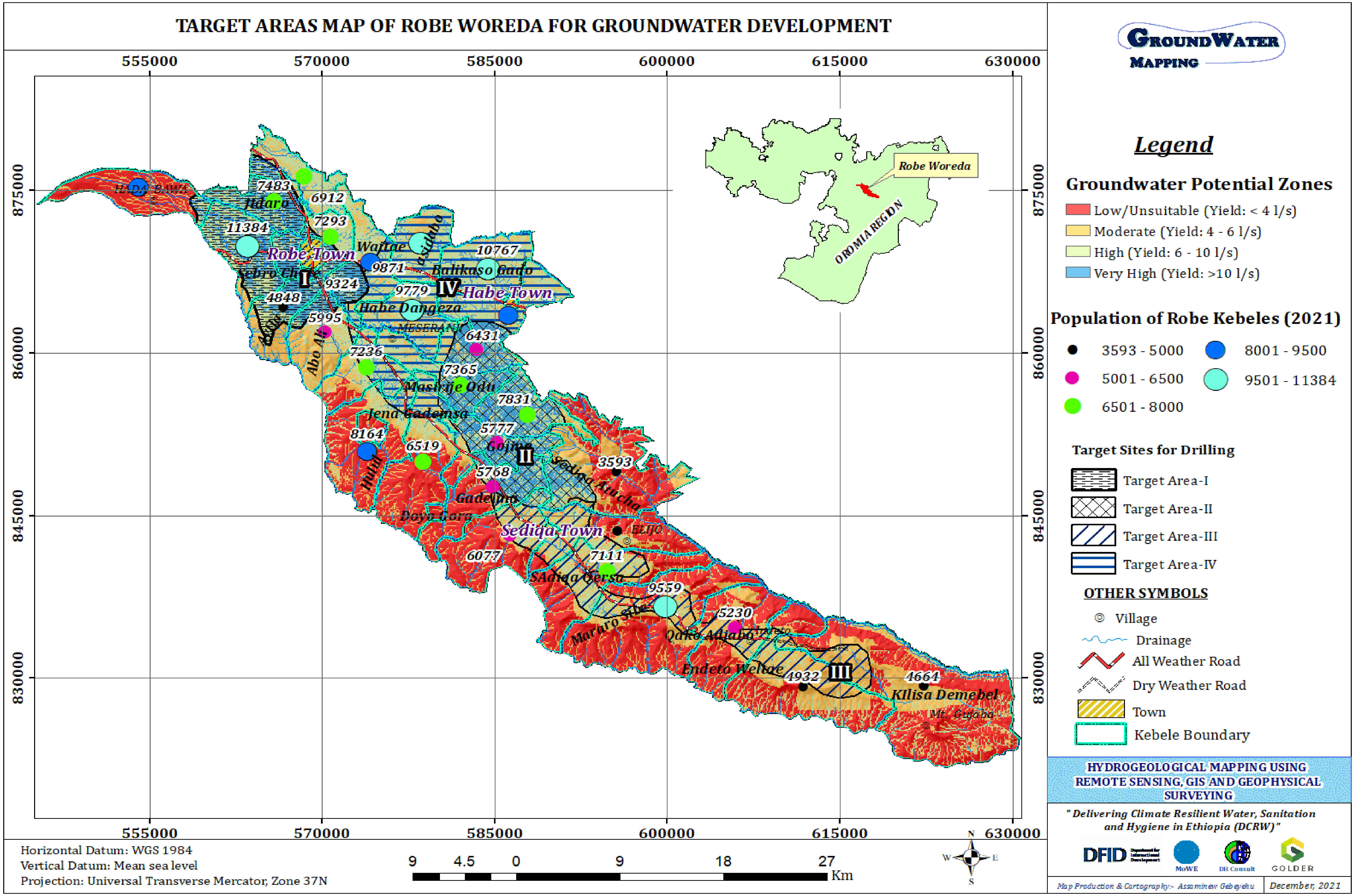

Figure 5-70:-Target Areas Map of Robe Woreda

5.7. Seweyna Woreda

5.7.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.05 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Seweyna woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-31). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-32. The weights assigned to the respective thematic maps as presented in Table 5-33 indicate that TWI was ranked the dominant factor with a normalized weight value of 0.41 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Seweyna woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Seweyna woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

GWPZI = (TWIwTWIwi + GGwGGwi + LDwLDwi + GRwGRwi)

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Seweyna woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e. 'very high', 'high', 'moderate' and 'low or poor', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-31 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Topographic Wetness Index (TWI)	9
Geology (GG)	8
Lineament density (LD)	7
Recharge (GR)	6

Table 5-32 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	TWI	GG	LD	GR	
TWI	1	1	3	5	0.41
GG	1	1	3	2	0.34
LD	1/3	1/3	1	2	0.15
GR	1/5	1/2	1/2	1	0.10

Table 5-33 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank
Topographic Wetness Index, 'TWI'	4.4 - 7.5	poor	1	0.11	0.41
	7.6 - 8.9	Moderate	2	0.15	
	9 - 11.9	Good	3	0.28	
	12 - 19.1	Very good	4	0.46	
Geology/ Lithology, 'GG'	Tertiary volcanics of lower, middle and plateau basaltic flows,	Very good	4	0.54	0.34
	Quaternary alluvial sediments and fans, Mesozoic sedimentary rocks of lower Hamanilielimestone, upper Gebredarre limestone, upper sandstone and Abduya sandstone, and cretaceous basalt	Good	3	0.30	
	Quaternary calcrete	poor	1	0.16	
Lineament Density,' LD' (Km/Km^2)	0 - 0.14	poor	1	0.11	0.15
	0.15 - 0.28	Moderate	2	0.15	
	0.29 - 0.42	Good	3	0.28	
	0.43 - 0.57	Very good	4	0.46	
Recharge, 'GR' (mm/y)	32.3 - 71.27	poor	1	0.11	0.10
	71.28 - 99.03	Moderate	2	0.15	
	99.04 - 123.4	Good	3	0.28	
	123.5 - 156.5	Very good	4	0.46	

5.7.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of Topographic Wetness Index (TWI), geology, lineament density and recharge together with their spatial distribution in Seweyna woreda are presented below:

I. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 4.4 and 19.1 (Figure 5-71). A closer look at the classification revealed that high elevated areas and drainage systems with steep slopes such as areas in southern regions of the woreda in particular have relatively lower TWI value while most of the low elevated and low-lying areas and drainage systems with gentle and flat slopes have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.46) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.11).

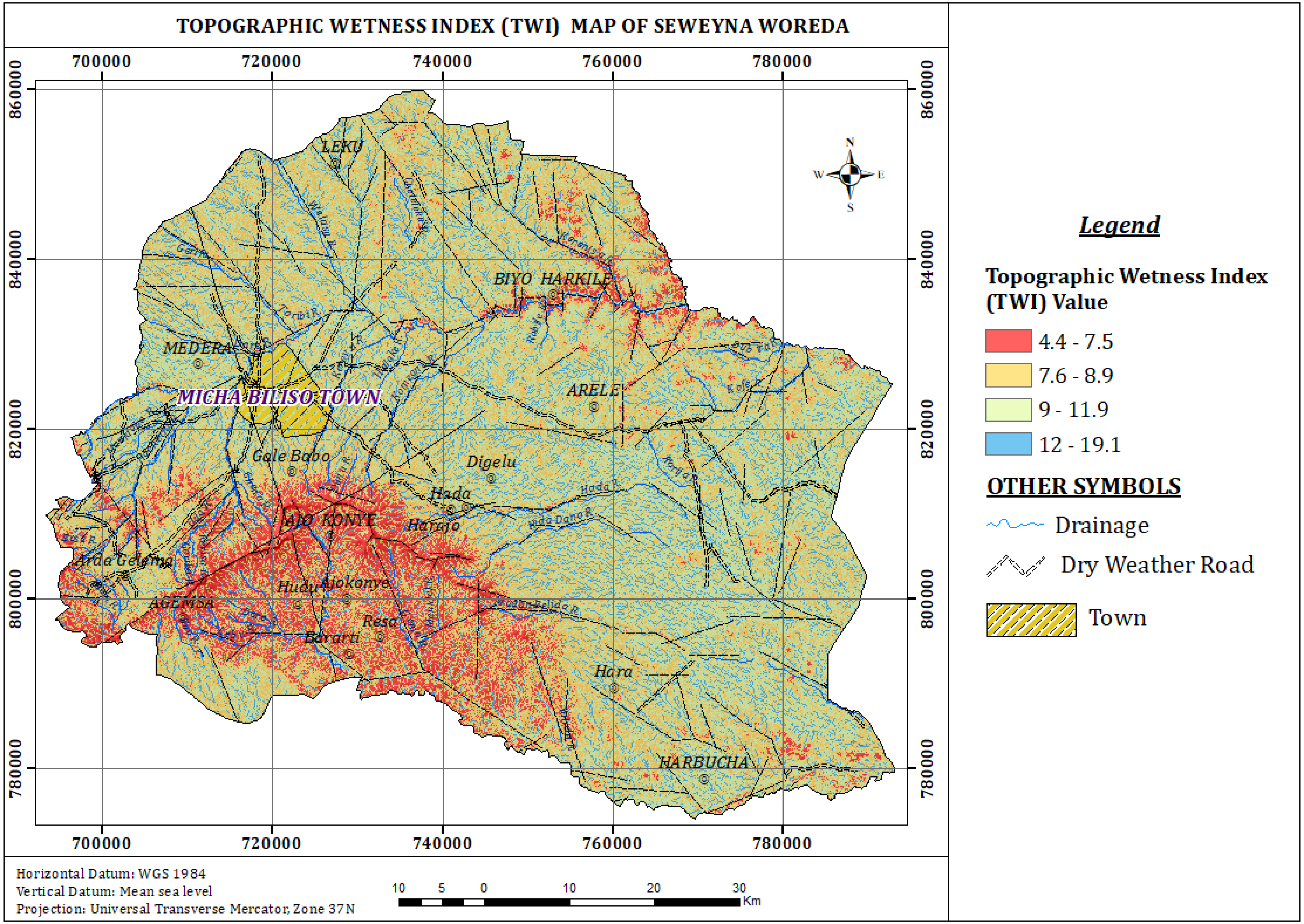

Figure 5-71. TWI Map of Seweyna Woreda

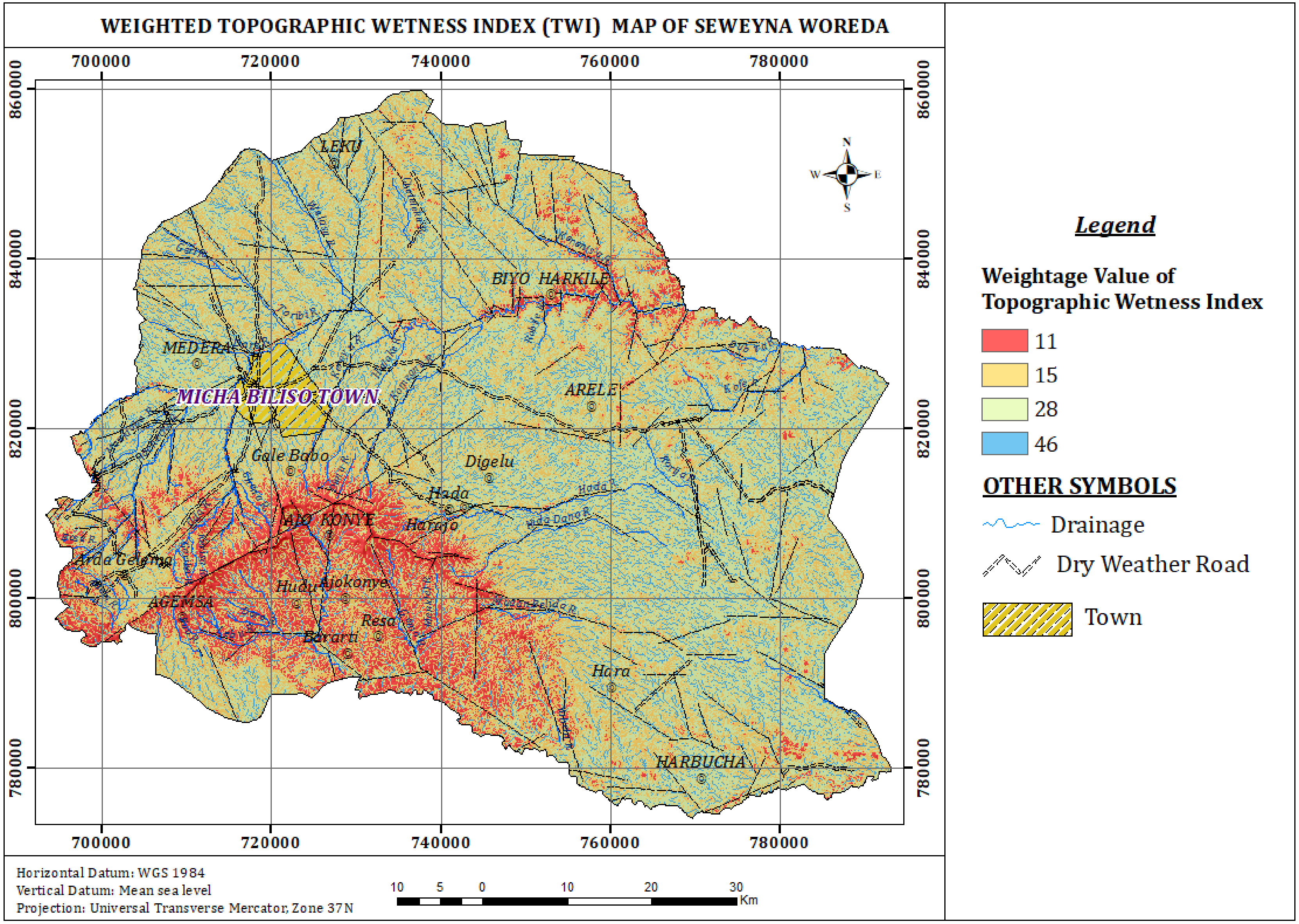

Figure 5-72. Weightage value of TWI Map of Seweyna Woreda

II. Geology/Grouped Hydrolithology

In general, most parts of the Seweyna woreda are underlain by Quaternary alluvial sediments, Mesozoic sedimentary rocks of upper Gabredarre limestone formation, Abduya sandstone and upper sandstones, whereas quaternary calcrete, Tertiary volcanics of lower, middle & plateu basalts, Cretaceous basalt, evaporites and lower Hamanilie limestone formation are also outcropped at limited areas places.

However, the lithological units found in the woreda area are further classified into threer major groups based on their significances to groundwater occurrence and productivity using borehole data on yield and transmissivity analysis in particular.

- Tertiary volcanics of lower, middle and plateau basaltic flows. (Very high productive with Qav. = 6 l/s)
- Quaternary alluvial sediments and fans, Mesozoic sedimentary rocks of lower Hamanilie limestone, upper Gebredarre limestone, upper sandstone and Abduya sandstone, and cretaceous basalt. (High productive with Qav = 4.2 l/s)
- Quaternary Calcrete. (Low productive with Qav = 3.5 l/s)

Mesozoic sedimentary rocks of upper sandstone, Abduya sandstone and upper Gabredare limestone associated with quaternary alluvial deposits are the main lithologic framework of the Seweyna woreda, and lower, middle & plateau basaltic rocks, sedimentary rocks of lower Hamanilie limestone, createaceous basalts, and quaternary calcrete are also outcropped at limited areas of central, southern and southweastern regions of the woreda (Figure 5-73).

Usually, massive unfractured lithologic units in volcanic and sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification, weathering and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of low productivity of Quaternary calcrete (0.16) \ high productivity of upper sandstone, Abduya sandstone, lower Hamanilie limestone and upper Gabredarre limestone associated with alluvial sediment deposits (0.30)\ very high productivity of Tertiary volcanics of lower, middle and plateau basaltic flows, (0.54) as shown in Figure 5-74.

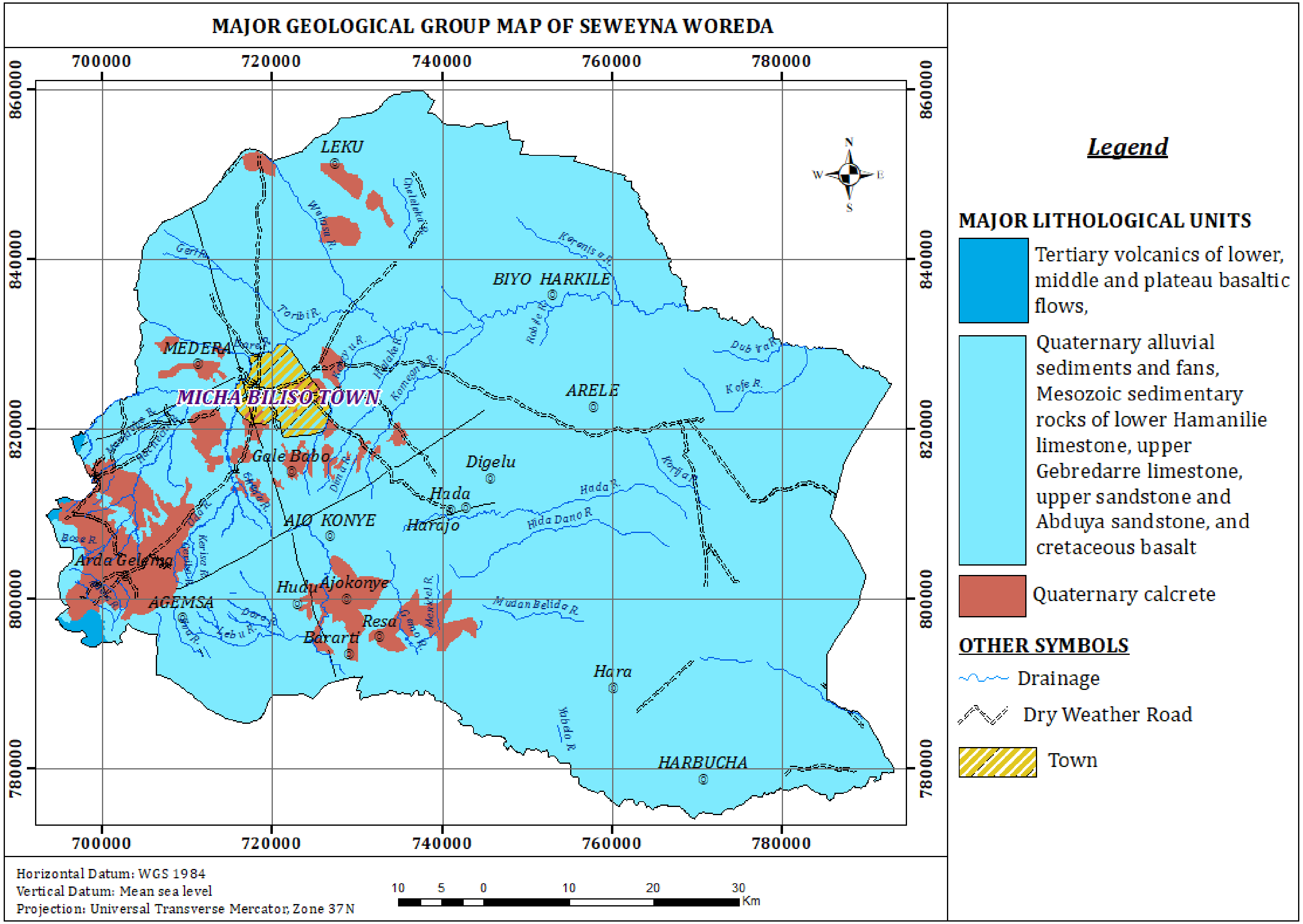

Figure 5-73. Grouped Lithological classification map of Seweyna Woreda

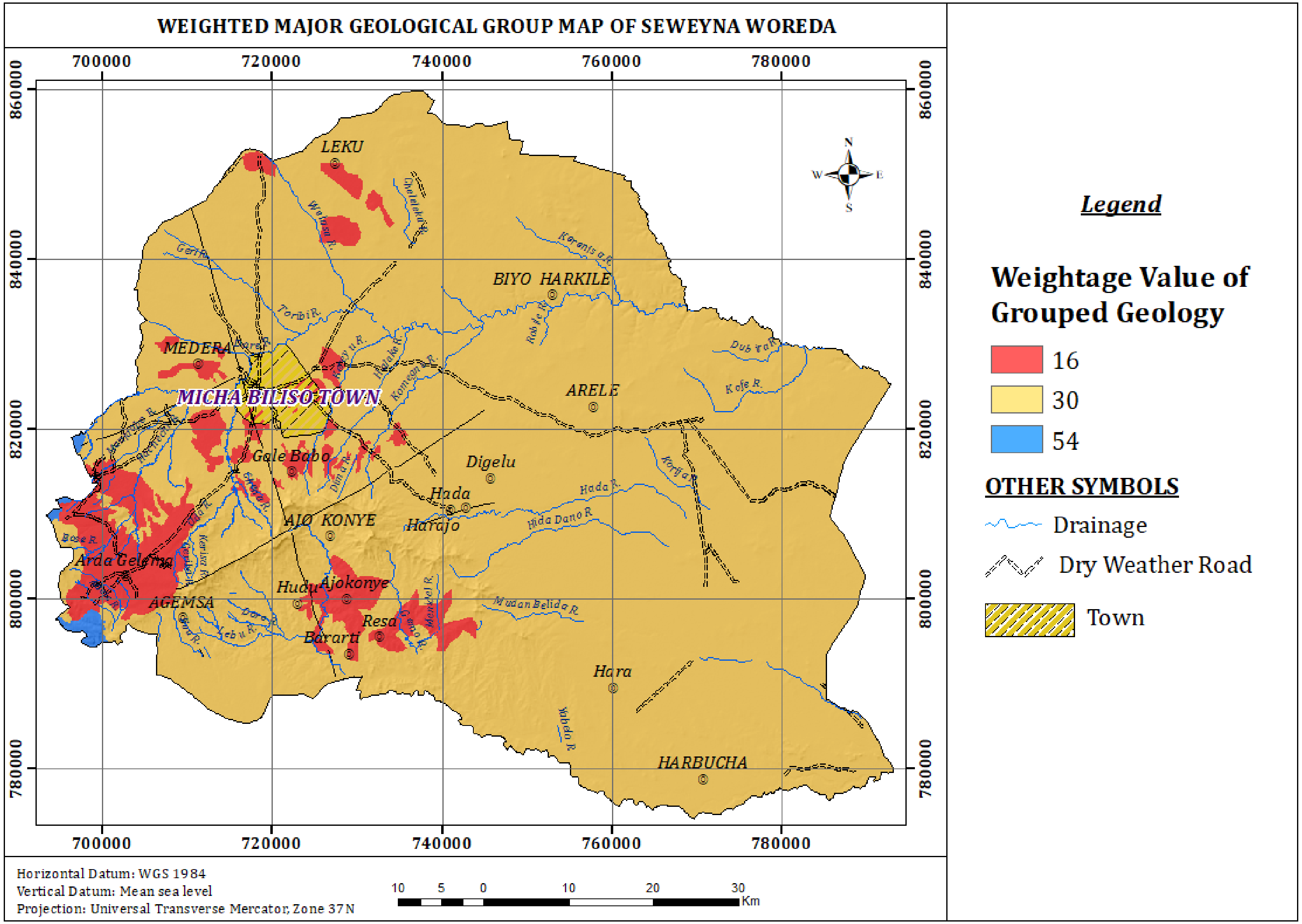

Figure 5-74. Weighted lithological classes' map of the Seweyna Woreda

I. Lineaments and Lineament Density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SE and NE–SW trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from 0.29 km/km^2 to 0.57 km/km^2 (Figure 5-75). Though the lineaments are highly widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by upper sandstone, Abduya sandstone and lower Hamanilie limestone that they have relatively higher lineament density of 0.29 km/km^2 to 0.57 km/km^2) compared with areas underlain by upper Gabredare limestone and alluvial sediments with lower lineament densities of (< 0.15 km/km^2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.46 was assigned to area with high density of lineaments, while a low weightage of 0.17 was assigned to areas with low lineament density (Figure 7-76).

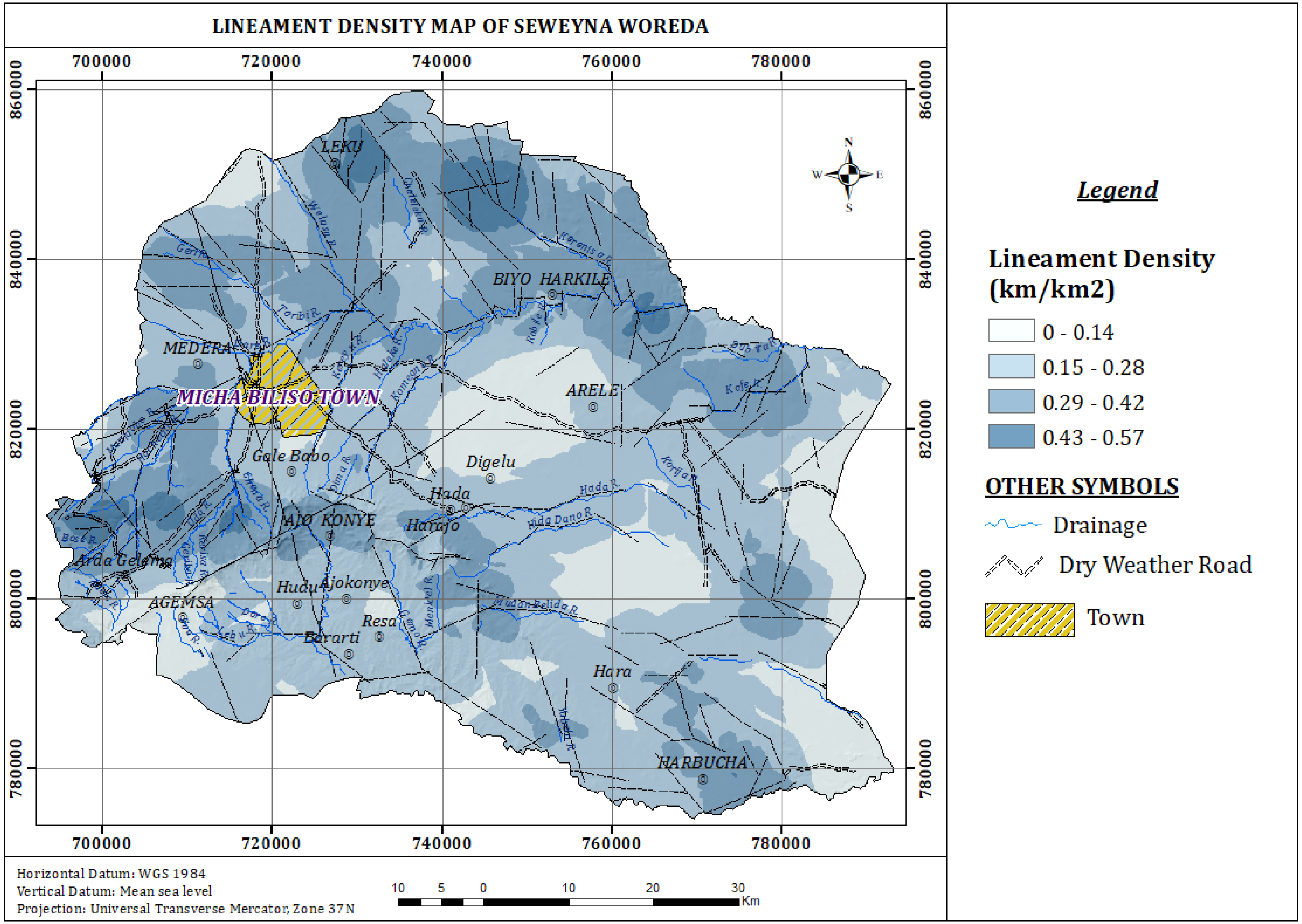

Figure 5-75. Lineament Density Map of Seweyna Woreda

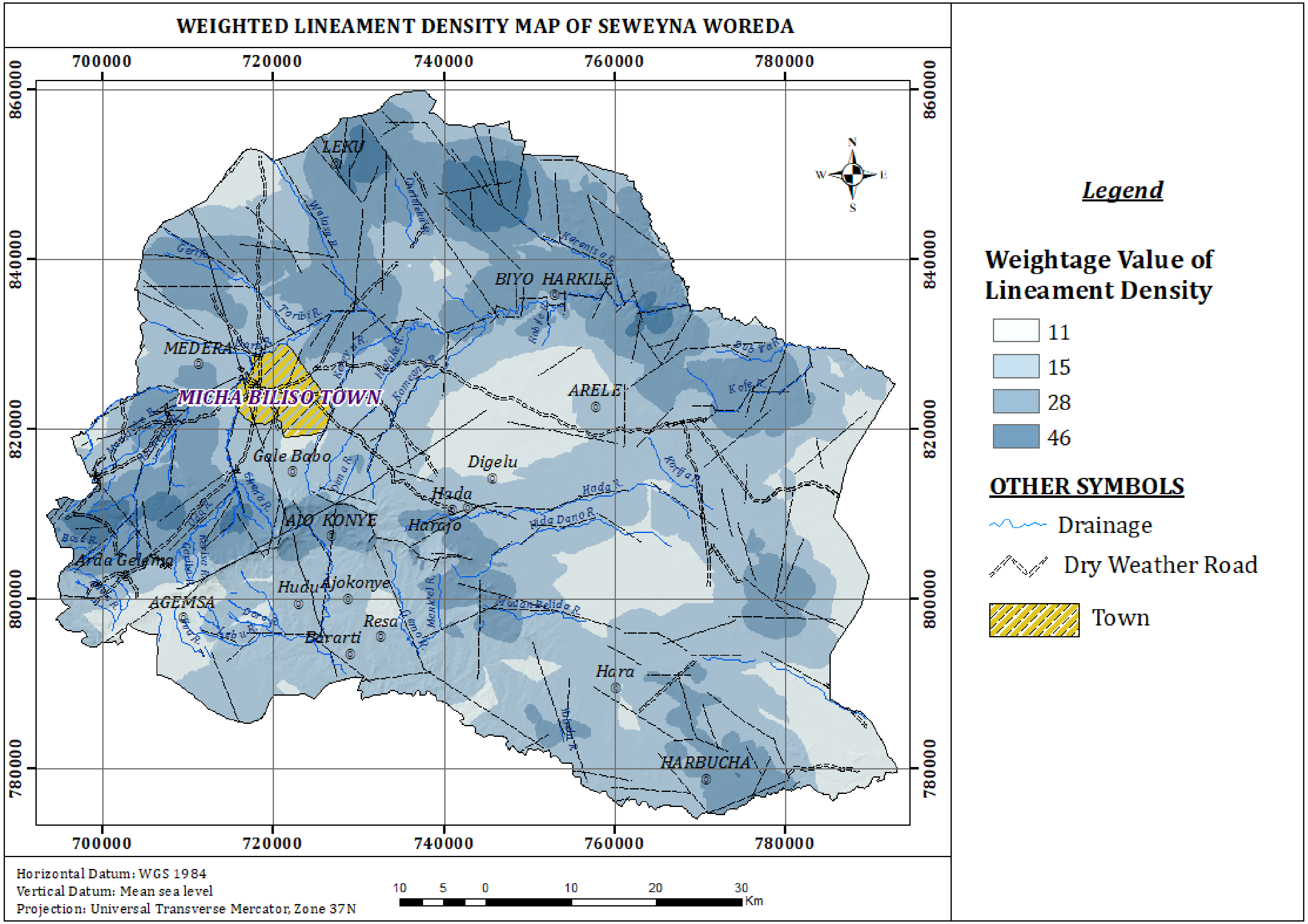

Figure 5-76. Weightage value of Lineament Density Map of Seweyna Woreda

II. Recharge

The spatial annual recharge rate distribution in the Seweyna woreda ranges from 32.3 to 156.5 mm/y suggesting groundwaters in limited centra and western elevated regions of the woreda area underlain by upper sandstone receive high amount of recharge while the central eastern low-lying regions underlain by upper Gabredarre limestone have relatively lower recharge amount due to very low infiltration rate of the lithological formation (Figure 5-77). Accordingly, areas with very high and high amount of recharge have weightage factor of 0.46 and 0.28, respectively signifying very good and good groundwater potential, respectively while areas with the moderate and lowest amount of recharge have weightage factor of 0.15 and 0.11, respectively, suggesting moderate and poor groundwater potentiality, respectively. Generally, the study area is characterized with high to very high mean annual recharge amount (> 99 mm/yr), whereas most of the central eastern areas of the woreda have moderate to low mean annual recharge amount (32 - 99 mm/yr).

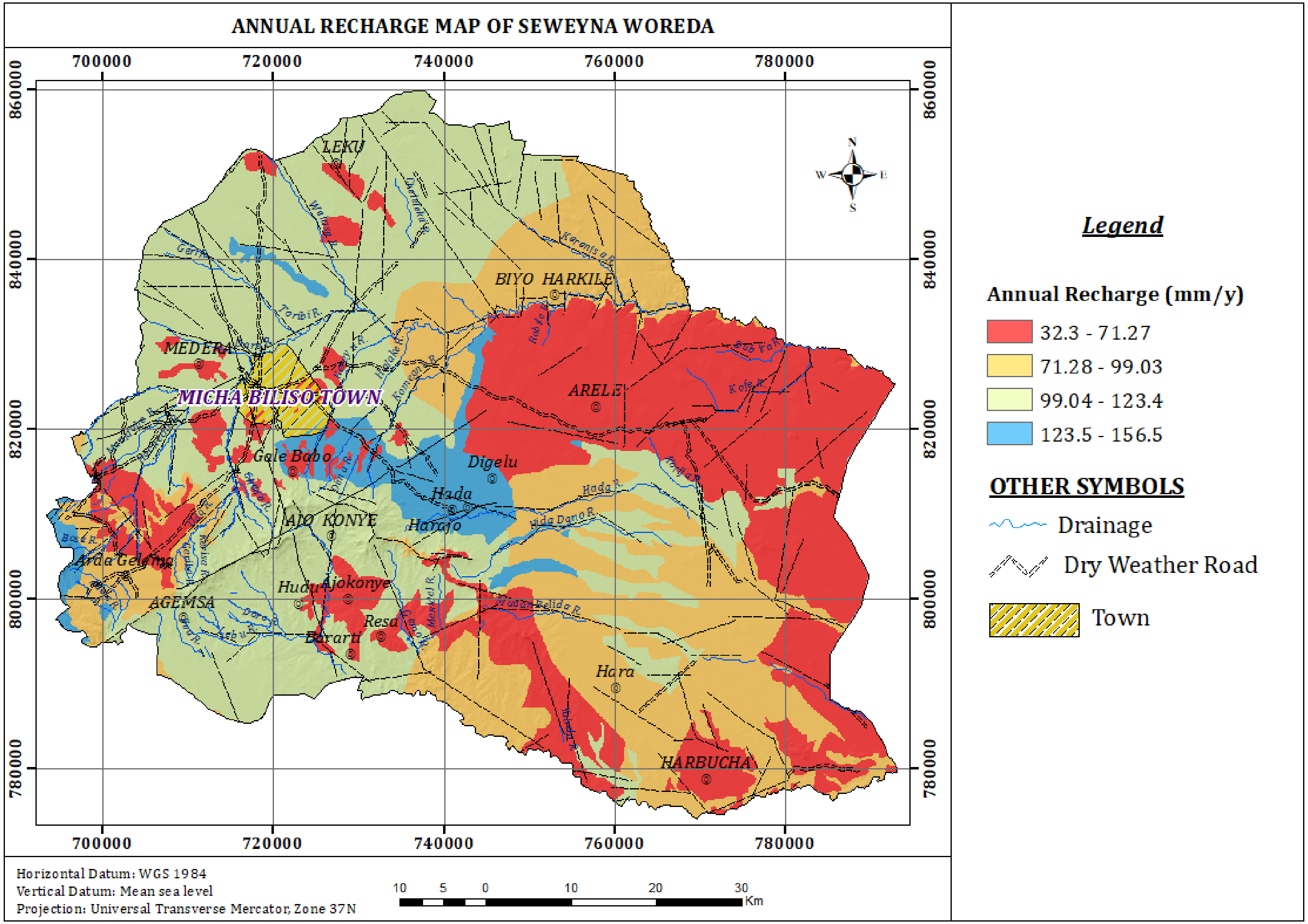

Figure 5-77. Annual Recharge Map of Seweyna Woreda

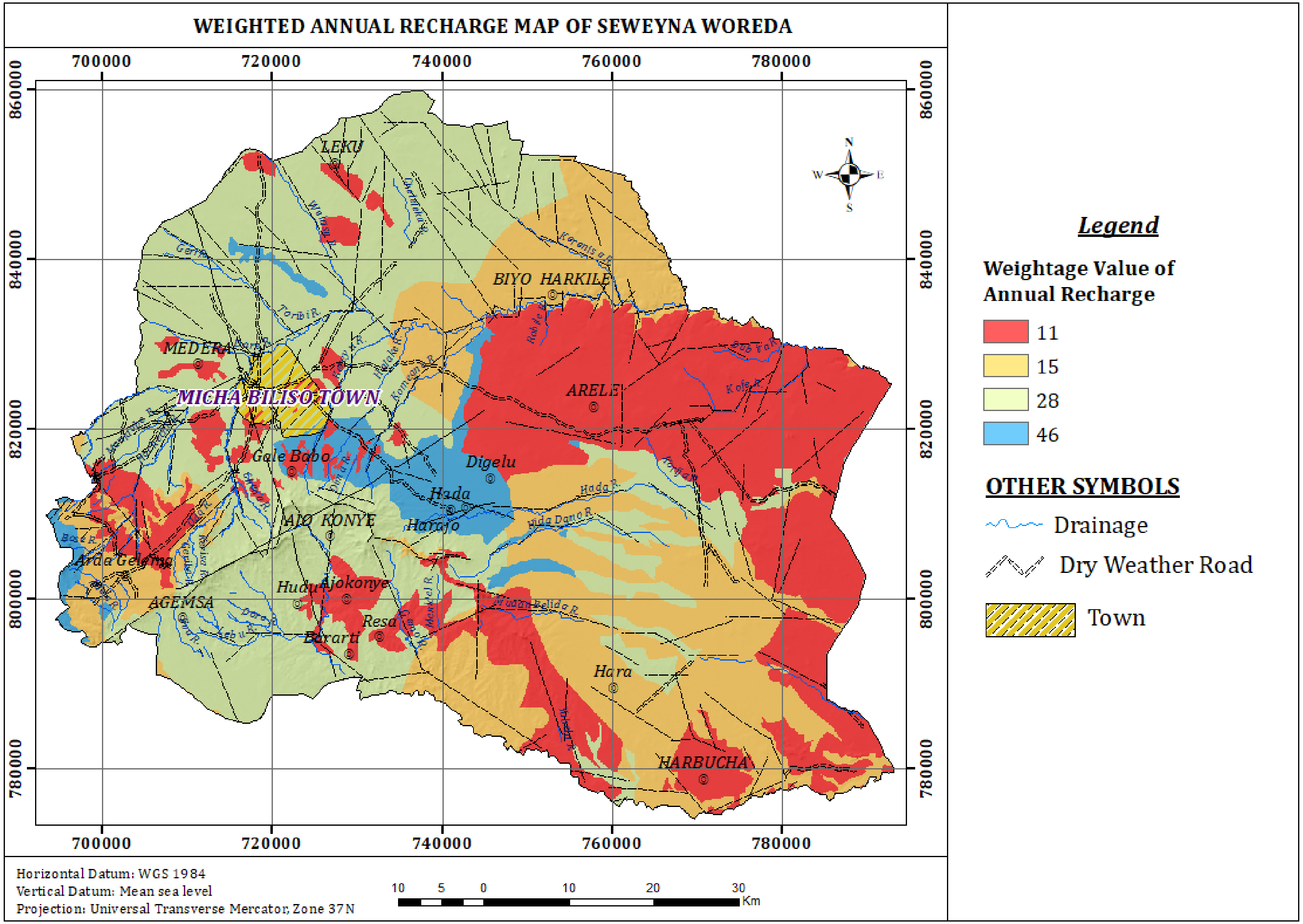

Figure 5-78. Weighted Annual Recharge classes' map of the Seweyna Woreda

5.7.3. Classification of Groundwater Potential Zones

The hydrogeological system of Seweyna woreda is comprised of three main lithological units as Mesozoic formation of upper sandstones, Abduya sandstone and upper Gabredarre limestone rocks. At both regional scale and local scale within the domain of Seweyna woreda, upper sandstone form extensive and high to very high productive aquifers. This sandstone rock forms aquifers with high to very high groundwater potential as revealed from existing borehole information. Apart from this, Abduya sandstone at northern and lower Hamanilie limestone formation at limited southestern region forms also a very high to very high groundwater potential.

Only the upper weathered and slightly fractured part of the volcanic and sedimentary rocks along lineamnets and faults have potential to store groundwater at shallow depth. Weathered and fractured sedimentary rocks of upper sandstone form major potential aquifer within the domain of Seweyna Woreda along lineament and fault lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-79). The potential groundwater zones (PGZ) of the Seweyna woreda revealed four distinct zones, namely low, moderate, high and very high zones, respectively as presented in Table 5-34.

The potential map, as presented in Figure 5-79, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that central southeastern and central southern region of the woreda generally have low potentials, while most elevated areas at western and northern regions, and low-lying eastern area generally exhibits high to very high potentials, respectively. The generally high to very high groundwater potentiality of the study area is a confirmation of generally high productive upper sandstone, whereas low groundwater potential areas have an indication of limited aquifers capabilities of lower Hamanilie limestone, upper Gabredarre limestone and quaternary calcrete.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the topographic wetness index and geology in addition to the lineament density and recharge control. In addition, areas underlain by upper sandstone especially in the central and western sections of the study area are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments, and apparently deep fracturing system have high and very high groundwater potential on the one hand. On the other hand, areas underlain by upper sandstone associated with lower limestone rocks and calcretes in the central southern regions of the woreda in particular are characterized by rugged and low-lying topography with relatively steep slopes, low recharge amount, and lower lineament densities, exhibit low groundwater potential. Moreover, low lineament densities and predominance of steep slope topography can be attributed to the observed low groundwater potentials. However, predominance of fractured and weathered upper sandstone, high lineament density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential. Summary of the groundwater potential zones identified in the Seweyna woreda is presented in the table below (Table 5-34).

Table 5-34. Classification of groundwater potential zones and coverage areas alongside the respective yield categories

Woreda Name	GWP Zones	Major Aquifer Units	Borehole Yield Classification (l/s)	
			Q (Range)	Mean 'Q'
Seweyna	Very High	Upper sandstone (Ka) & Abduya sandstone (Masst)	4 – 6.7	4.3
	High	upper sandstone (Ka) & upper Gabredarre limestone (Jg2)	2.5 - 5	4.2
	Moderate	Alluvial sediments (Qal1,2 &3) & upper Gabredarre limestone (Jg2)	3 – 3.9	3.3
	Low	upper sandstone (Ka) , upper Gabredarre Quaternary calcrete (Qcal)	2 – 3.8	2.8

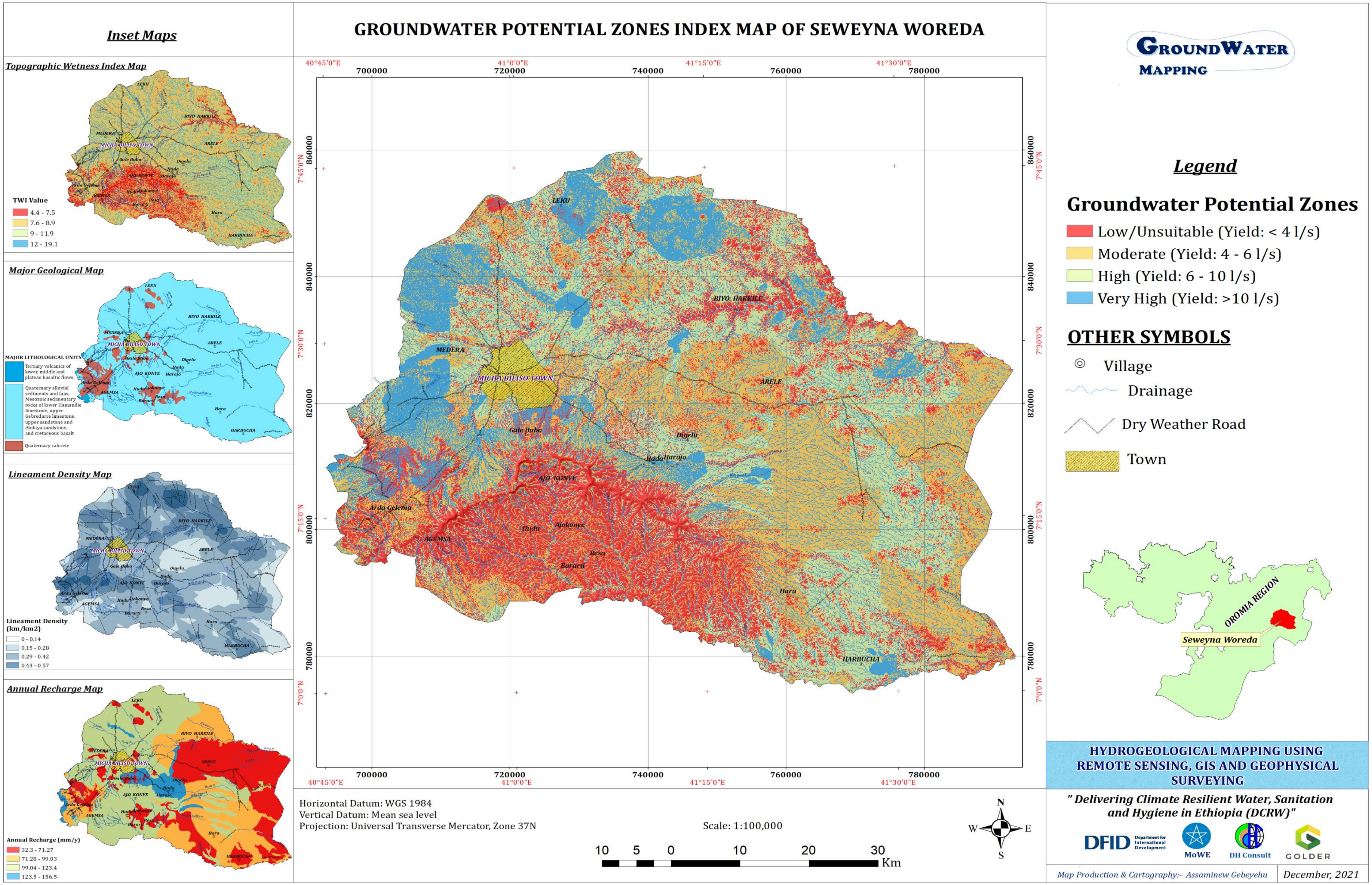

Figure 5-79:-Groundwater Potential Zones Map of Seweyna Woreda

5.7.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) are were collated for over 50 boreholes found around the woreda within the synoptic cluster boundary area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the synoptic area vary from 4 – 6.7 lit/sec (av. 4.3 lit/sec) in very high potential zones and varying from 2.5 lit/sec to 5 lit/sec (av. 4.2 lit/sec) in high potential zones as compared with 3 lit/sec to 3.9 lit/sec (av. 3.3 lit/ sec) in the moderate and from 2 to 3.8 lit/sec (av. 2.8 lit/sec) in the low potential zones (Figure 5-80). As shown in the Figure 5-80, the occurrence of number of wells with yield of in the range 2.5 - 5 lit/sec (high yield) and of > 4 lit/sec (very high yield) cut across mainly the upper sandstone, Abduya sandstone and upper Gabredarre limestone formations. However, the less frequency of wells within upper Gabredarre limestone formation and upper sandstone associated with calcrete in the low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (3 - 3.9 lit/sec) category is associated also with wells in the sedimentary rocks of upper Gabredarre limestone associated with recent alluvial deposits. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

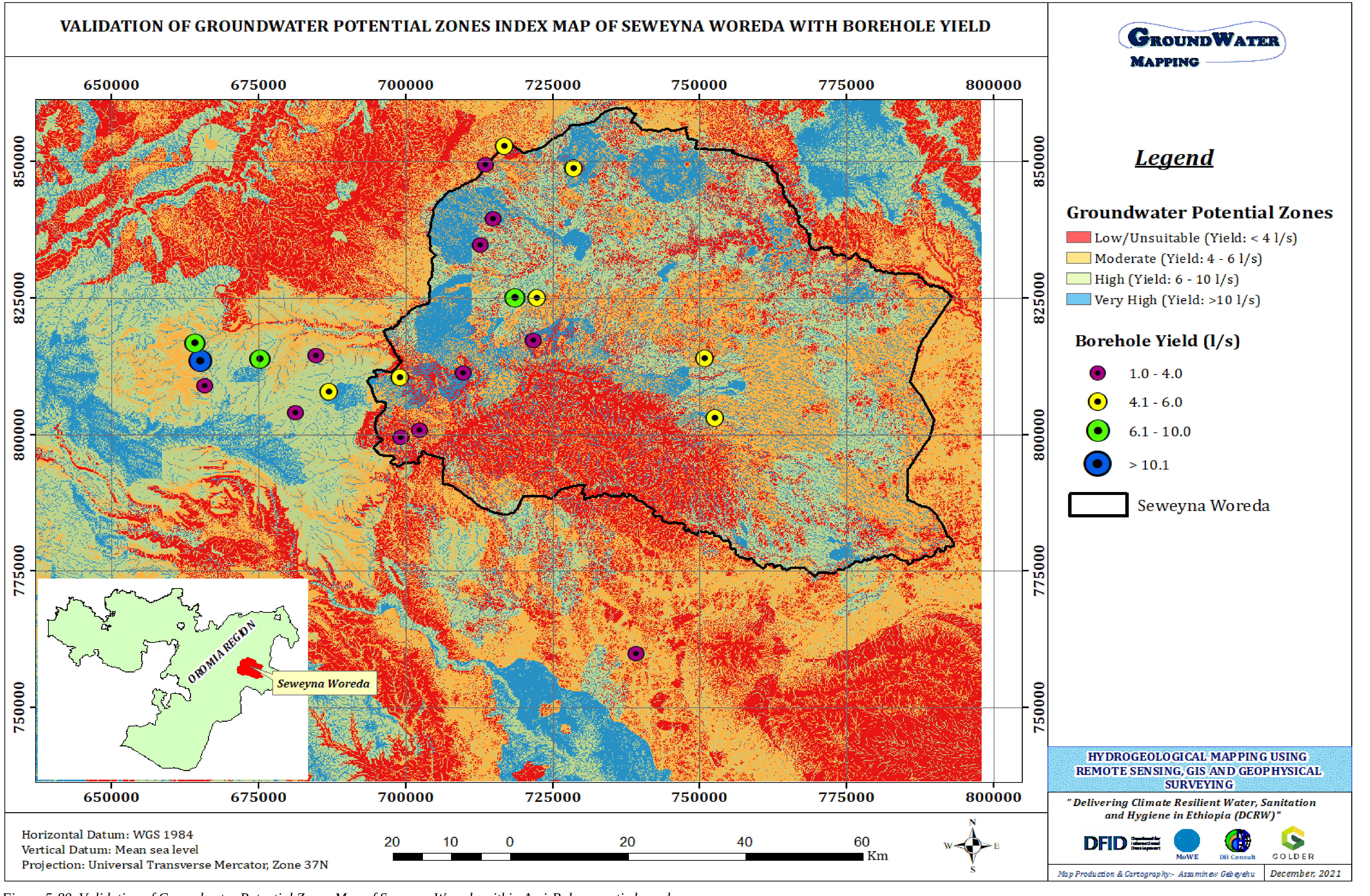

Figure 5-80. Validation of Groundwater Potential Zones Map of Seweyna Woreda within Arsi-Bale synoptic boundary

5.7.5. Projected Population and Water Demand

5.7.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-35 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P = Po\,(1 + r)^{n}$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Seweyna Woreda has been projected forward until 2036 using the growth rate of Oromia Regional State. The minimum and maximum population in the Woreda is 2,199 and 7,093 respectively. The total population of the Seweyna Woreda in 2036 is going to be 116,357.

5.7.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic

purposes greatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO) & (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer's life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24 hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from 1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-81 shows the distribution of water demand in each Kebeles of the Woreda. Boditi kebele water demand is the minimum with 198 M^3/day and maximum water demand is required for Sheku Kebele with 6,073 M^3/day respectively. The overall water demand for the projected population in the Seweyna Woreda is 15,890 M^3/day.

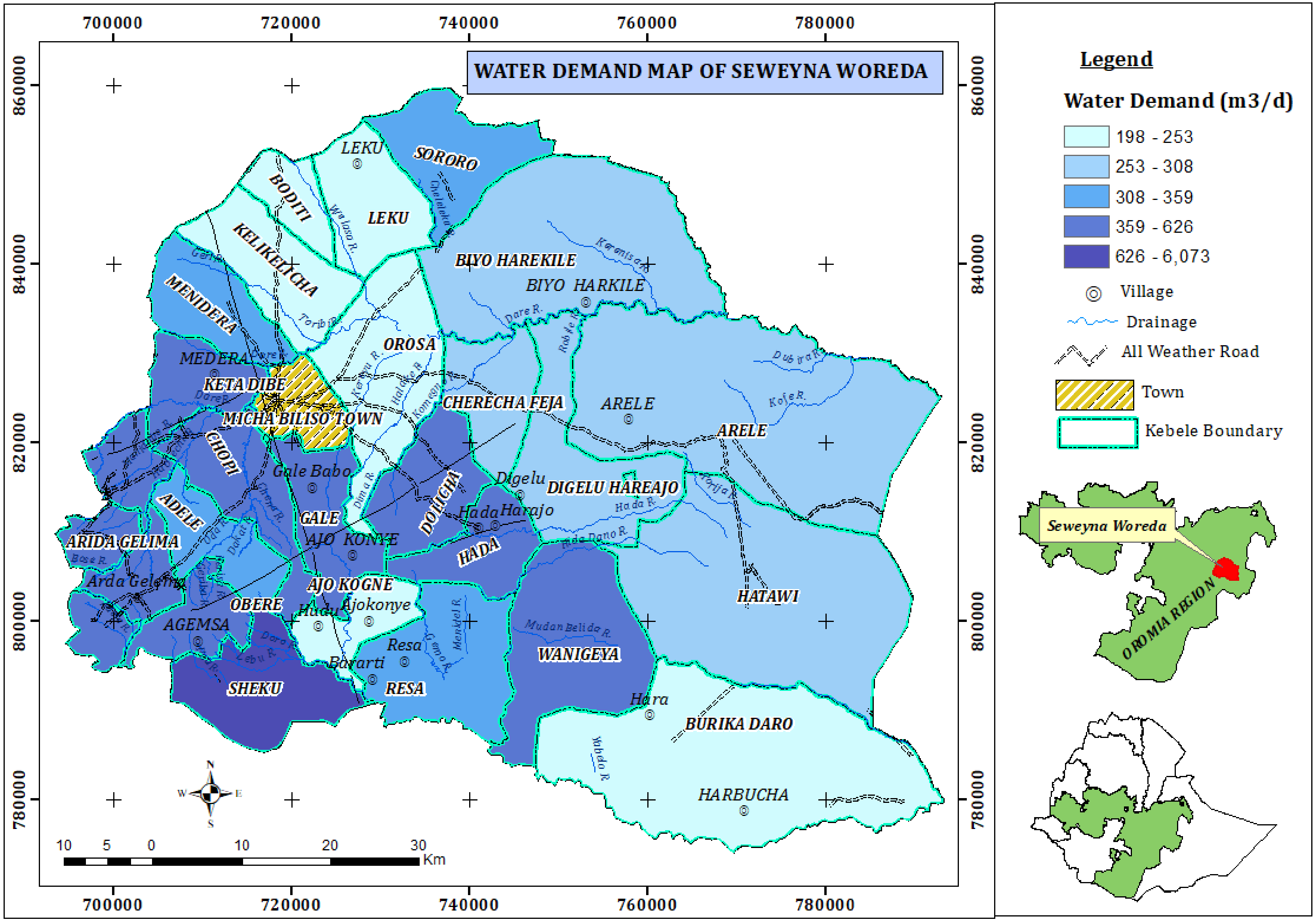

Figure 5-81:-Water Demand Map of Seweyna Woreda

5.7.6. Propsed Target Sites

Four target sites are identified and proposed within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficiaries and population density. With further discussion and consultation with stakeholders, two priority sites will be selected for further hydrogeological and geophysical investigations in phase III. The following are the four proposed sites:

Target Site-I:

This target site is located in the western regions of the woreda. It is situated in the identified very high potential zones with expected optimum borehole discharge of about 4 l/s. This target site is mainly underlain by upper sandstone rocks.

Target Site-II:

This target site is located in the northern part of the woreda. It is situated in the identified high and very high potential zones with expected optimum borehole discharge of about 4 l/s. This target site is mainly underlain by Abduya sandstone rocks.

Target Site-III:

This target site is located in the central eastern parts of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 3.8 l/s. This target site is mainly underlain by upper Gabredarre limestone rocks.

Target Site-IV:

This target site is located in the southeastern region of the woreda. It is situated in the identified high and very high potential zones with expected optimum borehole discharge of about 5 l/s. This target site is mainly underlain by upper sandstone rocks overlain by alluvial deposits.

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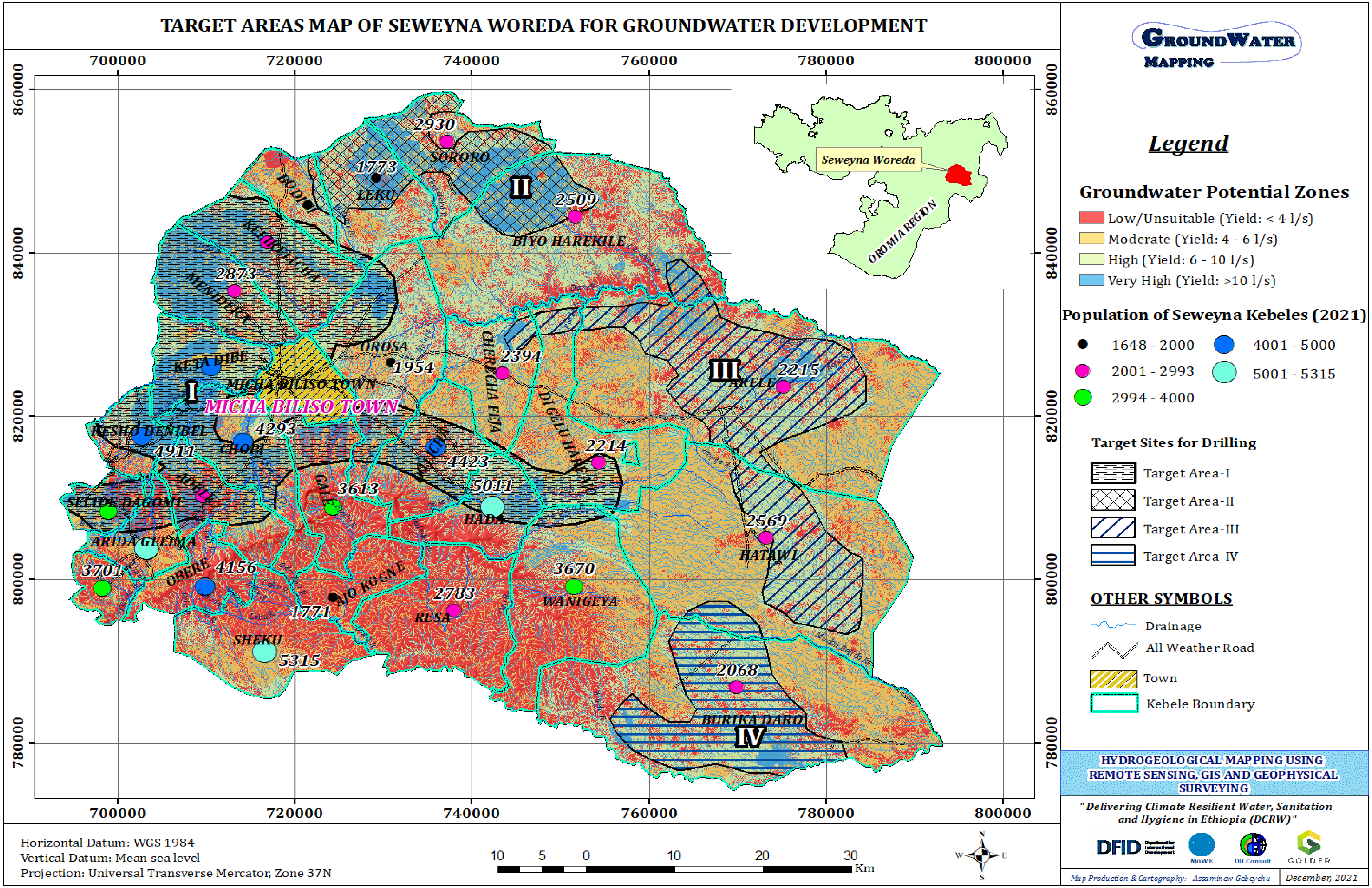

Figure 5-82:-Target Areas Map of Seweyna Woreda

5.8. Sude Woreda

5.8.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.05 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Sude woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-36). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-37. The weights assigned to the respective thematic maps as presented in Table 5-38 indicate that TWI was ranked the dominant factor with a normalized weight value of 0.41 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Sude woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Sude woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

GWPZI = (TWIwTWIwi + GGwGGwi + LDwLDwi + GRwGRwi)

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Sude woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e. 'very high', 'high', 'moderate' and 'low or poor', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-36 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Topographic Wetness Index (TWI)	9
Geology (GG)	8
Lineament density (LD)	7
Recharge (GR)	6

Table 5-37 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	TWI	GG	LD	GR	
TWI	1	1	3	5	0.41
GG	1	1	3	2	0.34
LD	1/3	1/3	1	2	0.15
GR	1/5	1/2	1/2	1	0.10

Table 5-38 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank
Topographic Wetness Index, 'TWI'	3.8 – 7.16	poor	1	0.11	0.41
	7.17 – 8.44	Moderate	2	0.15	
	8.45 - 11.8	Good	3	0.28	
	11.9 – 20.6	Very good	4	0.46	
Geology/ Lithology, 'GG'	Tertiary volcanics of lower, plateau & highland basaltic flows, and upper Hamanilie limesones.	Very good	4	0.54	0.34
	Tertiary volcanics of middle basaltic flows.	Good	3	0.30	
	Tertiary volcanics of upper pyroclasts & Mesozoic sedimentary rocks of upper sandstone	Moderate	2	0.16	
Lineament Density,' LD' (Km/Km^2)	0 - 0.08	poor	1	0.11	0.15
	0.09 - 0.2	Moderate	2	0.15	
	0.3 - 0.4	Good	3	0.28	
	0.5 - 0.9	Very good	4	0.46	
Recharge, 'GR' (mm/y)	48.1 - 50.8	poor	1	0.11	0.10
	50.9 - 107	Moderate	2	0.15	
	108 - 150	Good	3	0.28	
	151 - 160	Very good	4	0.46	

5.8.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of Topographic Wetness Index (TWI), geology, lineament density and recharge together with their spatial distribution in Sude woreda are presented below:

I. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 3.8 and 20.6. A closer look at the classification revealed that most the high elevated areas and drainage systems with steep slopes have relatively lower TWI value while the low lying areas and drainage systems with gentle and flat slopes such as areas extending from central to western regions of the woreda in particular have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.46) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.11).

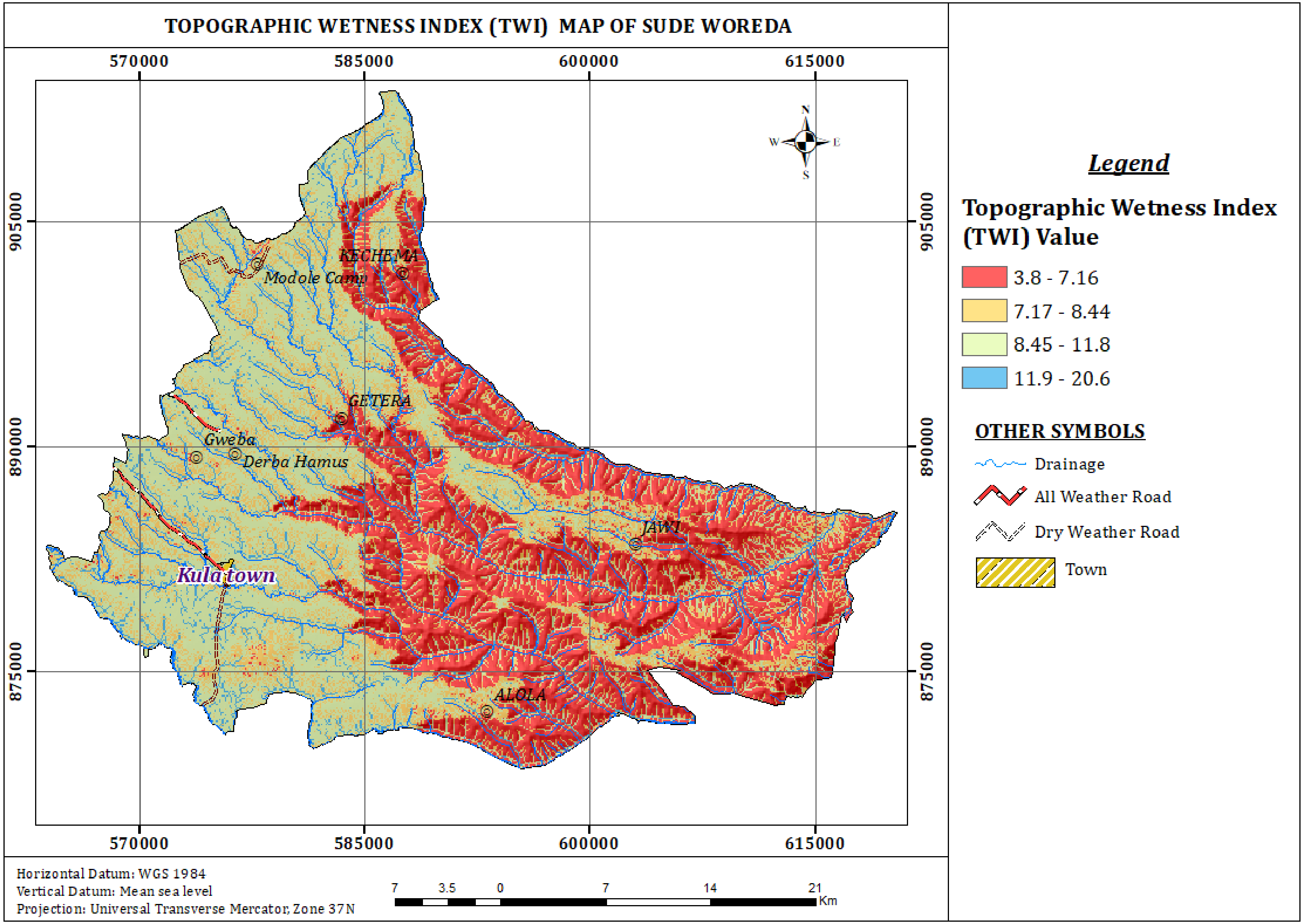

Figure 5-83. TWI Map of Sude Woreda

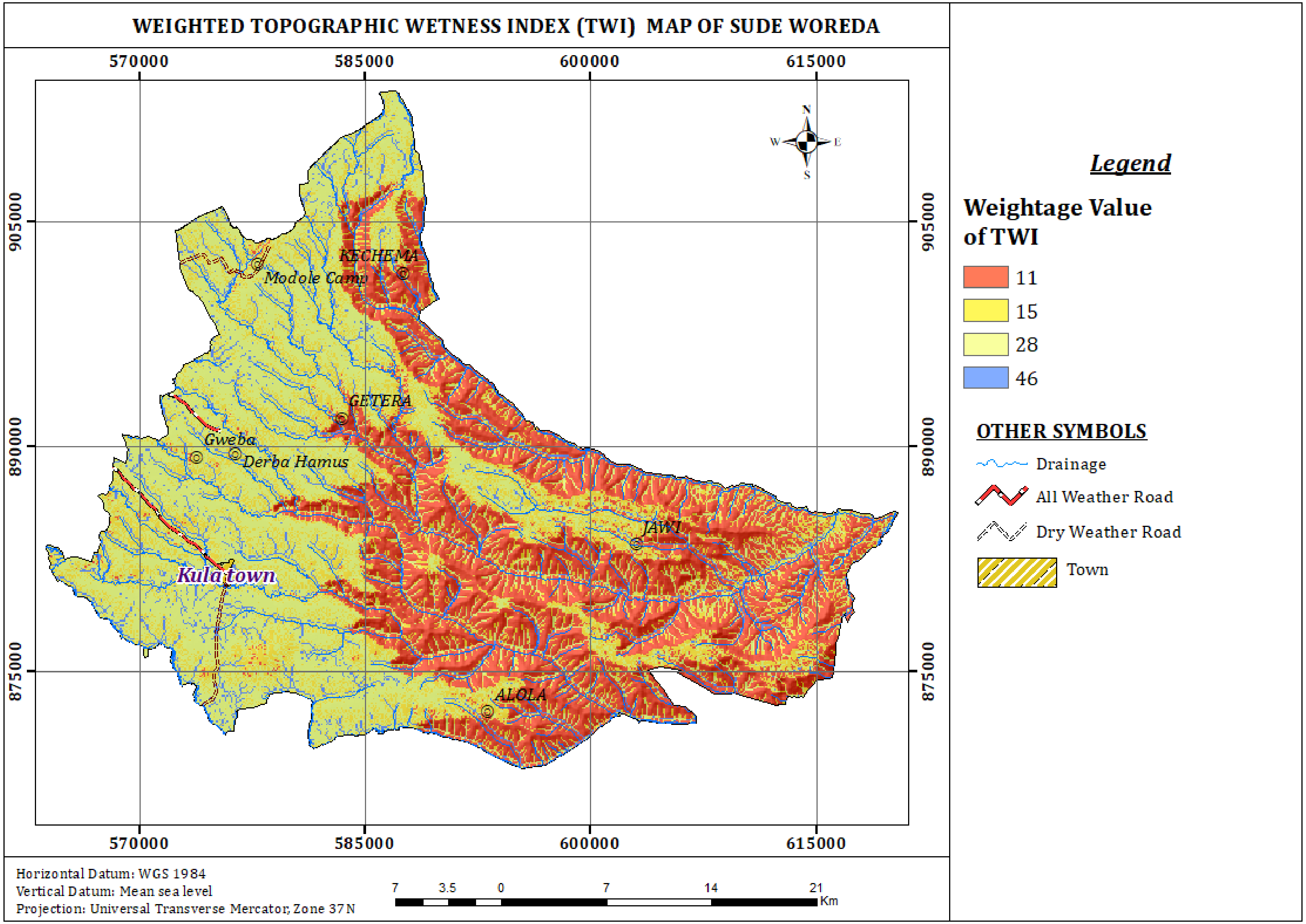

Figure 5-84. Weightage value of TWI Map of Sude Woreda

II. Geology/Grouped Hydrolithology

In general, most parts of the Sude woreda are underlain by Tertiary volcanic rocks of lower basalts, middle basalts, plateau basalts and upper pyroclsts. Whereas, Mesozoic sedimentary rocks of upper Hamanile limestone formation and upper sandstones are mainly outcropped at central and eastern parts of the woreda.

However, the lithological units found in the woreda area are further classified into three major groups based on their significances to groundwater occurrence and productivity using borehole data on yield and transmissivity analysis in particular.

- Tertiary volcanics of lower, plateau & highland basaltic flows, and upper Hamanilie limesones. (Very high productive with Qav. = 15 l/s)
- Tertiary volcanics of middle basaltic flows. (High productive with Qav = 7.2 l/s)
- Tertiary volcanics of upper pyroclasts & Mesozoic sedimentary rocks of upper sandstone (Moderately productive with Qav = 5.5 l/s)

Tertiary volcanics of lower basalts, middle basalt, plateau basalt, highland basalts, and upper pyroclastic falls and deposits are the main lithologic framework of the Sude woreda, and sedimentary rocks of upper Hamanilie limestone formation and upper sandstone are also outcropped at limited areas of the woreda (Figure 5-85).

Usually, massive unfractured lithologic units in volcanic and sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification, weathering and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of moderate productivity of upper pyroclasts and upper sandstone (0.16) \ high productivity of middle basaltic flows (0.30) \ very high productivity of Tertiary volcanics of lower, plateau and uppermost basaltic flows, and upper Hamanile limestone formation (0.54).

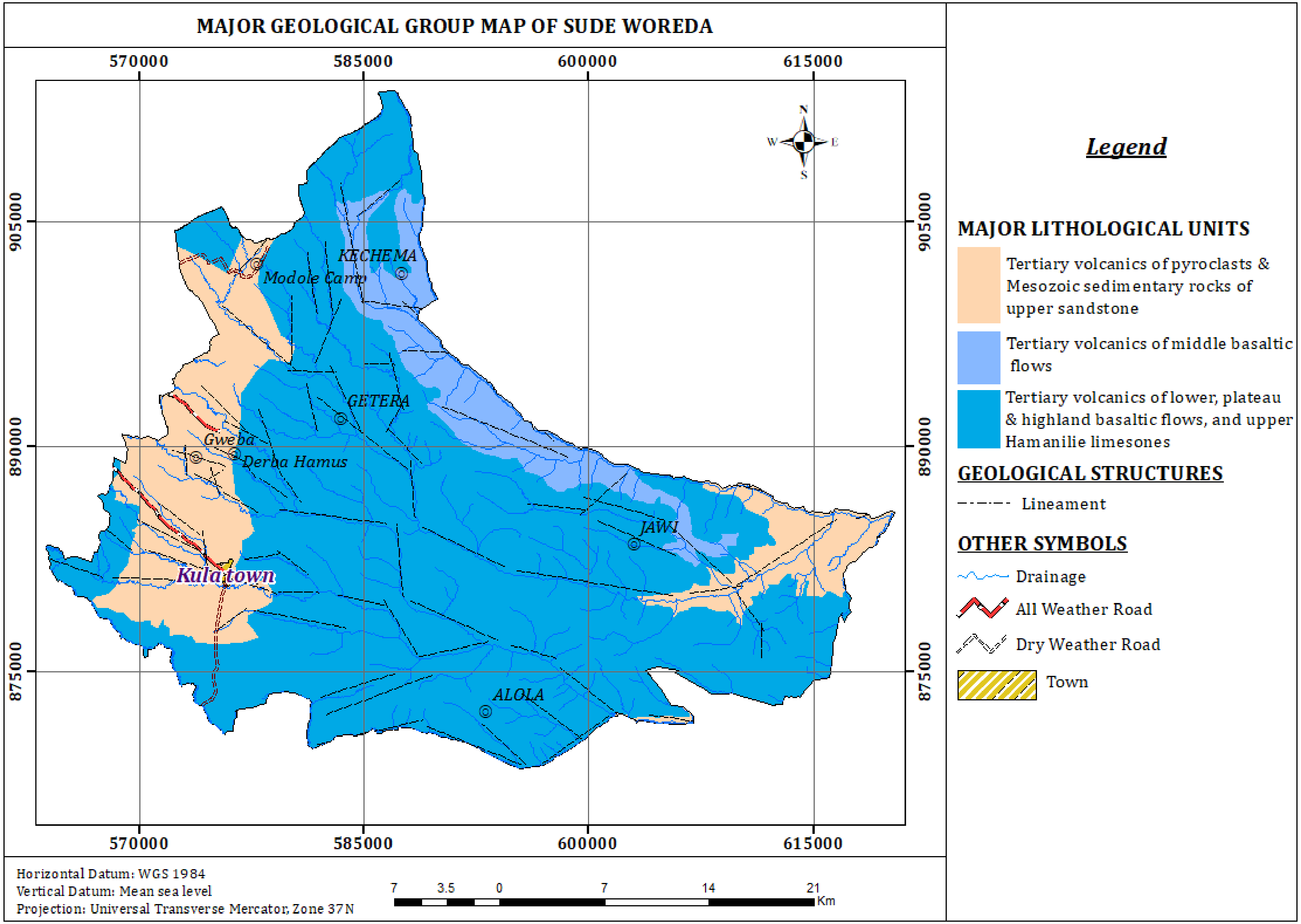

Figure 5-85. Grouped Lithological classification map of Sude Woreda

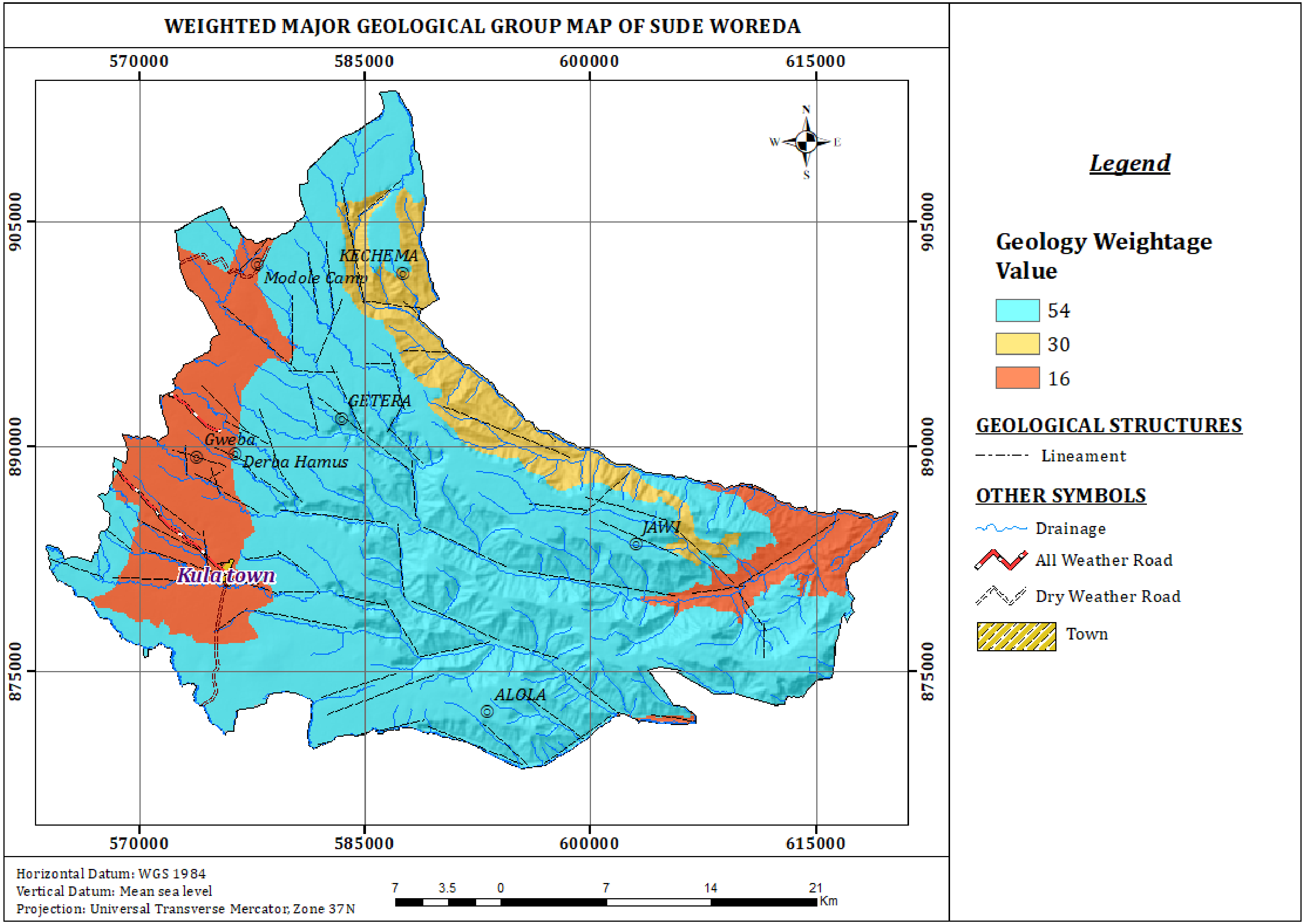

Figure 5-86. Weighted lithological classes' map of the Sude Woreda

III. Lineaments and Lineament Density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SE and NE–SW trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.3 km/km^2 to 0.4 km/km^2 (Figure 5-87). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by Tertiary volcanics of plateau basalt having relatively higher lineament density of 0.5 – 0.9 km/km^2) compared with areas underlain by sedimentary rocks of upper sandstone with lower lineament densities of (< 0.08 km/km^2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.46 was assigned to area with high density of lineaments, while a low weightage of 0.11 was assigned to areas with low lineament density (Figure 5-88).

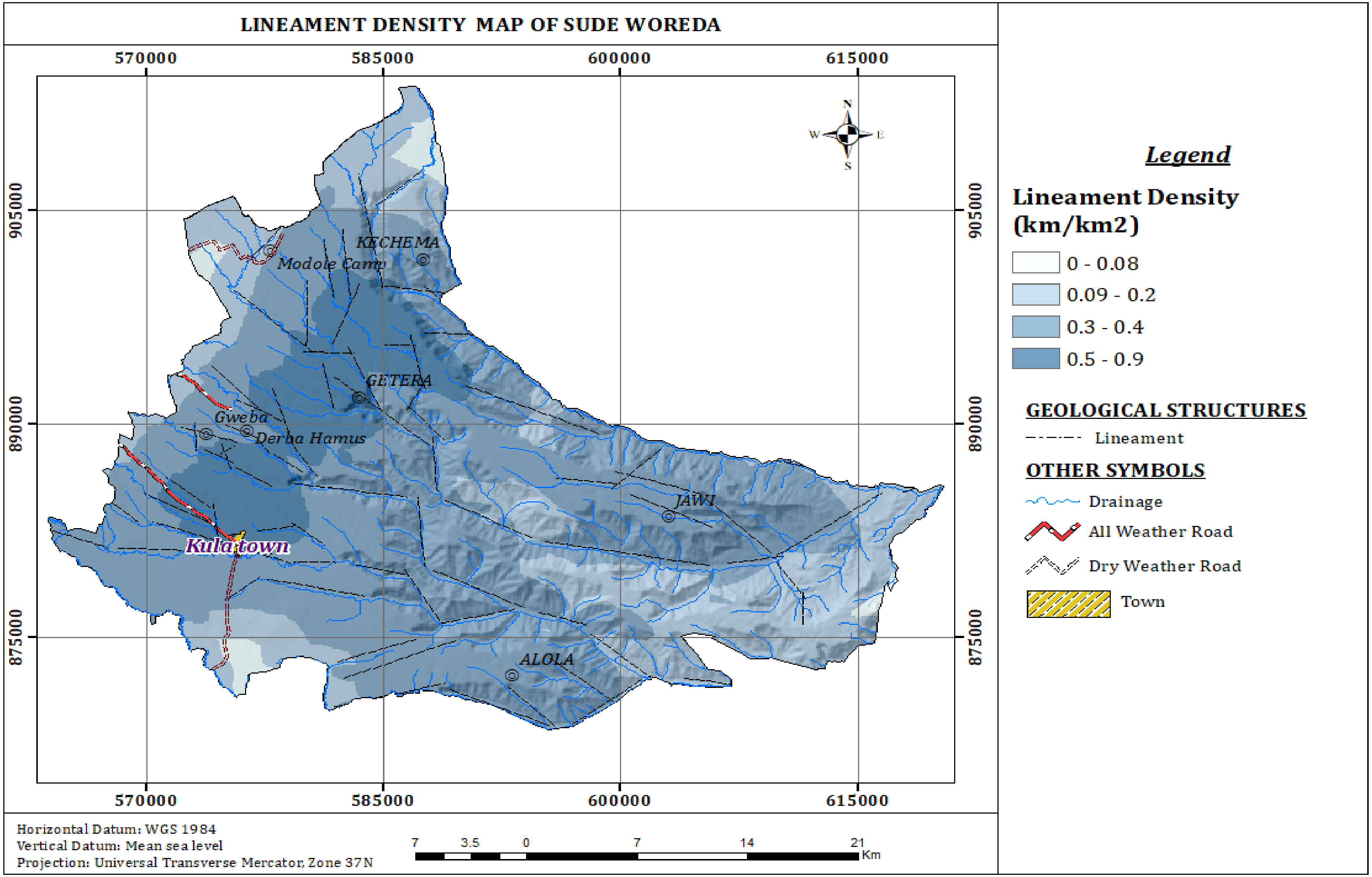

Figure 5-87. Lineament Density Map of Sude Woreda

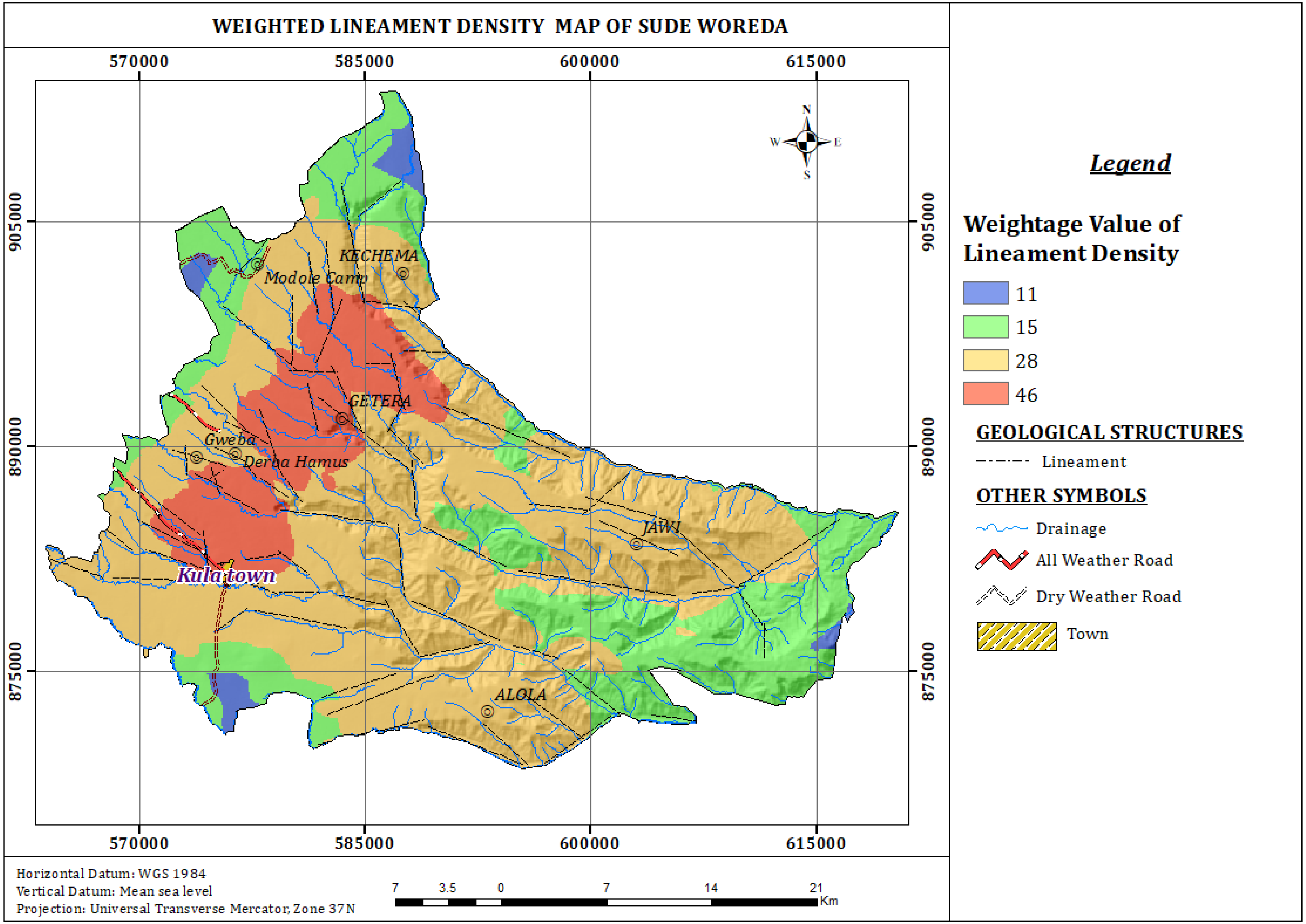

Figure 5-88. Weightage value of Lineament Density Map of Sude Woreda

IV. Recharge

The spatial annual recharge rate distribution in the Sude woreda ranges from 48.1 to 160 mm/y suggesting groundwaters in most central western and northern and southern peripherial regions of the woreda area underlain by Tertiary volcanics of plateau basaltic flows with upper sandstone receive high amount of recharge while the western elevated areas underlain by Tertiary volcanics of upper pyroclastic falls and deposits have relatively lower recharge amount due to very low infiltration rate of the lithological formation (Figure 5-89). Accordingly, areas with very high and high amount of recharge have weightage factor of 0.46 and 0.28, respectively signifying very good and good groundwater potential, respectively while areas with the moderate and lowest amount of recharge have weightage factor of 0.15 and 0.11, respectively, suggesting moderate and poor groundwater potentiality, respectively. Generally, the study area is characterized with very high mean annual recharge amount (> 108 mm/yr), whereas some of the central and western areas have moderate to low mean annual recharge amount (48-107 mm/yr).

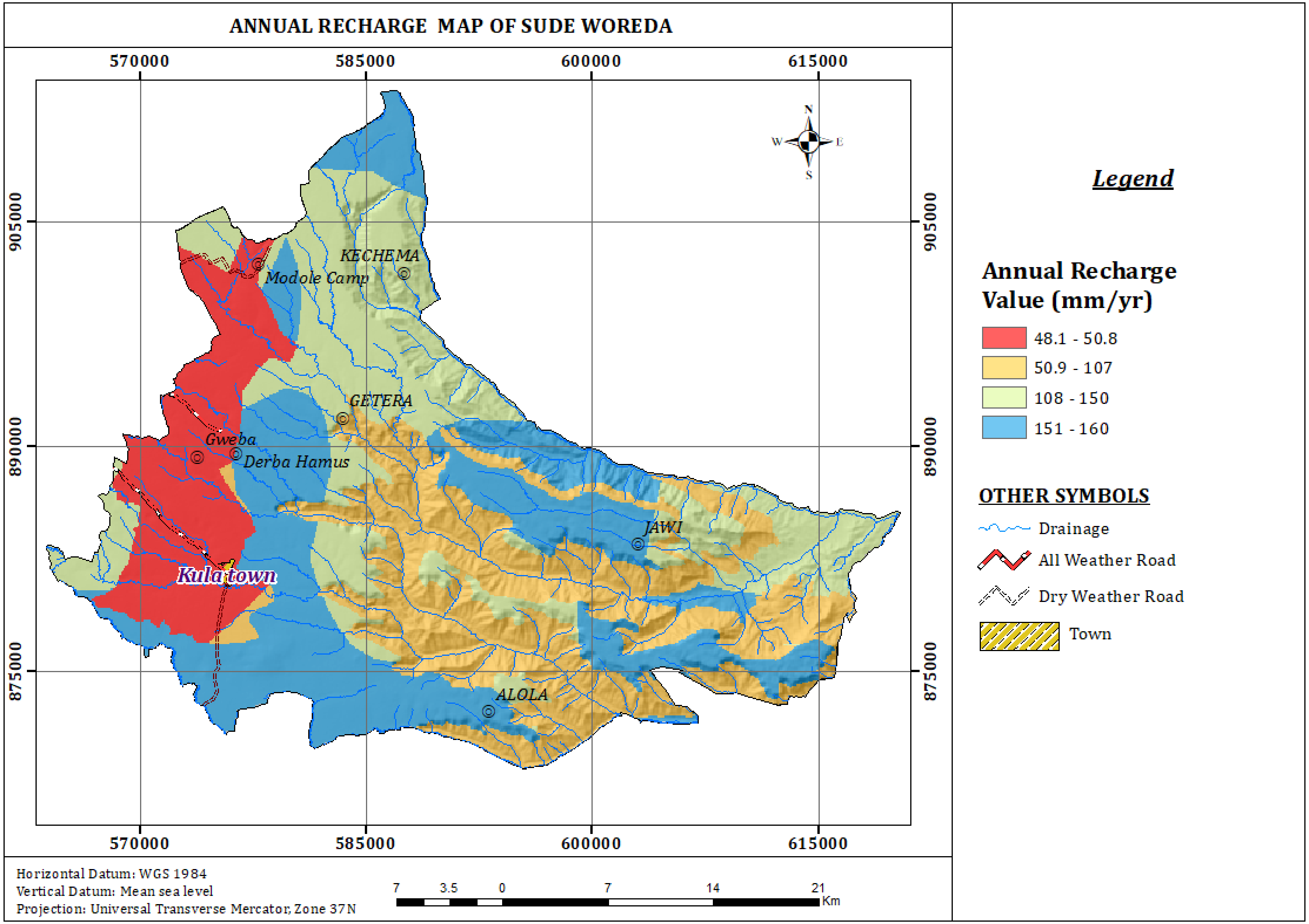

Figure 5-89. Annual Recharge Map of Sude Woreda

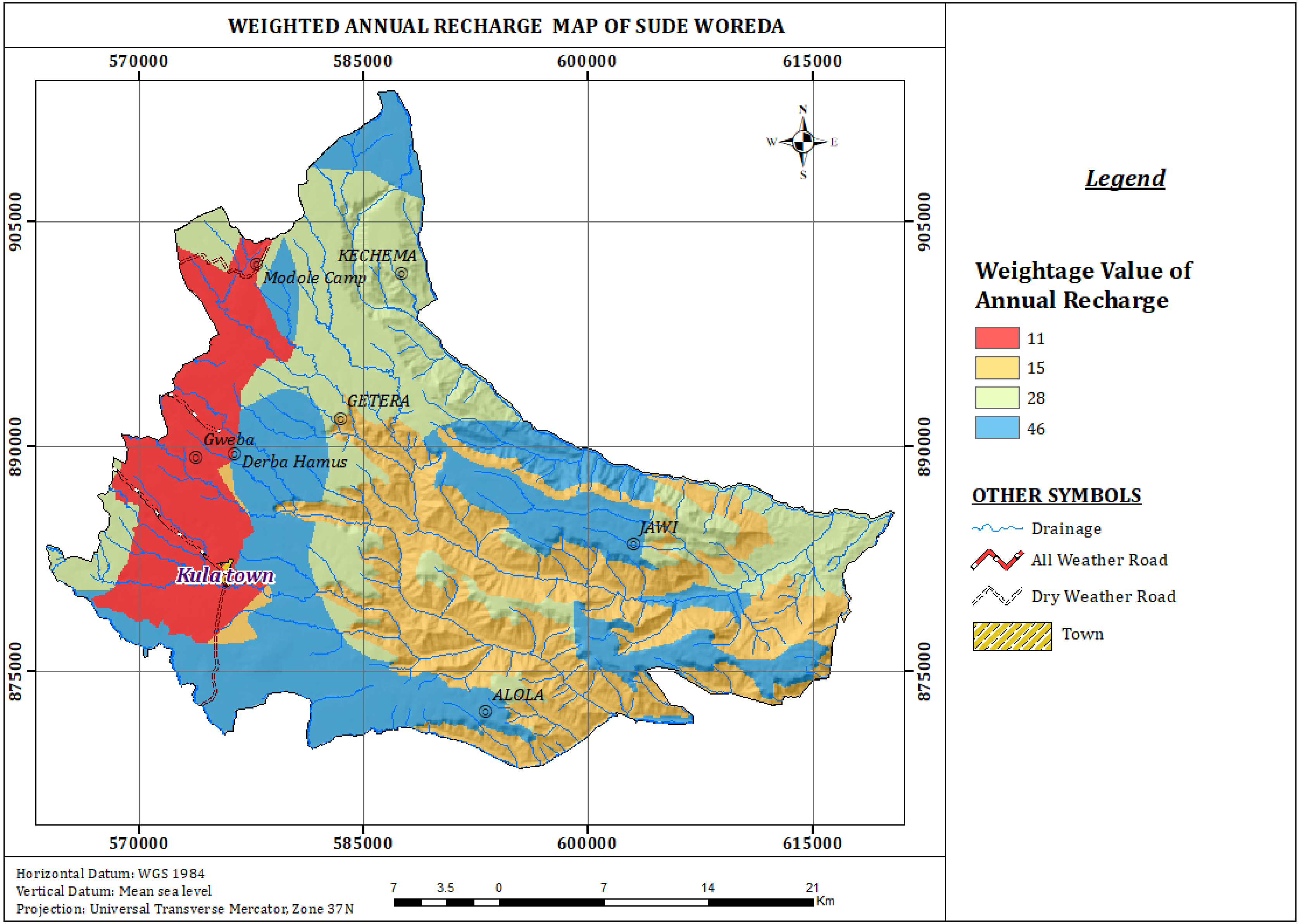

Figure 5-90. Weighted Annual Recharge classes' map of the Sude Woreda

5.8.3. Classification of Groundwater Potential Zones

The hydrogeological system of Sude woreda is comprised of three main lithological units as Tertiary volcanics, upper sandstone and upper Hamanlie limestone formations. At both regional scale and local scale within the domain of Sude woreda, plateau basalts form extensive and very high productive aquifers. Theses basaltic rocks form aquifers with very high groundwater potential as revealed from existing borehole information.

Only the upper weathered and slightly fractured part of the volcanic rocks along lineamnets and faults have potential to store groundwater at shallow depth. Weathered and fractured volcanic rocks of basaltic flows form major potential aquifer within the domain of Sude Woreda along lineament and fault lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-91). The potential groundwater zones (PGZ) of the Sude woreda revealed four distinct zones, namely low, moderate, high and very high zones, respectively as presented in Table 5-39.

The potential map, as presented in Figure 5-91, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that most western elevated areas, and northern and eastern peripheries the woreda generally have low potentials, while most areas at central western, northern and southern regions generally exhibits high to very high potentials, respectively. The generally high to very high groundwater potentiality of the study area is a confirmation of generally high productive aquifers of plateau basalts, whereas low groundwater potential areas have an indication of limited aquifers capabilities of upper pyroclasic formation.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the geology and topographic wetness index in addition to the lineament density and recharge control. In addition, areas underlain by plateau basalts especially in the central western sections of the study area are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments, and apparently deep fracturing system have high and very high groundwater potential on the one hand. On the other hand, areas underlain by upper pyroclastic formations in the northern and eastern and western peripheries and central regions of the woreda in particular are characterized by rugged and elevated topography with relatively steep slopes, and lower lineament densities, exhibit moderate to low groundwater potential while areas underlain by sedimentary rocks of lower Hamanilie limestone formation and lower basaltic flows have moderate potential. Moreover, low lineament densities and predominance of upper pyroclastic formation outcrops can be attributed to the observed low groundwater potentials at the most western margins of the study area. However, predominance of fractured and weathered volcanic rocks of basaltic flows, high lineament density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential exhibited at most central eastern portions of the study area. Summary of the groundwater potential zones identified in the Sude woreda is presented in the table below (Table 5-39).

Table 5-39. Classification of groundwater potential zones and coverage areas alongside the respective yield categories

Woreda Name	GWP Zones	Major Aquifer Units	Borehole Yield Classification (l/s)	
			Q (Range)	Mean 'Q'
Sude	Very High	Plateau basalt (Tv3(1))	10 - 32	23.7
	High	Middle basaltic flow (Tv2)	5.6 - 8	7
	Moderate	Upper Hamanilie limestone (Jh2) & Lower basalt (Tv1)	4 – 4.9	4.4
	Low	Upper sandstone (Ka) & Upper pyroclastics	2 - 4	2.8

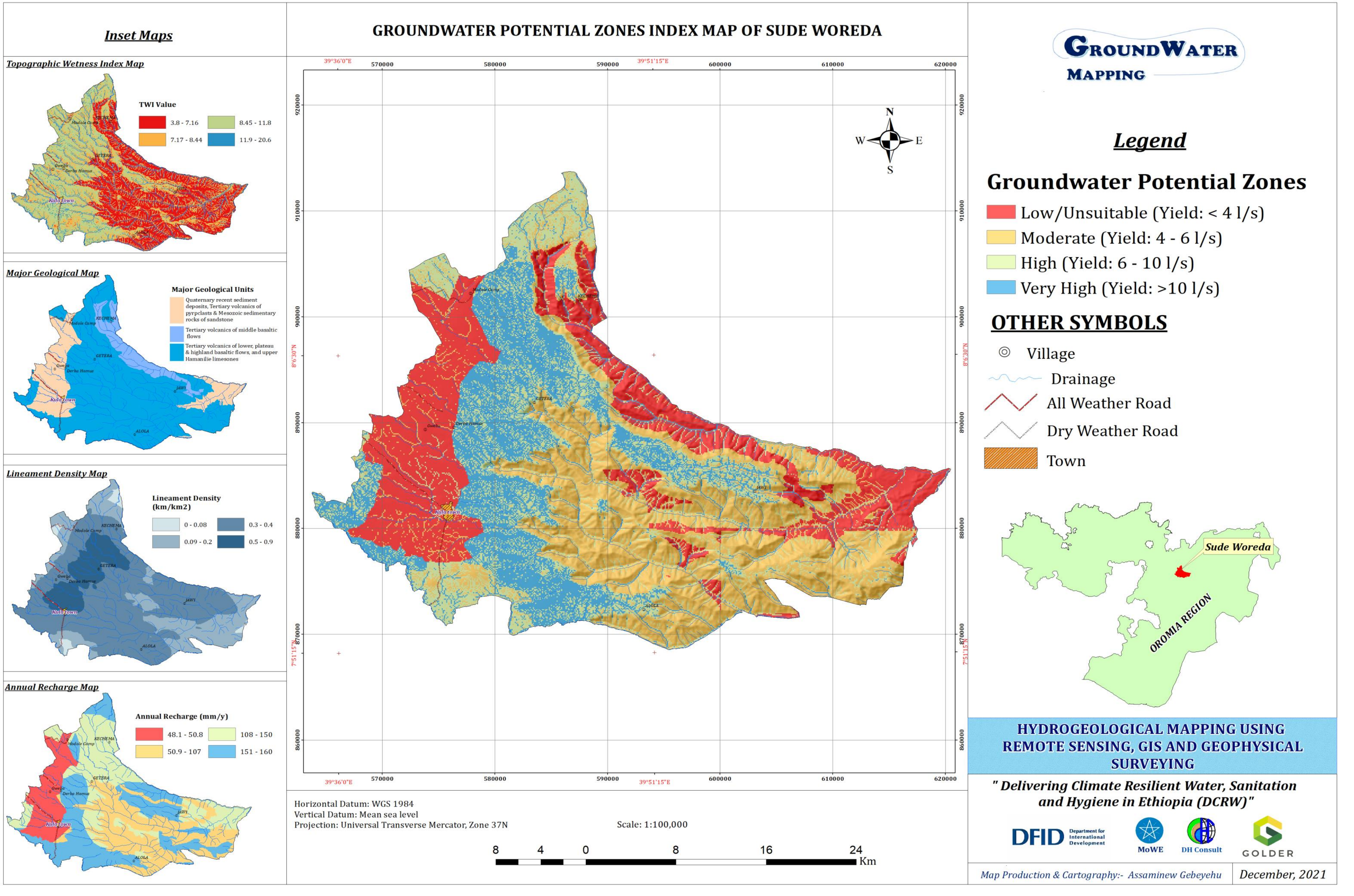

Figure 5-91 Groundwater Potential Zones Map of Sude Woreda

5.8.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) are were collated for over 30 boreholes found around the woreda within the synoptic cluster boundary area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the synoptic area vary from 10 to 32 lit/sec (av. 23.7 lit/sec) in very high potential zones and varying from 5.6 lit/sec to 8 lit/sec (av. 7 lit/sec) in high potential zones as compared with 4 lit/sec to 4.9 lit/sec (av. 4.5 lit/ sec) in the moderate and from 1.5 to 3.8 lit/sec (av. 2.7 lit/sec) in the low potential zones (Figure 5-92). As shown in the Figure 5-92, the occurrence of number of wells with yield of in the range 5.6 - 8 lit/sec (high yield) and of > 10 lit/sec (very high yield) cut across mainly the plateau basaltic rocks. However, the less frequency of wells within upper sandstone rocks in the low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (4-4.9 lit/sec) and high-yield (5.6 - 8 lit/sec) categories are associated also with wells in the Mesozoic sedimentary rocks and Tertiary volcanics of basaltic rocks. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

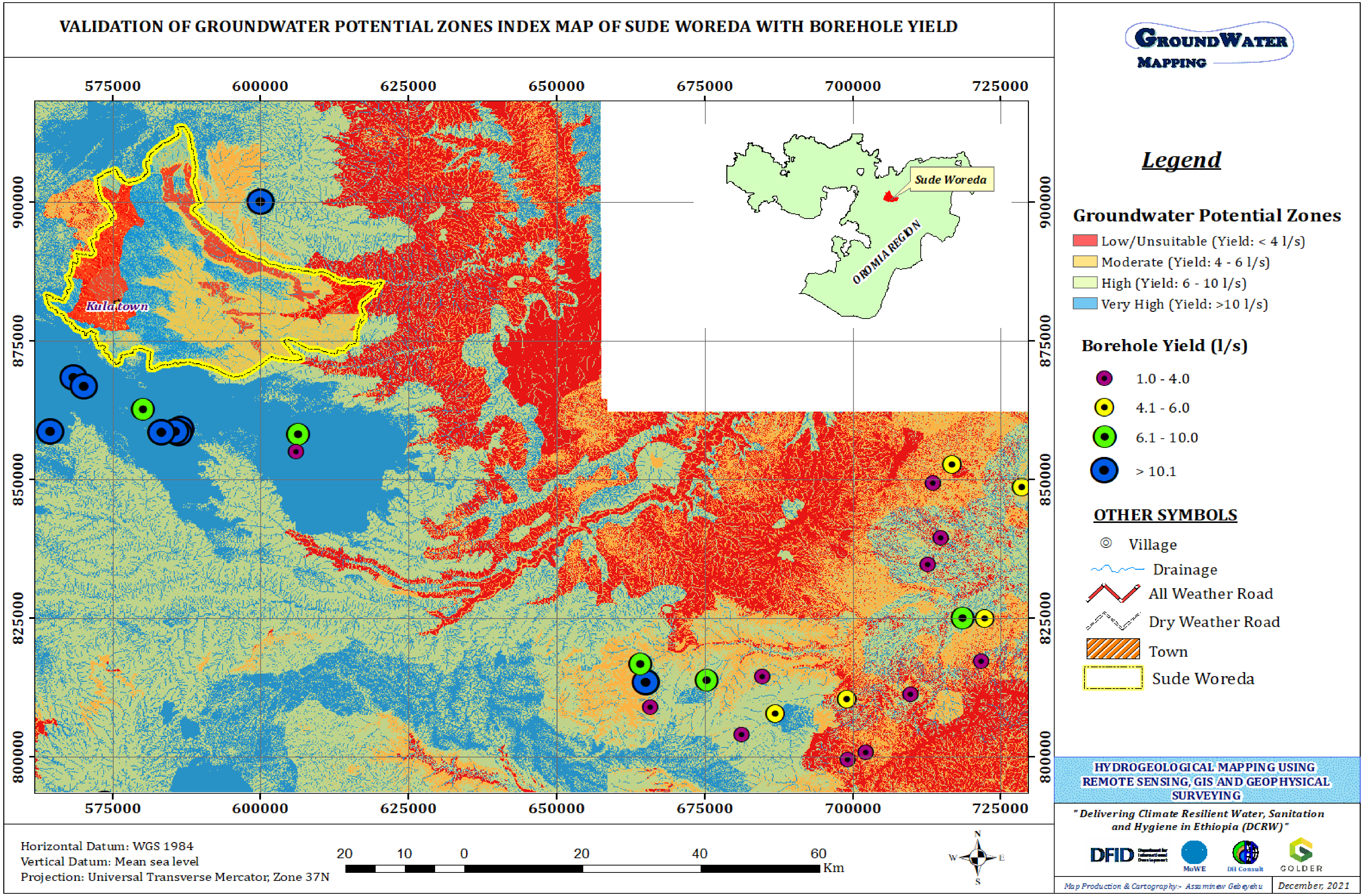

Figure 5-92. Validation of Groundwater Potential Zones Map of Sude Woreda within Arsi-Bale synoptic boundary

5.8.5. Projected Population and Water Demand

5.8.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-40 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P = Po(1 + r)^n$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Sude Woreda has been projected forward until 2036 using the growth rate of Oromia Regional State. The minimum and maximum population in the Woreda is 5,539 and 21,456 respectively. The total population of the Sude Woreda in 2036 is going to be 290,997.

5.8.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic

purposes greatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO) & (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer’s life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24 hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from 1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-93 shows the distribution of water demand in each Kebeles of the Woreda. Ekiya Molota and Semar Abdaye kebeles water demand is the minimum with 498 M^3/day and maximum water demand is required for Deksis Ersha Kebele with 1,928 M^3/day respectively. The overall water demand for the projected population in the Sude Woreda is 26,143 M^3/day.

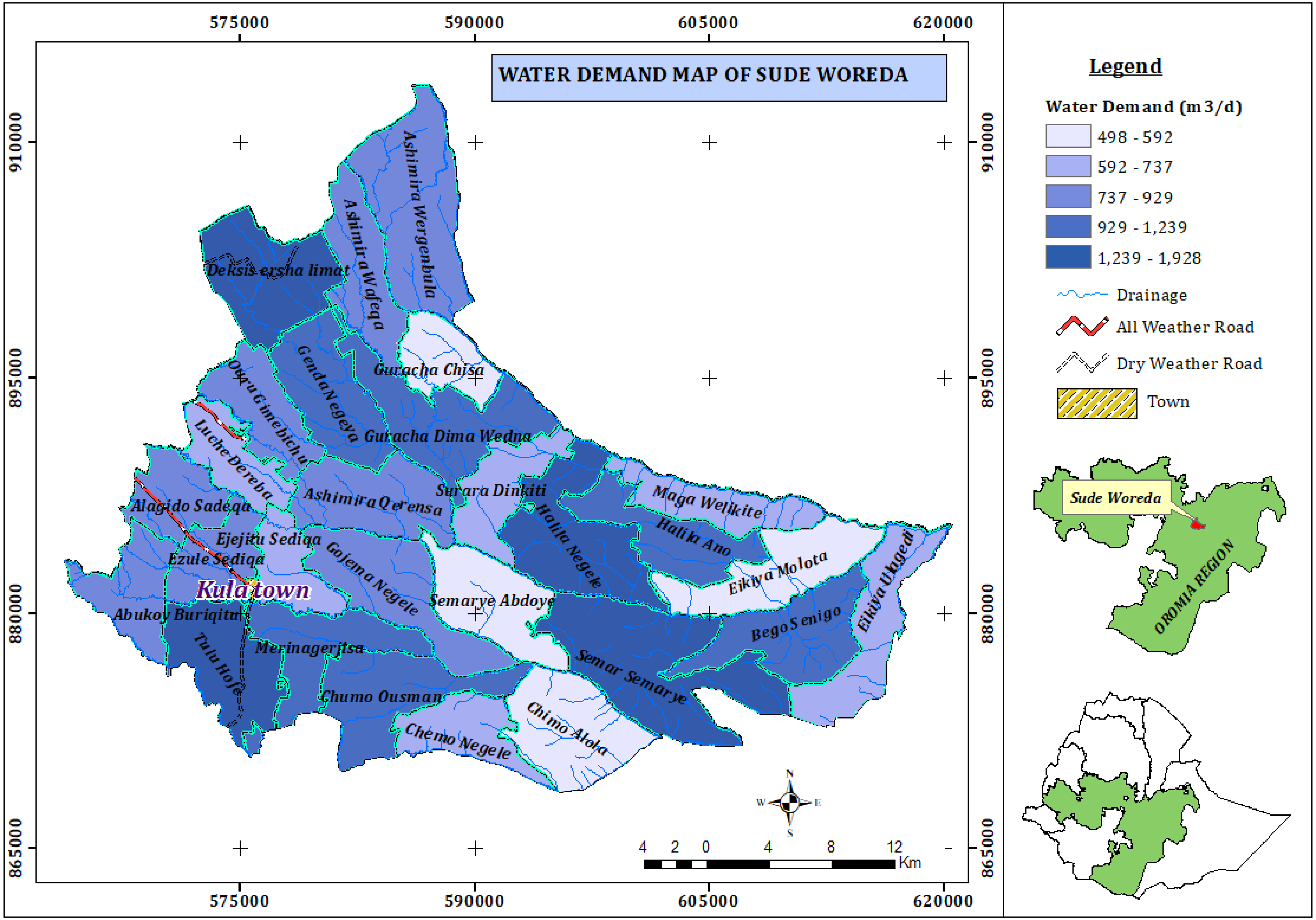

Figure 5-93:-Water Demand Map of Sude Woreda

5.8.6. Propsed Target Sites

Four target sites are identified and proposed within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficiaries and population density. With further discussion and consultation with stakeholders, two priority sites will be selected for further hydrogeological and geophysical investigations in phase III. The following are the four proposed sites:

Target Site-I:

This target site is located in the central western regions of the woreda. It is situated in the identified very high potential zones with expected optimum borehole discharge of about 11 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-II:

This target site is located in the central northern part of the woreda, around Halila Negele locality. It is situated in the identified very high and high potential zones with expected optimum borehole discharge of about 11 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-III:

This target site is located in the southwestern parts of the woreda, around southwest of Kula town. It is situated in the identified very high and high potential zones with expected optimum borehole discharge of about 14 l/s. This target site is mainly underlain by plateau and upper most basaltic rocks.

Target Site-IV:

This target site is located in the northern tip region of the woreda, around Kechema locality. It is situated in the identified high potential zones with expected optimum borehole discharge of about 11 l/s. This target site is mainly underlain by plateau basaltic rocks.

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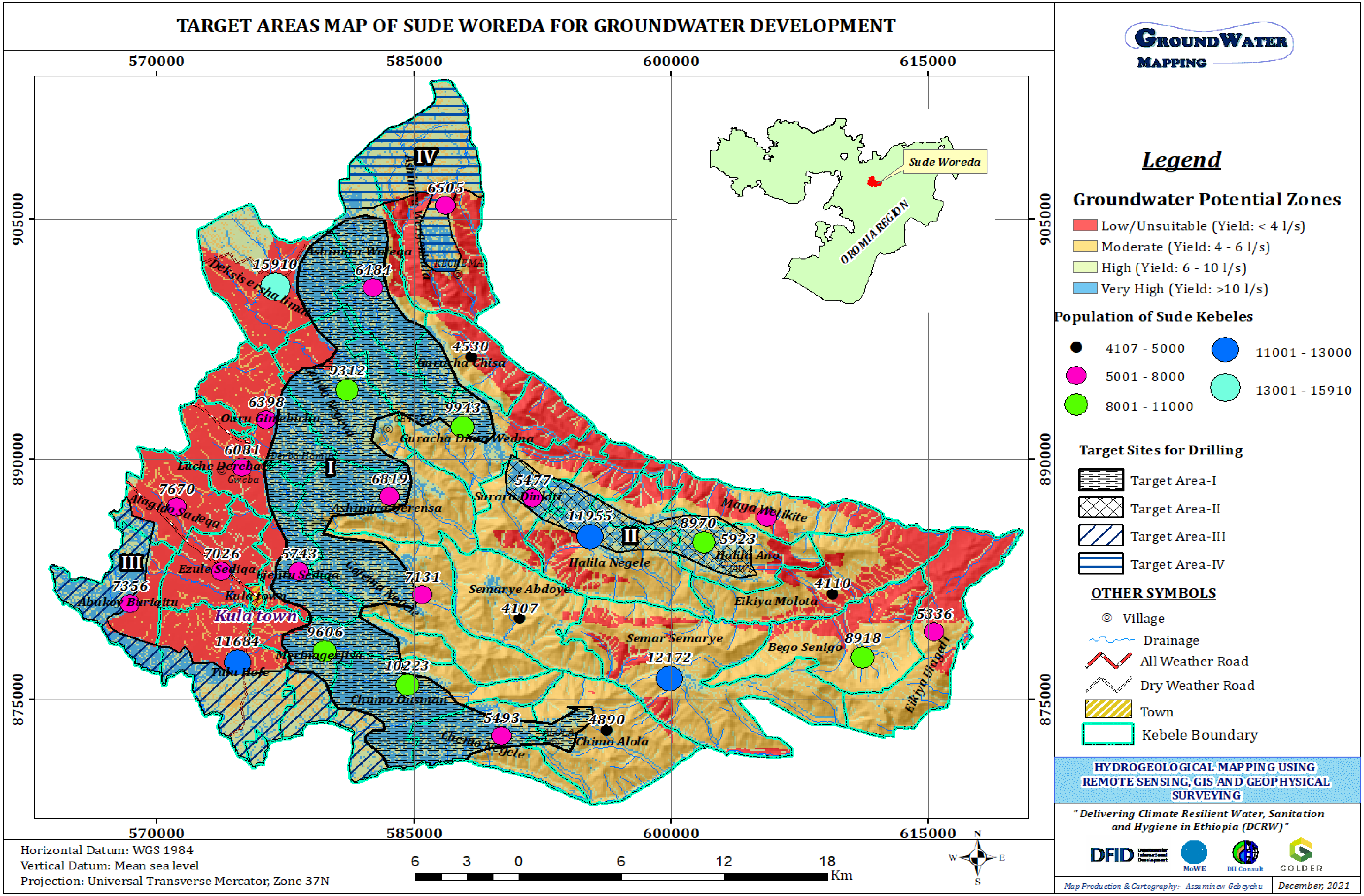

Figure 5-94:-Target Areas Map of Sude Woreda

5.9. Tena Woreda

5.9.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.05 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Tena woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-41). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-42. The weights assigned to the respective thematic maps as presented in Table 5-43 indicate that TWI was ranked the dominant factor with a normalized weight value of 0.41 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Tena woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Tena woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

$$GWPZI = (TWIwTWIwi + GGwGGwi + LDwLDwi + GRwGRwi)$$

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Tena woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e. 'very high', 'high', 'moderate' and 'low or poor', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-41 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Topographic Wetness Index (TWI)	9
Geology (GG)	8
Lineament density (LD)	7
Recharge (GR)	6

Table 5-42 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	TWI	GG	LD	GR	
TWI	1	1	3	5	0.41
GG	1	1	3	2	0.34
LD	1/3	1/3	1	2	0.15
GR	1/5	1/2	1/2	1	0.10

Table 5-43 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank
Topographic Wetness Index, 'TWI'	4.8 - 6.8	poor	1	0.11	0.41
	6.9 - 7.3	Moderate	2	0.15	
	7.4 - 9.3	Good	3	0.28	
	9.4 - 17.1	Very good	4	0.46	
Geology/ Lithology, 'GG'	Tertiary volcanics of lower and plateau basaltic flows, and upper Hamanilie limesone Formation	Very good	4	0.83	0.34
	Tertiary volcanics of trachytes	Moderate	2	0.17	
Lineament Density,' LD' (Km/Km^2)	0.18 - 0.33	poor	1	0.11	0.15
	0.34 - 0.49	Moderate	2	0.15	
	0.5 - 0.64	Good	3	0.28	
	0.65 - 0.79	Very good	4	0.46	
Recharge, 'GR' (mm/y)	95.5 - 105.8	poor	1	0.11	0.10
	105.9 - 115.3	Moderate	2	0.15	
	115.4 - 124.5	Good	3	0.28	
	124.6 - 168.9	Very good	4	0.46	

5.9.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of Topographic Wetness Index (TWI), geology, lineament density and recharge together with their spatial distribution in Tena woreda are presented below:

I. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 4.8 and 17.1. A closer look at the classification revealed that high elevated areas and drainage systems with steep slopes such as areas in northwestern regions of the woreda in particular have relatively lower TWI value while some of the southeastern low elevated and low-lying areas and drainage systems with gentle and flat slopes have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.46) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.11).

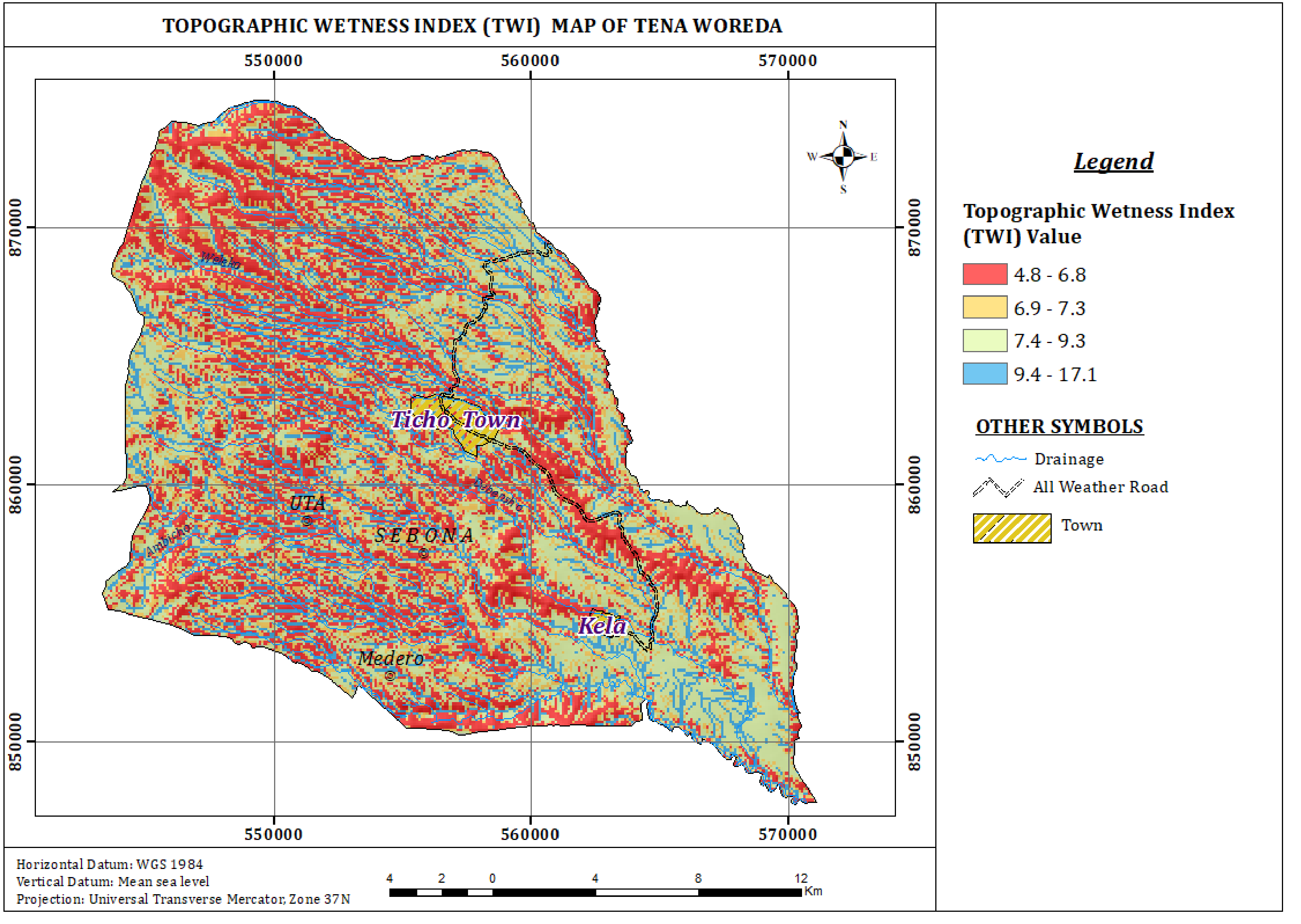

Figure 5-95. TWI Map of Tena Woreda

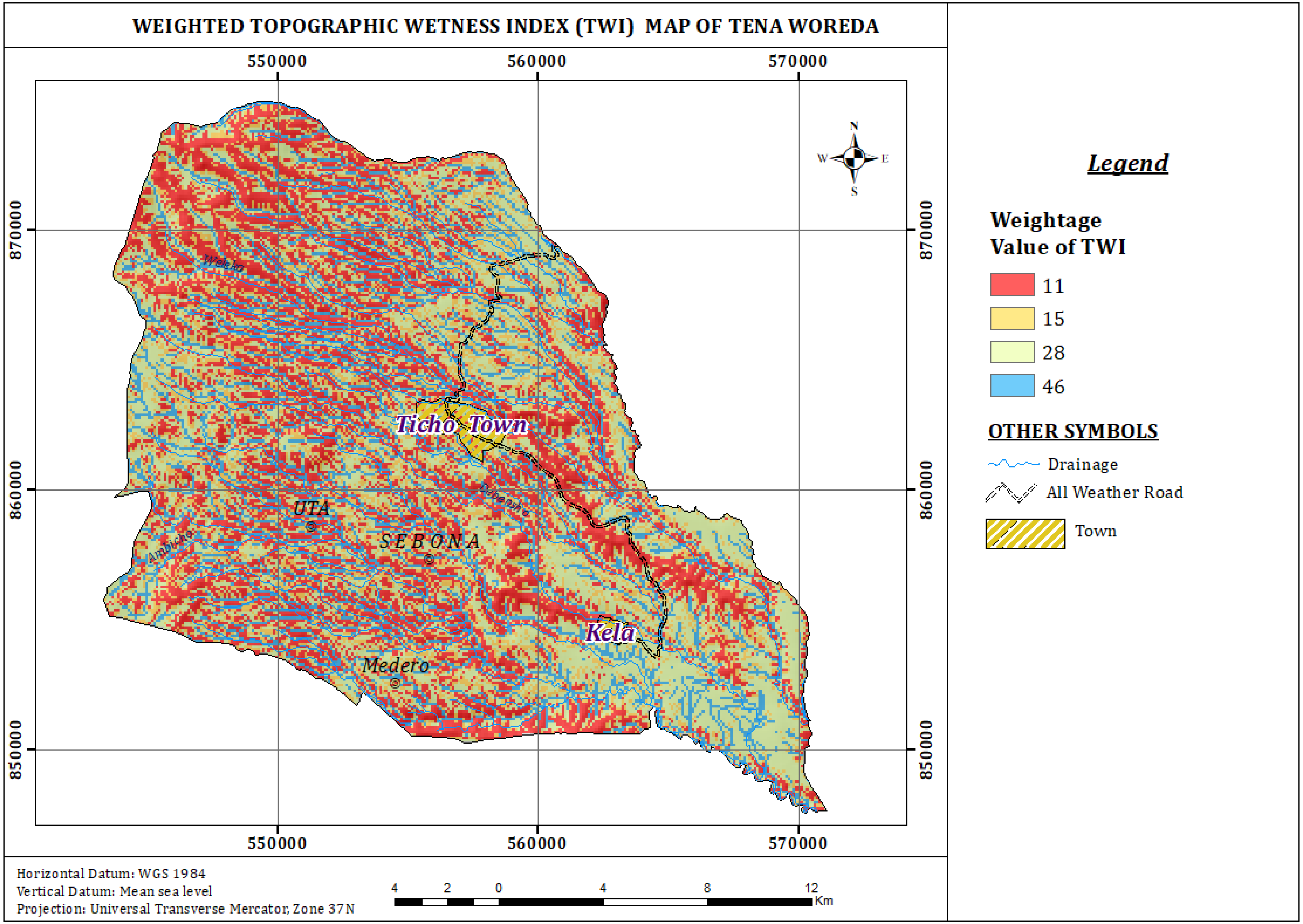

Figure 5-96. Weightage value of TWI Map of Tena Woreda

II. Geology/Grouped Hydrolithology

In general, most parts of the Tena woreda are underlain by Mesozoic sedimentary rocks of upper Hamanilie limestone formation, and Tertiary volcanics of lower and plateu basalts, and Pliocene and Gobesa trachytes.

However, the lithological units found in the woreda area are further classified into two major groups based on their significances to groundwater occurrence and productivity using borehole data on yield and transmissivity analysis in particular.

- Tertiary volcanics of lower and plateau basaltic flows, and upper Hamanilie limesone Formation. (Very high productive with Qav. = 22.8 l/s)
- Tertiary volcanics of trachytes. (Low productive with Qav = 3.3 l/s)

Tertiary volcanics of lower basalt, pleaocene trachytes and Gobesa trachytic flows are the main lithologic framework of the Tena woreda, and plateau basaltic rocks and sedimentary rocks of upper Hamanilie limestone are also outcropped at limited areas of central parts extending from north to south regions of the woreda (Figure 5-97).

Usually, massive unfractured lithologic units in volcanic and sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification, weathering and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of low productivity of trachytic flows (0.17) \ very high productivity of Tertiary volcanics of lower and plateau basaltic flows, and upper Hamanilie limestones (0.83).

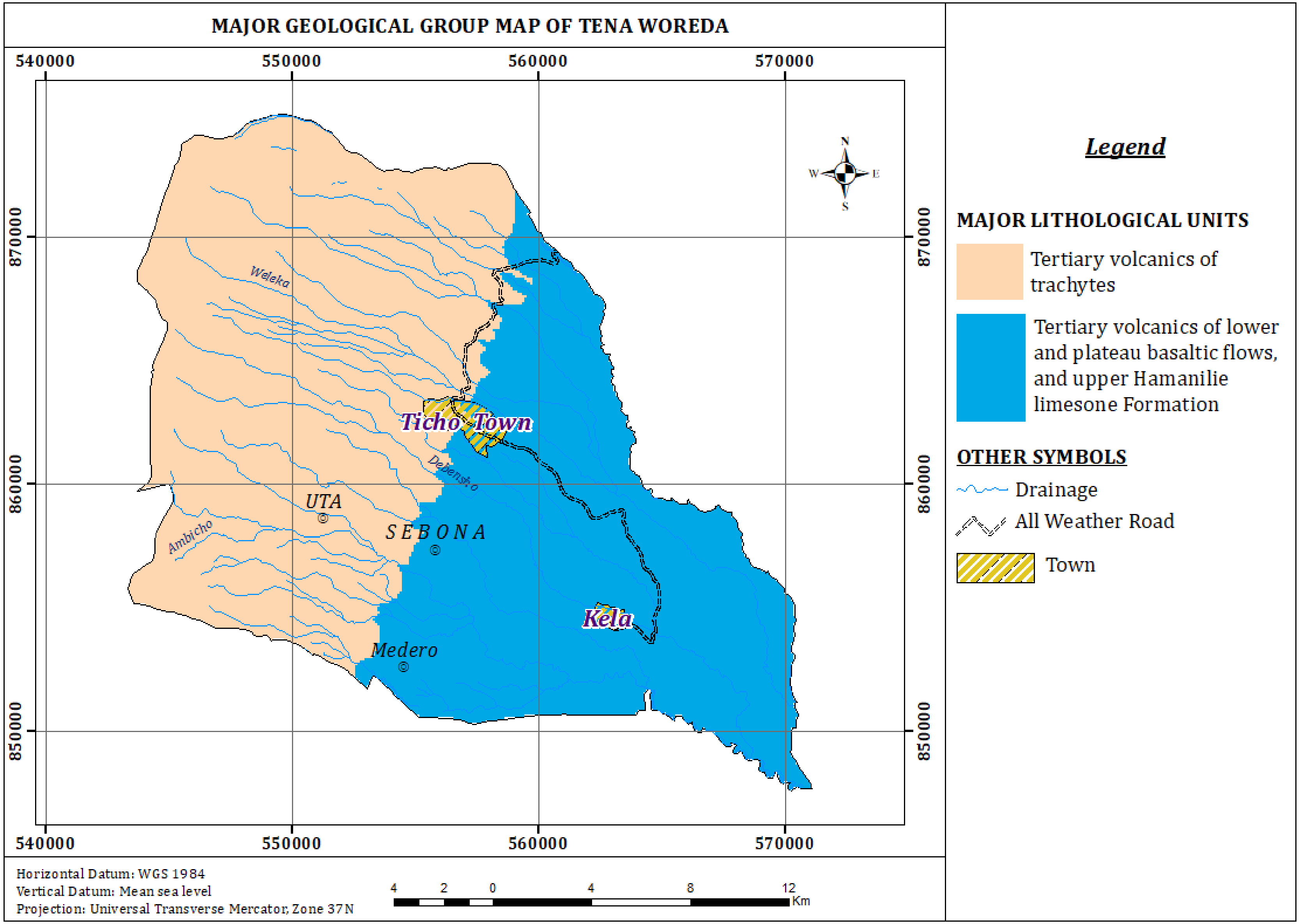

Figure 5-97. Grouped Lithological classification map of Tena Woreda

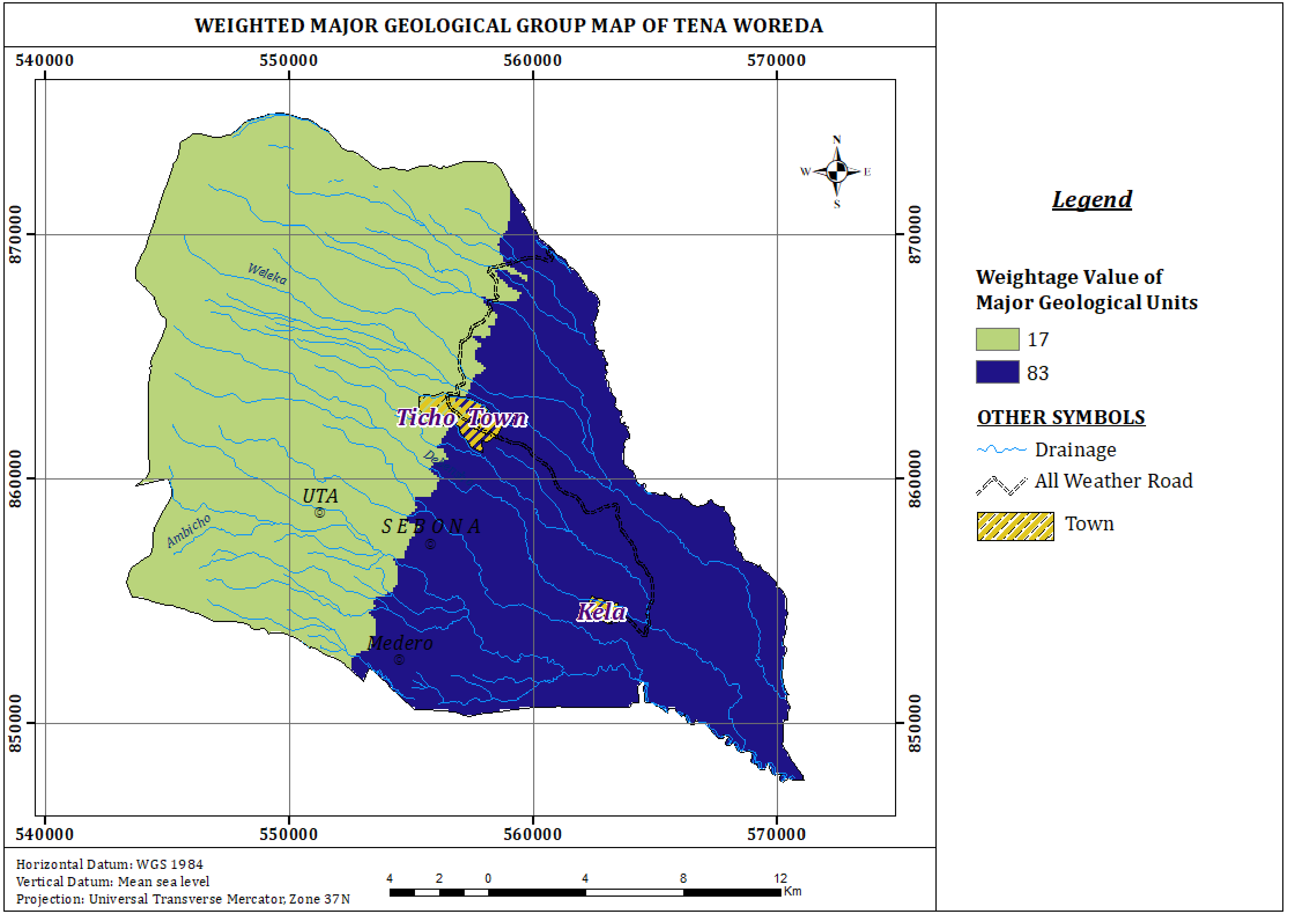

Figure 5-98. Weighted lithological classes' map of the Tena Woreda

III. Lineaments and Lineament Density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SE and NNW–SSE trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from 0.18 km/km^2 to 0.79 km/km^2 (Figure 5-99). Though the lineaments are highly widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by upper Hamanilie limestone, lower basaltic flows and plateau basalts that they have relatively higher lineament density of > 0.65 km/km^2) compared with areas underlain by pliocene trachytic flows with lower lineament densities of (< 0.33 km/km^2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.46 was assigned to area with high density of lineaments, while a low weightage of 0.17 was assigned to areas with low lineament density (Figure 5-100).

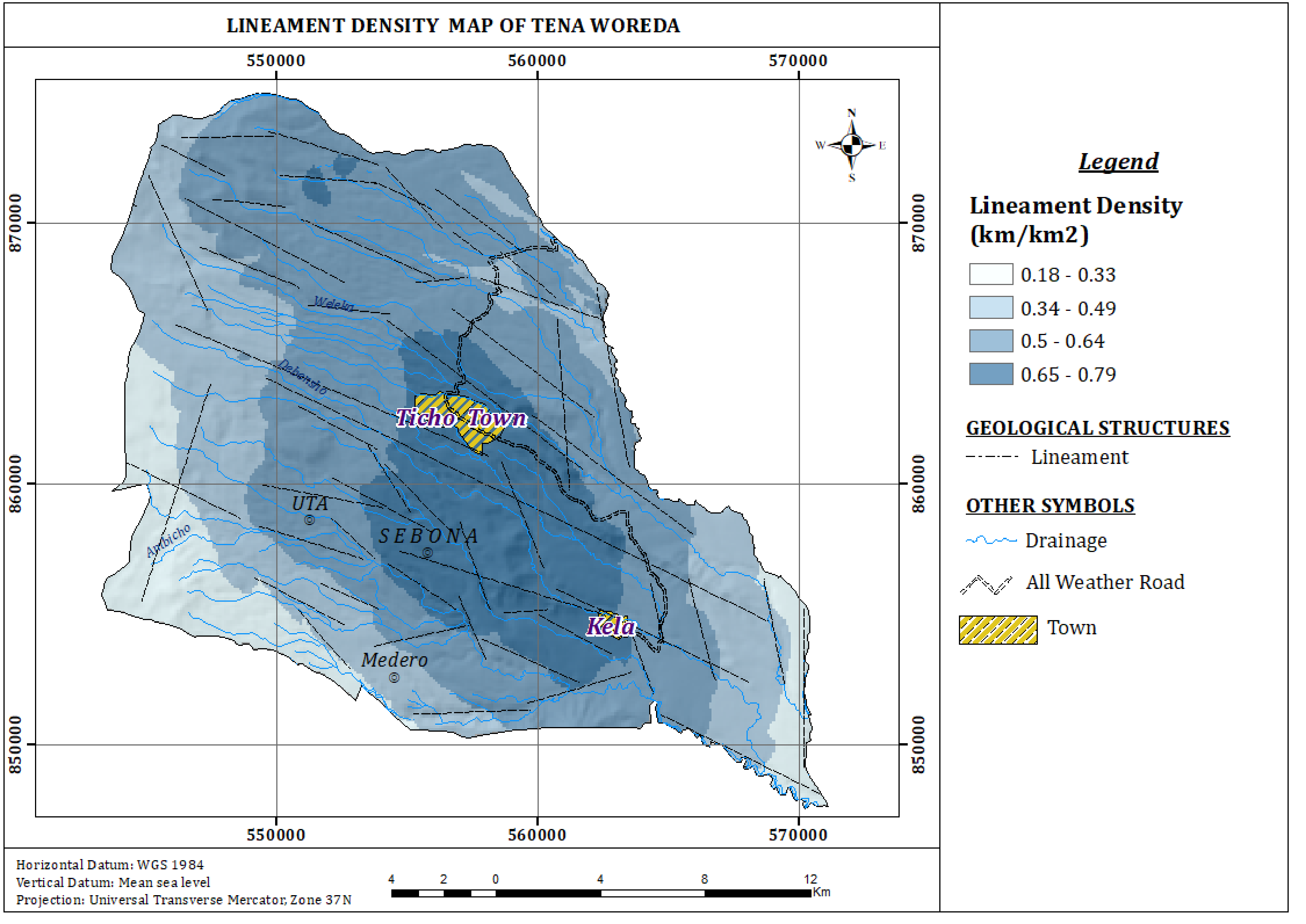

Figure 5-99. Lineament Density Map of Tena Woreda

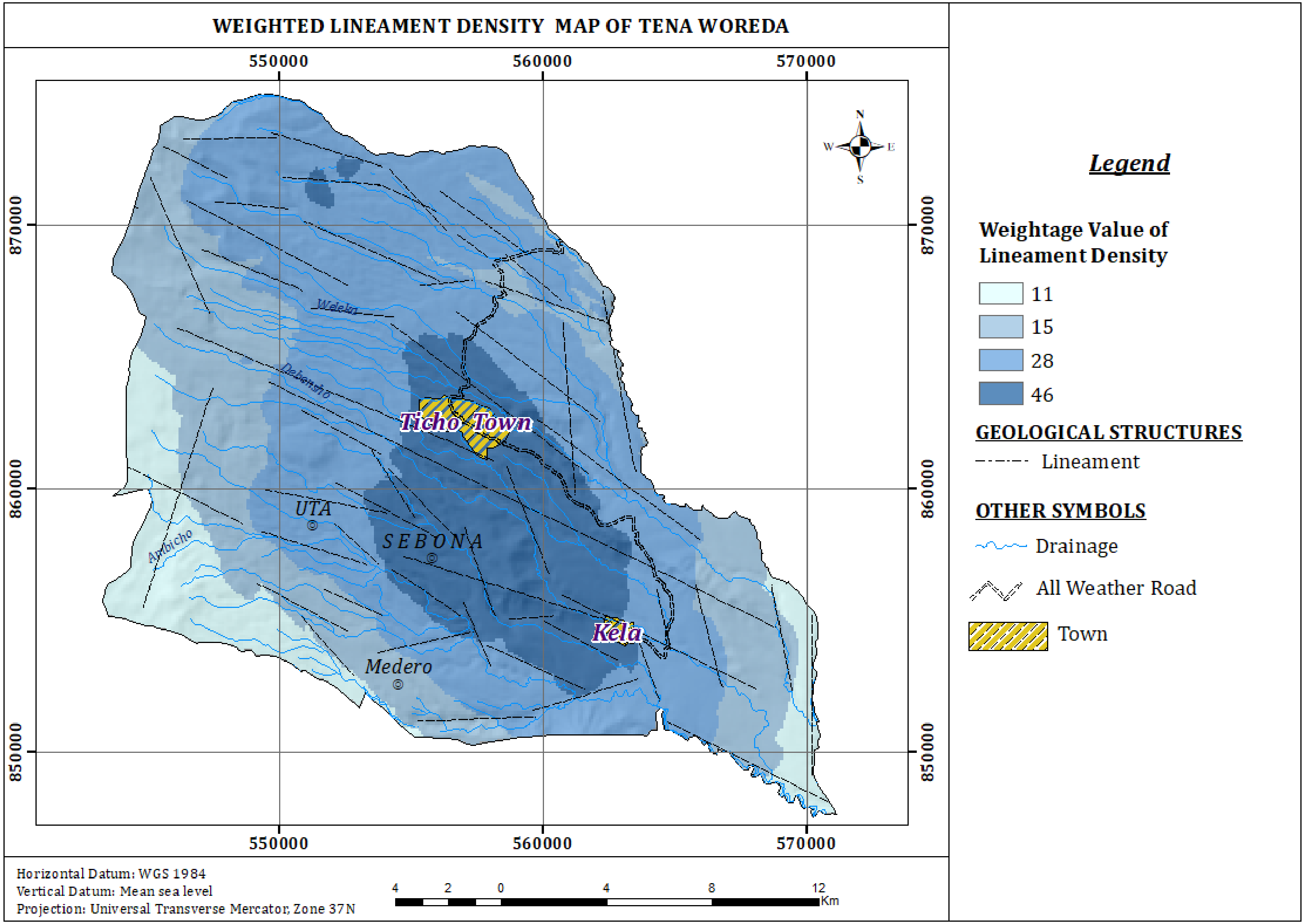

Figure 5-100. Weightage value of Lineament Density Map of Tena Woreda

IV. Recharge

The spatial annual recharge rate distribution in the Tena woreda ranges from 95.5 to 168.9 mm/y suggesting groundwaters in most centra and central and western elevated regions of the woreda area underlain by plateau basalts and Pliocene trachytes receive high amount of recharge while the southeastern low-lying regions underlain by lower basalt have relatively lower recharge amount due to very low infiltration rate of the lithological formation (Figure 5-101). Accordingly, areas with very high and high amount of recharge have weightage factor of 0.46 and 0.28, respectively signifying very good and good groundwater potential, respectively while areas with the moderate and lowest amount of recharge have weightage factor of 0.15 and 0.11, respectively, suggesting moderate and poor groundwater potentiality, respectively. Generally, the study area is characterized with moderate to low mean annual recharge amount (< 106 mm/yr), whereas most of the, central and western areas of the woreda have high to very high mean annual recharge amount (> 106 mm/yr).

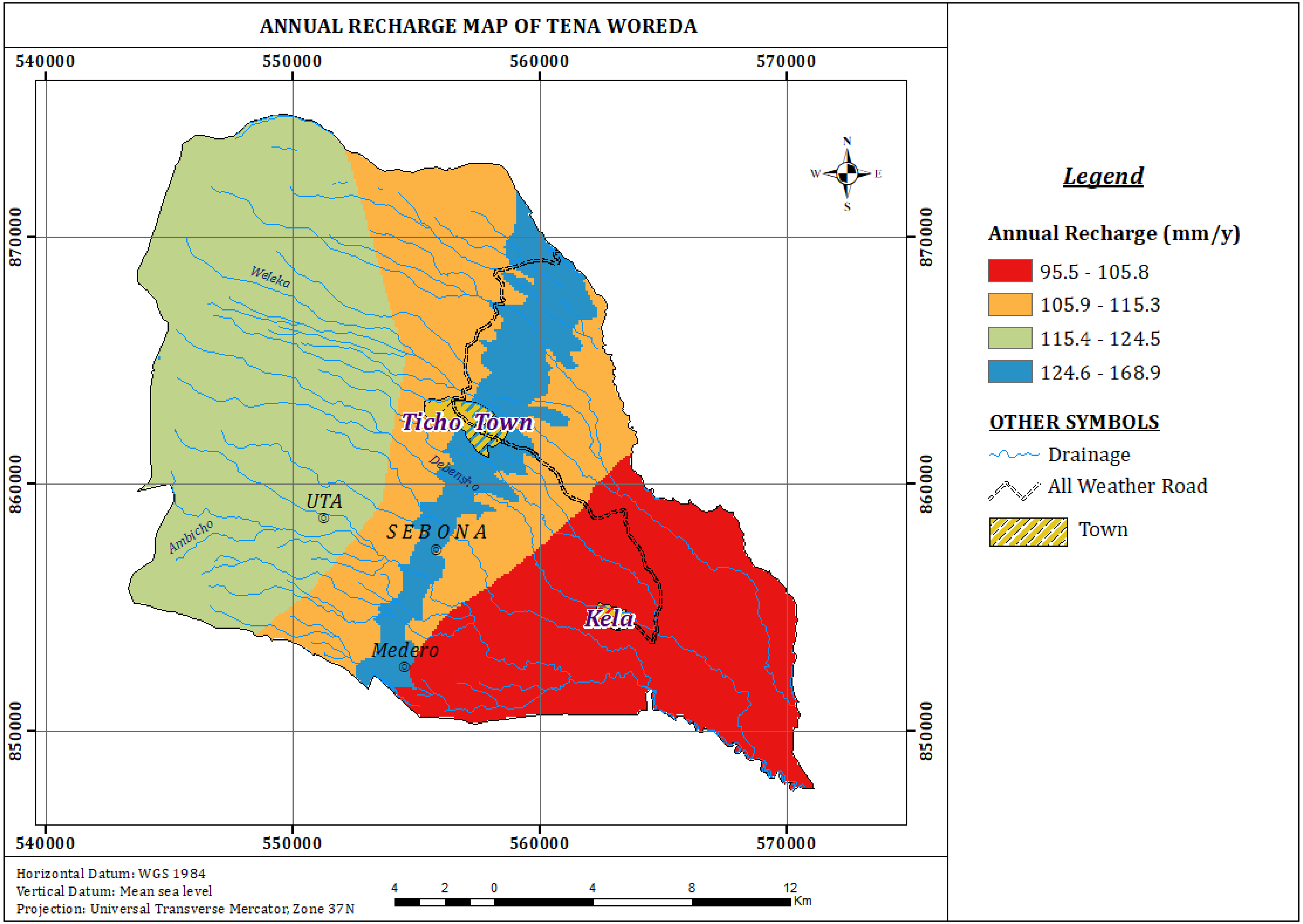

Figure 5-101. Annual Recharge Map of Tena Woreda

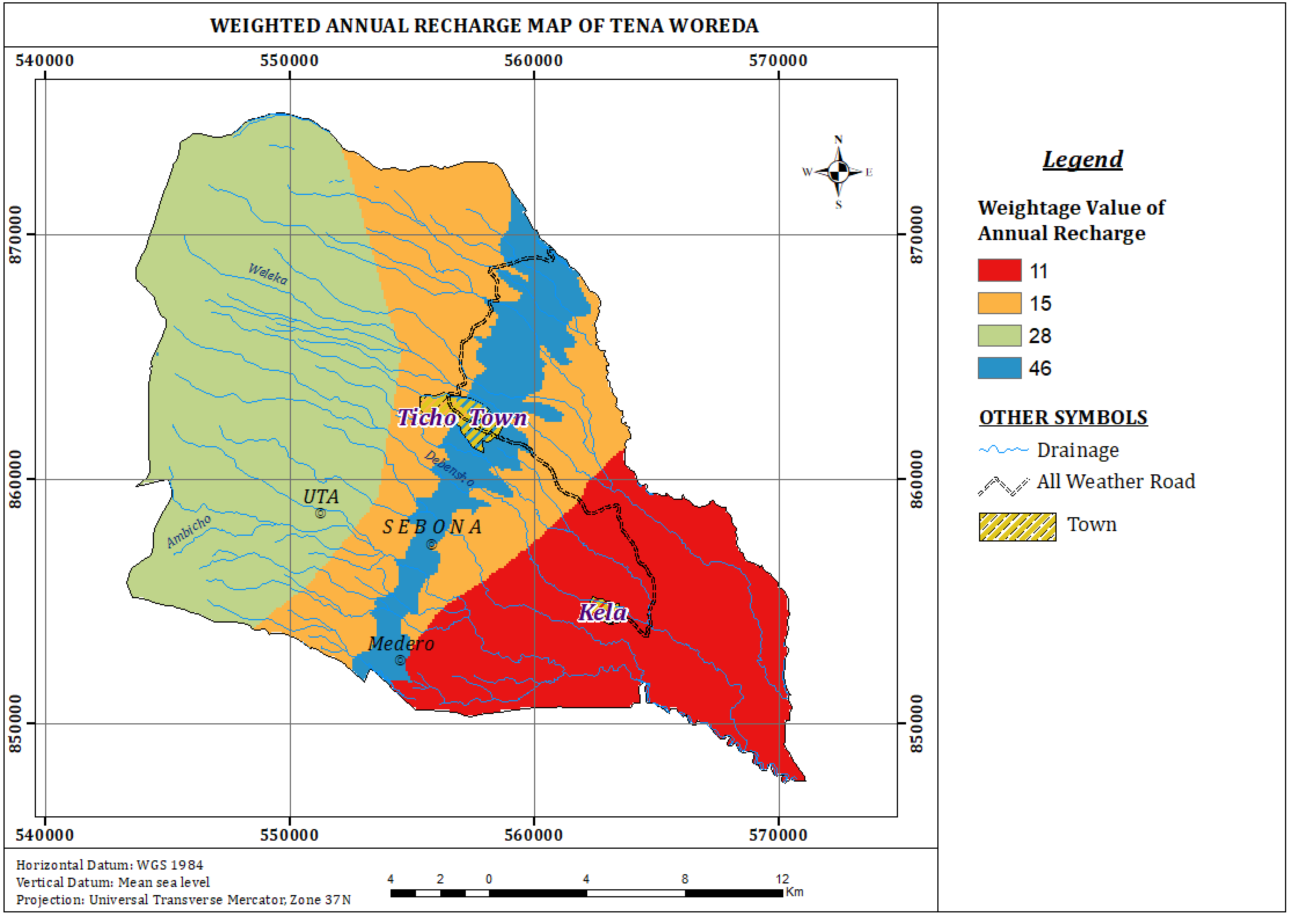

Figure 5-102. Weighted Annual Recharge classes' map of the Tena Woreda

5.9.3. Classification of Groundwater Potential Zones

The hydrogeological system of Tena woreda is comprised of five main lithological units as Mesozoic formation of upper limestone rocks and Tartiary volcanics of lower basalt, plateau basalt, pleocene trachytes and Gobesa trachytes. At both regional scale and local scale within the domain of Tena woreda, upper Hamanilie limestone, plateau basalt and lower basaltic flows form extensive and high to very high productive aquifers. This volcanic rocks of basalt and limestone rocks form aquifers with high to very high groundwater potential as revealed from existing borehole information whereas, the pleocene and Gobesa trachytes form moderate to low groundwater potential.

Only the upper weathered and slightly fractured part of the volcanic and sedimentary rocks along lineamnets and faults have potential to store groundwater at shallow depth. Weathered and fractured volcanic rocks of lower and plateau basalts form major potential aquifer within the domain of Tena Woreda along lineament and fault lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-103). The potential groundwater zones (PGZ) of the Tena woreda revealed four distinct zones, namely low, moderate, high and very high zones, respectively as presented in Table 5-44.

The potential map, as presented in Figure 5-103, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that central western regions of the woreda generally have low to moderate potentials, while most low-lying areas at central southeastern regions generally exhibits high to very high potentials. The generally high to very high groundwater potentiality of the study area is a confirmation of generally high productive of upper limestone, lower and plateau basaltic rocks, whereas low groundwater potential areas have an indication of limited aquifers capabilities of pleocene and Gobesa trachytic flows.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the topographic wetness index and geology in addition to the lineament density and recharge control. In addition, areas underlain by plateau basalt and upper limestone especially in the central sections of the study area are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments, and apparently deep fracturing system have high and very high groundwater potential on the one hand. On the other hand, areas underlain by trachytic flows in the central western regions of the woreda in particular are characterized by rugged and high elevated topography with relatively steep slopes, low recharge amount, and lower lineament densities, exhibit low groundwater potential. Moreover, low lineament densities and predominance of steep slope topography can be attributed to the observed low groundwater potentials. However, predominance of fractured and weathered upper limestone and plateau basalts, high lineament density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential.

Summary of the groundwater potential zones identified in the Tena woreda is presented in the table below (Table 5-44).

Table 5-44. Classification of groundwater potential zones and coverage areas alongside the respective yield categories

Woreda Name	GWP Zones	Major Aquifer Units	Borehole Yield Classification (l/s)	
			Q (Range)	Mean 'Q'
Tena	Very High	Plateau basalt (Tv3(1))	7 – 32	22.8
	High	Upper Hamanilie limestone (Jh2) & Lower basalt (Tv1)	22	22
	Moderate	Pleaocene trachyte (Tv7) & Gobesa Trachyte (Tv5)	1.5 - 5	3.3
	Low	Pleaocene trachyte (Tv7) & Gobesa Trachyte (Tv5)	1.5 - 5	3.3

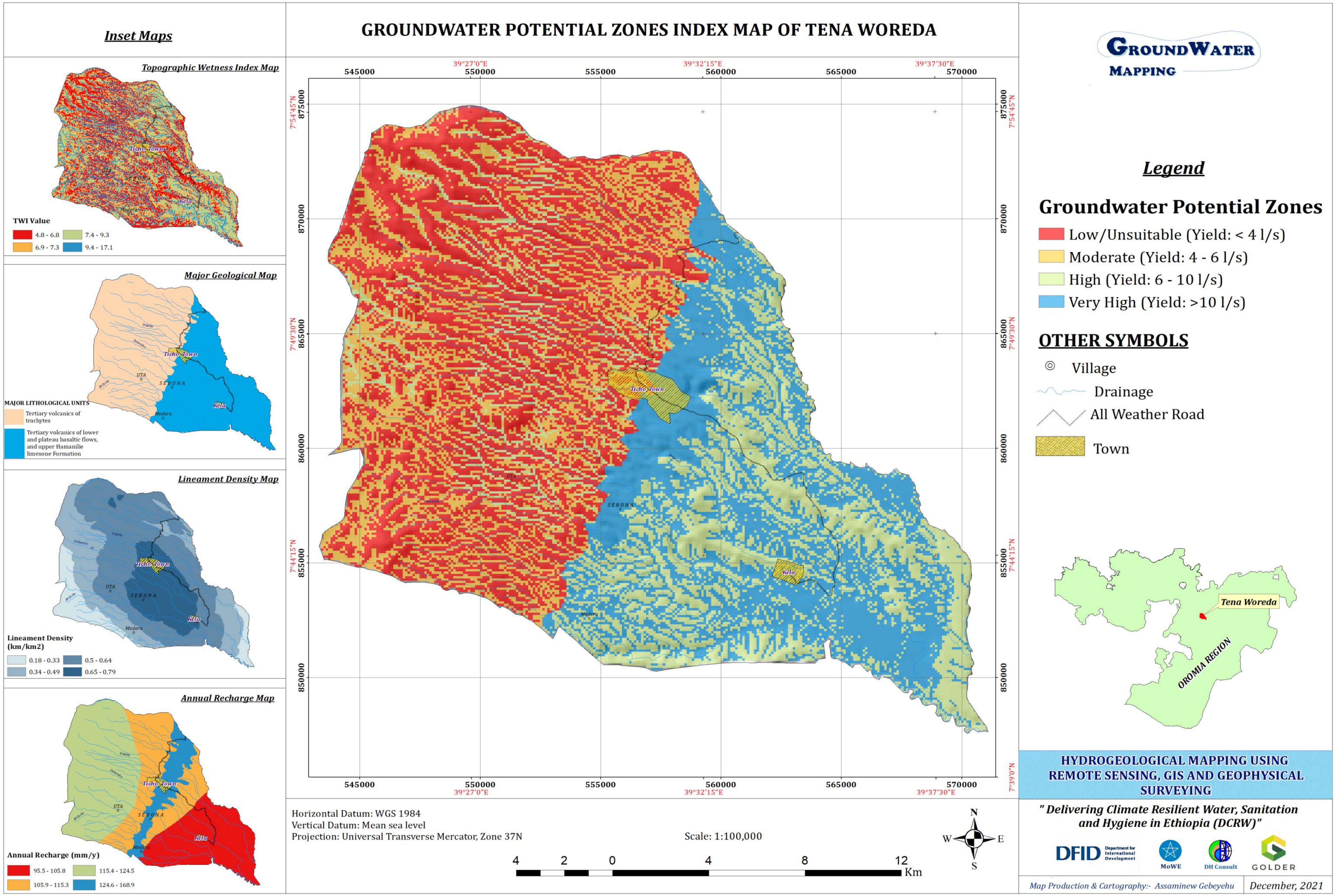

Figure 5-103. Groundwater Potential Zones Map of Tena Woreda

5.9.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) are were collated for over 50 boreholes found around the woreda within the synoptic cluster boundary area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the synoptic area vary from 7 – 32 lit/sec (av. 22.8 lit/sec) in very high potential zones and 22 lit/sec in high potential zones as compared with 1.5 lit/sec to 5 lit/sec (av. 3.3 lit/ sec) in both moderate low potential zones (Figure 5-104). As shown in the Figure 5-104, the occurrence of number of wells with yield of 22 lit/sec (high yield) and of > 20 lit/sec (very high yield) cut across mainly the lower basalt, plateau basalt and upper limestone formations. However, the less frequency of wells within trachytic flows in the low and moderate yield category (1.5 - 5 lit/sec) signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

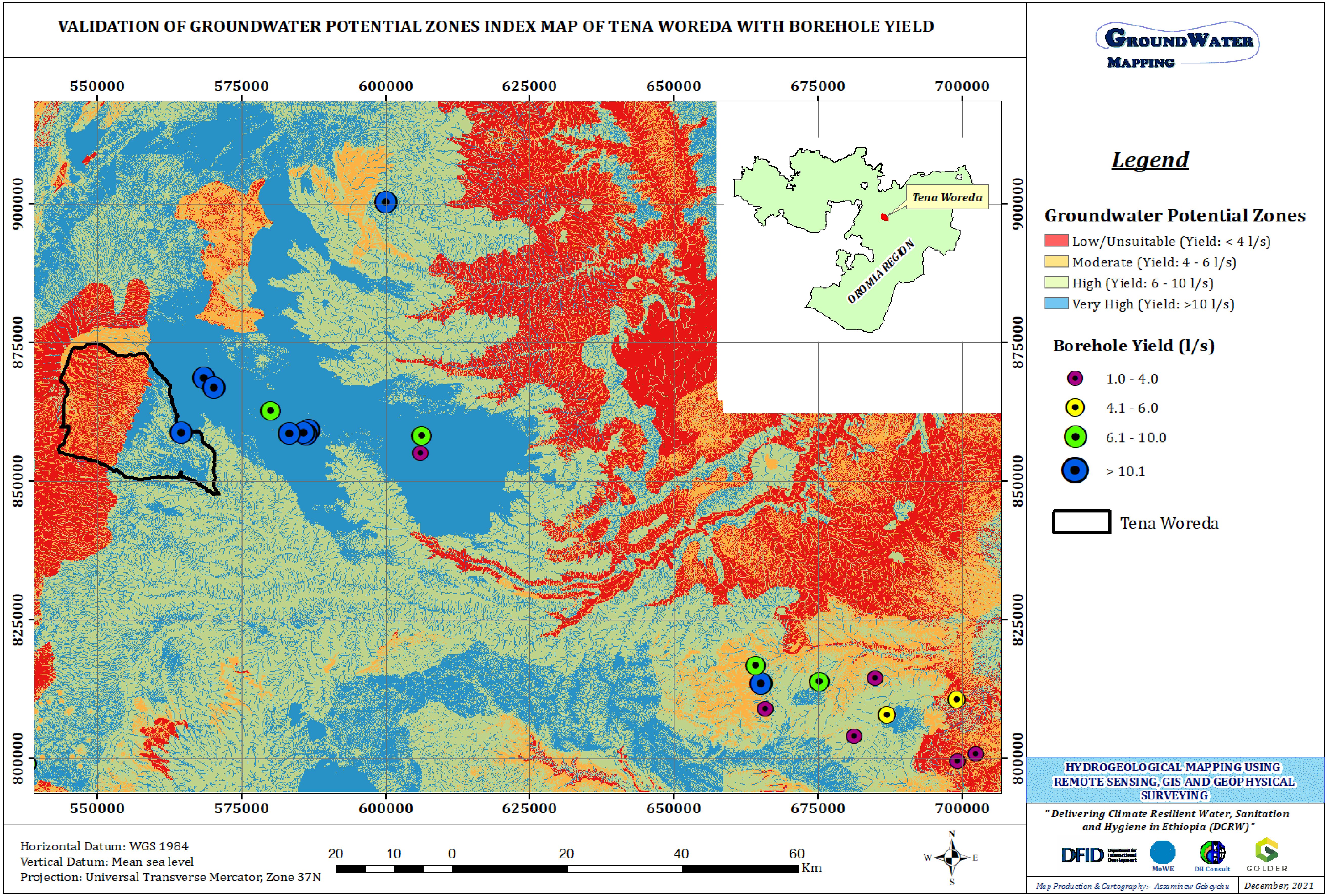

Figure 5-104. Validation of Groundwater Potential Zones Map of Tena Woreda within Arsi-Bale synoptic boundary

5.9.5. Projected Population and Water Demand of Tena

5.9.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-45 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P=Po\,(1 + r)^{n}$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Tena Woreda has been projected forward until 2036 using the growth rate of Oromia Regional State. The minimum and maximum population in the Woreda is 4,083 and 16,228 respectively. The total population of the Tena Woreda in 2036 is going to be 112,383.

5.9.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic

purposes greatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO) & (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer's life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24 hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from 1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-105 shows the distribution of water demand in each Kebeles of the Woreda. Haja Shale kebele water demand is the minimum with 367 M^3/day and maximum water demand is required for Wadagomsa Kebele with 1,458 M^3/day respectively. The overall water demand for the projected population in the Tena Woreda is 10,096 M^3/day.

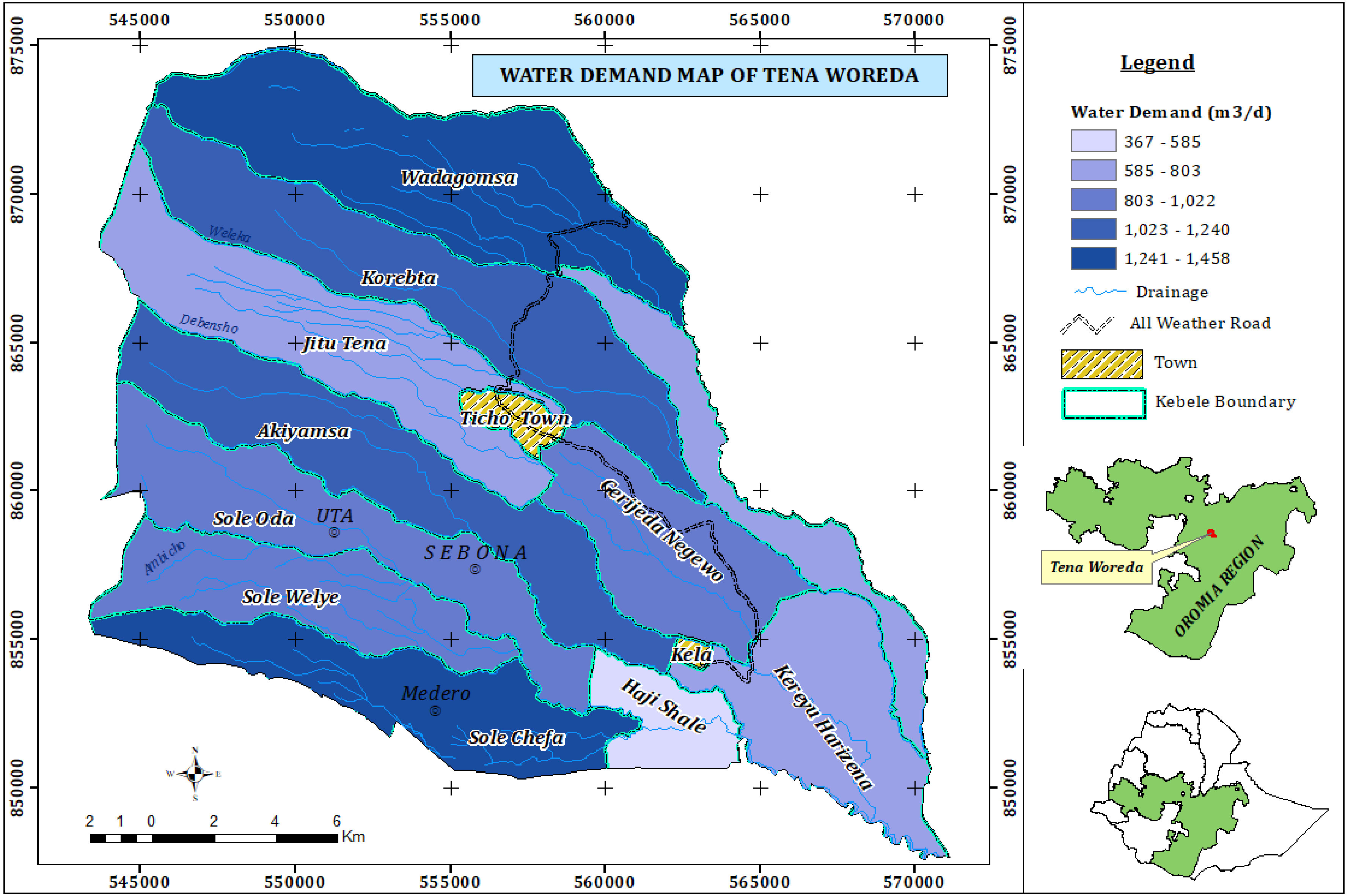

Figure 5-105:-Water Demand Map of Tena Woreda

5.9.6. Propsed Target Sites

Four target sites are identified and proposed within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficiaries and population density. With further discussion and consultation with stakeholders, two priority sites will be selected for further hydrogeological and geophysical investigations in phase III. The following are the four proposed sites:

Target Site-I:

This target site is located in the central regions of the woreda. It is situated in the identified very high potential zones with expected optimum borehole discharge of about 25 l/s. This target site is mainly underlain by plateau basaltic rocks.

Target Site-II:

This target site is located in the southeastern peripherial regions of the woreda. It is situated in the identified high and very high potential zones with expected optimum borehole discharge of about 22 l/s. This target site is mainly underlain by lower basaltic rocks.

Target Site-III:

This target site is located in the central southeastern regions of the woreda. It is situated in the identified high and very high potential zones with expected optimum borehole discharge of about 22 l/s. This target site is mainly underlain by lower basaltic rocks.

Target Site-IV:

This target site is located in the southern region of the woreda. It is situated in the identified high and very high potential zones with expected optimum borehole discharge of about 20 l/s. This target site is mainly underlain by lower basalt, plateau basalt and upper limestone rocks.

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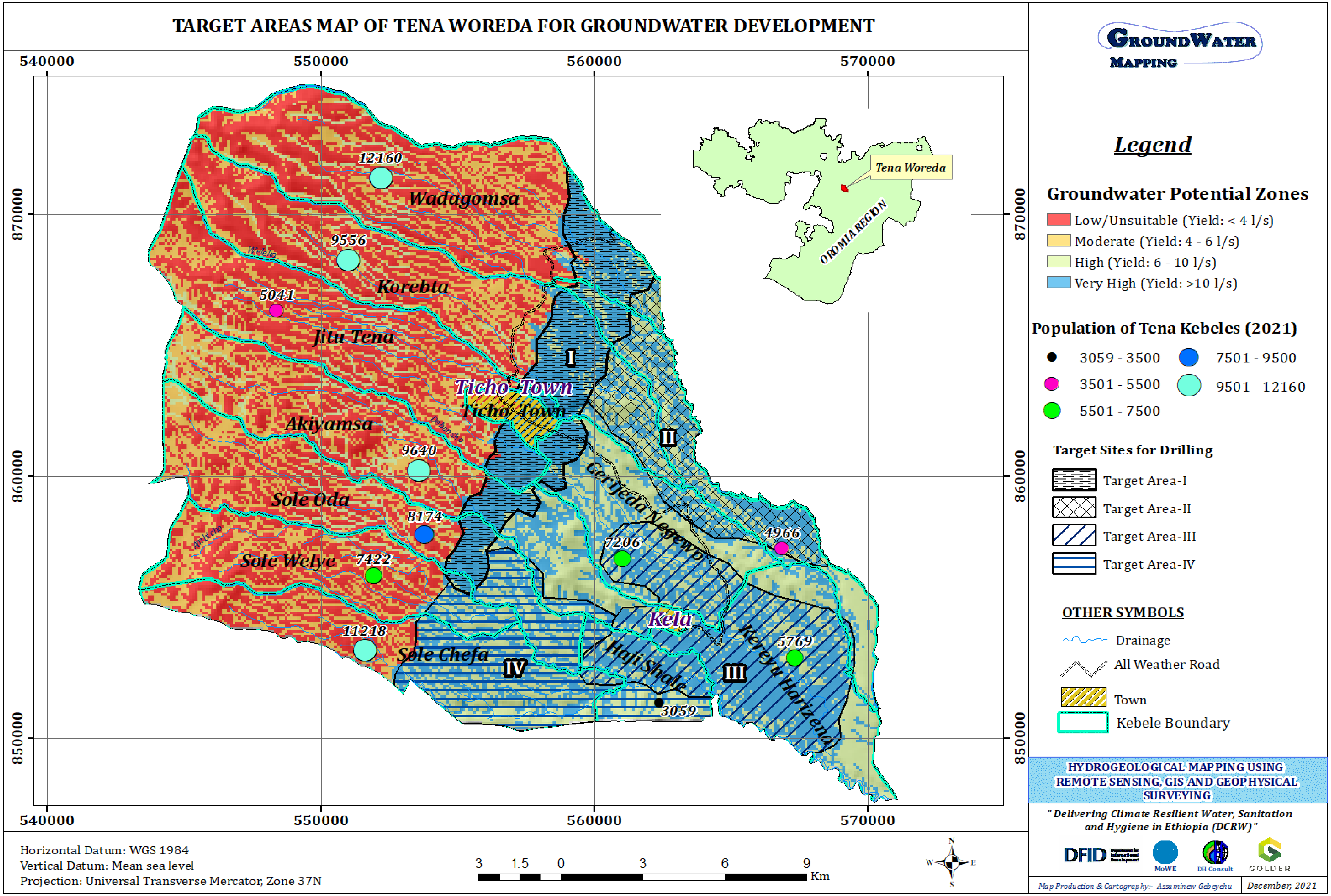

Figure 5-106:-Target Areas Map of Tena Woreda

5.10. Adadle Woreda

5.10.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.03 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Adadle woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-46). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-47. The weights assigned to the respective thematic maps as presented in Table 5-48 indicate that geology was ranked the dominant factor with a normalized weight value of 0.53 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Adadle woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Adadleworeda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

GWPZI = (GGwGGwi + LDwLDwi + TWIwTWIwi + GRwGRwi)

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Adadleworeda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e., 'high', 'moderate, 'low and very low', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-46 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Geology (GG)	5
Lineament density (LD)	3
Topographic Wetness Index (TWI)	1
Recharge (GR)	1

Table 5-47 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	GG	LD	TWI	GR	
GG	1	3	5	3	0.53
LD	1/3	1	3	1	0.21
TWI	1/5	1/3	1	1	0.10
GR	1/3	1	1	1	0.16

Table 5-48 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank	Area (km^2)	Area (%)
Geology/ Lithology, 'GG'	Baslat and Fluvial sand silt (Stream channel deposit)	Good	3	0.50	0.53	583.31	10
	Mesozoic sedimentary rocks	Moderate	2	0.30		3,252.37	30
	Gypsum rocks	poor	1	0.17		5,054.15	60
Lineament Density,' LD' (Km/Km^2)	0 - 0.23	poor	1	0.10	0.21	4,546.77	51
	0.24 - 0.47	Good	2	0.20		3,363.21	38
	0.48 – 0.70	Moderate	3	0.30		922.58	10
	0.71 – 0.93	Very good	4	0.40		57.3	1
Topographic Wetness Index, 'TWI'	4.19 – 7.34	poor	1	0.10	0.1	3,557.83	40
	7.35 – 9.1	Good	2	0.20		4,715.47	53
	9.11 – 11.8	Moderate	3	0.30		607.62	7
	11.9 – 19.1	Very good	4	0.40		9.0	0.01
Recharge, 'GR' (mm/y)	23.2 – 28.5	poor	1	0.10	0.16	5,383.	0.94
	28.6 – 48	Good	2	0.20		222.15	0.026
	48.1 – 97	Moderate	3	0.30		131.44	0.015
	97.1 - 190	Very good	4	0.40		91.58	0.01

5.10.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of geology, rainfall, lineament density, geomorphology, land slope, soil type, land use/land cover, groundwater depth and drainage density together with their spatial distribution in *Adadleworeda*are presented below:

I. Geology/lithology

In general, most parts of the Adadle woreda are underlain by Mesozoic sedimentary rocks of limestone and gypsum with shale. Tertiaryvolcanics and Quaternary deposits of alluvial are mostly found oncentral and eastern parts of the woreda.

However, the lithological units found in the woreda area are further classified into four major groups based on their significances to groundwater occurrence and productivity using borehole data on yield analysis in particular.

- Fluvial sand silt (Stream channel deposit) (high productive with Q >5.0 l/s)
- Limestone locally cherty (KoraheBeletUen) with Sandstone, siltstone intercalations with local limestone (KoraheAmbaradom) (moderately productive with Q =2.0-5.0 l/s)
- Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle) very low productive with Q =0.05-0.5 l/s)

The mesozoicsedimentary rocks are the main lithologic framework of the Adadle woreda which together covered a total area of about 3,655.5 km^2 or 91 % of the woreda area, tertiary volcanics and quaternary recent sediments covered about 359 km^2 (9 %)of the woreda area (Figure 5-107).

Usually, massive unfracturedlithologic units in sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification and weathered overburden, and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the weathered regolith units, karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of low productivity of Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle)(0.17) \moderate productivity of Limestone locally cherty (Korahe_BeletUen) with Sandstone, siltstone intercalations with local limestone (KoraheAmbaradom) (0.33)/ high productivity Fluvialsandsilt(Streamchanneldeposit)(0.5).

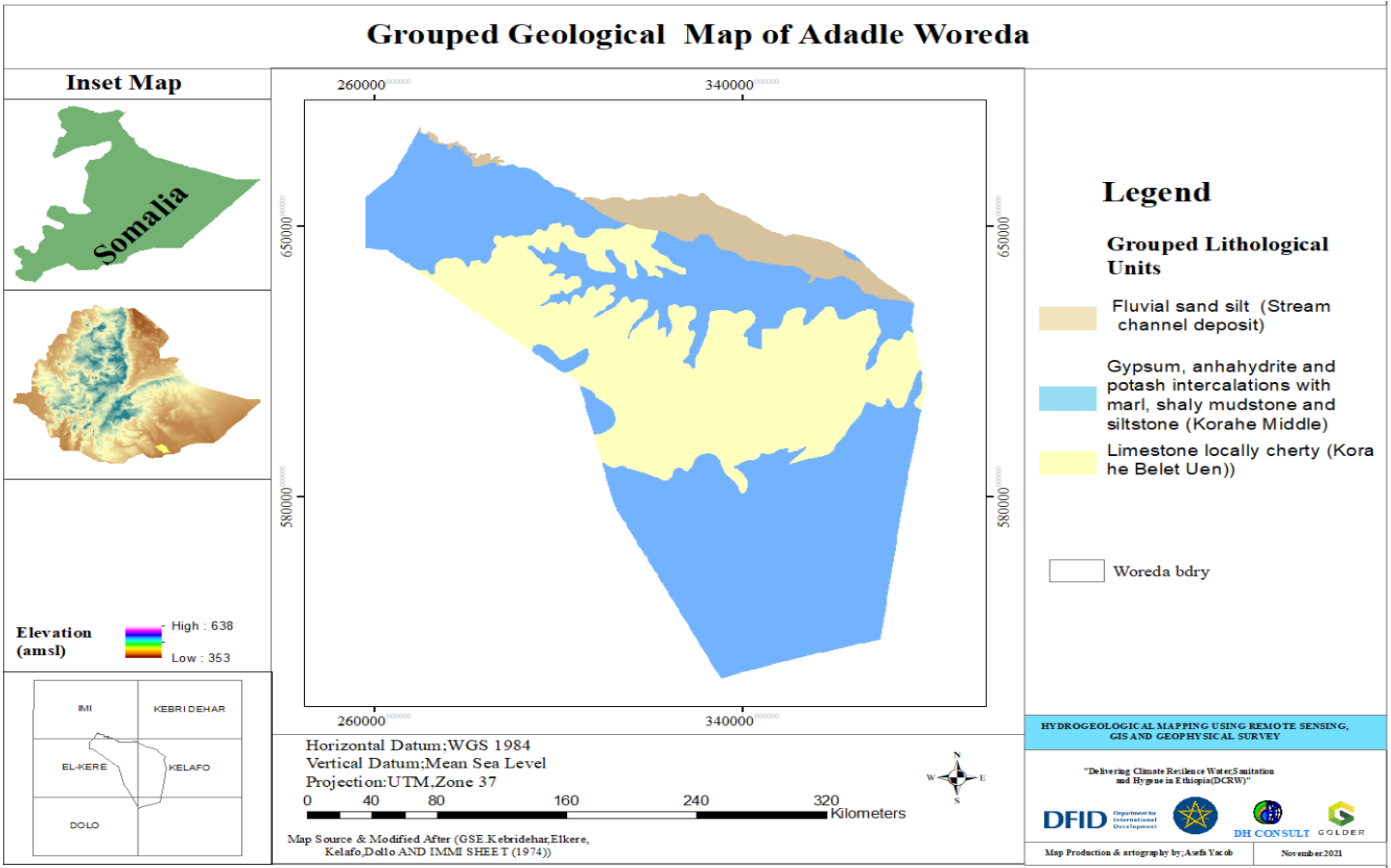

Figure 5-107 Grouped Lithological classification map of Adadleworeda

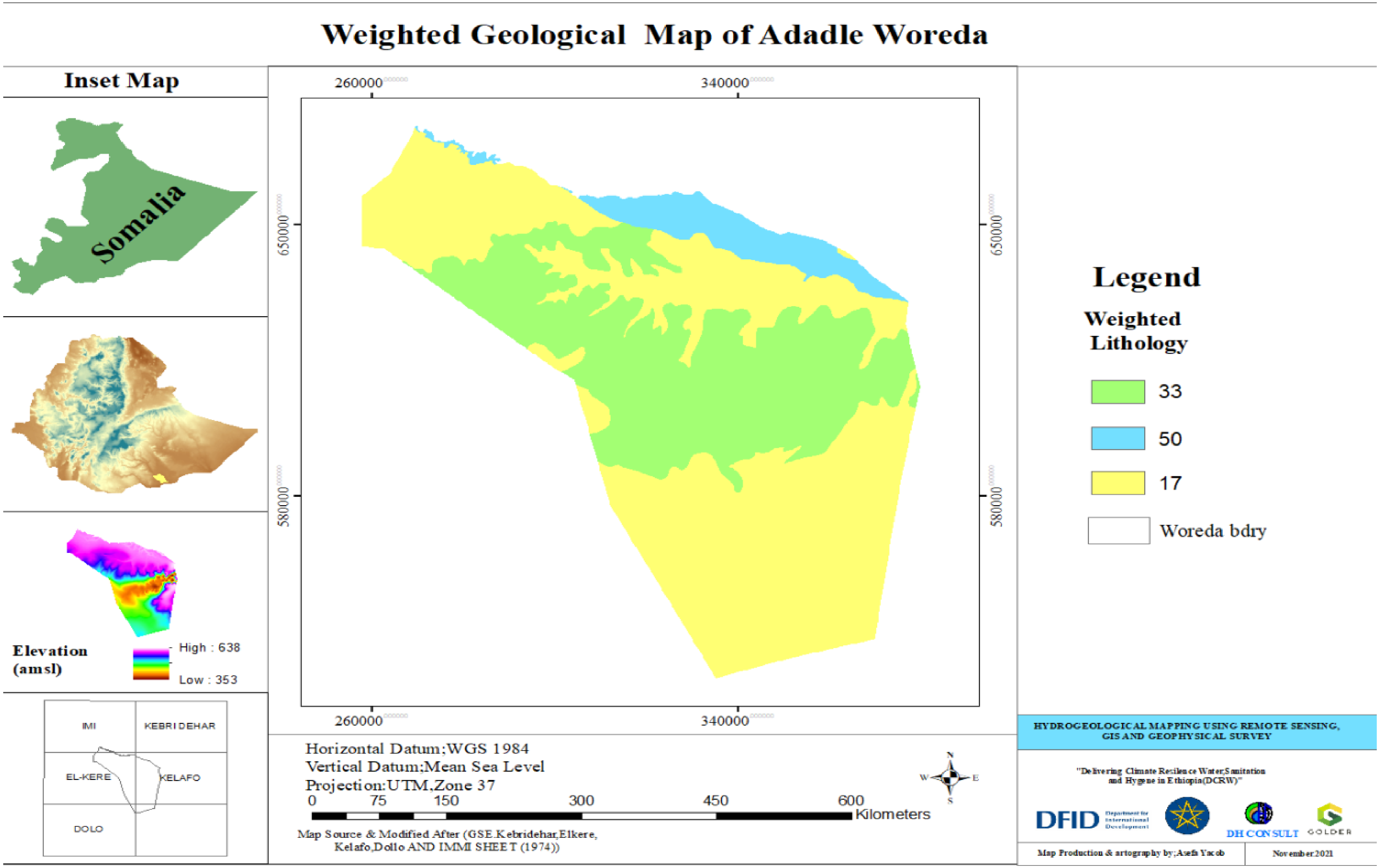

Figure 5-108 Weighted lithological classes' map of the Adadleworeda

II. *Lineaments and lineament density*

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SEand N–S trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.26 km/km2 to 1.06 km/km^2 (Figure 5-109). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by mesozoic sediments having relatively higher lineament density of 0.79 – 1.06 km/km2 compared with areas underlain by sedimentary rocks of gypsum with lower lineament densities of (<0.26 km/km2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.40 was assigned to area with high density of lineaments, while a low weightage of 0.10 was assigned to areas with low lineament density (Figure 5-110).

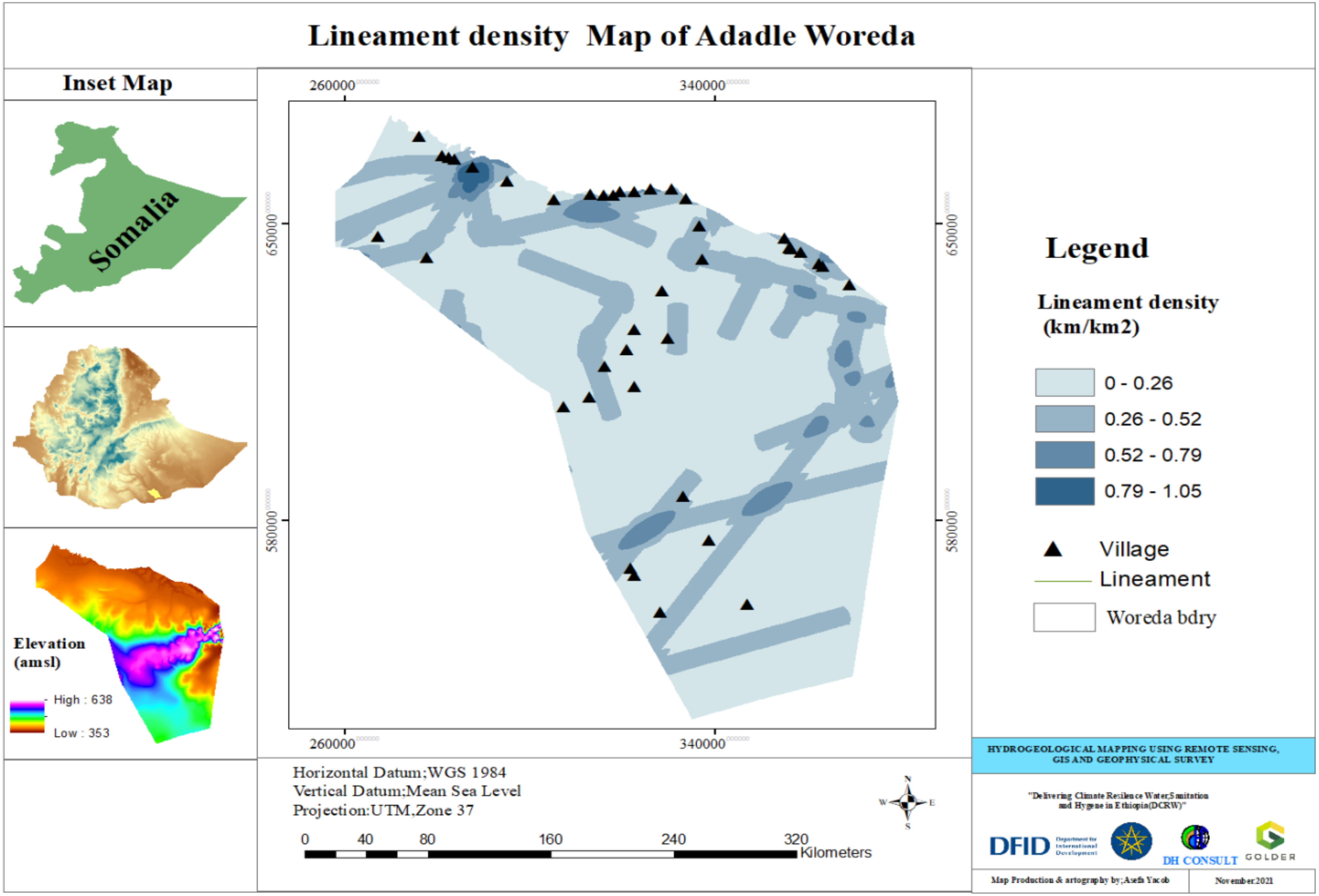

Figure 5-109 Lineament Density Map ofAdadleworeda

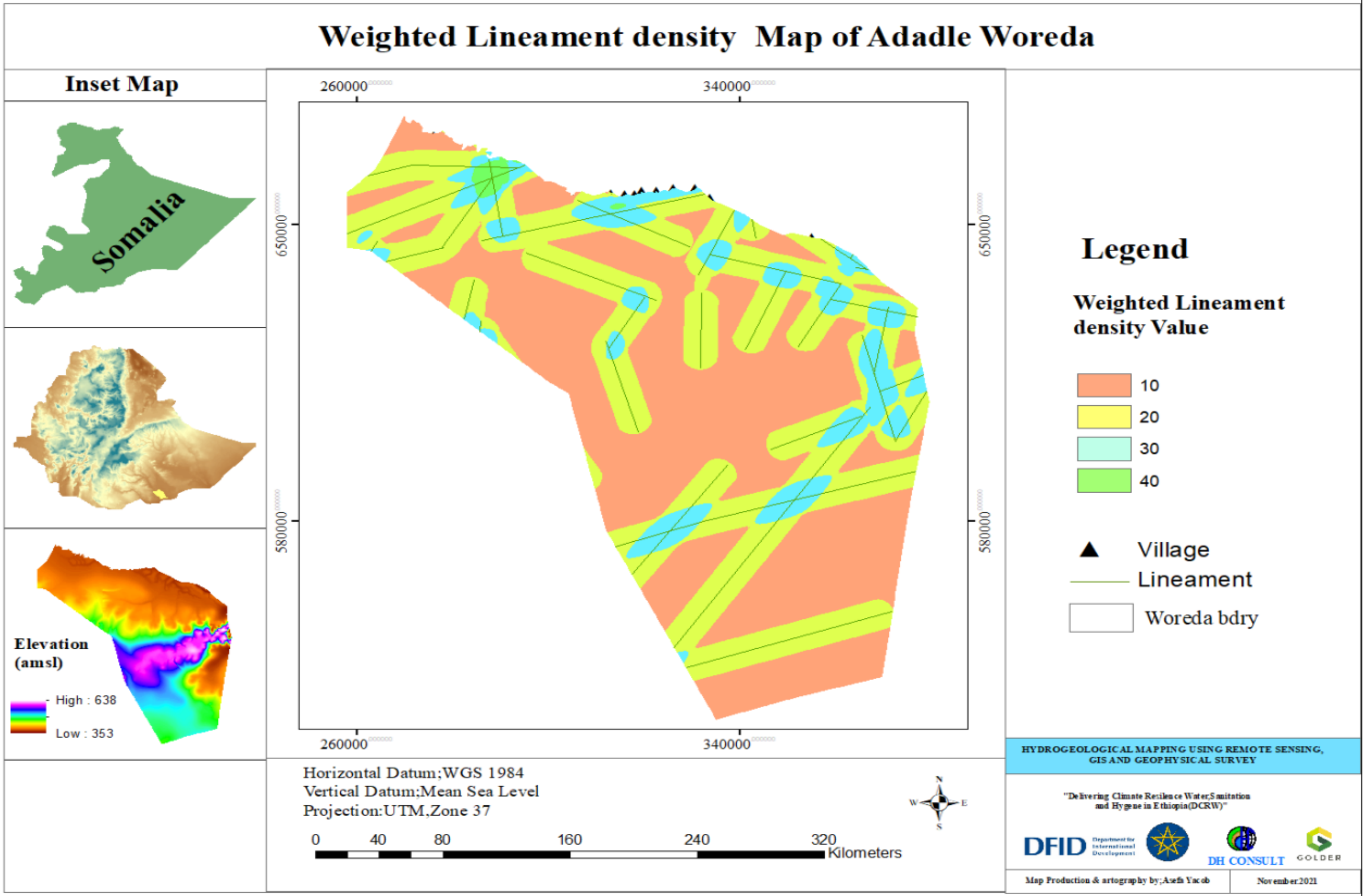

Figure 5-110. Weightage value of Lineament Density Map of Adadle woreda

III. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 5.15 and 14.73. A closer look at the classification revealed that most the high elevated areas and drainage systems with steep slopes have relatively lower TWI value while the low-lying areas and drainage systems with gentle and flat slopes have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.40) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.10).

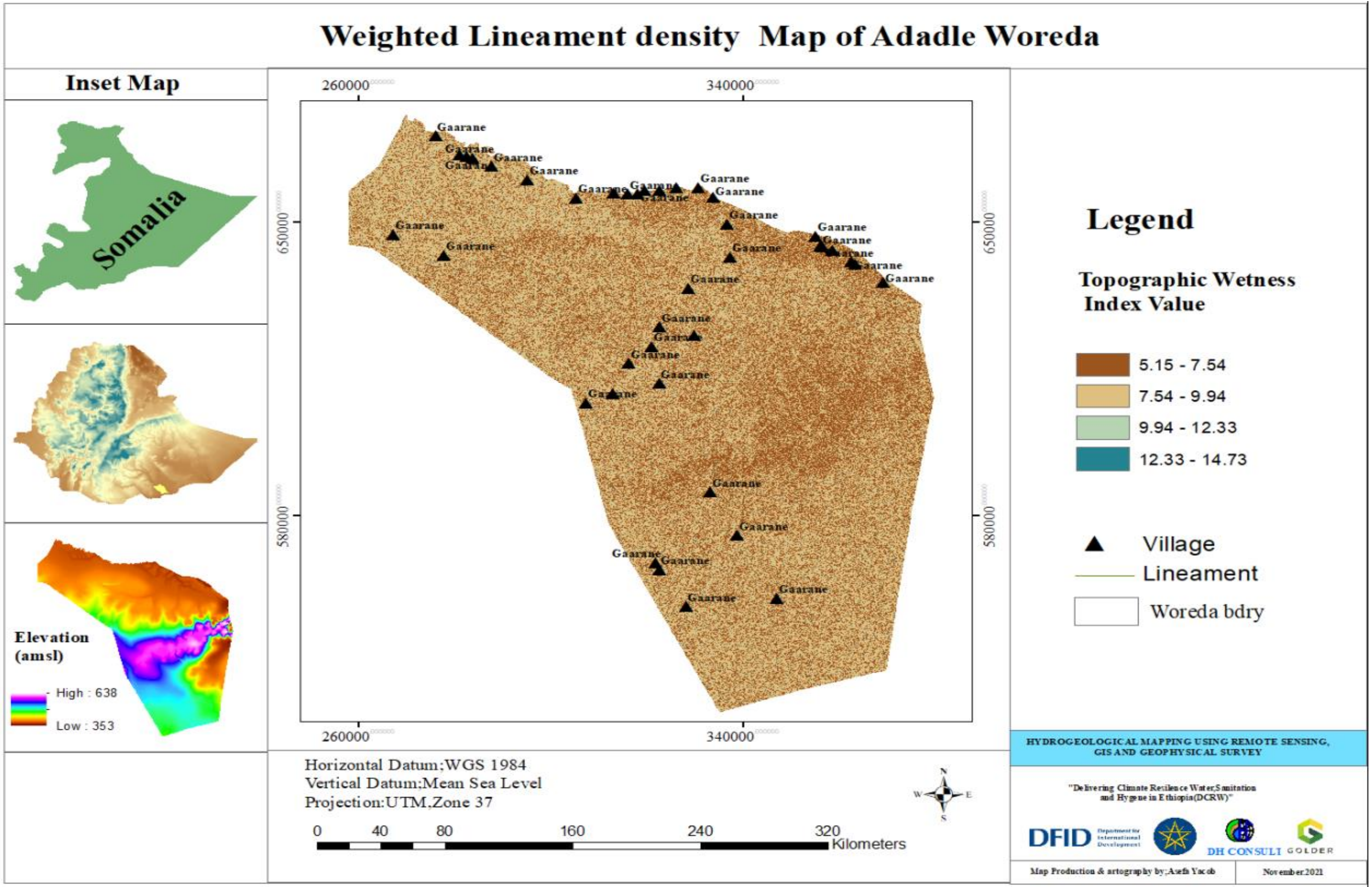

Figure 5-111 TWI Map of Adadle woreda

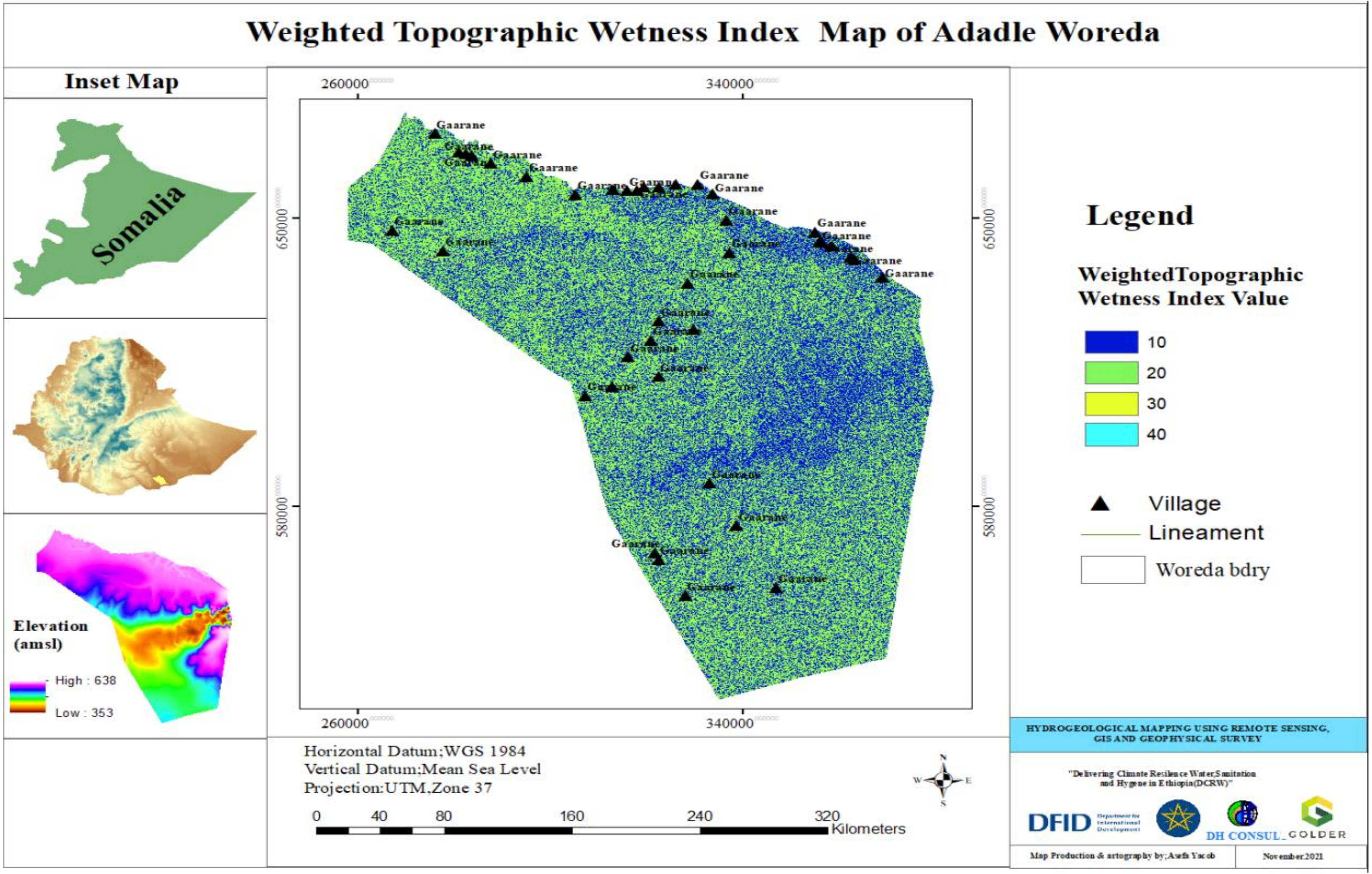

Figure 5-112. Weightage value of TWI Map of Adadle woreda

IV. Recharge

The spatial annual recharge rate distribution in the Adadleworedaranges from 11.48 to 54.48 mm/y suggesting groundwaters in most part of the woreda area underlain by basement complex receive low amount of recharge while areas underlain by sedimentary rocks and quaternary sediments have relatively higher recharge amount (Figure 5-113). Accordingly, areas with higher and moderate amount of recharge have weightage factor of 0.40 and 0.30, respectively signifying very good and moderate groundwater potential which covers about 578.49 km2 (7 %) and 2.73 km2 (0.03 %), respectively while areas with the lowest amount of recharge have weightage factor of 0.10, suggesting poor groundwater potentiality and represent about 5,383.14 km2 (60 %). A closer look at the recharge thematic map revealed that most parts of the woreda have relatively moderate recharge (22.23-32.98 mm/y). Generally, the study area is characterized with lowmean annual recharge amount (<11.48mm /y).

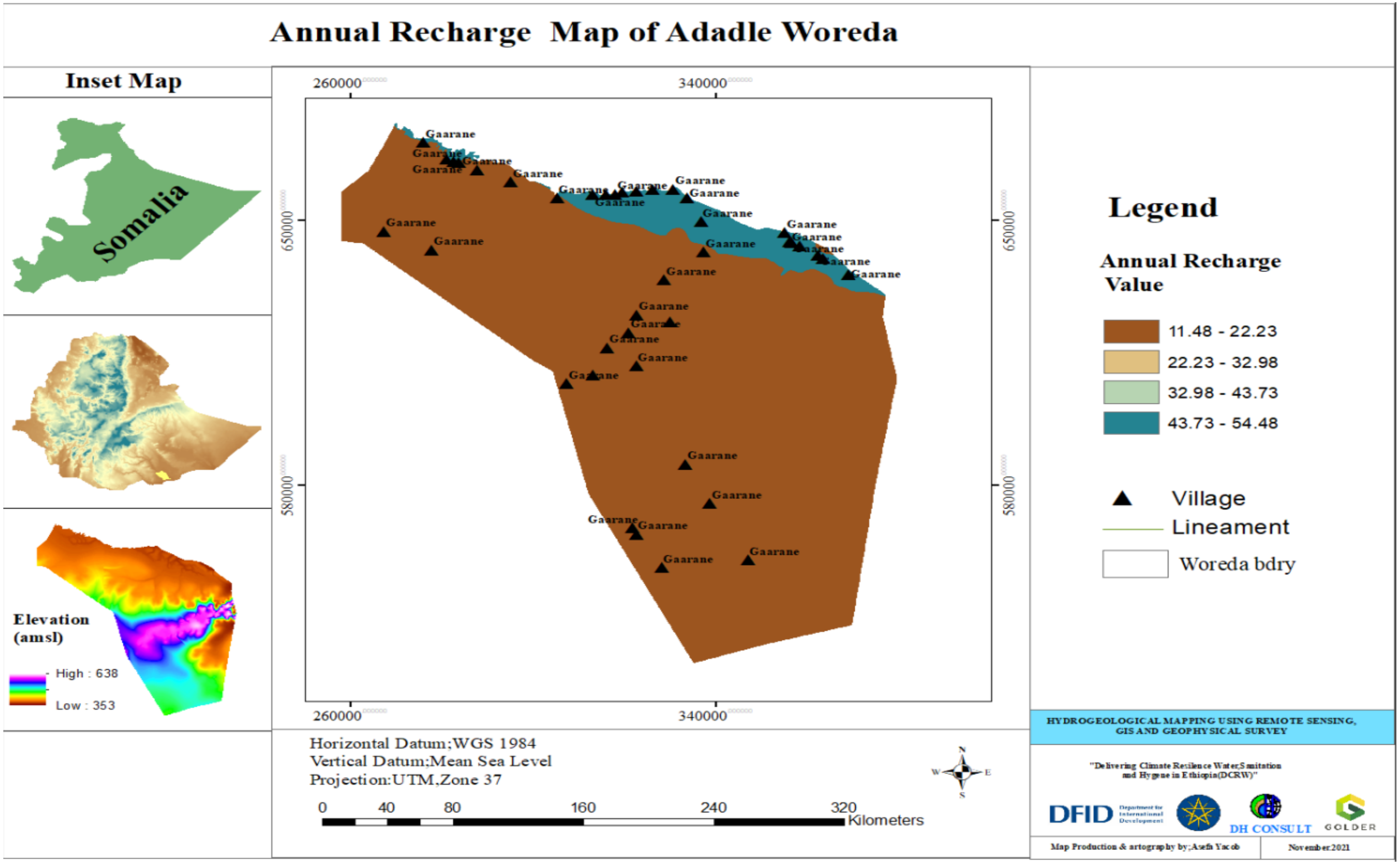

Figure 5-113.. Annual Recharge Map of Adadle woreda

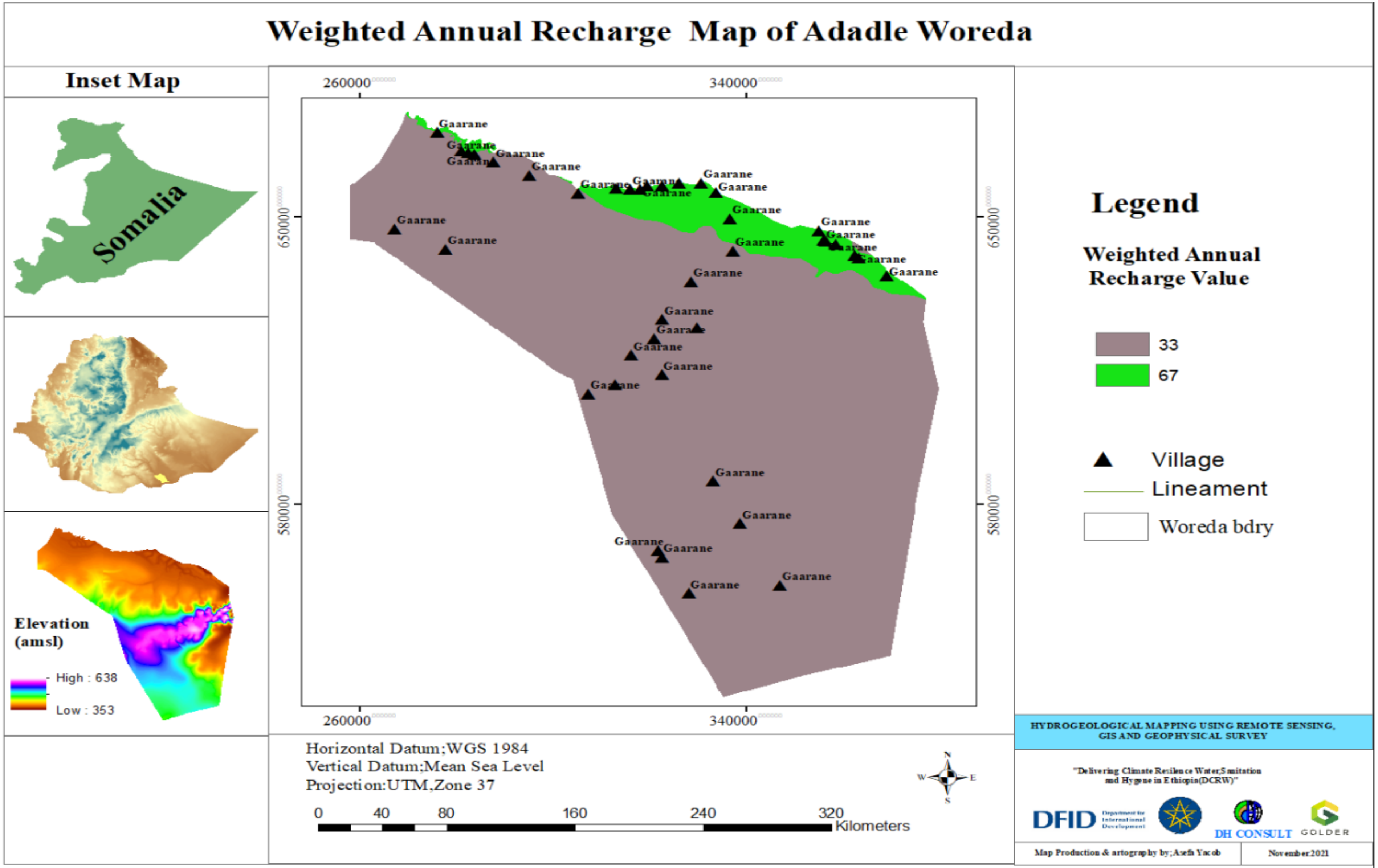

Figure 5-114. Weighted Annual Recharge classes' map of the Adadle woreda

5.10.3. Classification of Groundwater Potential Zones

The hydrogeological system of Adadleis comprised of four main lithological units as Fluvial sand silt (Stream channel deposit), Limestone locally cherty (KoraheBeletUen) with Sandstone, siltstone intercalations with local limestone (KoraheAmbaradom), Shale mudstone limetone intercalations (Gabradarre) and Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle). At regional scale, Baslat and Fluvial sand silt (Stream channel deposit) form extensive and highly productive aquifers. Within the domain of *Adadle woreda*, thequaternary deposits form aquifers with high groundwater potential.

At regional scale, the Limestone Formation and lower sandstone form extensive and moderately productive aquifers having high hydraulic conductivity. However, at local scale, within the domain of AddadileWoreda, due to the geomorphic setup, the Limestone Formation and the underlying units do not form high potential aquifer as revealed from existing borehole information rather the Weathered and slightly fractured sedimentary rocks with overlying Quaternary deposit form major potential aquifer with moderate productivity within the domain of *Adadle woreda* along lineament lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-115). The potential groundwater zones (PGZ) of the *Adadle woreda* revealed four distinct zones, namely very low,low, moderate and high zones whose distribution and extents are 5,383.14 km2 (60 %), 2,925.50 km2 (30 %), 2.73 km2 (3%) and578.49 km2 (7 %), respectively as presented in Table 5-49.

The potential map, as presented in Figure 5-115, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that most elevated areas around the peripheries and central parts of the AdadleWoreda generally have very low potentials with area coverage of about 60 %, while limited areas at central regions generally exhibits moderateto low potentials representing about 3 % and 30 % of the study area, respectively. The generally high to moderate groundwater potentiality of the study area as reflected by 7 % coverage is a confirmation of generally moderate to high productive aquifers of recent alluvial and sedimentary deposits, whereas low to very low groundwater potential areas have an indication of limited aquifers capabilities of gypsum and shale with marl intercalation.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the geology and lineament density in addition to the topographic wetness index control. In addition, areas underlain by recent quaternary deposits especially in the central and southern sections of the study area which are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments and apparently deep fracturing and weathering have high and moderate groundwater potential on the one hand. On the other hand, areas underlain by sedimentary rocks of limestone and gypsum in the majority of the woreda areas are characterized by small ridges and steep slopes, lower recharge and lineament densities, exhibit low groundwater potential while areas underlain by sedimentary rocks associated with sediments have medium potential. Moreover, high drainage densities and predominance of limestone rock outcrops can be attributed to the observed low groundwater potentials at the most part of the study area. However, predominance of recent sediments and sedimentary rock outcrops, low drainage density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential exhibited at central and western portions of the study area. Summary of the groundwater potential zones identified in the *Adadleworeda*is presented in the table below (Table 5-49).

Table 5-49.Classification of groundwater potential zones and coverage areas alongside the respective yield and transmissivity categories

Woreda Name	GWP Zones	Area (km^2)	Area (%)	Major Aquifer Units	Borehole Yield Classification (l/s)
					Q (Range)
Haromaya	High	578. 14	7	quaternary Sediments	>5
	Moderate	2.73	3	Sedimentary Rocks limestone	2-5
	Low	2,925.50	30	Sedimentary Rocks Gypsum	0.5-2
	Very Low	495,383.	60	Shale and marl	0.05-0.5

5.10.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) were collated for boreholes in and around the study woreda area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the study area vary from >5 lit/sec in high potential zones and varying 2- 5 lit/sec in moderate potential zones, 0.5 lit/sec to 2 lit/sec in the low and from 0.05-0.5 lit/sec in the very low potential zones (Figure 5-115). As shown in the figure, the occurrence of number of wells with yield of in the range 2- 5 lit/sec (moderate yield) and of >5 lit/sec (high yield) cut across mainly the recent quaternary deposits and sedimentary rocks. However, the less frequency of wells within gypsum and shale rock in the low and very low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (2- 5 lit/sec) and high-yield (>5 lit/sec) categories are associated also with wells in the Mesozoic sedimentary rocks and quaternary alluvial deposits along river channel. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such basement and sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

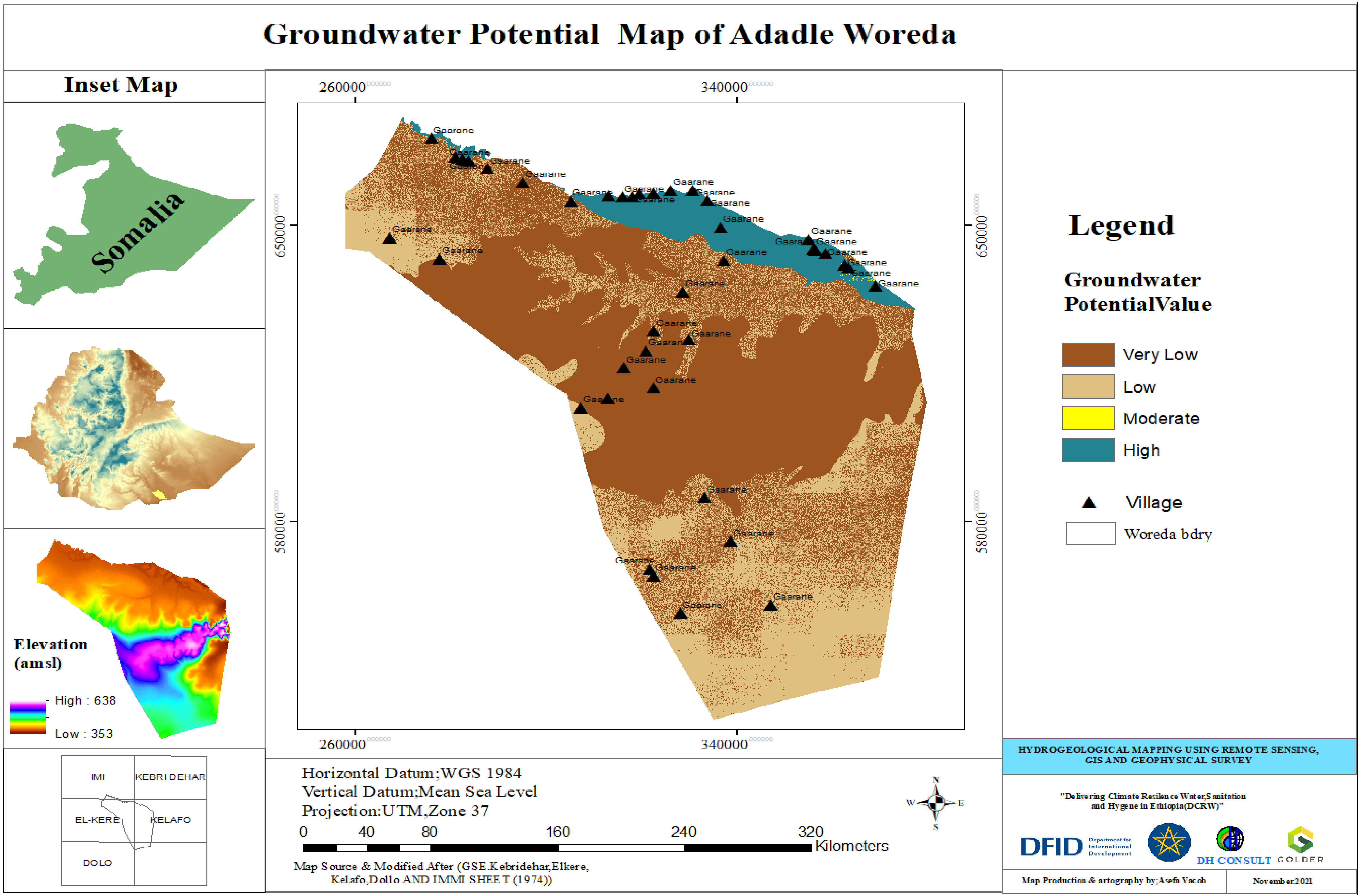

Figure 5-115. Groundwater Potential Zones Map of Adadle woreda

5.10.5. PopulationprojectionandWater Demand

5.10.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-50 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P = Po\,(1 + r)^{n}$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of AdadleWoreda has been projected forward until 2036 using the growth rate of Somali Regional State. The minimum and maximum population in the Woreda is 5,644and 23,745 respectively. The total population of the AdadleWoreda in 2036 is going to be 123,259.

5.10.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic purposesgreatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO)& (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer's life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24-hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-116 shows the distribution of water demand in each Kebeles of the Woreda. HilogaDudokebele water demand is the minimum 592 M^3/day and maximum water demand is required forBolihagareKebele with2488 M^3/day respectively. The overall water demand for the projected population in the AdadleWoreda is 12,918M^3/day.

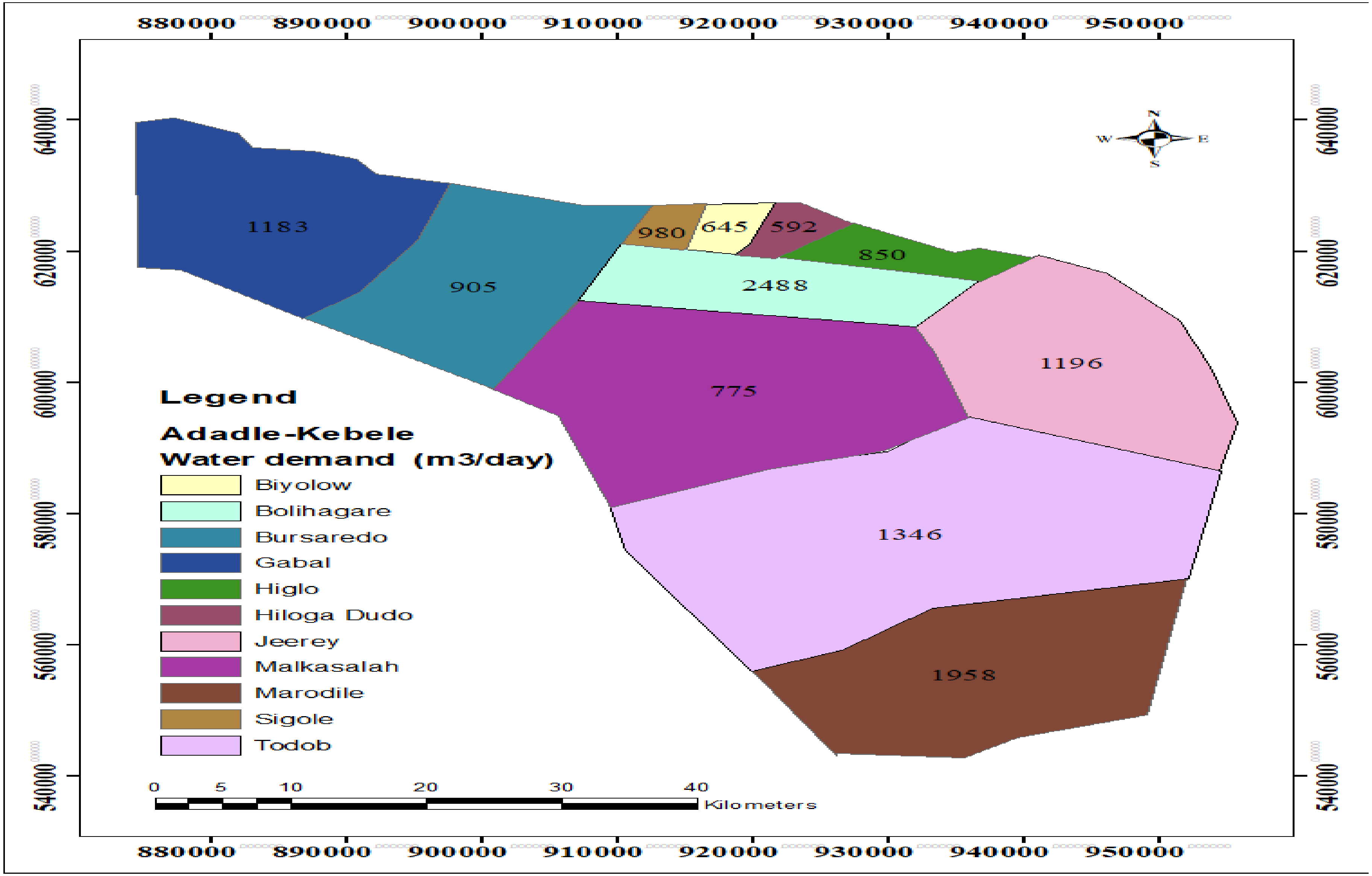

Figure 5-116. Water Demand Map of Adadile woreda

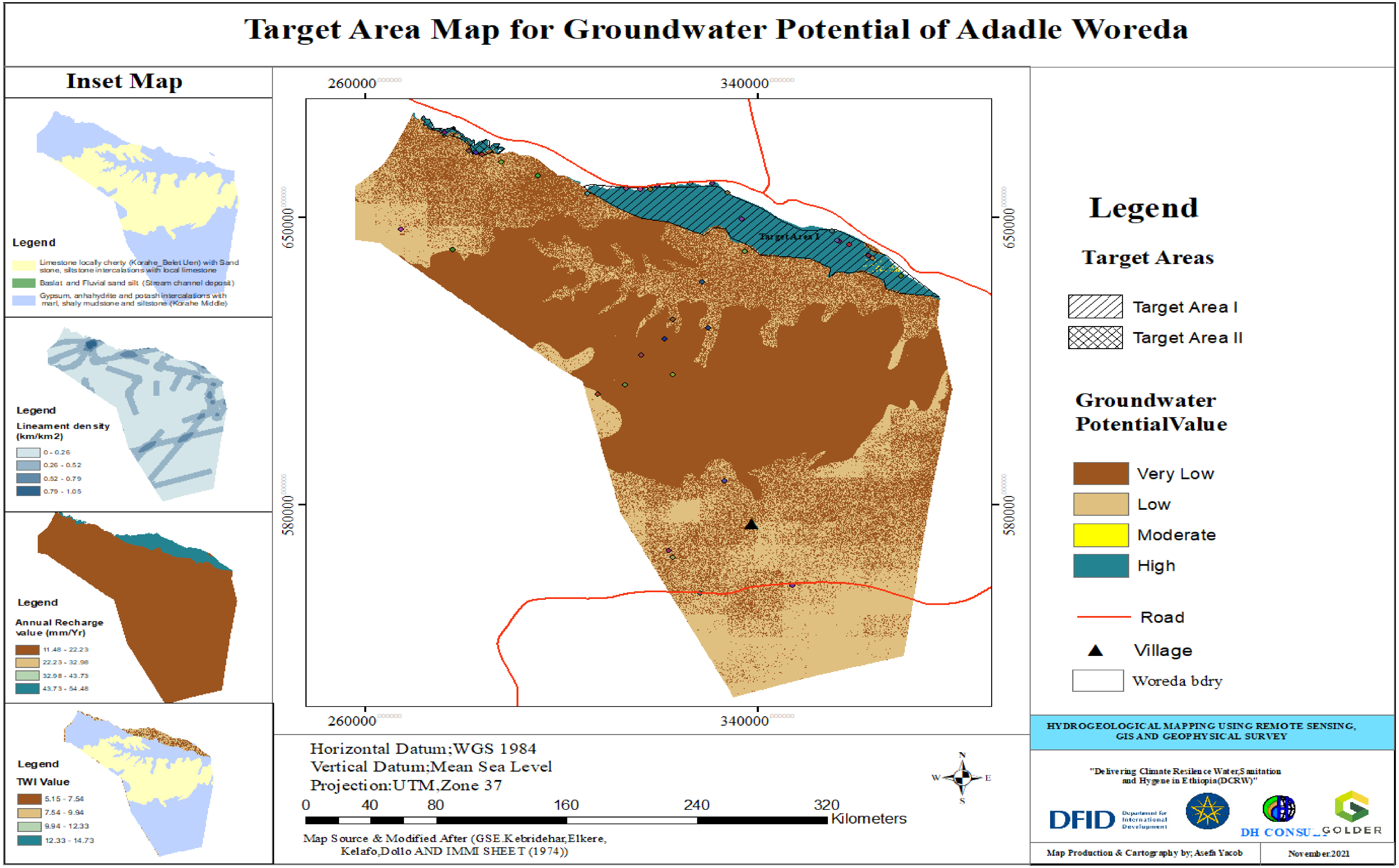

Figure 5-117:-Target Areas Map of Adadleworeda

5.10.6. Propsed Target Sites

Proposed target sites are identified, prioritized and selected within the woredabased on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficieries, population density and discussion made with the woreda's stakeholders so that to understand and identify kebeles with sever water shortage in particular. Accordingly, four priority target sites were selected and delineated within the Adadleworedafor detail studies to be carried out in order to verify further and locate appropriate borehole drilling sites.

Target Site-I:

This target site is located in the northern part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 5.0 l/s. This target site is mainly underlain by Tertiary volcanics and quaternary recent deposits of alluvial sediments.

Target Site-II:

This target site is located in the northern part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 5.0 l/s. This target site is mainly underlain by Tertiary volcanics and quaternary recent deposits of alluvial sediments.

5.11. Dihun Woreda

5.11.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.03which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Duhun woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-51). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-52. The weights assigned to the respective thematic maps as presented in Table 5-53 indicate that geology was ranked the dominant factor with a normalized weight value of 0.53 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Duhun woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Adadle woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

$$GWPZI = (GGwGGwi + LDwLDwi + TWIwTWIwi + GRwGRwi)$$

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Duhun woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e., 'high', 'moderate, 'low and very low', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-51 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Geology (GG)	5
Lineament density (LD)	3
Topographic Wetness Index (TWI)	1
Recharge (GR)	1

Table 5-52 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	GG	LD	TWI	GR	
GG	1	3	5	3	0.53
LD	1/3	1	3	1	0.21
TWI	1/5	1/3	1	1	0.10
GR	1/3	1	1	1	0.16

Table 5-53 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank	Area (km^2)	Area (%)
Geology/ Lithology, 'GG'	Gravelly Sand.Fluvial sand silt (Stream channel deposit)	Good	3	0.50	0.53	1,514.75	38
	Mesozoic sedimentary rocks	Moderate	2	0.33		944.11	23
	Gypsum rocks	poor	1	0.17		1,559.52	39
Lineament Density,' LD' (Km/Km^2)	0—0.27	poor	1	0.10	0.21	763.79	19.1
	0.27-0.55	Good	2	0.20		1,854.86	46.1
	0.55-0.82	Moderate	3	0.30		1,225.25	30.5
	0.82-1.10	Very good	4	0.40		169.09	4.2
Topographic Wetness Index, 'TWI'	4.34-10.02	poor	1	0.10	0.1	2,567.41	64
	7.18-10.02	Good	2	0.20		1,403.13	35
	10.02-12.86	Moderate	3	0.30		40.58	1
	12.86-15.70	Very good	4	0.40		7.04	0.2
	14.88-35.93	poor	1	0.10		1,630.01	41

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank	Area (km^2)	Area (%)
Recharge, 'GR' (mm/y)	35.93-56.98	Good	2	0.20	0.16	868.76	22
	56.98-78.03	Moderate	3	0.30		366.01	9
	78.03-99.07	Very good	4	0.40		1,131.13	28

5.11.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of geology, rainfall, lineament density, geomorphology, land slope, soil type, land use/land cover, groundwater depth and drainage density together with their spatial distribution in *Duhun woreda* are presented below:

I. Geology/lithology

In general, most parts of the *Duhun woreda* are underlain by Mesozoic sedimentary rocks of limestone sandstone, shale and gypsum with Gravely sand silt (Alluvial fan deposit). Quaternary deposits of alluvial and sandstone are mostly found oncentral and eastern parts of the woreda.

However, the lithological units found in the woreda area are further classified intothree major groups based on their significances to groundwater occurrence and productivity using borehole data on yield analysis in particular.

- Gravely sand silt (Alluvial fan deposit) (high productive with Q >5.0 l/s)
- Limestone locally cherty (Korahe Belet Uen) with Sandstone, siltstone intercalations with local limestone (Korahe Ambaradom) (moderately productive with Q =2.0-5.0 l/s)
- Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle) very low productive with Q =0.05-0.5 l/s)

The Mesozoic sedimentary rocks are the main lithologic framework of the *Duhun woreda* which together covered a total area of about 2,503.65 km2 or 62 % of the woreda area, quaternary recent sediments covered about 1,514.74 km2 (38%) of the woreda area (Figure 5-118).

Usually, massive unfractured lithologic units in sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification and weathered overburden, and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the weathered regolith units, karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of low productivity of Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle) (0.17) \moderate productivity of Limestone locally cherty (KoraheBelet Uen) with Sandstone, siltstone intercalations with local limestone (Korahe Ambaradom) (0.33)/ high productivity Gravelly sand, Fluvial sand silt (Stream channel deposit) (0.50).

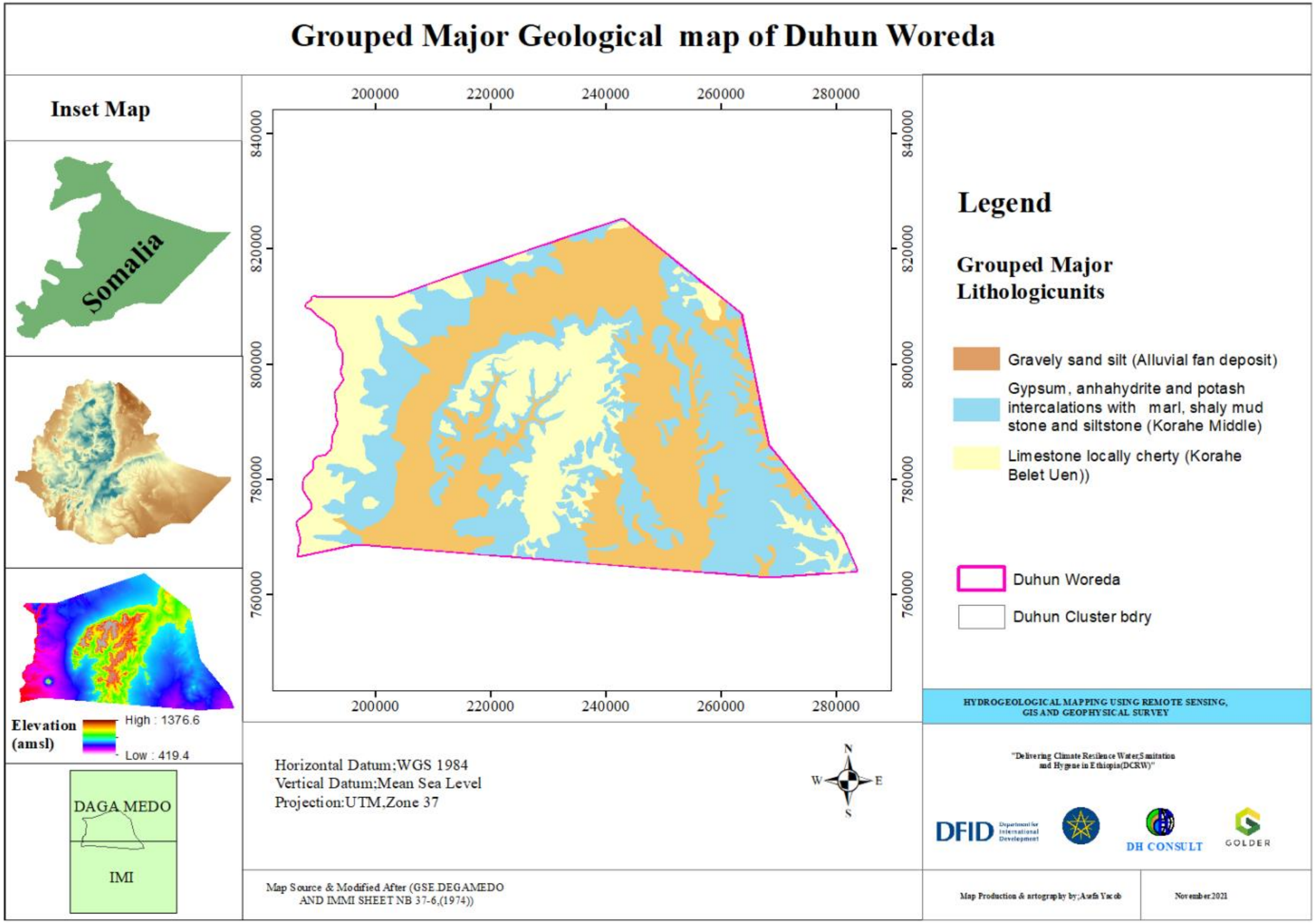

Figure 5-118. Grouped Lithological classification map of Duhun woreda

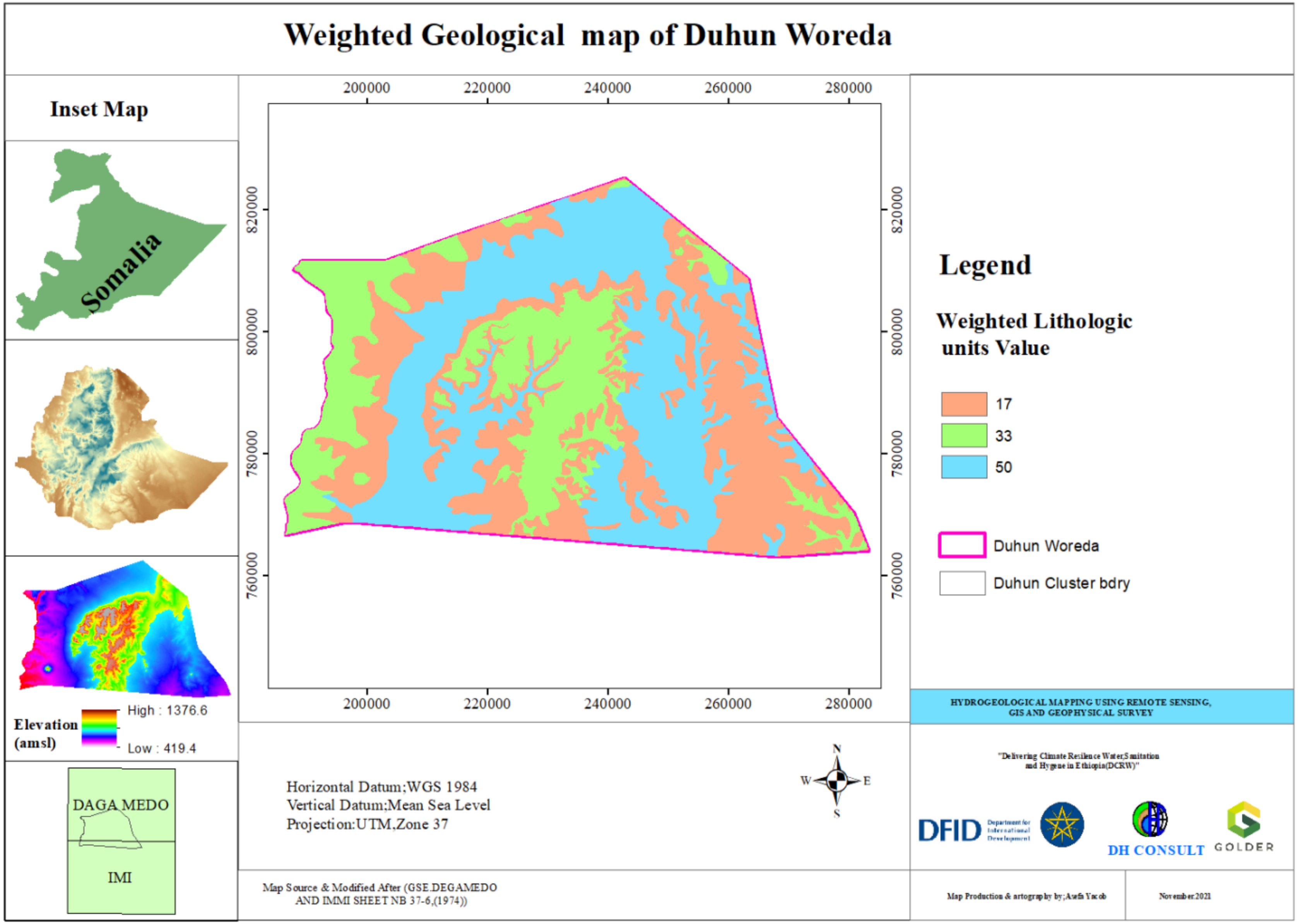

Figure 5-119. Weighted lithological classes' map of the Duhun woreda

II. Lineaments and lineament density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SEand N–S trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.21 km/km2 to 0.87 km/km2 (Figure 5-120). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by mesozoic sediments having relatively higher lineament density of 0.65-0.87 km/km2 compared with areas underlain by sedimentary rocks of gypsum with lower lineament densities of (<0.21 km/km2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.40 was assigned to area with high density of lineaments, while a low weightage of 0.10 was assigned to areas with low lineament density (Figure 5-121).

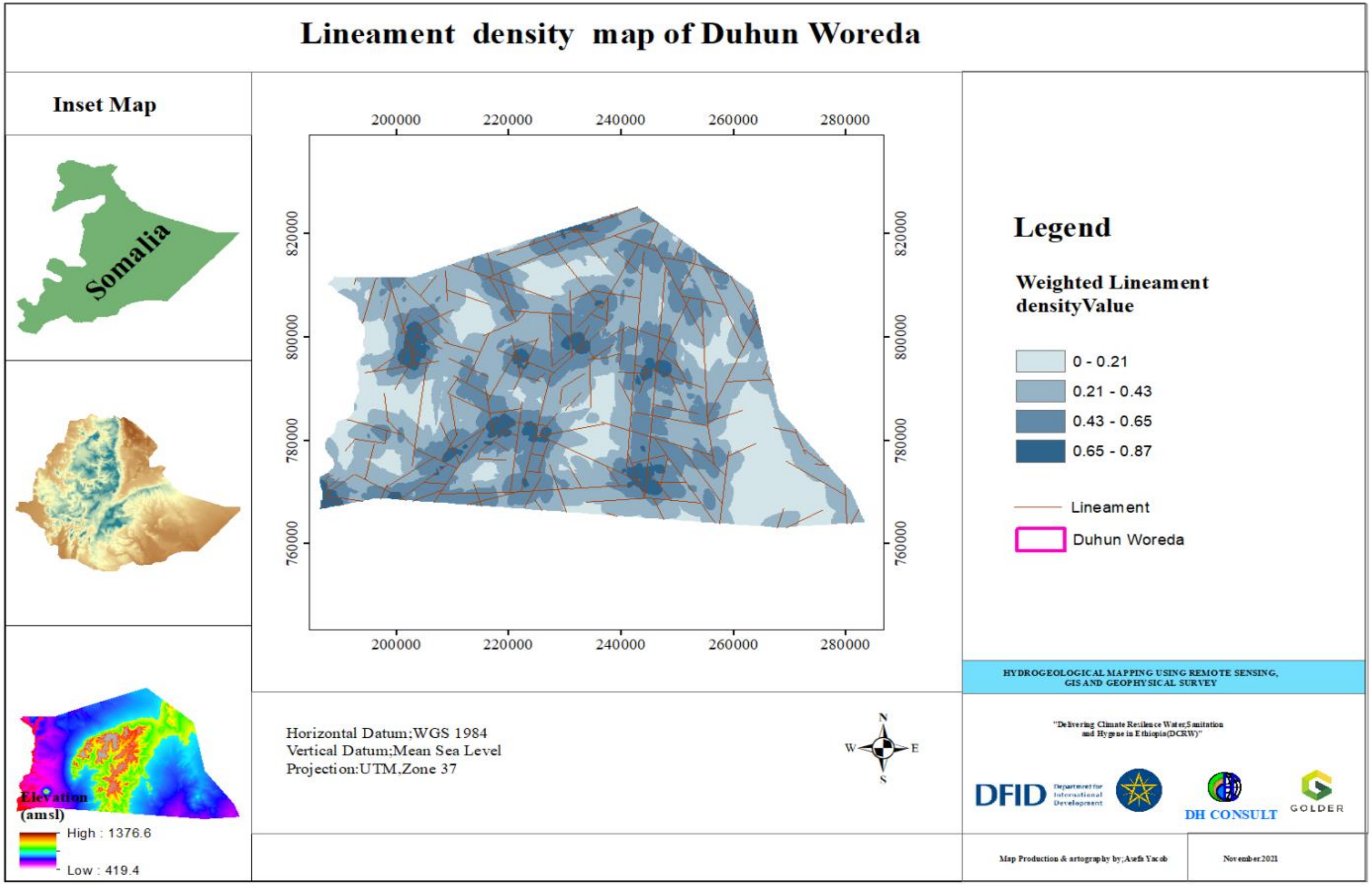

Figure 5-120. Lineament Density Map of Duhun woreda

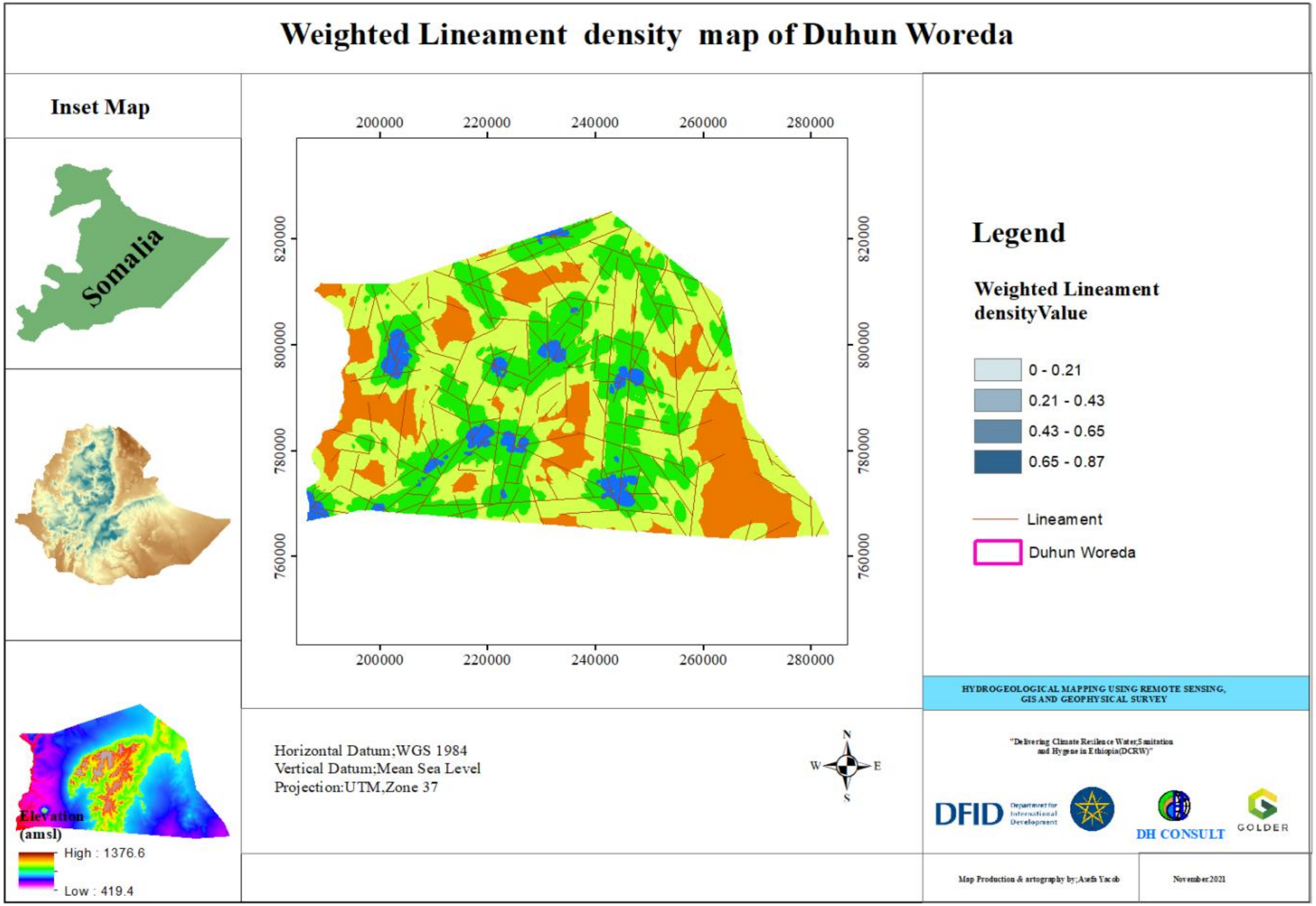

Figure 5-121. Weightage value of Lineament Density Map of Duhun woreda

III. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 2.08 and 11.92. A closer look at the classification revealed that most the high elevated areas and drainage systems with steep slopes have relatively lower TWI value while the low-lying areas and drainage systems with gentle and flat slopes have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.40) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.10).

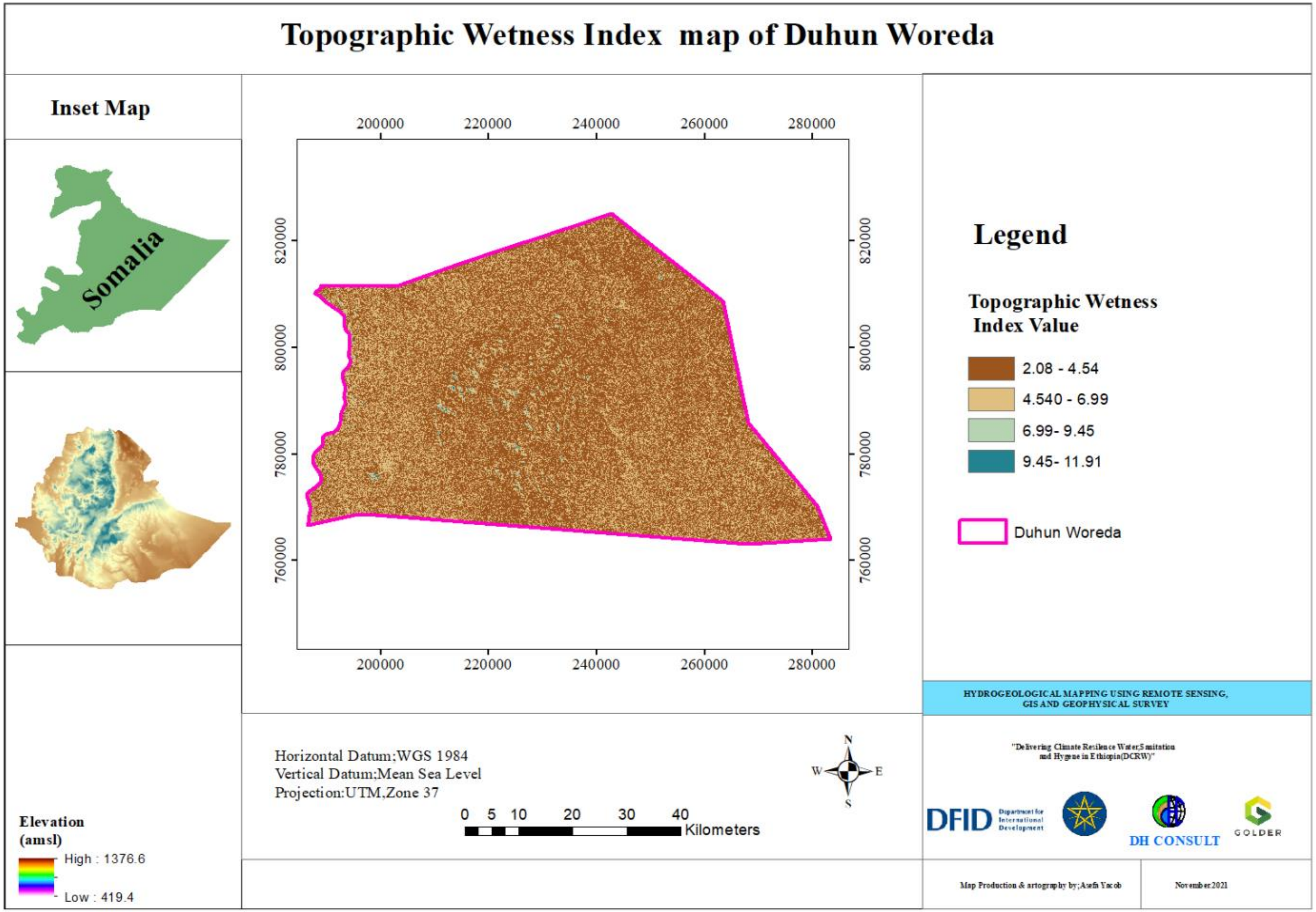

Figure 5-122. TWI Map of Duhun woreda

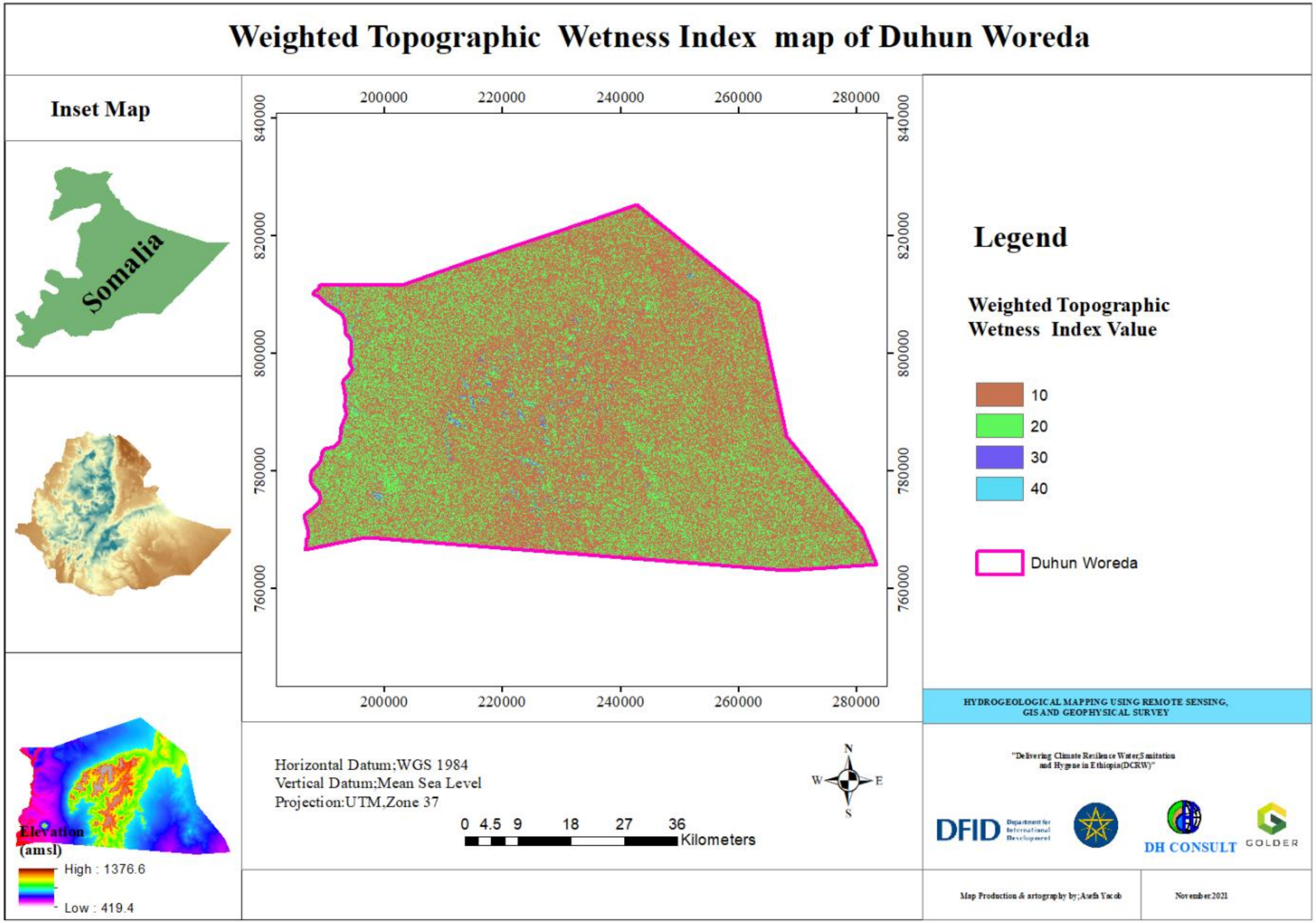

Figure 5-123. Weightage value of TWI Map of Duhun woreda

IV. Recharge

The spatial annual recharge rate distribution in the Duhunworedaranges from 11.48 to 99.07 mm/y suggesting groundwaters in most part of the woreda area underlain by sedimentary rocks and quaternary sediments have relatively higher recharge amount (Figure 5-124). Accordingly, areas with higher and moderate amount of recharge have weightage factor of 0.50 and 0.33, respectively signifying very good and moderate groundwater potential which covers about 1,436.73 km2 (37 %) and 78.60 km2 (2 %), respectively while areas with the lowest amount of recharge have weightage factor of 0.17, suggesting poor groundwater potentiality and represent about 1,559.01 km2 (39 %). A closer look at the recharge thematic map revealed that most parts of the woreda have relatively good recharge distribution.

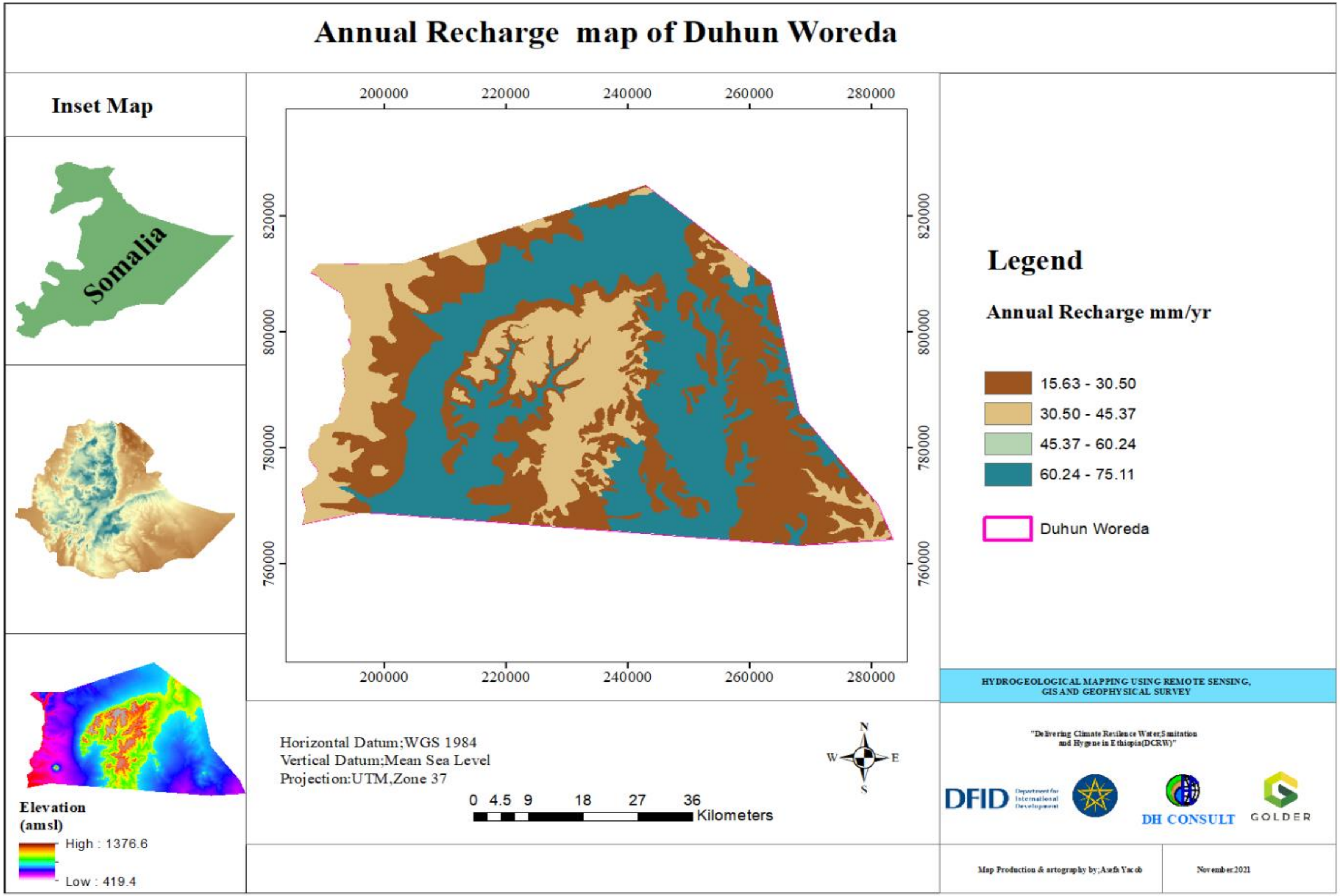

Figure5-124.Annual RechargeMap of Elkere woreda

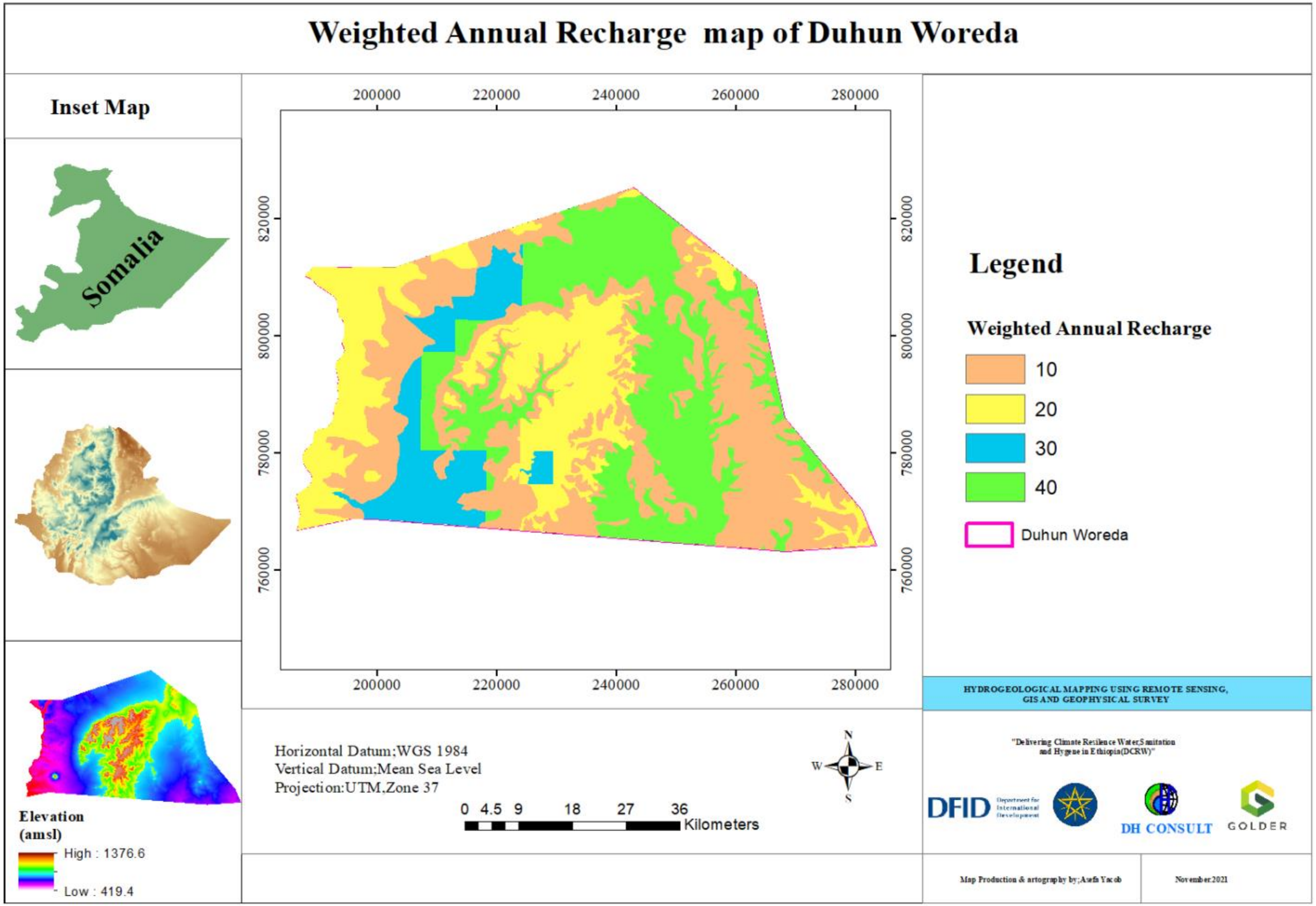

Figure 5-125. Weighted Annual Recharge classes' map of the Duhun woreda

5.11.3. Classification of Groundwater Potential Zones

The hydrogeological system of Duhun woreda is comprised of four main lithological units as Fluvial sand silt (Stream channel deposit), Limestone locally cherty (Korahe Belet Uen) with Sandstone, siltstone intercalations with local limestone (Korahe Ambaradom), Shale mudstone limetone intercalations (Gabradarre) and Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle). At regional scale, Baslat and Fluvial sand silt (Stream channel deposit) form extensive and highly productive aquifers. Within the domain of Dihun woreda, theses, quaternary deposits form aquifers with high groundwater potential.

At regional scale, the Limestone Formation and lower sandstone form extensive and moderately productive aquifers having high hydraulic conductivity. However, at local scale, within the domain of Duhun Woreda, due to the geomorphic setup, the Limestone Formation and the underlying units do not form high potential aquifer as revealed from existing borehole information rather the Weathered and slightly fractured sedimentary rocks with overlying Quaternary deposit form major potential aquifer with moderate productivity within the domain of Dihun woreda along lineament lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-126). The potential groundwater zones (PGZ) of the Duhun woreda revealed four distinct zones, namely very low,low, moderate and high zones whose distribution and extents are 1,559.01km2 (39 %),943.63km2 (23 %), 78.60km2 (2%) and1,436.73km2 (37 %), respectively as presented in Table 5-54.

The potential map, as presented in Figure 5-126, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that most elevated areas around the peripheries and central parts of the Dihun woreda generally have very low potentials with area coverage of about 39 %, while limited areas at central regions generally exhibits moderateto low potentials representing about 2 % and 23 % of the study area, respectively. The generally high to moderate groundwater potentiality of the study area as reflected by 37 % coverage is a confirmation of generally moderate to high productive aquifers of recent alluvial and sedimentary deposits, whereas low to very low groundwater potential areas have an indication of limited aquifers capabilities of gypsum and shale with marl intercalation.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the geology and lineament density in addition to the topographic wetness index control. In addition, areas underlain by recent quaternary deposits especially in the central and southern sections of the study area which are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments and apparently deep fracturing and weathering have high and moderate groundwater potential on the one hand. On the other hand, areas underlain by sedimentary rocks of limestone and gypsum in the majority of the woreda areas are characterized by small ridges and steep slopes, lower recharge and lineament densities, exhibit low groundwater potential while areas underlain by sedimentary rocks associated with sediments have medium potential. Moreover, high drainage densities and predominance of limestone rock outcrops can be attributed to the observed low groundwater potentials at the most part of the study area. However, predominance of recent sediments and sedimentary rock outcrops, low drainage density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential exhibited at central and western portions of the study area. Summary of the groundwater potential zones identified in the *Duhun woreda* is presented in the table below (Table 5-54).

Table 5-54.Classification of groundwater potential zones and coverage areas alongside the respective yield and transmissivity categories

Woreda Name	GWP Zones	Area (km^2)	Area (%)	Major Aquifer Units	Borehole Yield Classification (l/s)
					Q (Range)
Dihun	High	1,436.73	37	Quaternary Sediments	>5
	Moderate	78.60	2	Sedimentary Rocks limestone	2-5
	Low	943.63	23	Sedimentary Rocks Gypsum	0.5-2
	Very Low	1,559.01	39	Shale and marl	0.05-0.5

5.11.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) were collated for boreholes in and around the study woreda area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the study area vary from >5 lit/sec in high potential zones and varying 2- 5 lit/sec in moderate potential zones, 0.5 lit/sec to 2 lit/sec in the low and from 0.05-0.5 lit/sec in the very low potential zones. As shown in the Figure 5-126, the occurrence of number of wells with yield of in the range 2- 5 lit/sec (moderate yield) and of >5 lit/sec (high yield) cut across mainly the recent quaternary deposits and sedimentary rocks. However, the less frequency of wells within gypsum and shale rock in the low and very low yield category signifies the generally low potential of these rocks as high lighted by the GIS-based potential map. In addition, the moderate-yield (2- 5 lit/sec) and high-yield (>5 lit/sec) categories are associated also with wells in the Mesozoic sedimentary rocks and quaternary alluvial deposits along river channel. This is also consistent with the very, low, moderate, high groundwater potential classification of the GIS map for these rocks' unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such basement and sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

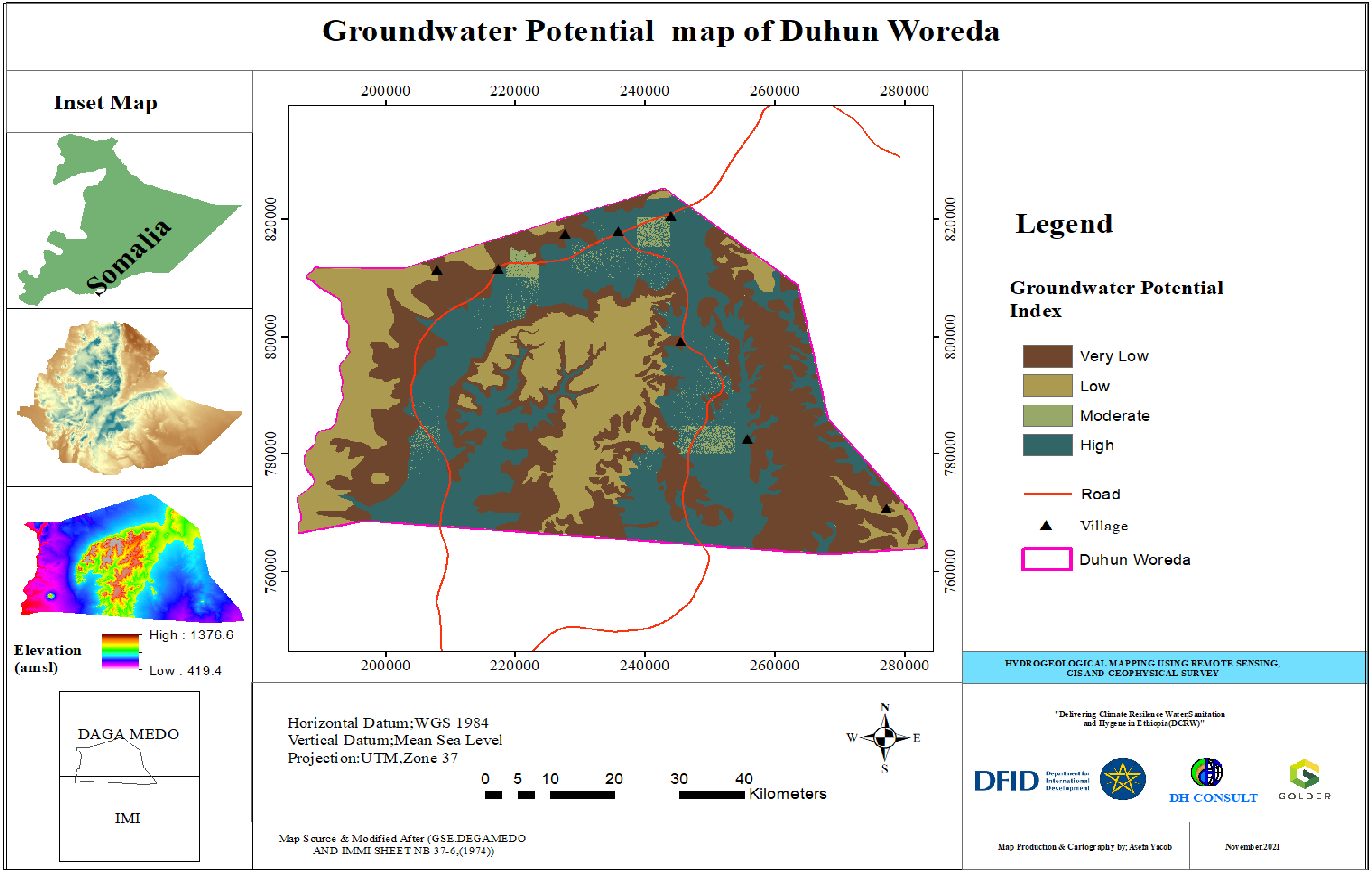

Figure 5-126. Groundwater Potential Zones Map of Duhun woreda

5.11.5. Population projection and Water Demand

5.11.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly these values are adopted in forecasting future population of the town.

Table 5-55 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
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Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P = Po\,(1 + r)^{n}$$

Where P – projected population

Po – current population

n – Number of years for projection

r – Population growth rate

The population of Duhun Woreda has been projected forward until 2036 using the growth rate of Somali Regional State. The minimum and maximum population in the Woreda is 7,026 and 16,565 respectively. The total population of the Duhun Woreda in 2036 is going to be 50,192.10.

5.11.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic purposesgreatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO)& (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer's life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24-hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-127 shows the distribution of water demand in each Kebeles of the Woreda. Karchachabo kebele water demand is the minimum 545 M3/day and maximum water demand is required for duhun Kebele with 2488 M3/day respectively. The overall water demand for the projected population in the Duhun Woreda is 1,285 M3/day.

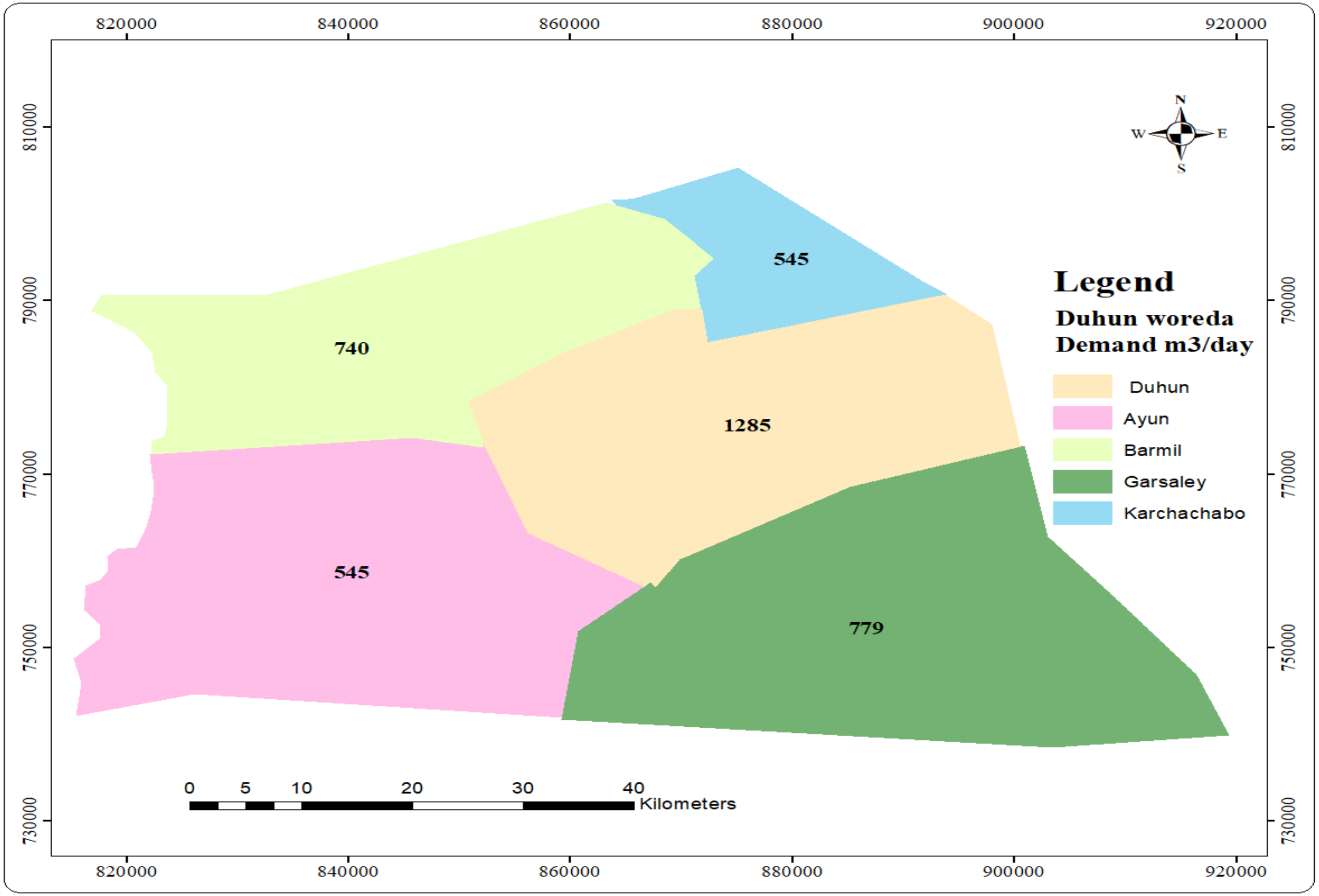

Figure 5-127. Water Demand Map of Duhun woreda

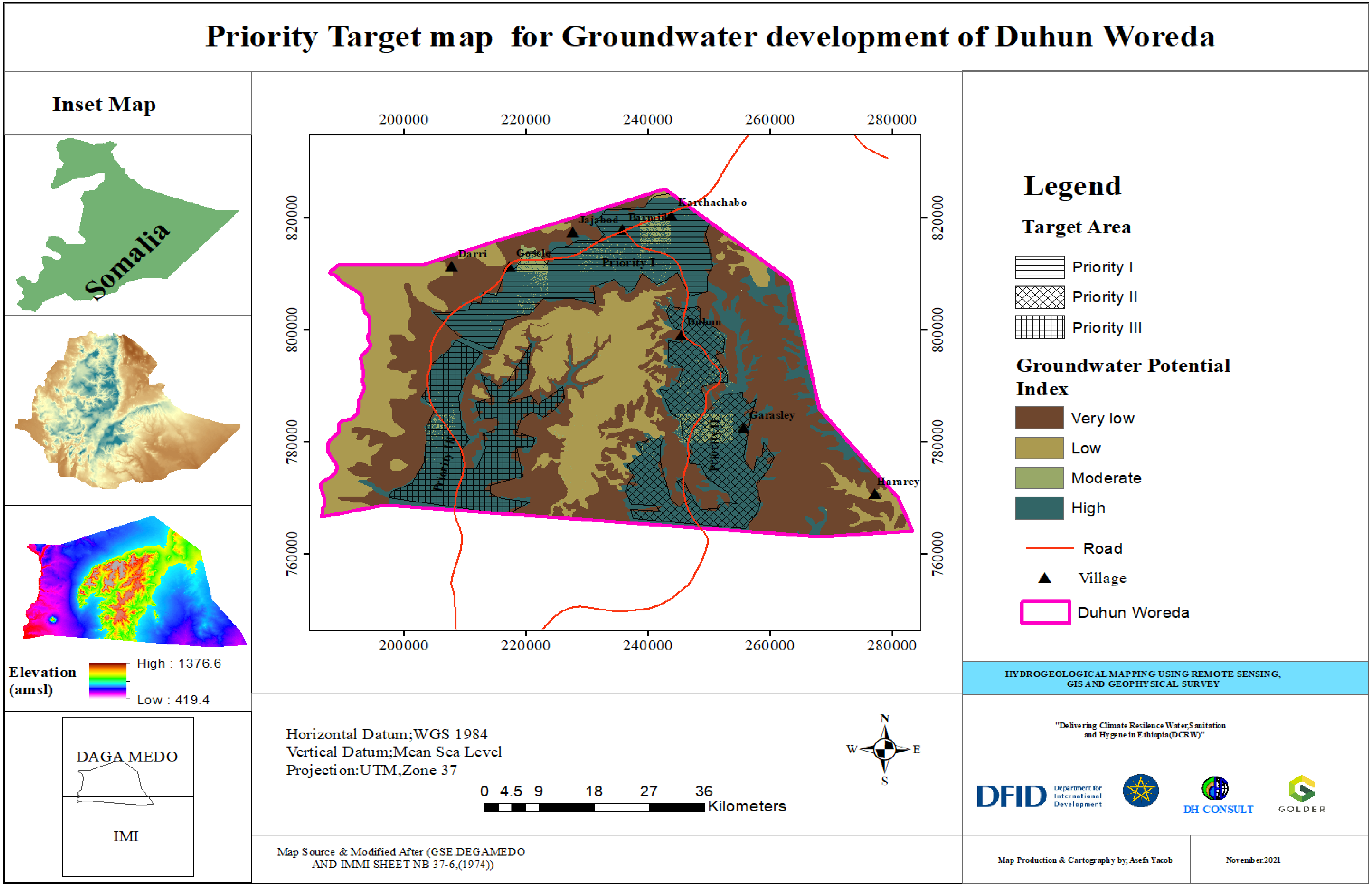

Figure 5-128.-Target Areas Map of Duhun woreda

5.11.6. Propsed Target Sites

Proposed target sites are identified, prioritized and selected within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficieries, population density and discussion made with the woreda's stakeholders so that to understand and identify kebeles with sever water shortage in particular. Accordingly, four priority target sites were selected and delineated within the Duhun woreda for detail studies to be carried out in order to verify further and locate appropriate borehole drilling sites.

Target Site-I:

This target site is located in the northern part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 5.0 l/s. This target site is mainly underlain by quaternary recent deposits of alluvial sediments.

Target Site-II:

This target site is located in the eastern part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 5.0 l/s. This target site is mainly underlain by quaternary recent deposits of alluvial sediments.

Target Site-III:

This target site is located in the western part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 5.0 l/s. This target site is mainly underlain by quaternary recent deposits of alluvial sediments.

5.12. Dolobay Woreda

5.12.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.03 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Dolobay woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-56). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-57. The weights assigned to the respective thematic maps as presented in Table 5-58 indicate that geology was ranked the dominant factor with a normalized weight value of 0.39 while recharge is the least accounted factor with a normalized weight of 0.06 for groundwater occurrence in the study Dolobay Woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Haromaya woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

$$GWPZI = (GGwGGwi + LDwLDwi + TWIwTWIwi + GRwGRwi)$$

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Haromaya woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e., 'very high', 'high', 'moderate' and 'low or poor', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g., yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-56 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Geology (GG)	5
Lineament density (LD)	3
Topographic Wetness Index (TWI)	1
Recharge (GR)	1

Table 5-57 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	GG	LD	TWI	GR	
GG	1	3	5	3	0.53
LD	1/3	1	3	1	0.21
TWI	1/5	1/3	1	1	0.10
GR	1/3	1	1	1	0.16

Table 5-58 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank	Area (km^2)	Area (%)
Geology/ Lithology, 'GG'	Quaternary deposits of recent alluvium & lacustrine sediments	Very good	4	0.40	0.53	21.8	3.9
	Mesozoic sedimentary rocks	Moderate	3	0.30		175.6	31.8
	Gypsum rocks	Good	2	0.20		355.6	64.3
	Shale	poor	1	0.10			
Lineament Density,' LD' (Km/Km^2)	0 - 0.23	poor	1	0.10	0.21	3,654.93	91
	0.24 - 0.47	Good	2	0.20		112.85	3
	0.48 – 0.70	Moderate	3	0.30		92.51	2
	0.71 – 0.93	Very good	4	0.40		153.32	4
	4.19 – 7.34	poor	1	0.10	0.1	1,928.86	51

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank	Area (km^2)	Area (%)
Topographic Wetness Index, 'TWI'	7.35 – 9.1	Good	2	0.20		1,797.78	48
	9.11 – 11.8	Moderate	3	0.30		280.80	0.8
	11.9 – 19.1	Very good	4	0.40		6.38	0.2
Recharge, 'GR' (mm/y)	23.2 – 28.5	poor	1	0.10	0.16	1,010.19	25
	28.6 – 48	Good	2	0.20		1,594.24	40
	48.1 – 97	Moderate	3	0.30		1,151.51	29
	97.1 - 190	Very good	4	0.40		257.64	6

5.12.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of geology, rainfall, lineament density, geomorphology, land slope, soil type, land use/land cover, groundwater depth and drainage density together with their spatial distribution in Dolobay Woredaare presented below:

I. Geology/lithology

In general, most parts of the *Dolobay Woreda* are underlain by Mesozoic sedimentary rocks of limestone and ggypsum with shale. Tertiary volcanics and Quaternary deposits of alluvial are mostly found oncentral and eastern parts of the woreda.

However, the lithological units found in the woreda area are further classified into four major groups based on their significances to groundwater occurrence and productivity using borehole data on yield analysis in particular.

a) Baslat and Fluvial sand silt (Stream channel deposit) (high productive with Q >5.0 l/s)

b) Limestone locally cherty (Korahe Belet Uen) with Sandstone, siltstone intercalations with local limestone (Korahe Ambaradom) (moderately productive with Q =2.0-5.0 l/s)

c) Shale mudstone limetone intercalations (Gabradarre) (low productive with Q =0.5-2.3 l/s)

d) Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle) very low productive with Q =0.05-0.5 l/s)

The mesozoicsedimentary rocks are the main lithologic framework of the *Dolobay Woreda* which together covered a total area of about 3,655.5 km2 or 91 % of the woreda area, tertiary volcanics and quaternary recent sediments covered about 359 km2 (9 %)of the woreda area (Figure 5-129).

Usually, massive unfractured lithologic units in sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification and weathered overburden, and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the weathered regolith units, karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of very low productivity of shale and marl intercalation (0.10) \ low productivity of gypsum unit (0.2)/ moderate productivity of sedimentary rocks (0.30) \ high productivity tertiary volcanics and quaternaryalluviall sediments (0.4) (Figure 5-30)..

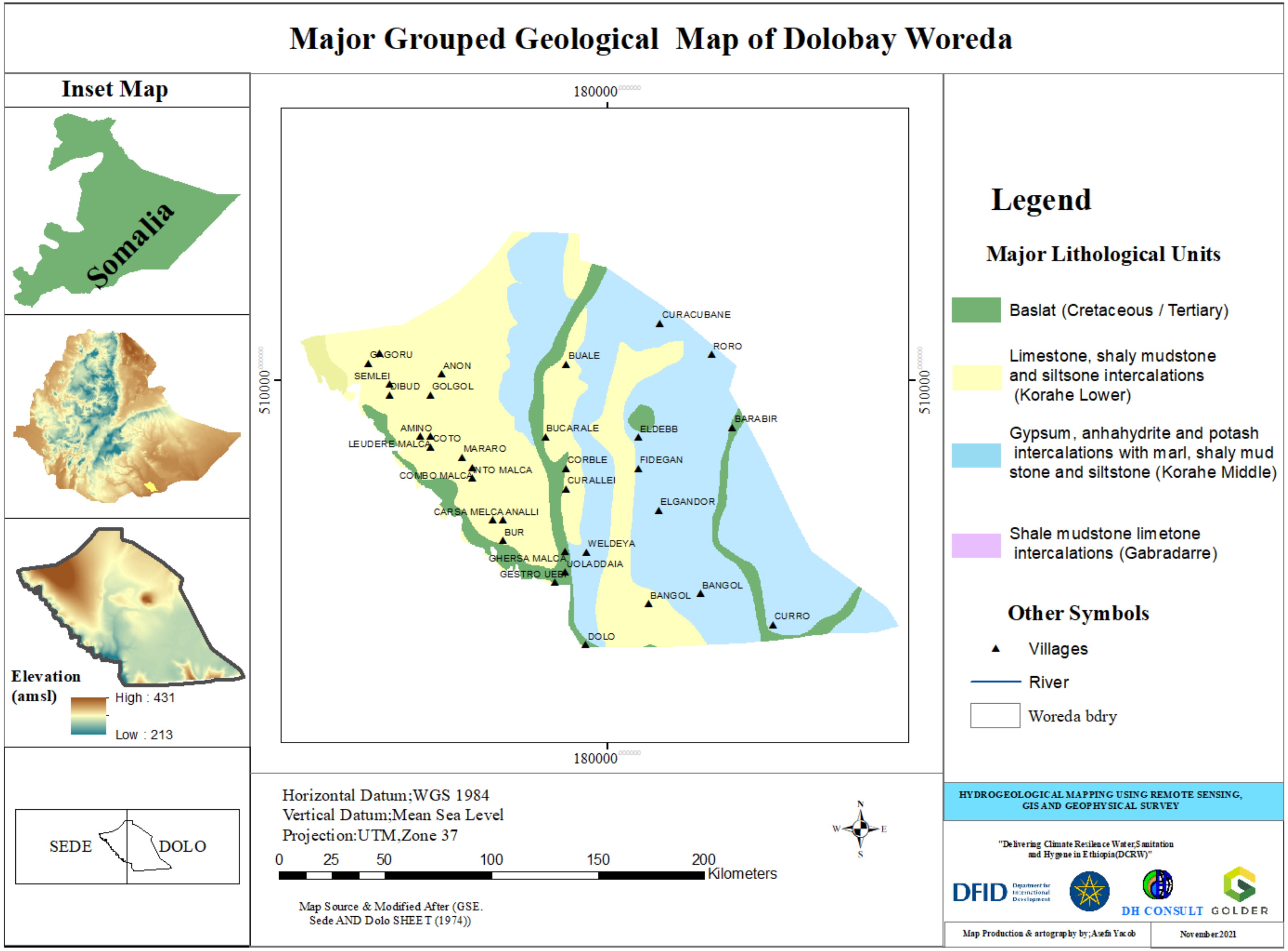

Figure 5-129. Grouped Lithological classification map of Dolobay Woreda

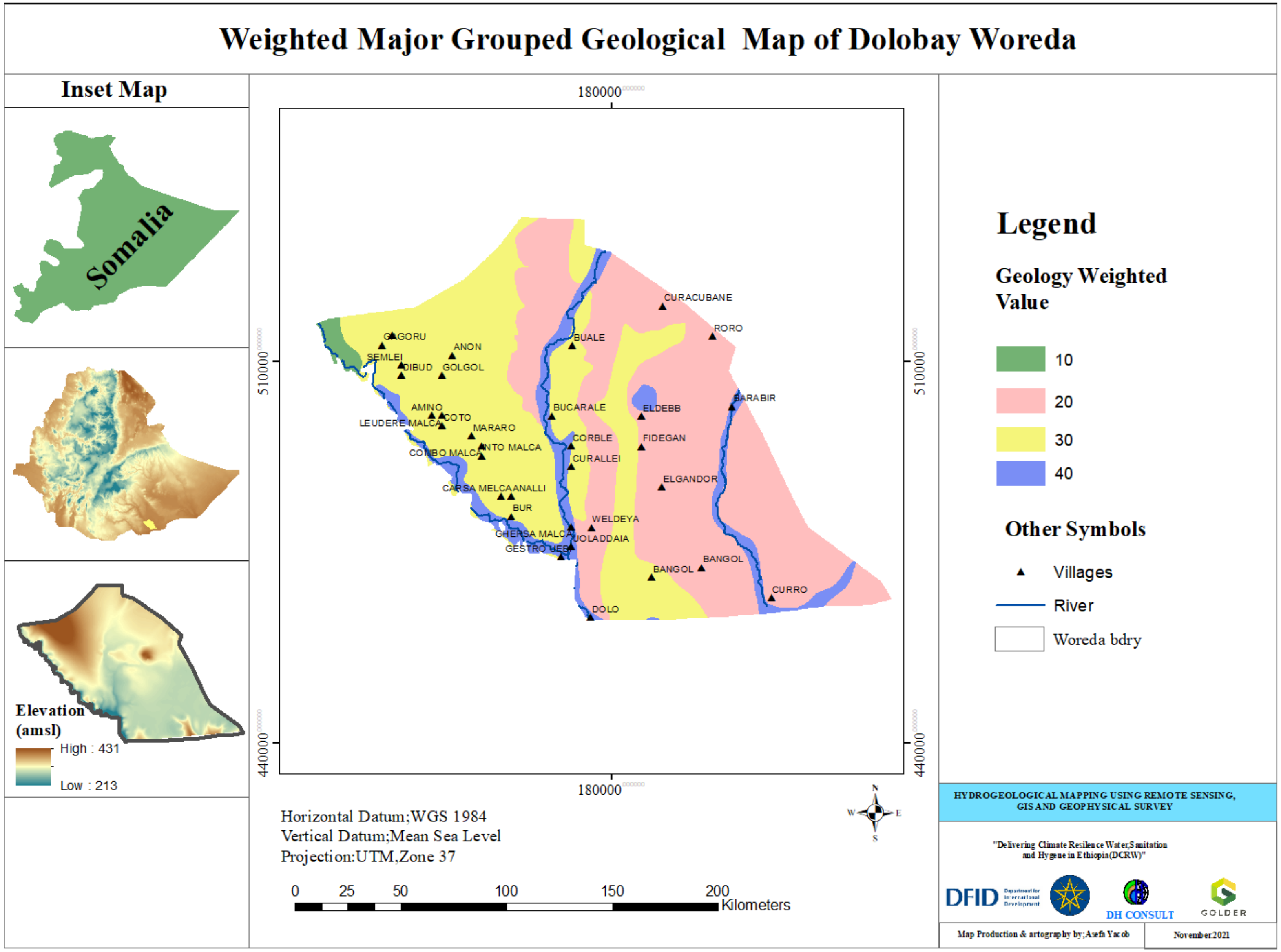

Figure5-130.Weighted lithological classes'map of the Dolobay Woreda

II. Lineaments and lineament density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SEand N–S trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.1 km/km2 to 1.1 km/km^2 (Figure 5-131). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by Mesozoic sediments having relatively higher lineament density of 0.6 – 1.1 km/km2) compared with areas underlain by sedimentary rocks of gypsum and shale with lower lineament densities of (< 0.1 km/km2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.40 was assigned to area with high density of lineaments, while a low weightage of 0.10 was assigned to areas with low lineament density (Figure 5-132).

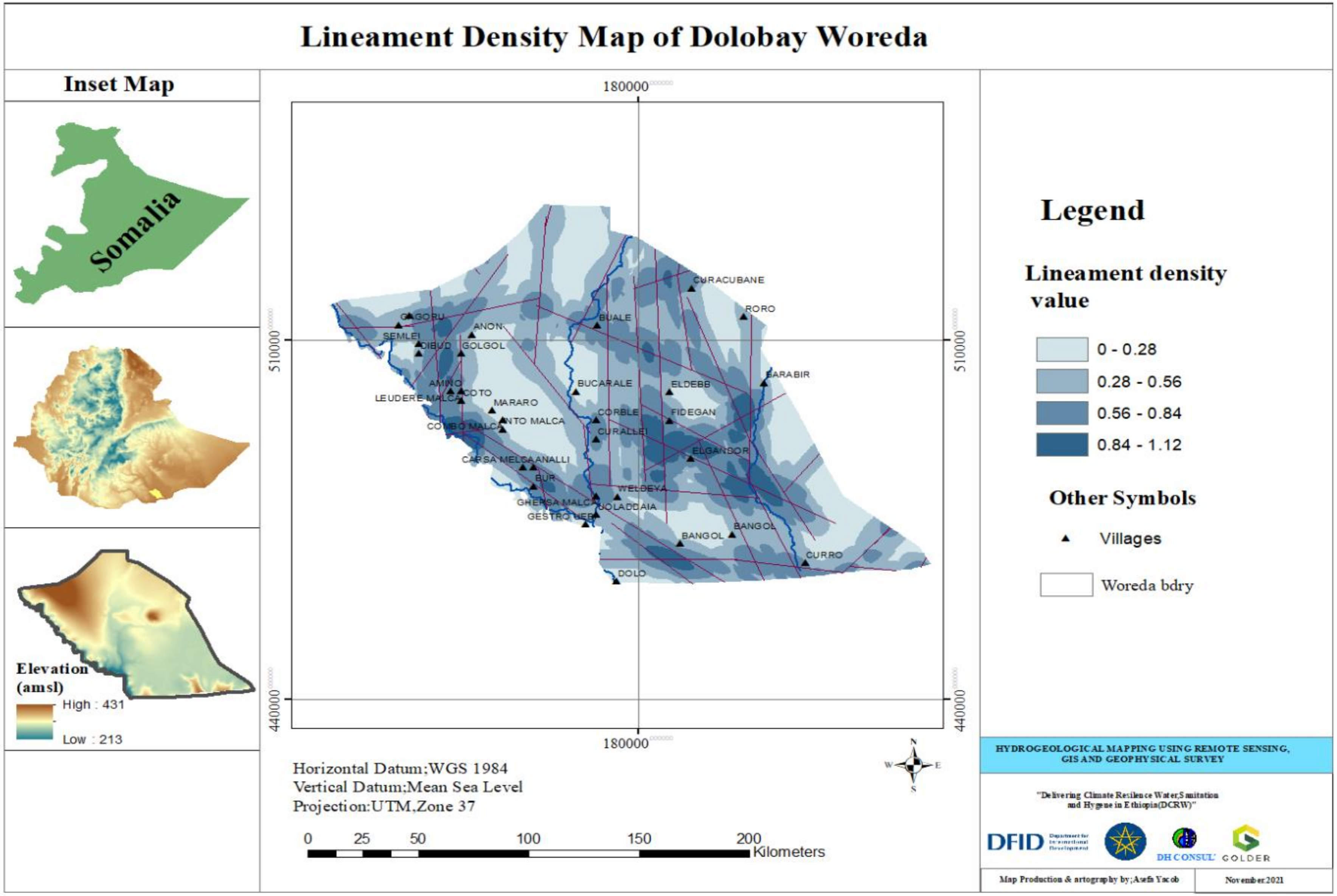

Figure 5-131. Lineament Density Map of Dolobay Woreda

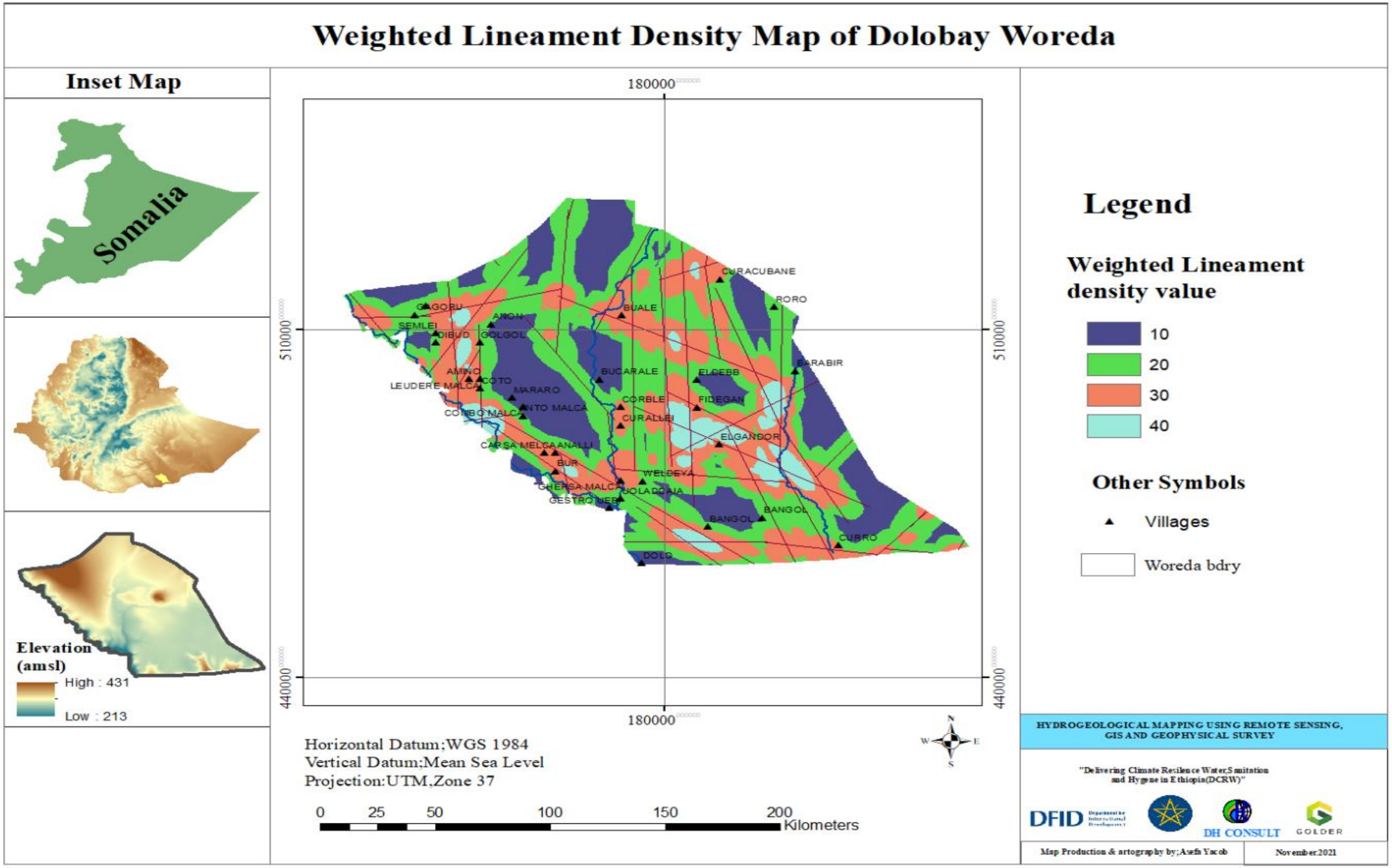

Figure5-132.Weightage value of Lineament Density Map of Dolobay Woreda

III. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 5.69 and 14.45. A closer look at the classification revealed that most the high elevated areas and drainage systems with steep slopes have relatively lower TWI value while the low-lying areas and drainage systems with gentle and flat slopes have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.40) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.10).

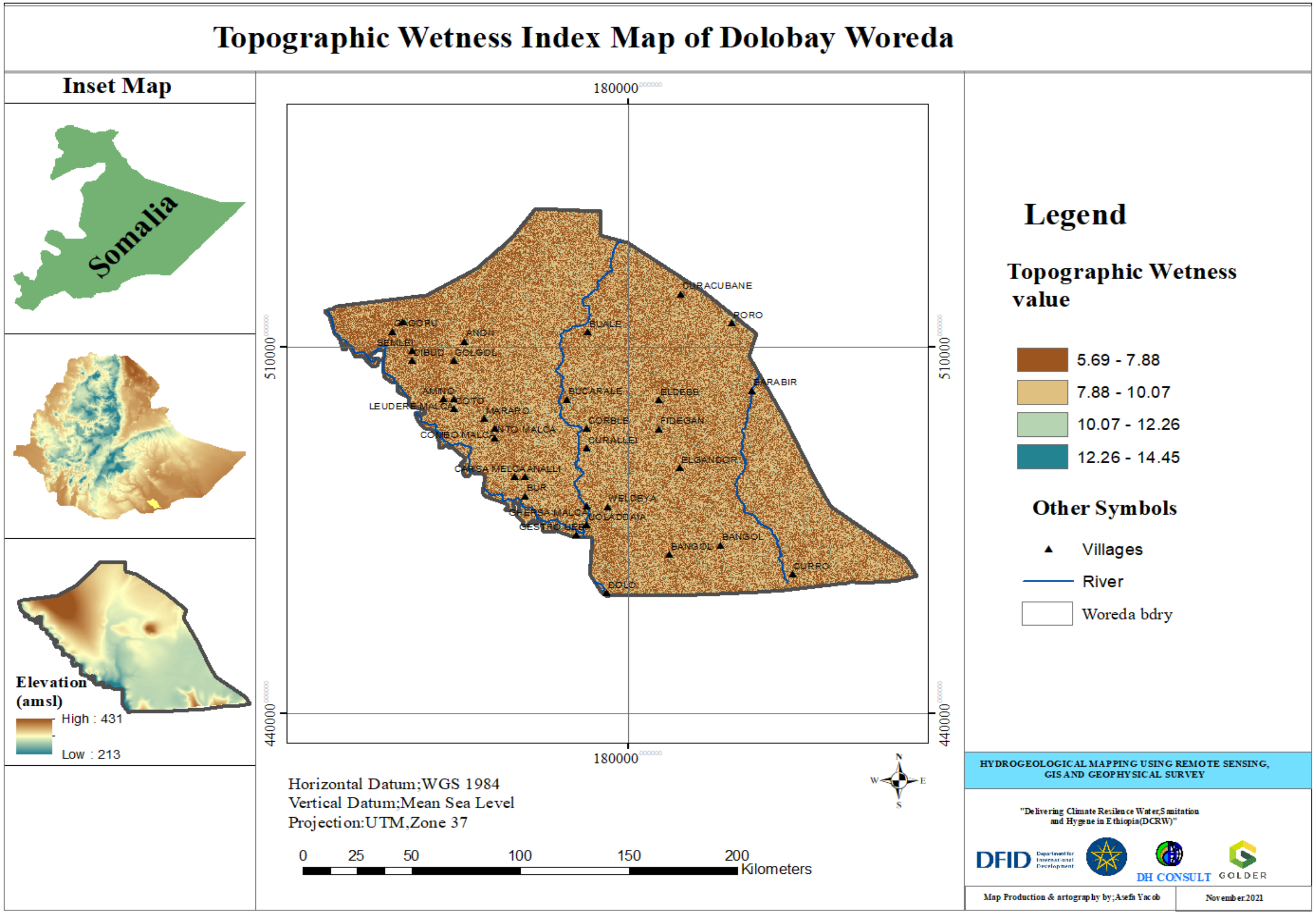

Figure 5-133. TWI Map of Dolobay Woreda

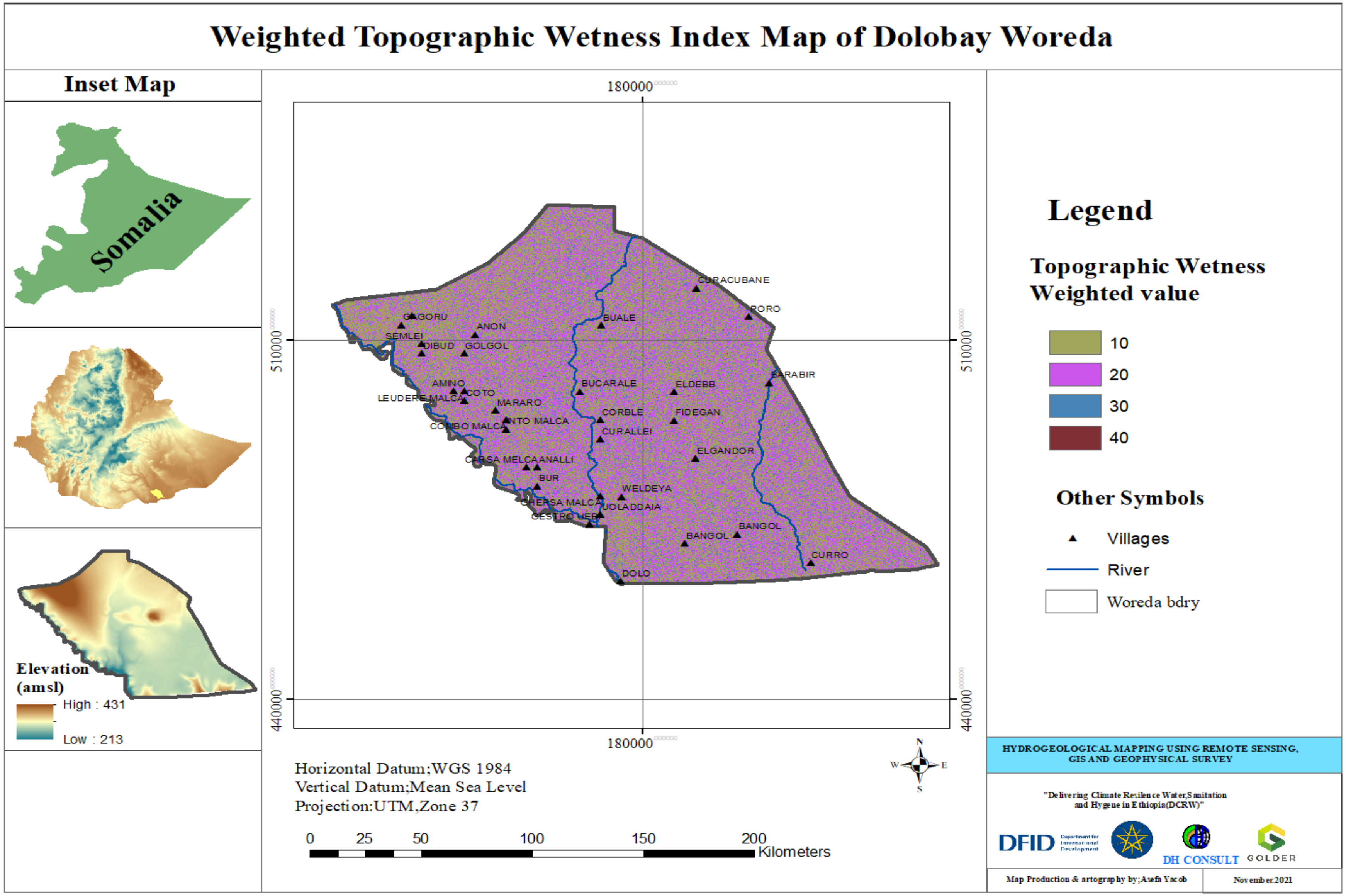

Figure5-134.Weightage value of TWI Map of Dolobay Woreda

IV. Recharge

The spatial annual recharge rate distribution in the Haromaya woreda ranges from 23.2 to 190 mm/y suggesting groundwaters in most part of the woreda area underlain by basement complex receive low amount of recharge while areas underlain by sedimentary rocks and quaternary sediments have relatively higher recharge amount (Figure 5-135). Accordingly, areas with higher and moderate amount of recharge have weightage factor of 0.40 and 0.30, respectively signifying very good and moderate groundwater potential which covers about 1,928 km2 (0.51 %) and 1,797.8 km2 (0.48 %), respectively while areas with the lowest amount of recharge have weightage factor of 0.10, suggesting poor groundwater potentiality and represent about 6.39 km2 (0.002 %). A closer look at the recharge thematic map revealed that most parts of the woreda have relatively high recharge (72.47mm /y). Generally, the study area is characterized with high mean annual recharge amount, whereas only limited areas at western and southerm parts have low mean annual recharge amount (<13.35mm).

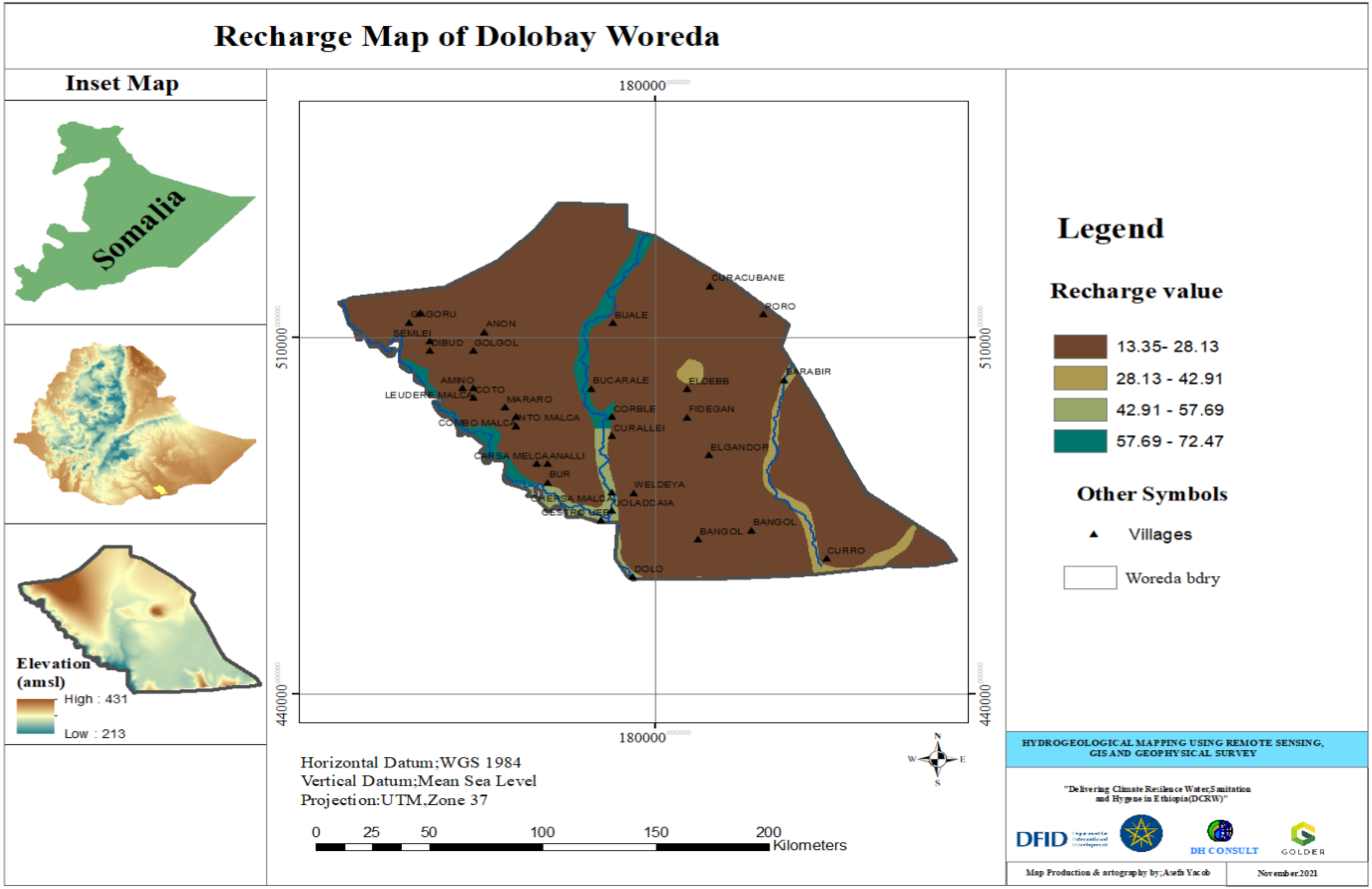

Figure 5-135. Annual Recharge Map of Dolobay Woreda

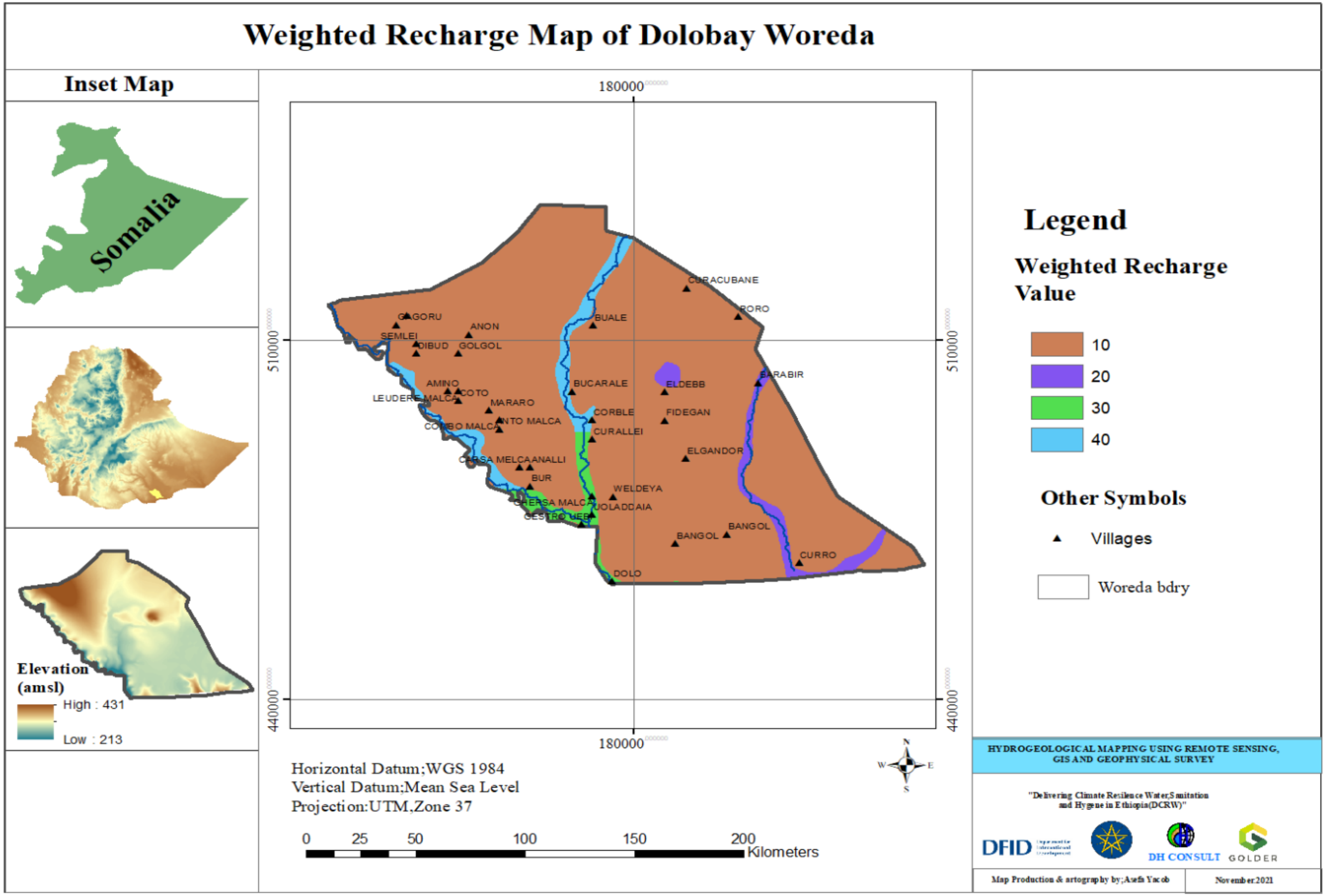

Figure 5-136. Weighted Annual Recharge classes' map of the Dolobay Woreda

5.12.3. Classification of Groundwater Potential Zones

The hydrogeological system of Dolobay woreda is comprised of four main lithological units as Baslat and Fluvial sand silt (Stream channel deposit), Limestone locally cherty (Korahe Belet Uen) with Sandstone, siltstone intercalations with local limestone (Korahe Ambaradom), Shale mudstone limetone intercalations (Gabradarre) and Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle). At regional scale, Baslat and Fluvial sand silt (Stream channel deposit) form extensive and highly productive aquifers. Within the domain of Dolobay Woreda, theses, Baslat and quaternary deposits form aquifers with high groundwater potential.

At regional scale, the Limestone Formation and lower sandstone form extensive and moderately productive aquifers having high hydraulic conductivity. However, at local scale, within the domain of Dolobay Woreda, due to the geomorphic setup, the Limestone Formation and the underlying units do not form high potential aquifer as revealed from existing borehole information rather the Weathered and slightly fractured sedimentary rocks with overlying Quaternary deposit form major potential aquifer with moderate productivity within the domain of Dolobay Woreda along lineament lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-137). The potential groundwater zones (PGZ) of the Dolobay Woreda revealed four distinct zones, namely very low,low, moderate and high zones whose distribution and extents are 3,498.14 km2 (90 %), 268.75 km2 (7 %), 105.35 km2 (2%) and141.34 km2 (1 %), respectively as presented in Table 5-59.

The potential map, as presented in Figure 5-137, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that most elevated areas around the peripheries and central parts of the Dolobay Woreda generally have low potentials with area coverage of about 90 %, while limited areas at central regions generally exhibits moderateto low potentials representing about 2 % and 1 % of the study area, respectively. The generally high to moderate groundwater potentiality of the study area as reflected by 3 % coverage is a confirmation of generally moderate to high productive aquifers of recent alluvial and sedimentary deposits, whereas low to very low groundwater potential areas have an indication of limited aquifers capabilities of gypsum and shale with marl intercalation.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the geology and lineament density in addition to the topographic wetness index control. In addition, areas underlain by recent quaternary deposits especially in the central and southern sections of the study area which are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments and apparently deep fracturing and weathering have high and moderate groundwater potential on the one hand. On the other hand, areas underlain by sedimentary rocks of limestone and gypsum in the majority of the woreda areas are characterized by small ridges and steep slopes, lower recharge and lineament densities, exhibit low groundwater potential while areas underlain by sedimentary rocks associated with sediments have medium potential. Moreover, high drainage densities and predominance of limestone rock outcrops can be attributed to the observed low groundwater potentials at the most part of the study area. However, predominance of recent sediments and sedimentary rock outcrops, low drainage density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential exhibited at central and western portions of the study area. Summary of the groundwater potential zones identified in the Dolobay Woreda is presented in the table below (Table 5-59).

Table 5-59.Classification of groundwater potential zones and coverage areas alongside the respective yield and transmissivity categories

Woreda Name	GWP Zones	Area (km^2)	Area (%)	Major Aquifer Units	Borehole Yield Classification (l/s)
					Q (Range)
Dolobay	High	1	6.6	Tertiary volcanics and quaternary Sediments	>5
	Moderate	2	11.8	Sedimentary Rocks limestone	2-5
	Low	7	33.2	Sedimentary Rocks Gypsum	0.5-2
	Very Low	90	48.4	Shale and marl	0.05-0.5

5.12.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) were collated for boreholes in and around the study woreda area. The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the study area vary from >5 lit/sec in high potential zones and varying 2-5 lit/sec in moderate potential zones,0.5 lit/sec to 2 lit/sec in the low and from 0.05-0.5 lit/sec in the very low potential zones (Figure 5-137). As shown in the figure, the occurrence of number of wells with yield of in the range 2- 5 lit/sec (moderate yield) and of >5 lit/sec (high yield) cut across mainly the recent quaternary deposits and sedimentary rocks. However, the less frequency of wells within gypsum and shale rock in the low and very low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (2- 5 lit/sec) and high-yield (>5 lit/sec) categories are associated also with wells in the Mesozoic sedimentary rocks and quaternary alluvial deposits along river channel. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks' unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such basement and sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

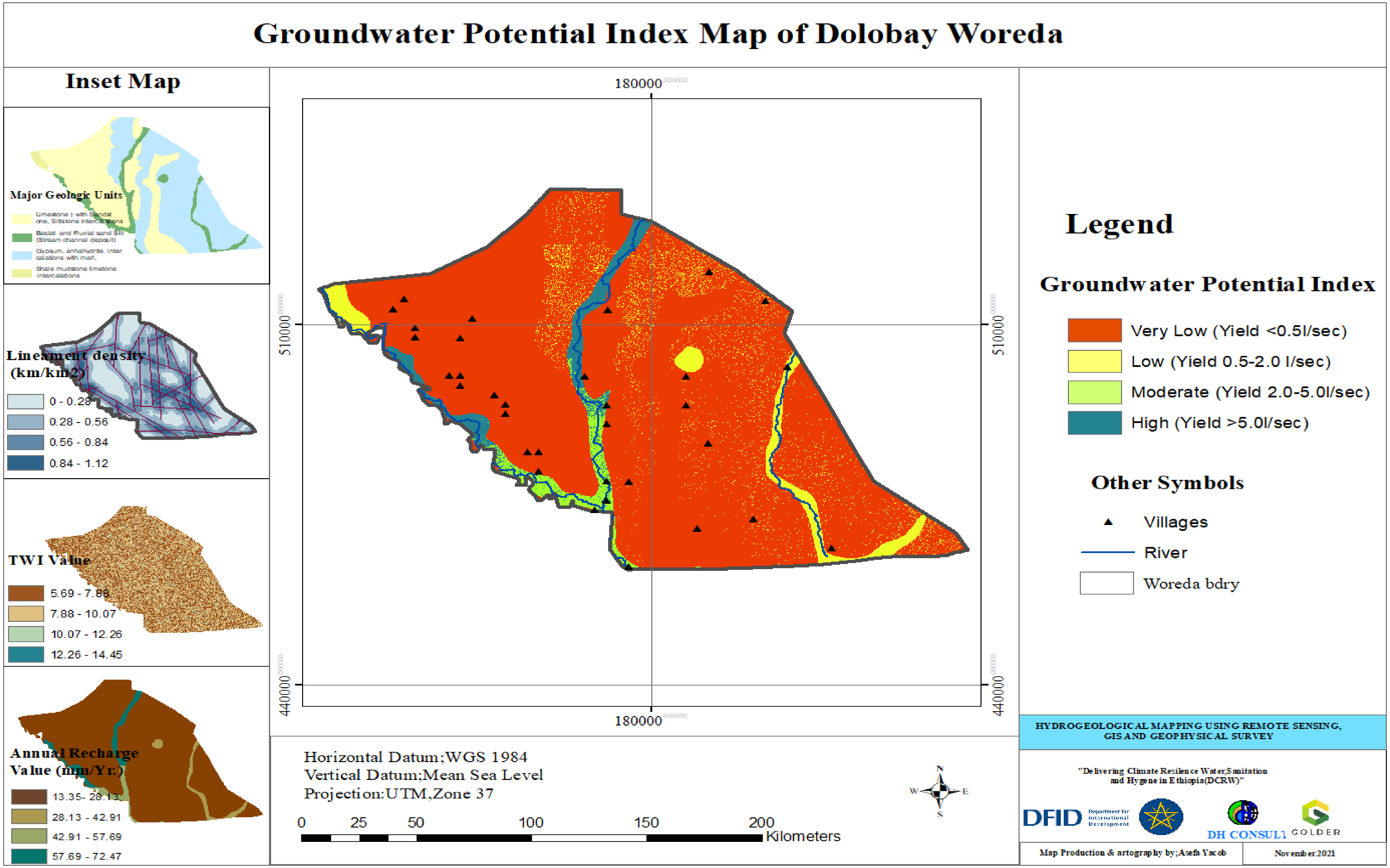

Figure 5-137. Groundwater Potential Zones Map of Dolobay Woreda

5.12.5. Population projection and Water Demand

5.12.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly these values are adopted in forecasting future population of the town.

Table 5-60 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P = Po\,(1 + r)^{n}$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of DolobayWoreda has been projected forward until 2036 using the growth rate of Somali Regional State. The minimum and maximum population in the Woreda is 8,501 and 13,173 respectively. The total population of the Dolobayin 2036 is going to be 157,936.

5.12.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic purposesgreatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO)& (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer's life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24 hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-138 shows the distribution of water demand in each Kebeles of the Woreda. Waladayo kebele water demand is the minimum 9340 M3/day and maximum water demand is required for Dolobay Kebele with 17,800 M3/day respectively. The overall water demand for the projected population in the Dolobay Woreda is 173,528 M3/day.

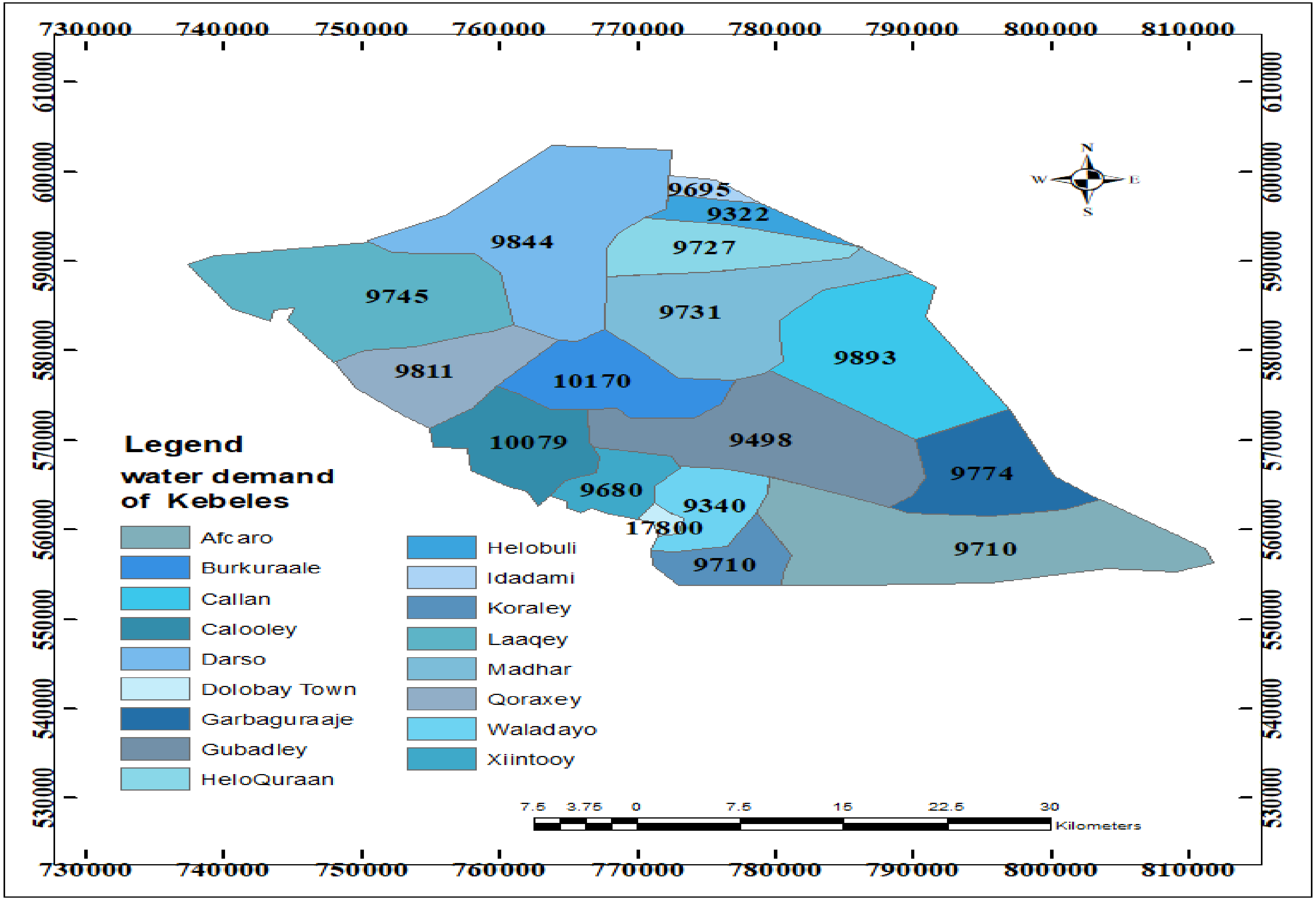

Figure5-138:-Water demand map of Dolobay woreda

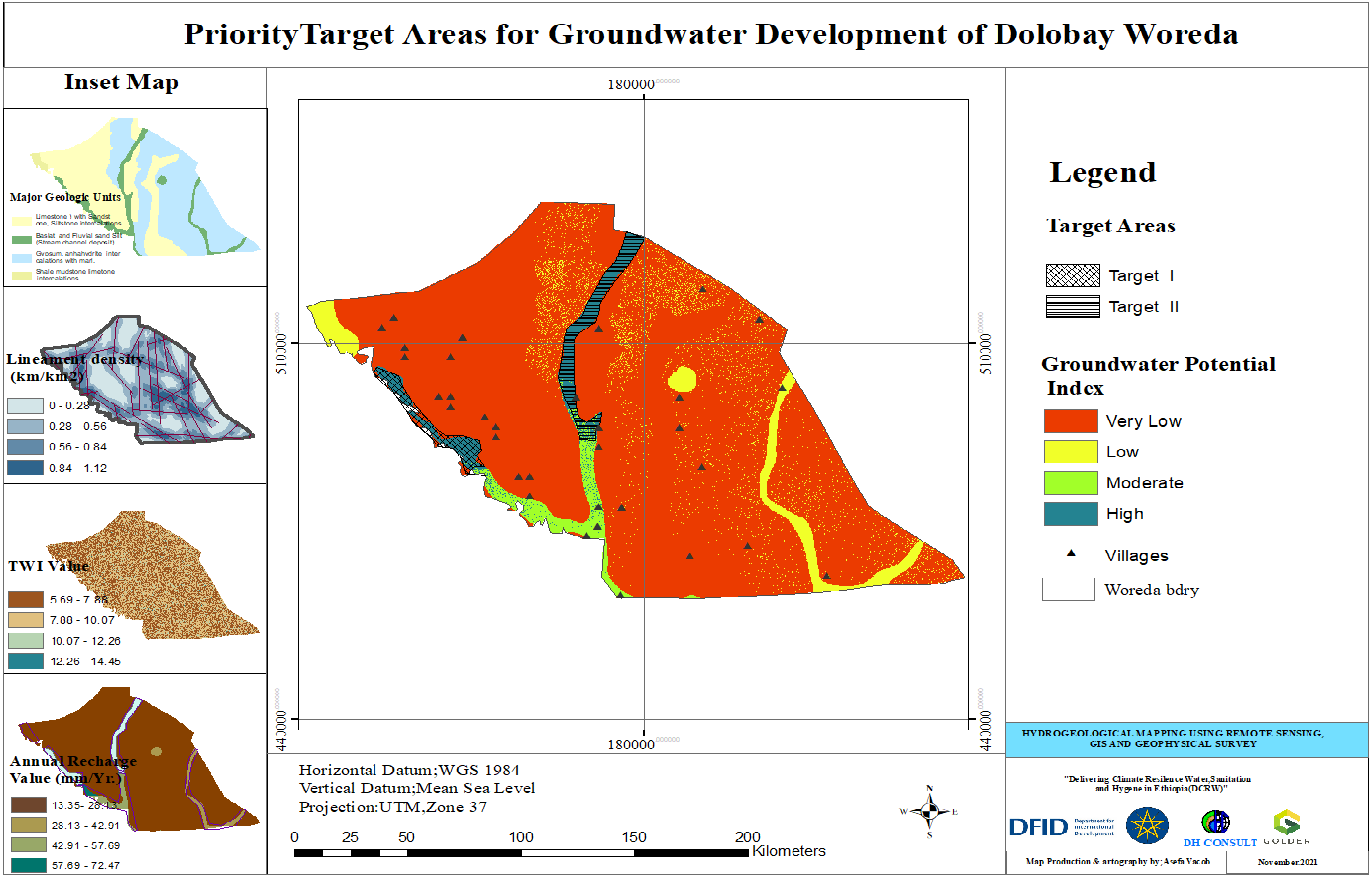

Figure 5-139:-Target Areas Map of Dolobay Woreda

5.12.6. Propsed Target Sites

Proposed target sites are identified, prioritized and selected within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficieries, population density and discussion made with the woreda's stakeholders so that to understand and identify kebeles with sever water shortage in particular. Accordingly, four priority target sites were selected and delineated within the Dolobay woreda for detail studies to be carried out in order to verify further and locate appropriate borehole drilling sites.

Target Site-I:

This target site is located in the western part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 5.0 l/s. This target site is mainly underlain by Tertiary volcanics and quaternary recent deposits of alluvial sediments.

Target Site-II:

This target site is located at central and Southern part of the woreda. It is situated mainly in the identified moderate potential zones with expected optimum borehole discharge of about 2-5 l/s. This target site is mainly underlain by Mesozoic sedimentary rocks of lower sandstone and limestone intercalated with marl.

5.13. Elkere Woreda

5.13.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.03 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Elkere woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-61). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-62. The weights assigned to the respective thematic maps as presented in Table 5-63 indicate that geology was ranked the dominant factor with a normalized weight value of 0.53 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Elkere woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Adadle woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

$$GWPZI = (GGwGGwi + LDwLDwi + TWIwTWIwi + GRwGRwi)$$

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Adadle woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e., 'high', 'moderate, 'low and very low', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-61 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Geology (GG)	5
Lineament density (LD)	3
Topographic Wetness Index (TWI)	1
Recharge (GR)	1

Table 5-62 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	GG	LD	TWI	GR	
GG	1	3	5	3	0.53
LD	1/3	1	3	1	0.21
TWI	1/5	1/3	1	1	0.10
GR	1/3	1	1	1	0.16

Table 5-63 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank	Area (km^2)	Area (%)
Geology/ Lithology, 'GG'	Fluvial sand silt (Stream channel deposit)	Good	3	0.50	0.53	50.4	0.7
	Mesozoic sedimentary rocks	Moderate	2	0.33		5,248.71	79
	Gypsum rocks	poor	1	0.17		1,384.9	20.7
Lineament Density,' LD' (Km/Km^2)	0—0.27	poor	1	0.10	0.21	3,252.87	48.7
	0.27-0.55	Good	2	0.20		2,500	37.4
	0.55-0.82	Moderate	3	0.30		830.15	12.4
	0.82-1.10	Very good	4	0.40		94.4	1.4
Topographic Wetness Index, 'TWI'	4.34-10.02	poor	1	0.10	0.1	3,294.67	49
	7.18-10.02	Good	2	0.20		3,161.30	47
	10.02-12.86	Moderate	3	0.30		226.60	3.4

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank	Area (km^2)	Area (%)
	12.86-15.70	Very good	4	0.40		1.58	0.02
Recharge, 'GR' (mm/y)	14.88-35.93	poor	1	0.10	0.16	6,633.6	99
	35.93-56.98	Good	2	0.20		2.89	0.04
	56.98-78.03	Moderate	3	0.30			
	78.03-99.07	Very good	4	0.40		47.52	0.7

5.13.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of geology, rainfall, lineament density, geomorphology, land slope, soil type, land use/land cover, groundwater depth and drainage density together with their spatial distribution in Adadle woreda are presented below:

I. Geology/lithology

In general, most parts of the *Elkere woreda* are underlain by Mesozoic sedimentary rocks of limestone and gypsum with shale, Quaternary deposits of alluvial are mostly found oncentral and eastern parts of the woreda.

However, the lithological units found in the woreda area are further classified into four major groups based on their significances to groundwater occurrence and productivity using borehole data on yield analysis in particular.

a) Fluvial sand silt (Stream channel deposit) (high productive with Q >5.0 l/s)

b) Limestone locally cherty (Korahe Belet Uen) with Sandstone, siltstone intercalations with local limestone (Korahe Ambaradom) (moderately productive with Q =2.0-5.0 l/s)

c) Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle) very low productive with Q =0.05-0.5 l/s)

The Mesozoic sedimentary rocks are the main lithologic framework of the *Elkere woreda*which together covered a total area of about 6,633.5 km2 or 99.7 % of the woreda area, tertiary quaternary recent sediments covered about 50.41 km2 (0.7%)of the woreda area (Figure 5-140).

Usually, massive unfractured lithologic units in sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification and weathered overburden, and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the weathered regolith units, karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of low productivity of Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle) (0.17) \moderate productivity of Limestone locally cherty (KoraheBelet Uen) with Sandstone, siltstone intercalations with local limestone (Korahe Ambaradom) (0.33)/ high productivity Fluvial sand silt (Stream channel deposit) (0.50).

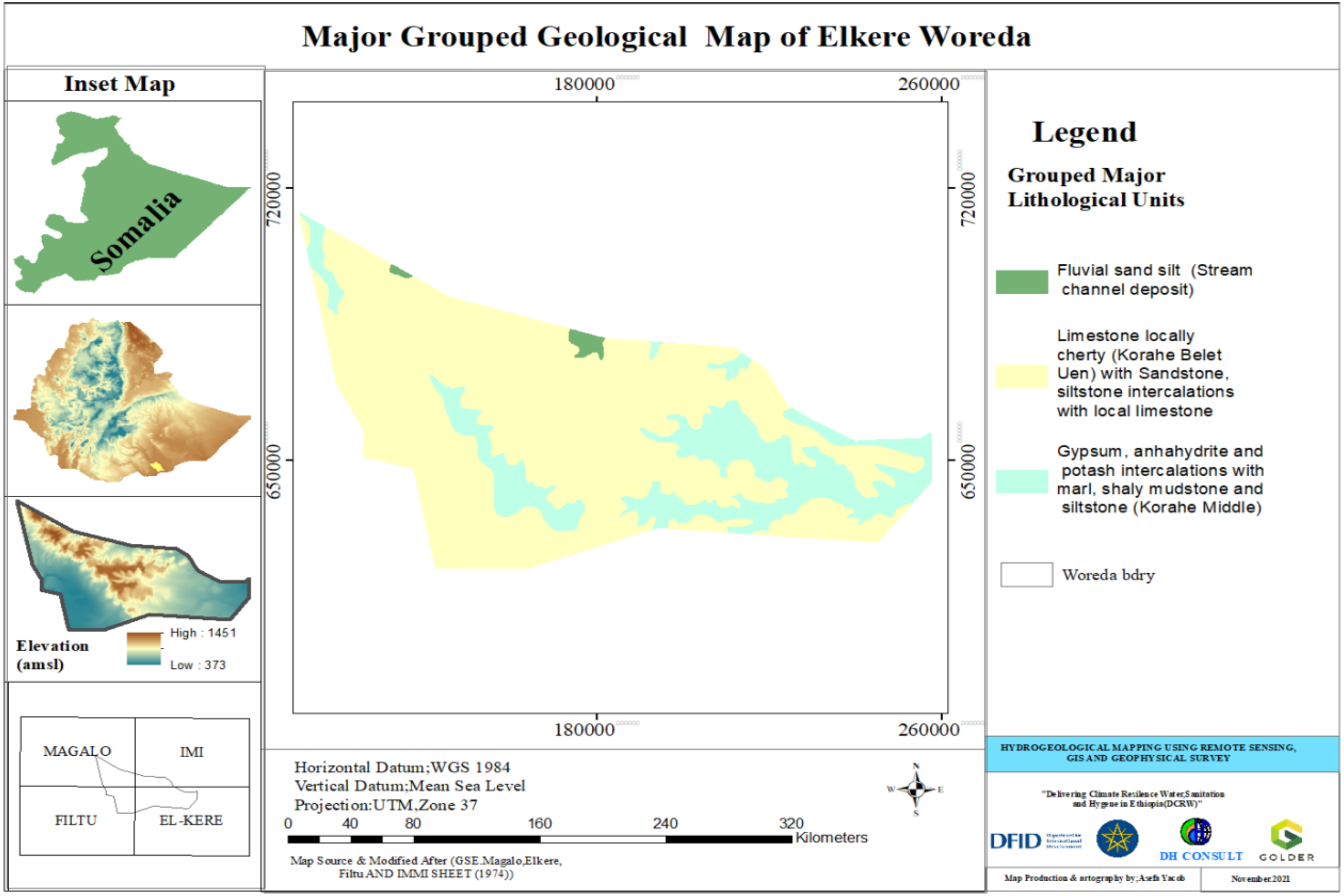

Figure 5-140. Grouped Lithological classification map of Elkere woreda

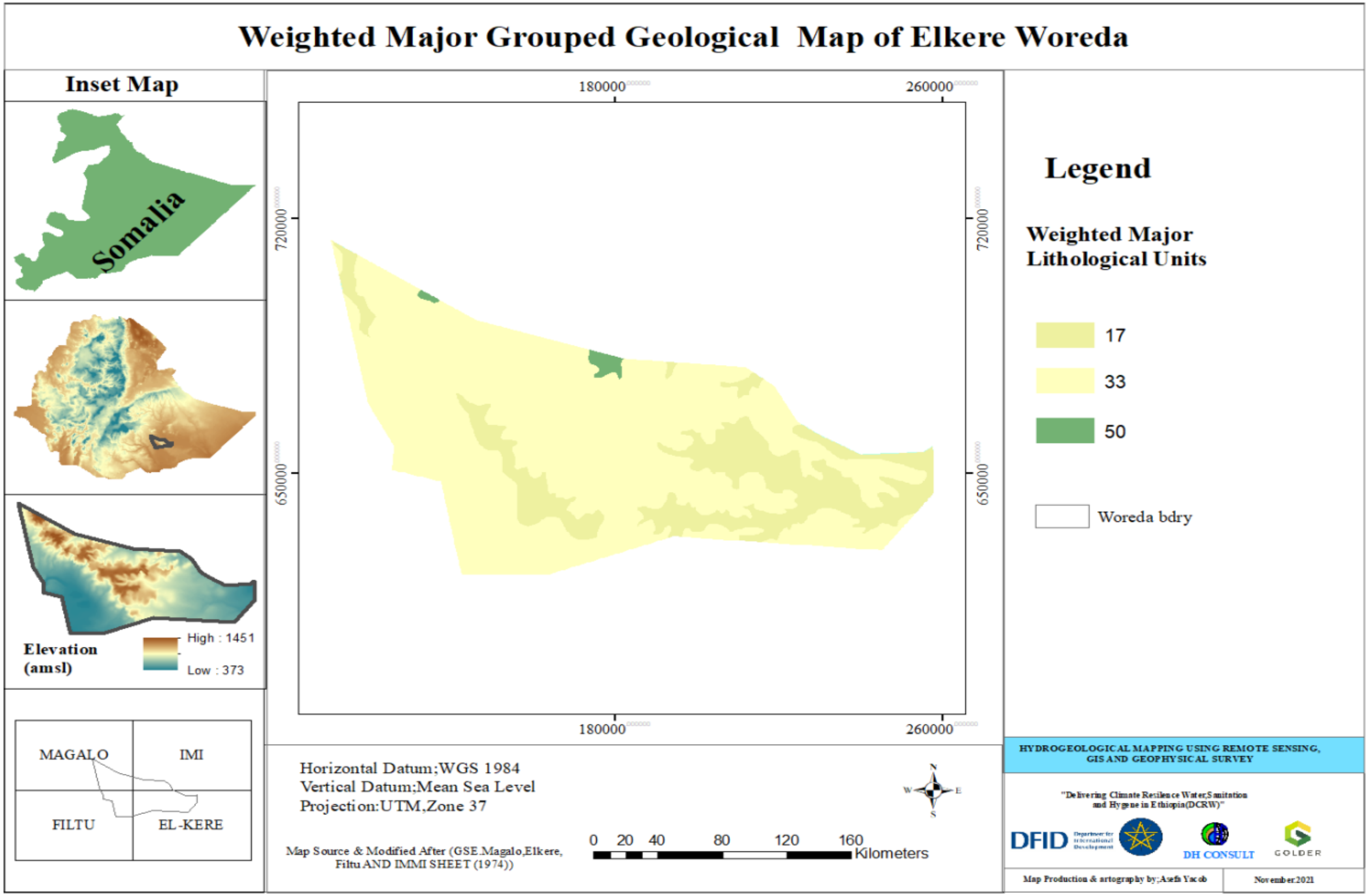

Figure 5-141. Weighted lithological classes' map of the Elkere woreda

II. Lineaments and lineament density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SEand N–S trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.27 km/km2 to 1.10 km/km2 (Figure 5-142). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by mesozoic sediments having relatively higher lineament density of 0.82 – 1.10 km/km2 compared with areas underlain by sedimentary rocks of gypsum with lower lineament densities of (<0.27 km/km2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.40 was assigned to area with high density of lineaments, while a low weightage of 0.10 was assigned to areas with low lineament density (Figure 5-143).

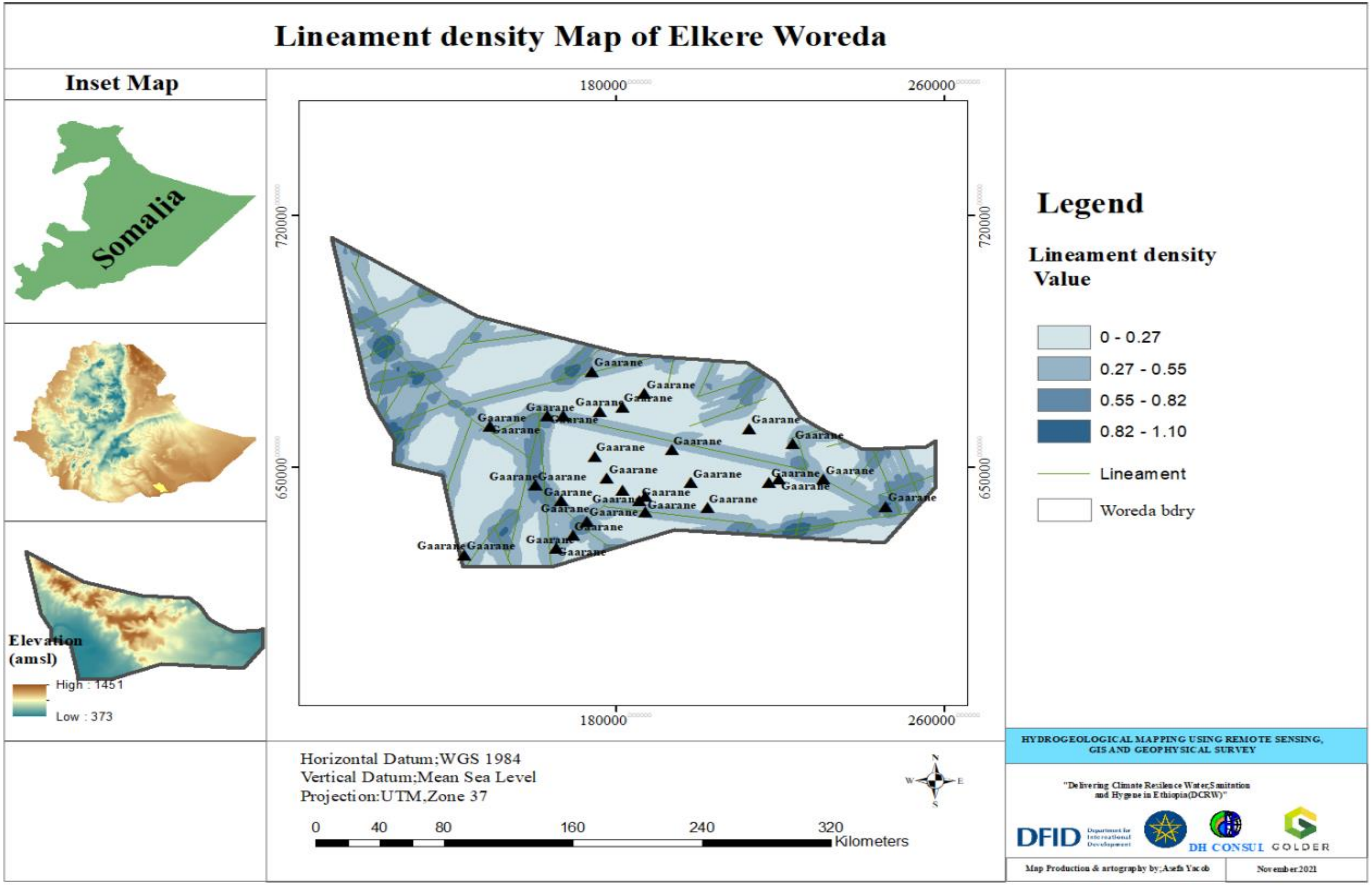

Figure 5-142. Lineament Density Map of Elkere woreda

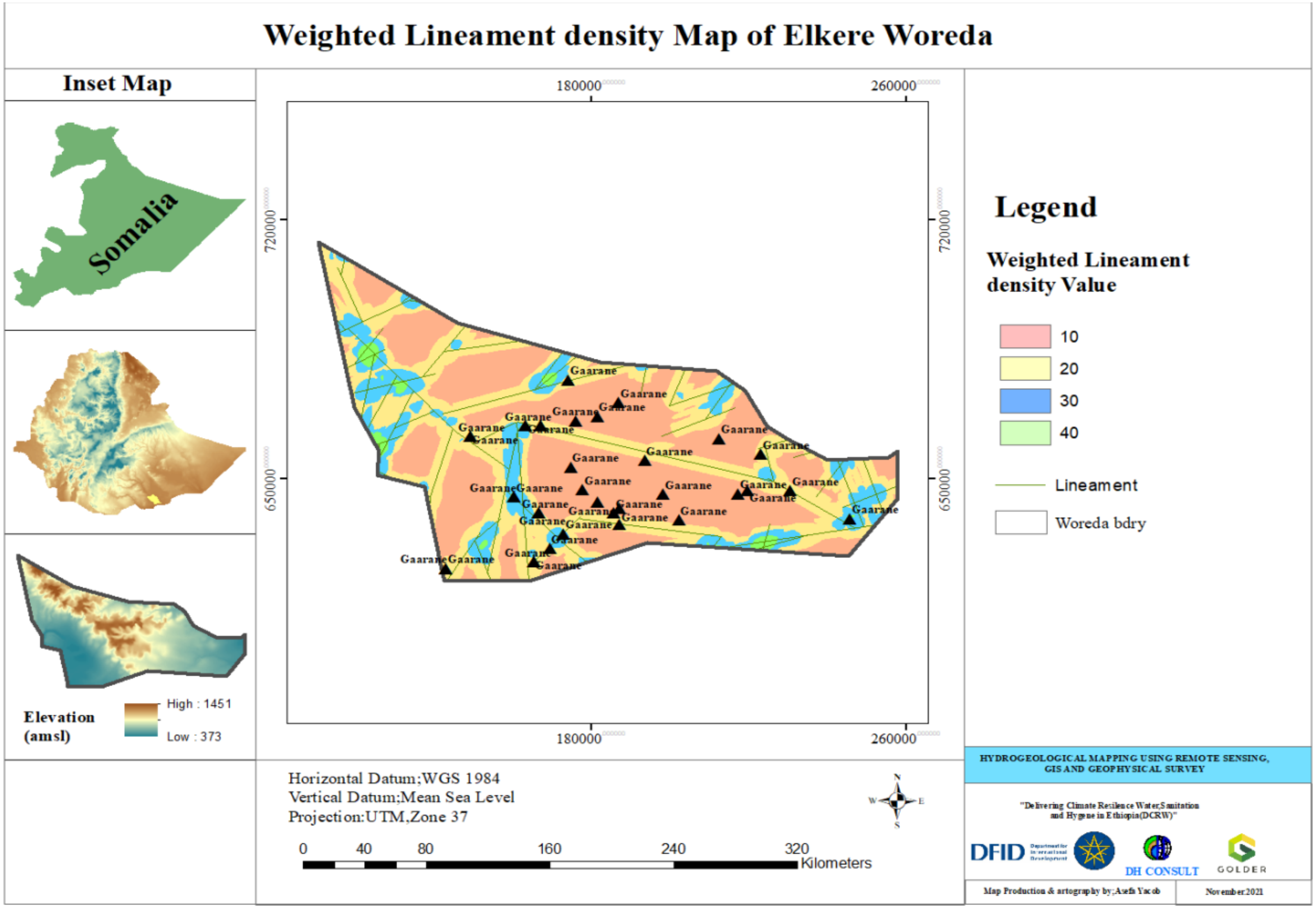

Figure 5-143Weightage value of Lineament Density Map of Elkere woreda

III. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 4.34 and 15.87. A closer look at the classification revealed that most the high elevated areas and drainage systems with steep slopes have relatively lower TWI value while the low-lying areas and drainage systems with gentle and flat slopes have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.40) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.10).

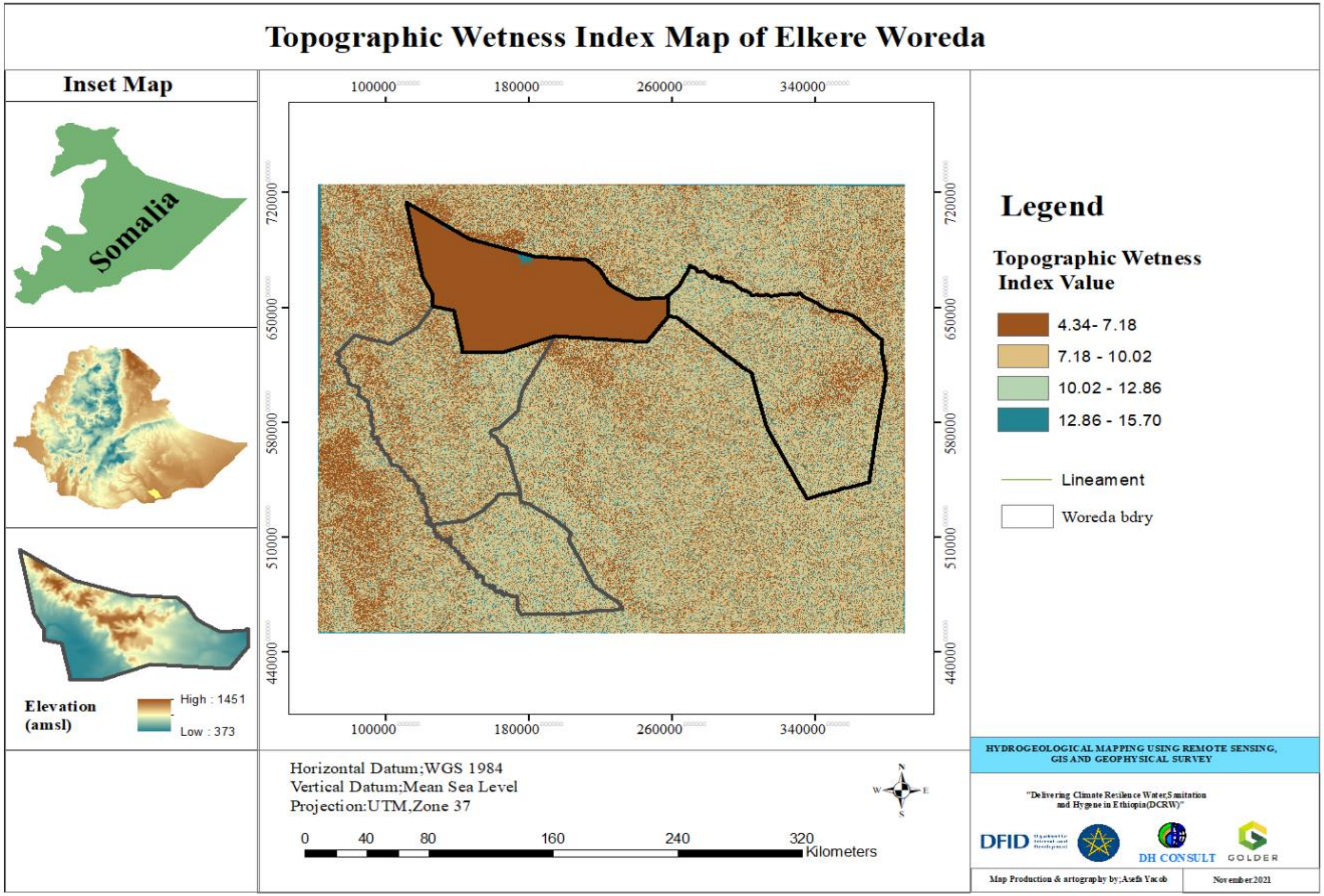

Figure 5-144. TWI Map of Elkere woreda

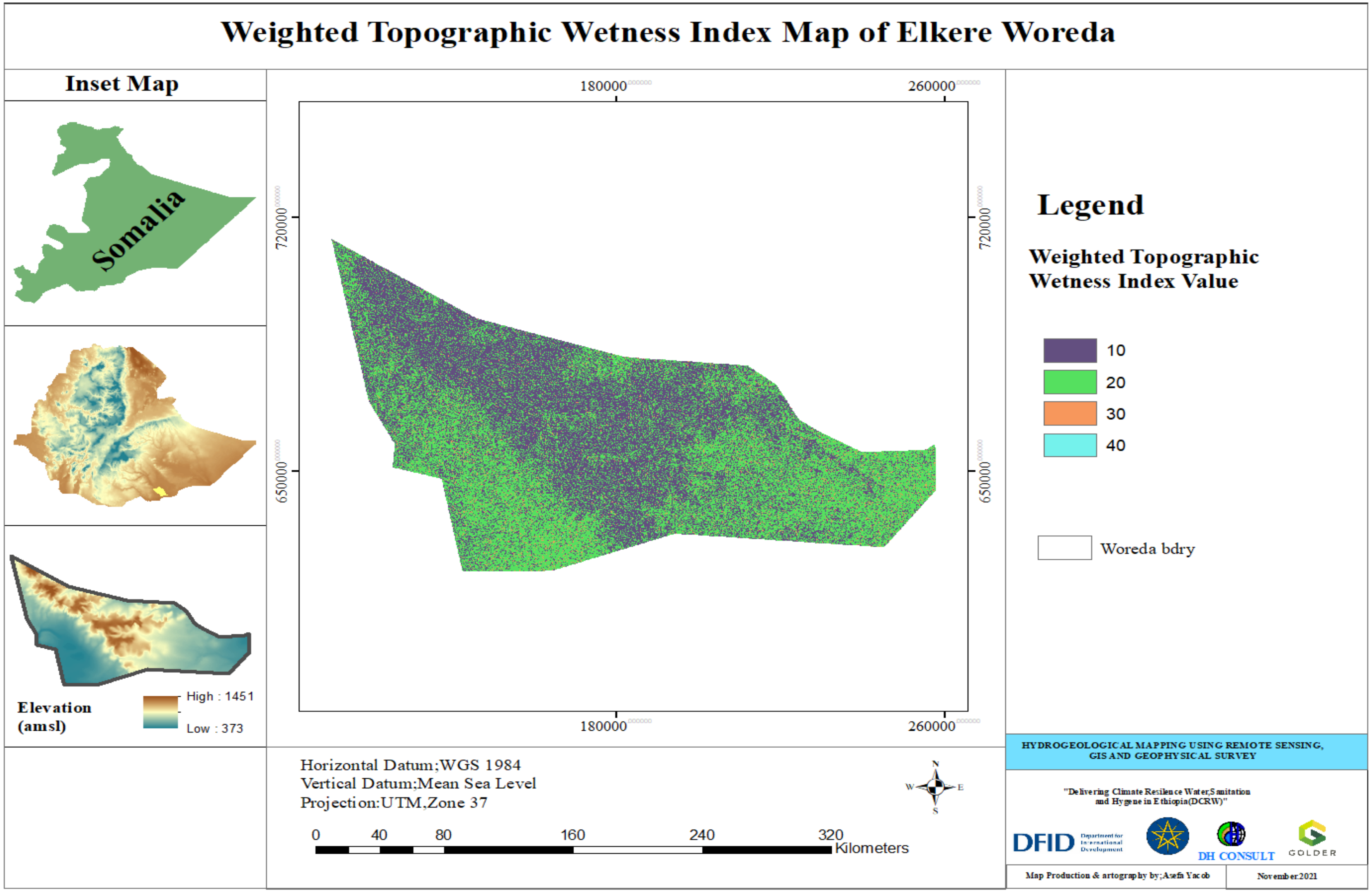

Figure 5-145.Weightage value of TWI Map of Elkere woreda

IV. Recharge

The spatial annual recharge rate distribution in the Elkere woredaranges from 11.48 to 99.07 mm/y suggesting groundwaters in most part of the woreda area underlain by sedimentary rocks and quaternary sediments have relatively higher recharge amount (Figure 5-146). Accordingly, areas with higher and moderate amount of recharge have weightage factor of 0.50 and 0.33, respectively signifying very good and moderate groundwater potential which covers about 6,633.61 km2 (99 %) and 2.89 km2 (0.04 %), respectively while areas with the lowest amount of recharge have weightage factor of 0.17, suggesting poor groundwater potentiality and represent about 47.53 km2 (0.7 %). A closer look at the recharge thematic map revealed that most parts of the woreda have relatively low recharge (14.83-35.93 mm/y). Generally, the study area is characterized with lowmean annual recharge amount (<14.83mm /y).

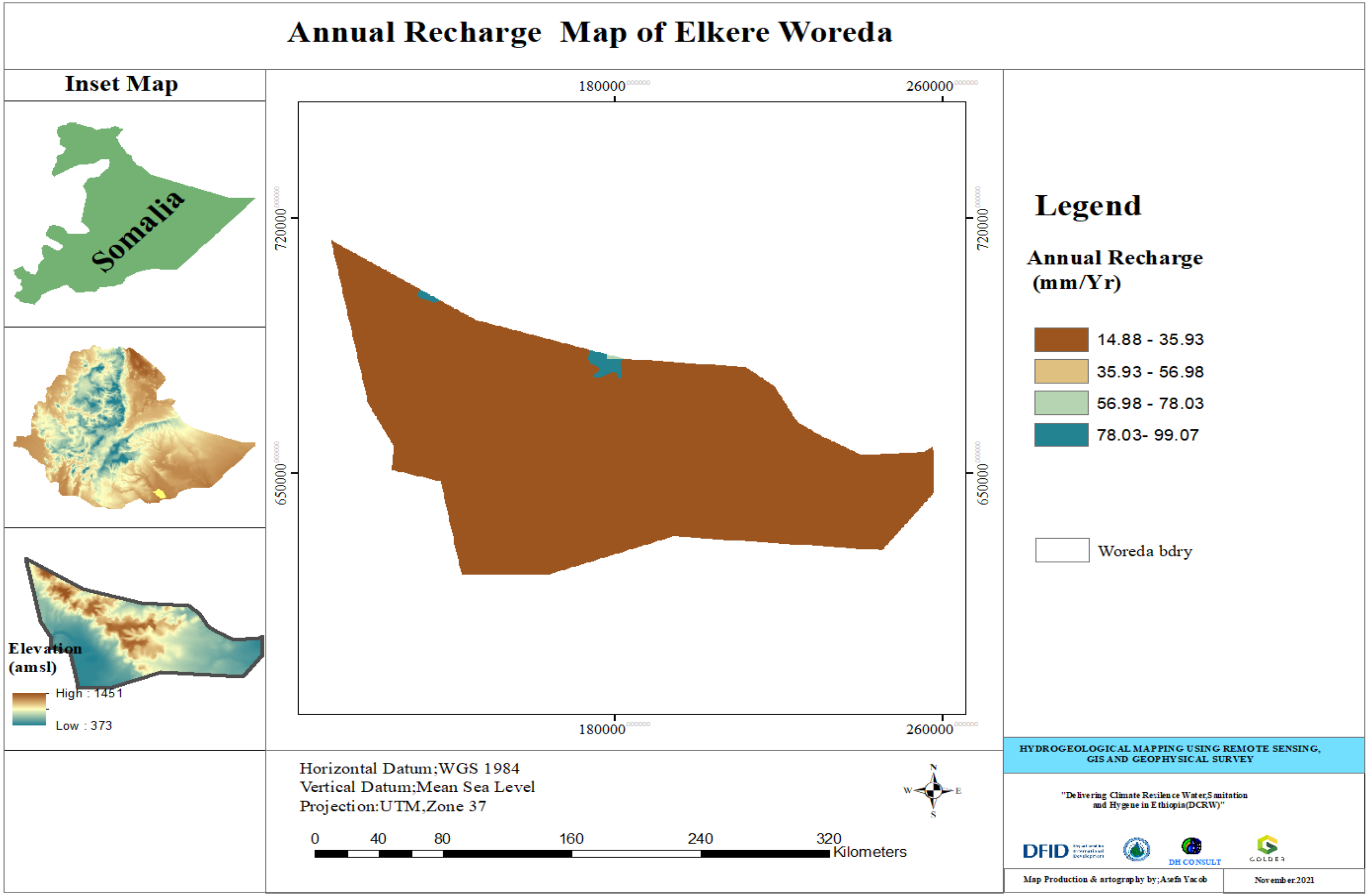

Figure 5-146. Annual Recharge Map of Elkere woreda

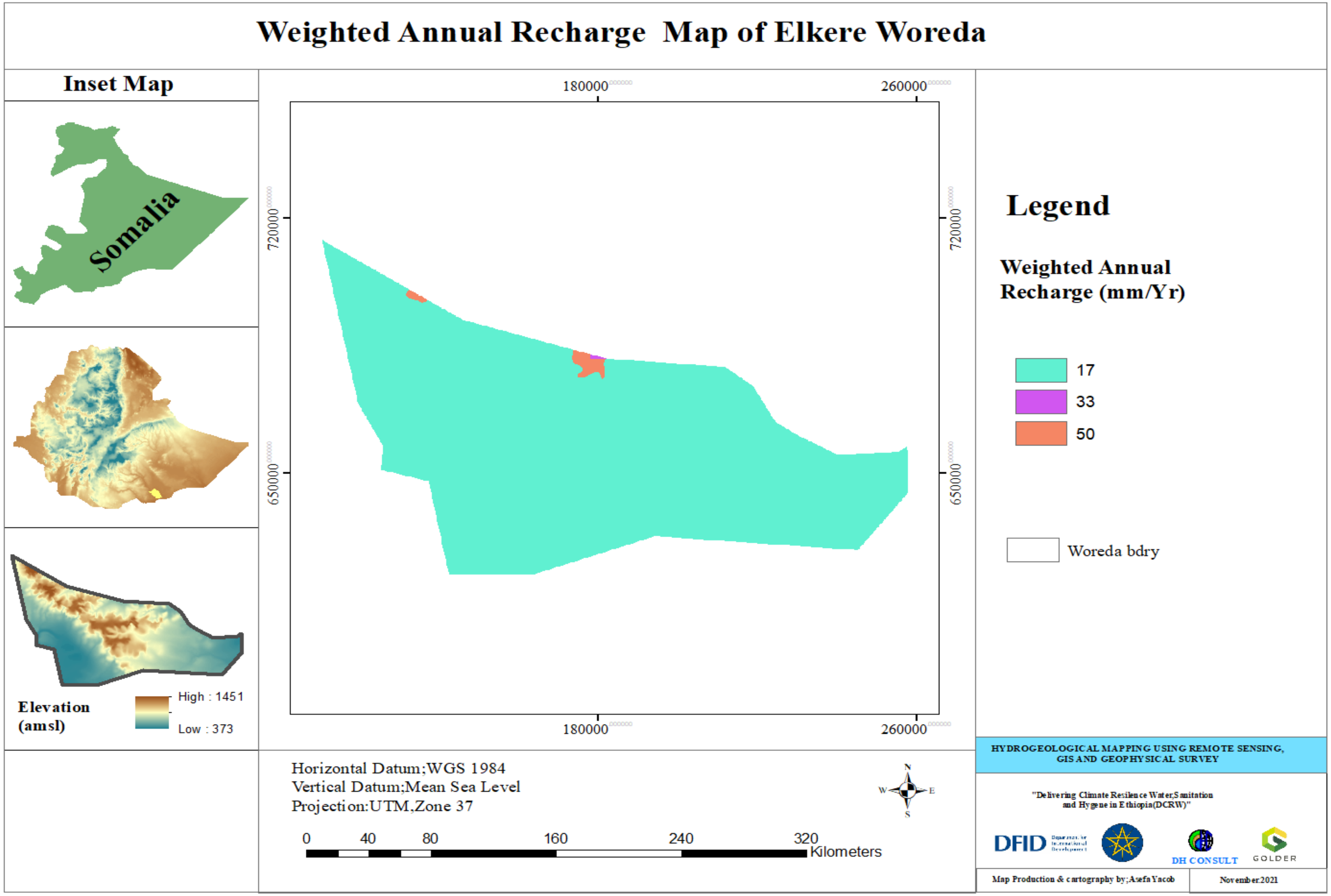

Figure 5-147. Weighted Annual Recharge classes' map of the Elkere woreda

5.13.3. Classification of Groundwater Potential Zones

The hydrogeological system of Dolobay woreda is comprised of four main lithological units as Baslat and Fluvial sand silt (Stream channel deposit), Limestone locally cherty (Korahe Belet Uen) with Sandstone, siltstone intercalations with local limestone (Korahe Ambaradom), Shale mudstone limetone intercalations (Gabradarre) and Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle). At regional scale, Baslat and Fluvial sand silt (Stream channel deposit) form extensive and highly productive aquifers. Within the domain of *Elkere woreda*, theses, Baslat and quaternary deposits form aquifers with high groundwater potential.

At regional scale, the Limestone Formation and lower sandstone form extensive and moderately productive aquifers having high hydraulic conductivity. However, at local scale, within the domain of Elkere Woreda, due to the geomorphic setup, the Limestone Formation and the underlying units do not form high potential aquifer as revealed from existing borehole information rather the Weathered and slightly fractured sedimentary rocks with overlying Quaternary deposit form major potential aquifer with moderate productivity within the domain of *Elkere woreda*along lineament lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-148). The potential groundwater zones (PGZ) of the *Elkere woreda*revealed four distinct zones, namely very low,low, moderate and high zones whose distribution and extents are 6,499.71 km2 (97 %), 133.67 km2 (2 %), 2.35 km2 (0.035%) and47.76 km2 (0.71 %), respectively as presented in Table 5-64.

The potential map, as presented in Figure 5-148, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that most elevated areas around the peripheries and central parts of the *Elkere woreda*generally have very low potentials with area coverage of about 97 %, while limited areas at central regions generally exhibits moderateto low potentials representing about 2 % and 0.035 % of the study area, respectively. The generally high to moderate groundwater potentiality of the study area as reflected by 0.71 % coverage is a confirmation of generally moderate to high productive aquifers of recent alluvial and sedimentary deposits, whereas low to very low groundwater potential areas have an indication of limited aquifers capabilities of gypsum and shale with marl intercalation.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the geology and lineament density in addition to the topographic wetness index control. In addition, areas underlain by recent quaternary deposits especially in the central and southern sections of the study area which are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments and apparently deep fracturing and weathering have high and moderate groundwater potential on the one hand. On the other hand, areas underlain by sedimentary rocks of limestone and gypsum in the majority of the woreda areas are characterized by small ridges and steep slopes, lower recharge and lineament densities, exhibit low groundwater potential while areas underlain by sedimentary rocks associated with sediments have medium potential. Moreover, high drainage densities and predominance of limestone rock outcrops can be attributed to the observed low groundwater potentials at the most part of the study area. However, predominance of recent sediments and sedimentary rock outcrops, low drainage density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential exhibited at central and western portions of the study area. Summary of the groundwater potential zones identified in the Elkere *woreda*is presented in the table below (Table 5-64).

Table 5-64.Classification of groundwater potential zones and coverage areas alongside the respective yield and transmissivity categories

Woreda Name	GWP Zones	Area (km^2)	Area (%)	Major Aquifer Units	Borehole Yield Classification (l/s)
					Q (Range)
Elkere	High	47.75	0.71	quaternary Sediments	>5
	Moderate	2.35	0.035	Sedimentary Rocks limestone	2-5
	Low	133.67	2	Sedimentary Rocks Gypsum	0.5-2
	Very Low	6,499.71	97	Shale and marl	0.05-0.5

5.13.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) were collated for boreholes in and around the study woreda area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the study area vary from >5 lit/sec in high potential zones and varying 2- 5 lit/sec in moderate potential zones, 0.5 lit/sec to 2 lit/sec in the low and from 0.05-0.5 lit/sec in the very low potential zones. As shown in the figure 5-148, the occurrence of number of wells with yield of in the range 2- 5 lit/sec (moderate yield) and of >5 lit/sec (high yield) cut across mainly the recent quaternary deposits and sedimentary rocks. However, the less frequency of wells within gypsum and shale rock in the low and very low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (2- 5 lit/sec) and high-yield (>5 lit/sec) categories are associated also with wells in the Mesozoic sedimentary rocks and quaternary alluvial deposits along river channel. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such basement and sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

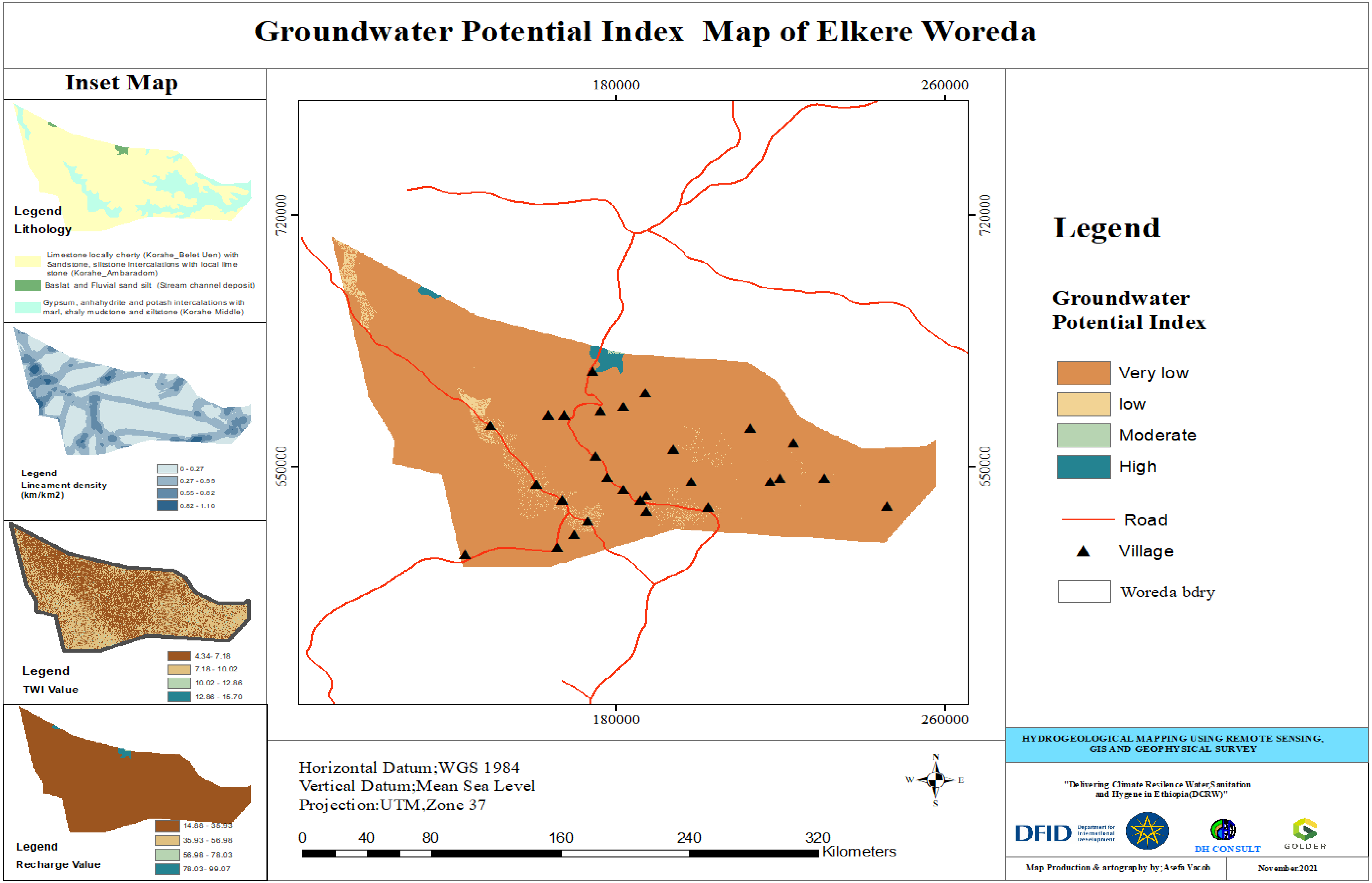

Figure 5-148. Groundwater Potential Zones Map of Elkere woreda

5.13.5. Population projection and Water Demand

5.13.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-65 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P = P_o (1 + r)^n$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Elkere Woreda has been projected forward until 2036 using the growth rate of Somali Regional State. The minimum and maximum population in the Woreda is 5,771 and 13,198 respectively. The total population of the Elkerea Woreda in 2036 is going to be 115,428.

5.13.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic

purposesgreatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO)& (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer's life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24-hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 5-149 shows the distribution of water demand in each Kebeles of the Woreda. Awraga kebele water demand is the minimum with 448 M3/day and maximum water demand is required for Elkari Kebeles with1024 M3/day respectively. The overall water demand for the projected population in the Elkere Woreda is 8,954 M3/day.

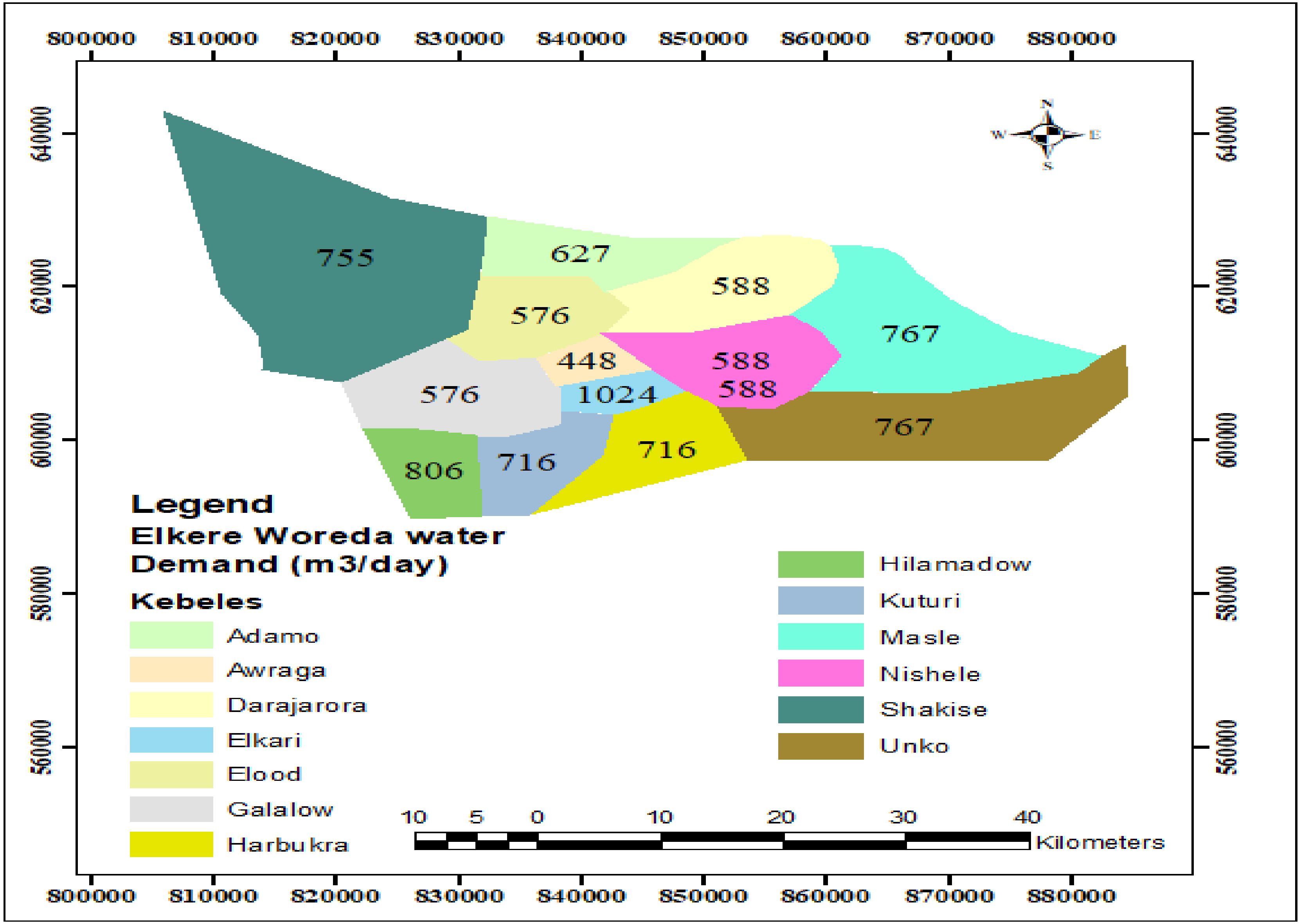

Figure 5-149:-Water Demand map of Elkere woreda Kebeles

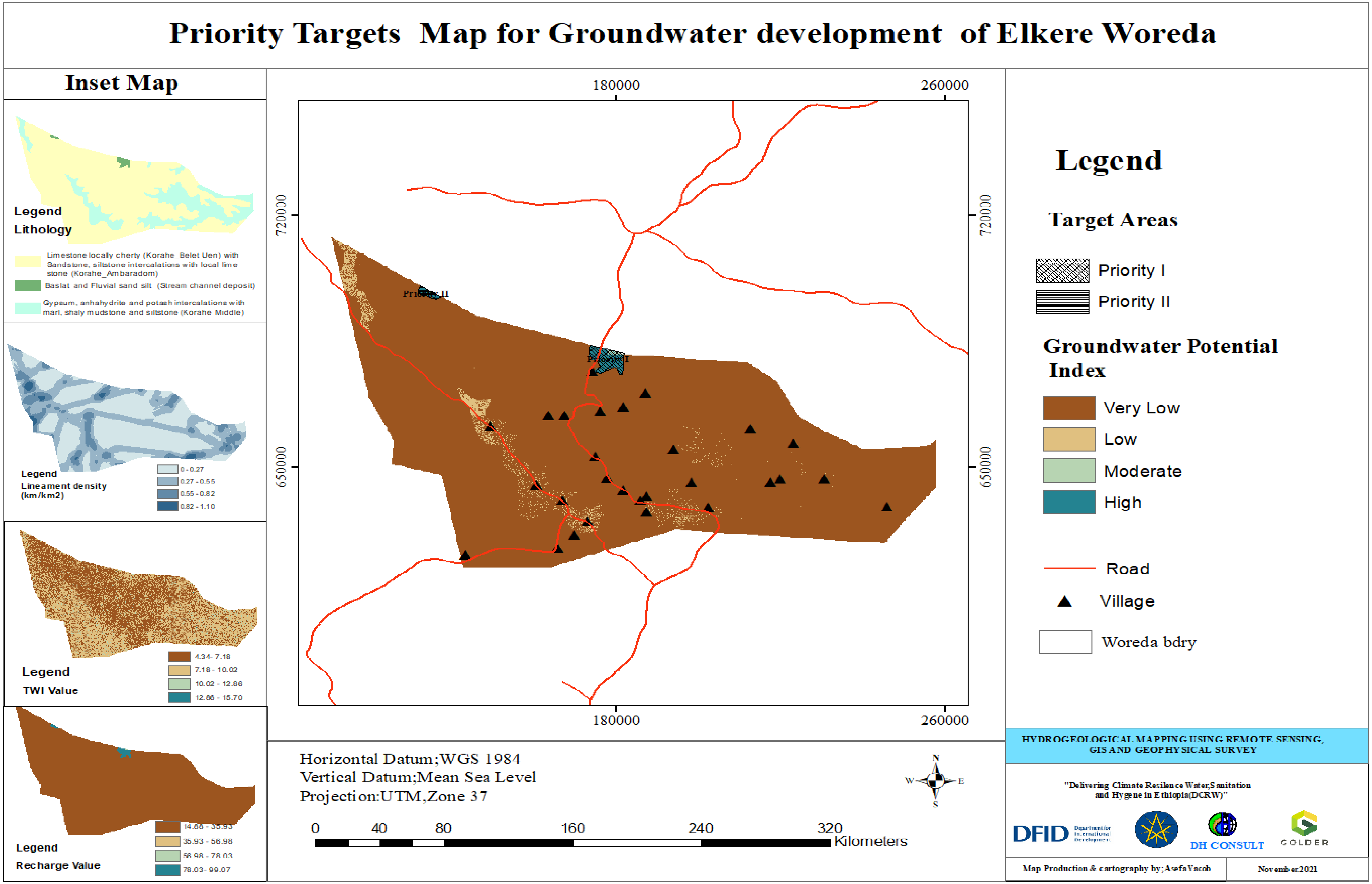

Figure 5-150:-Target Areas Map of Elkere woreda

5.13.6. Propsed Target Sites

Proposed target sites are identified, prioritized and selected within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficieries, population density and discussion made with the woreda's stakeholders so that to understand and identify kebeles with sever water shortage in particular. Accordingly, four priority target sites were selected and delineated within the Elkere woreda (Figure 5-150) for detail studies to be carried out in order to verify further and locate appropriate borehole drilling sites.

Target Site-I:

This target site is located in the northern part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 5.0 l/s. This target site is mainly underlain by Tertiary volcanics and quaternary recent deposits of alluvial sediments.

Target Site-II:

This target site is located at northern part of the woreda. It is situated mainly in the identified moderate potential zones with expected optimum borehole discharge of about 2-5 l/s. This target site is mainly underlain by Mesozoic sedimentary rocks of lower sandstone and limestone intercalated with marl

5.14. Chereti Woreda

5.14.1. Weights Assignment

For this study woreda, the CR was estimated to be 0.03 which is far below the threshold consistency value of 0.10.

Suitable weights were assigned to the four themes and their individual features after understanding their hydrogeological importance in causing groundwater occurrence in the Chereti woreda. The normalized weights of the individual themes and their different features were obtained through the Saaty's analytical hierarchy process (AHP). The weights assigned to the themes are presented in Table 5-66). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 5-67. The weights assigned to the respective thematic maps as presented in Table 5-68 indicate that geology was ranked the dominant factor with a normalized weight value of 0.53 while recharge is the least accounted factor with a normalized weight of 0.10 for groundwater occurrence in the study Chereti woreda.

After deriving the normal weights of all the thematic layers and feature under individual themes, all the thematic layers were integrated with one another using ArcGIS software in order to demarcate groundwater potential zones index (GWPZI) in the Chereti woreda. The index was computed by the integration of the total normalized weights of different polygons using equation stated below.

$$GWPZI = (GGwGGwi + LDwLDwi + TWIwTWIwi + GRwGRwi)$$

Where, GG is the geology, LD is lineament density, TWI is topographic wetness index, GR is Recharge, w is normalized weight of a theme and wi is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS 10.8 platform, a composite groundwater potential index (GWPI) for the study area (Haromaya woreda) was generated on the basis of which the overall groundwater potential zones map was produced. In the final integrated layer was divided into four equal classes, i.e. 'very high', 'high', 'moderate' and 'low or poor', in order to delineate groundwater potential zones. Finally, well/ borehole data (e.g. yield) was collated from existing wells in the study area. This data was used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 5-66 Weights of the four thematic layers for groundwater potential zoning

Themes	Assigned Weights
Geology (GG)	5
Lineament density (LD)	3
Topographic Wetness Index (TWI)	1
Recharge (GR)	1

Table 5-67 Normalized weights and pair-wise comparison matrix of the four thematic layers for groundwater potential zoning

Theme	Theme				Normalized weight
	GG	LD	TWI	GR	
GG	1	3	5	3	0.53
LD	1/3	1	3	1	0.21
TWI	1/5	1/3	1	1	0.10
GR	1/3	1	1	1	0.16

Table 5-68 Assigned and normalized weights for the individual features of the four thematic layers for groundwater potential zoning

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank	Area (km^2)	Area (%)
Geology/ Lithology, 'GG'	Quaternary deposits of recent alluvium & lacustrine sediments	Very good	4	0.40	0.53	445.17	5.2
	Mesozoic sedimentary rocks	Moderate	3	0.30		4,358.22	51
	Gypsum rocks	Good	2	0.20		308.7	3.6
	Shale	poor	1	0.10		3,389.72	0.4
Lineament Density,' LD' (Km/Km^2)	0 - 0.23	poor	1	0.10	0.21	3,867.90	0.45
	0.24 - 0.47	Good	2	0.20		3,730.74-	0.44
	0.48 – 0.70	Moderate	3	0.30		808.3	0.095
	0.71 – 0.93	Very good	4	0.40		95.17	0.01
Topographic Wetness Index, 'TWI'	4.19 – 7.34	poor	1	0.10	0.1	1,997.4	0.24
	7.35 – 9.1	Good	2	0.20		5701.30	0.67
	9.11 – 11.8	Moderate	3	0.30		790.68	0.09
	11.9 – 19.1	Very good	4	0.40		11.68	0.001

Theme	Class	Groundwater Prospect	Weight assigned	Normalized weight	Rank	Area (km^2)	Area (%)
Recharge, 'GR' (mm/y)	23.2 – 28.5	poor	1	0.10	0.16	8,056.64	0.94
	28.6 – 48	Good	2	0.20		222.15	0.026
	48.1 – 97	Moderate	3	0.30		131.44	0.015
	97.1 - 190	Very good	4	0.40		91.58	0.01

5.14.2. Integration of Thematic Layers for Groundwater Potential Zoning

The details of geology, rainfall, lineament density, geomorphology, land slope, soil type, land use/land cover, groundwater depth and drainage density together with their spatial distribution in Chereti woreda are presented below:

I. Geology/lithology

In general, most parts of the Chereti woredaare underlain by Mesozoic sedimentary rocks of limestone and gypsum with shale. Tertiary volcanics and Quaternary deposits of alluvial are mostly found oncentral and eastern parts of the woreda.

However, the lithological units found in the woreda area are further classified into four major groups based on their significances to groundwater occurrence and productivity using borehole data on yield analysis in particular.

a) Baslat and Fluvial sand silt (Stream channel deposit) (high productive with Q >5.0 l/s)
b) Limestone locally cherty (Korahe Belet Uen) with Sandstone, siltstone intercalations with local limestone (Korahe Ambaradom) (moderately productive with Q =2.0-5.0 l/s)
c) Shale mudstone limetone intercalations (Gabradarre) (low productive with Q =0.5-2.3 l/s)
d) Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle) very low productive with Q =0.05-0.5 l/s)

The Mesozoic sedimentary rocks are the main lithologic framework of the Chereti woredawhich together covered a total area of about 3,655.5 km2 or 91 % of the woreda area, tertiary volcanics and quaternary recent sediments covered about 359 km2 (9 %)of the woreda area (Figure 5-151).

Usually, massive unfractured lithologic units in sedimentary settings have little influence on groundwater availability except in cases with secondary porosity through the development of karstification and weathered overburden, and fractured bedrock units, which form potential groundwater zones. Hence, on the basis of the presence and nature of the weathered regolith units, karstification and fracture systems, appropriate weights are assigned to the different lithological units in the study area. The weightage in terms of increasing groundwater potentiality is in the order of very low productivity of shale and marl intercalation (0.10) \ low productivity of gypsum unit (0.2)/ moderate productivity of sedimentary rocks (0.30) \ high productivity tertiary volcanics and quaternaryalluviall sediments (0.4).

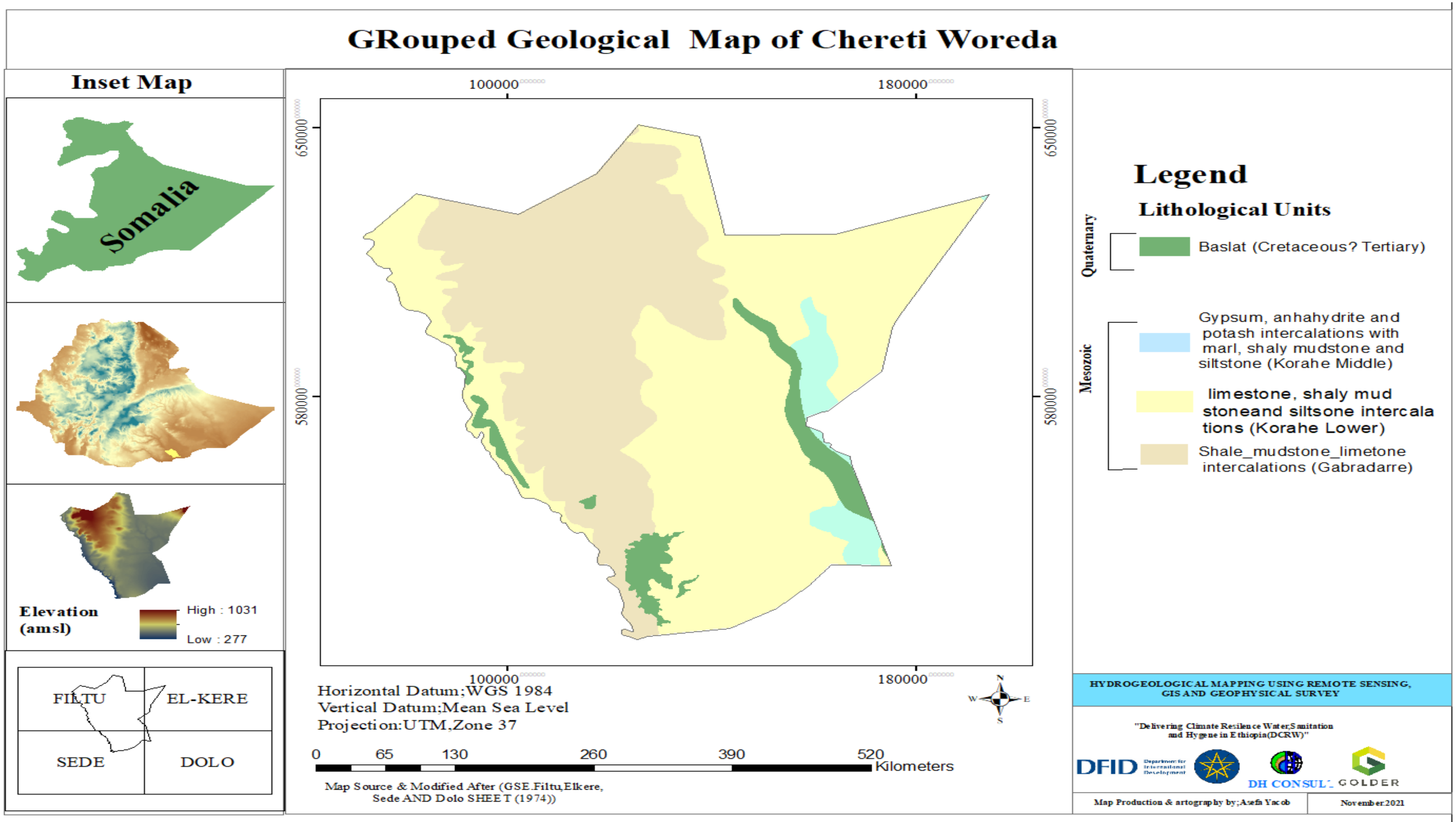

Figure 5-151. Grouped Lithological classification map of Chereti woreda

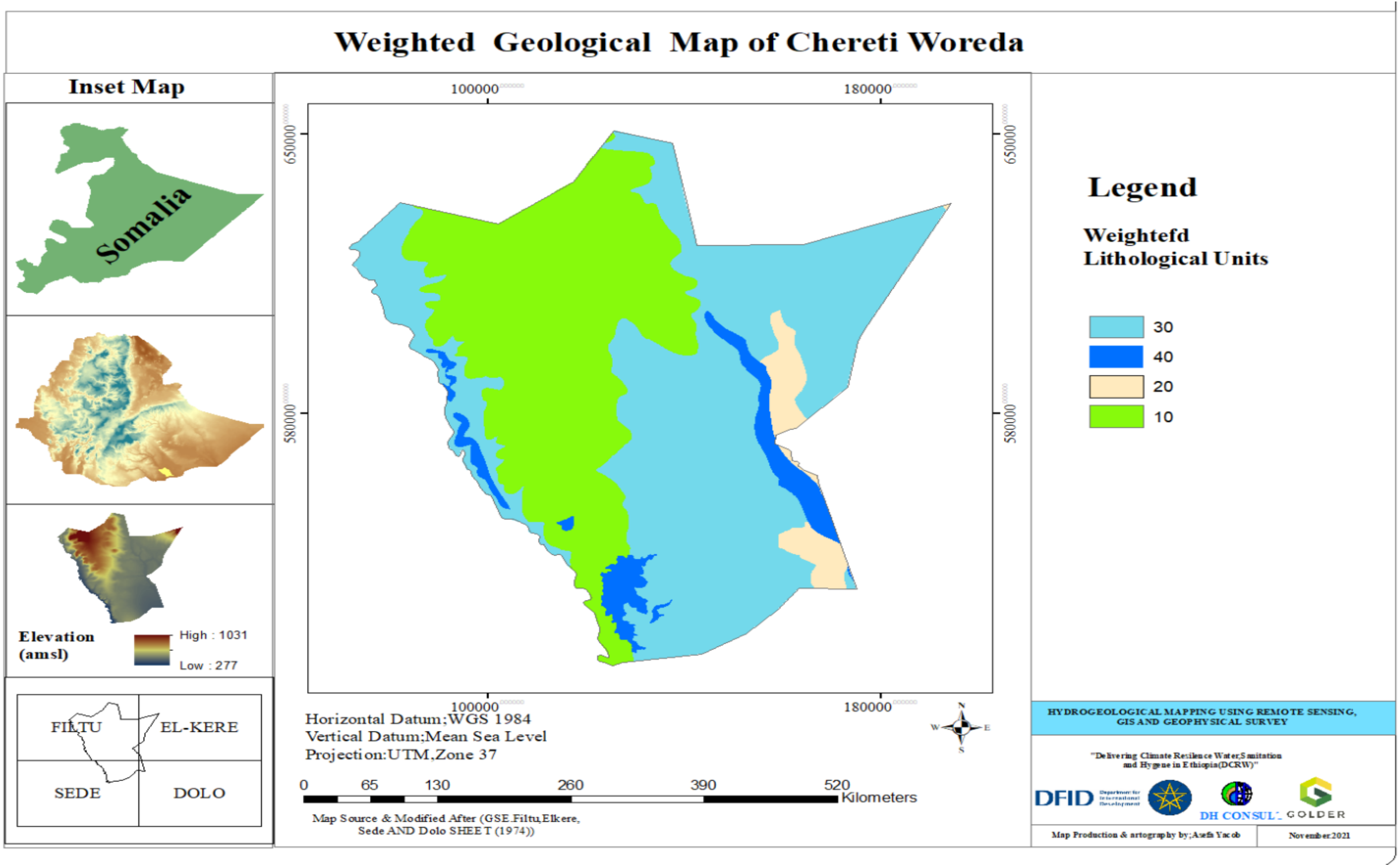

Figure 5-152. Weighted lithological classes' map of the Chereti woreda

II. Lineaments and lineament density

The study area is highly affected by lineaments and/or fractures consequent to a number of tectonic activities in the past. Two prominent directions identified are NW-SEand N–S trending lineaments. Usually, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of lineaments usually denotes a permeable zone. For most of the study area, the lineament density varies from less than 0.29 km/km2 to 1.17 km/km2 (Figure 5-153). Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with areas underlain by mesozoic sediments having relatively higher lineament density of 0.88 – 1.17 km/km2) compared with areas underlain by sedimentary rocks of gypsum and shale with lower lineament densities of (<0.29 km/km2).

Thus, areas with higher lineament density are regarded as good for groundwater development. Consequently, higher weightage of 0.40 was assigned to area with high density of lineaments, while a low weightage of 0.10 was assigned to areas with low lineament density (Figure 5-154).

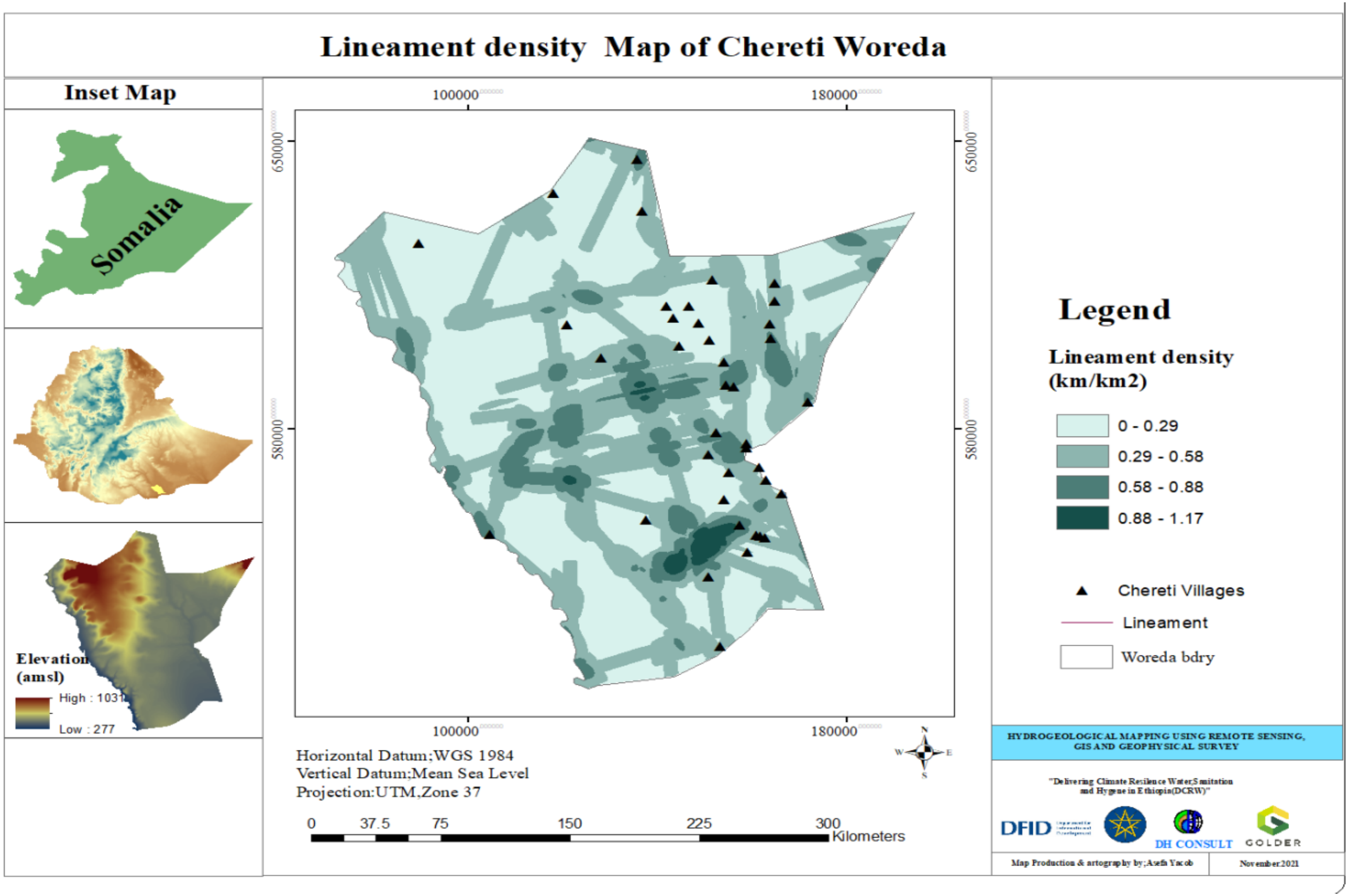

Figure 5-153. Lineament Density Map o f Chereti woreda

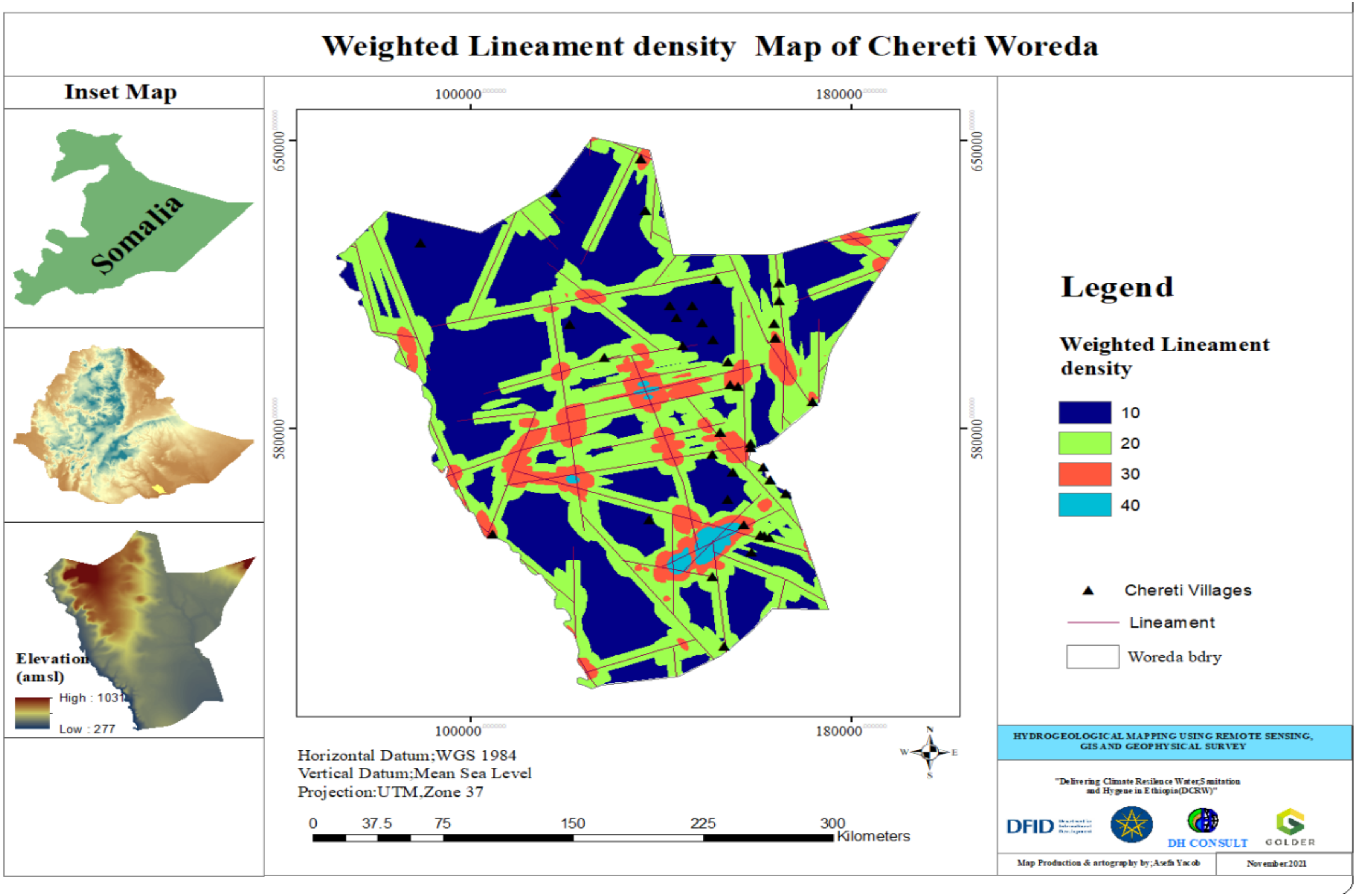

Figure 5-154. Weightage value of Lineament Density Map of Chereti woreda

III. Topographic Wetness Index (TWI)

In this study area, the TWI value ranges between 4.5 and 11.68. A closer look at the classification revealed that most the high elevated areas and drainage systems with steep slopes have relatively lower TWI value while the low-lying areas and drainage systems with gentle and flat slopes have relatively higher wetness index value where runoff waters from highlands flow and accumulates mostly. Therefore, an area with higher value of TWI has good prospect for groundwater occurrence and flow, and accordingly high weightage value (0.40) was assigned to this class. Whereas, areas with lowest TWI value are steep slopes which triggers runoff were considered with low groundwater prospect and given low weightage value (0.10).

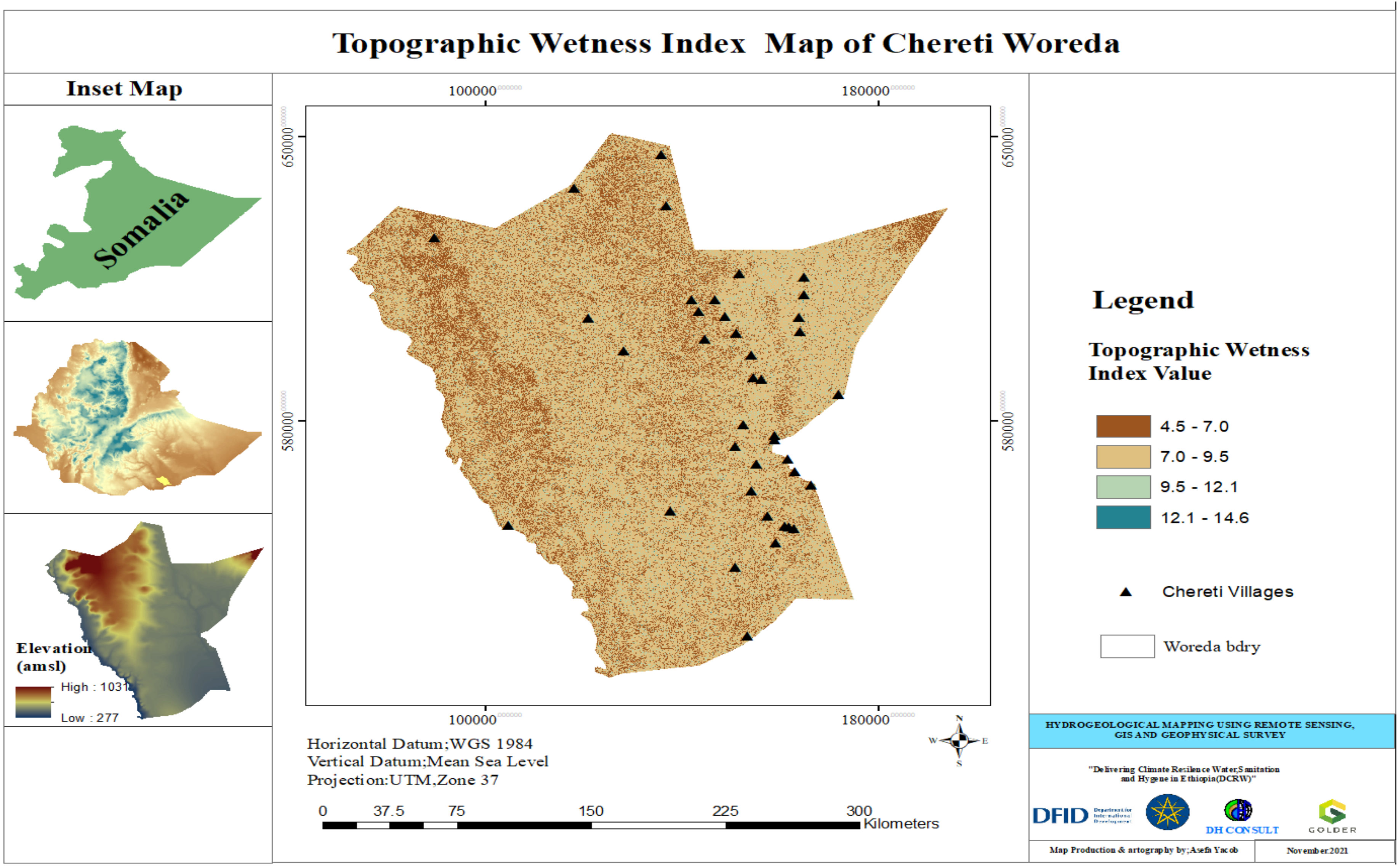

Figure 5-155. TWI Map of Chereti woreda

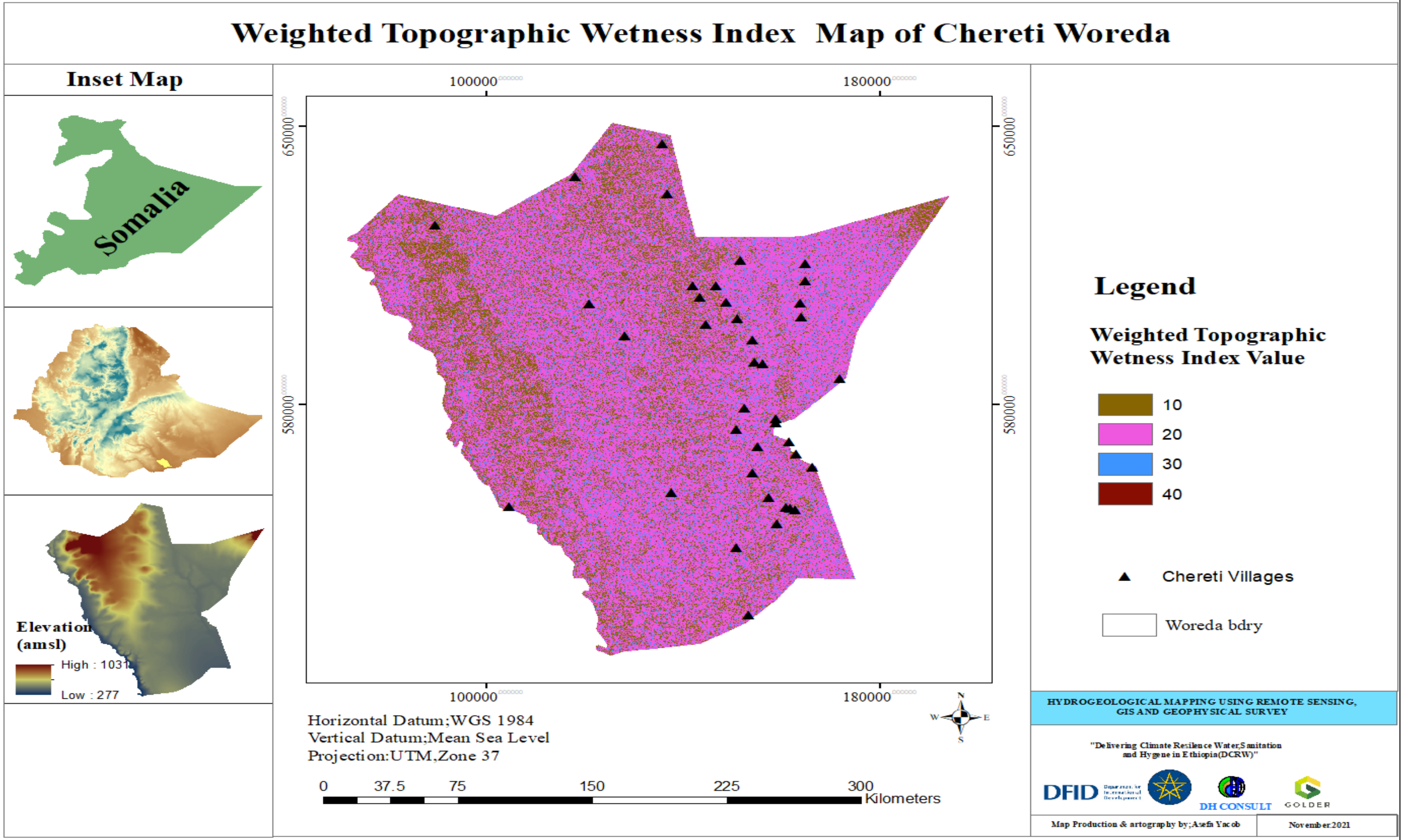

Figure 5-156. Weightage value of TWI Map of Chereti woreda

IV. Recharge

The spatial annual recharge rate distribution in the Chereti woreda ranges from 23.2 to 190 mm/y suggesting groundwaters in most part of the woreda area underlain by basement complex receive low amount of recharge while areas underlain by sedimentary rocks and quaternary sediments have relatively higher recharge amount (Figure 5-157). Accordingly, areas with higher and moderate amount of recharge have weightage factor of 0.40 and 0.30, respectively signifying very good and moderate groundwater potential which covers about 91.58 km2 (0.01 %) and 131.44 km2 (0.015 %), respectively while areas with the lowest amount of recharge have weightage factor of 0.10, suggesting poor groundwater potentiality and represent about 8,056.64 km2 (0.94 %). A closer look at the recharge thematic map revealed that some parts of the woreda have relatively high recharge (75.6 mm /y). Generally, the study area is characterized with low mean annual recharge amount, whereas only limited areas at western and southerm parts have moderat mean annual recharge amount (>75.6mm).

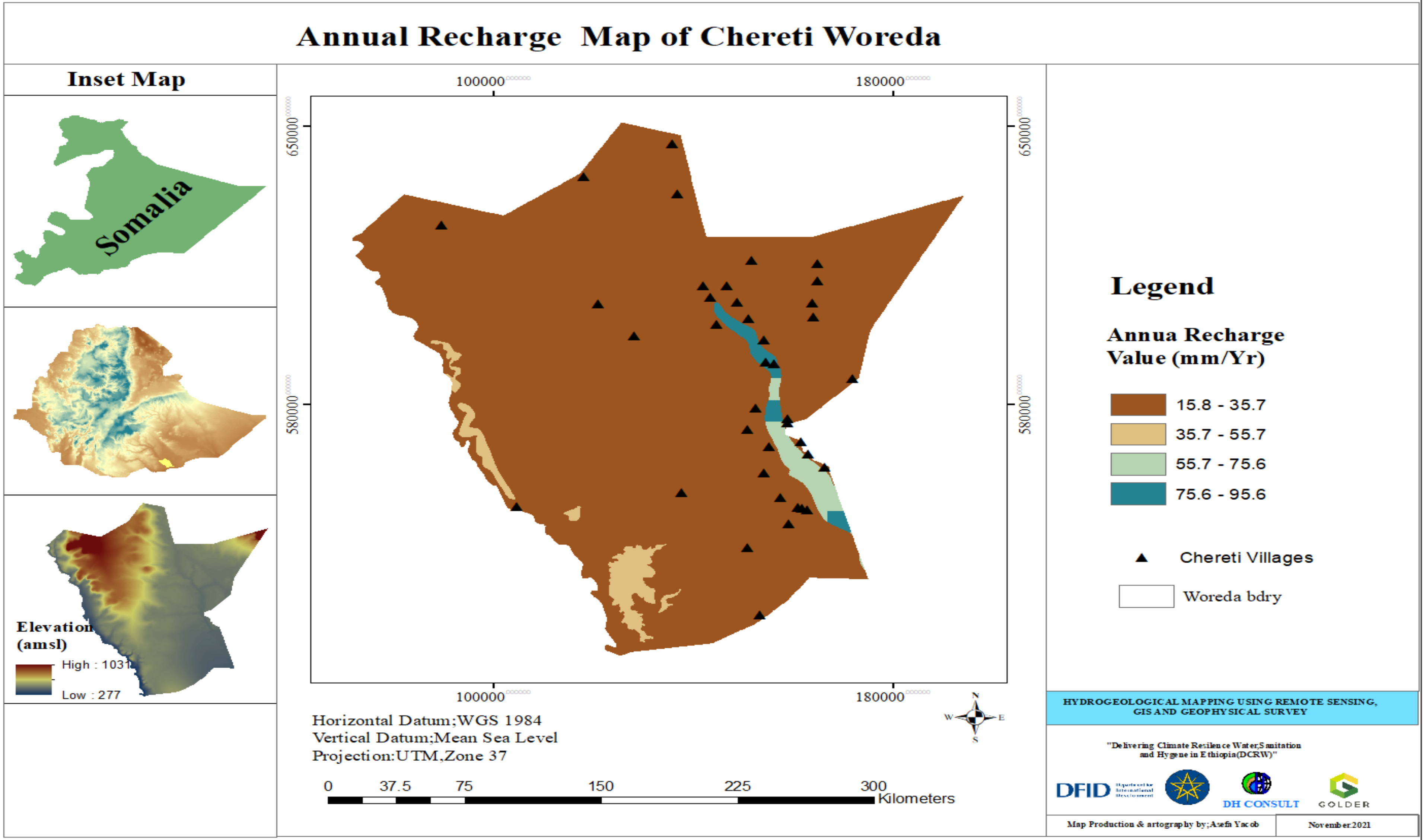

Figure 5-157. Annual Recharge Map of Chereti woreda

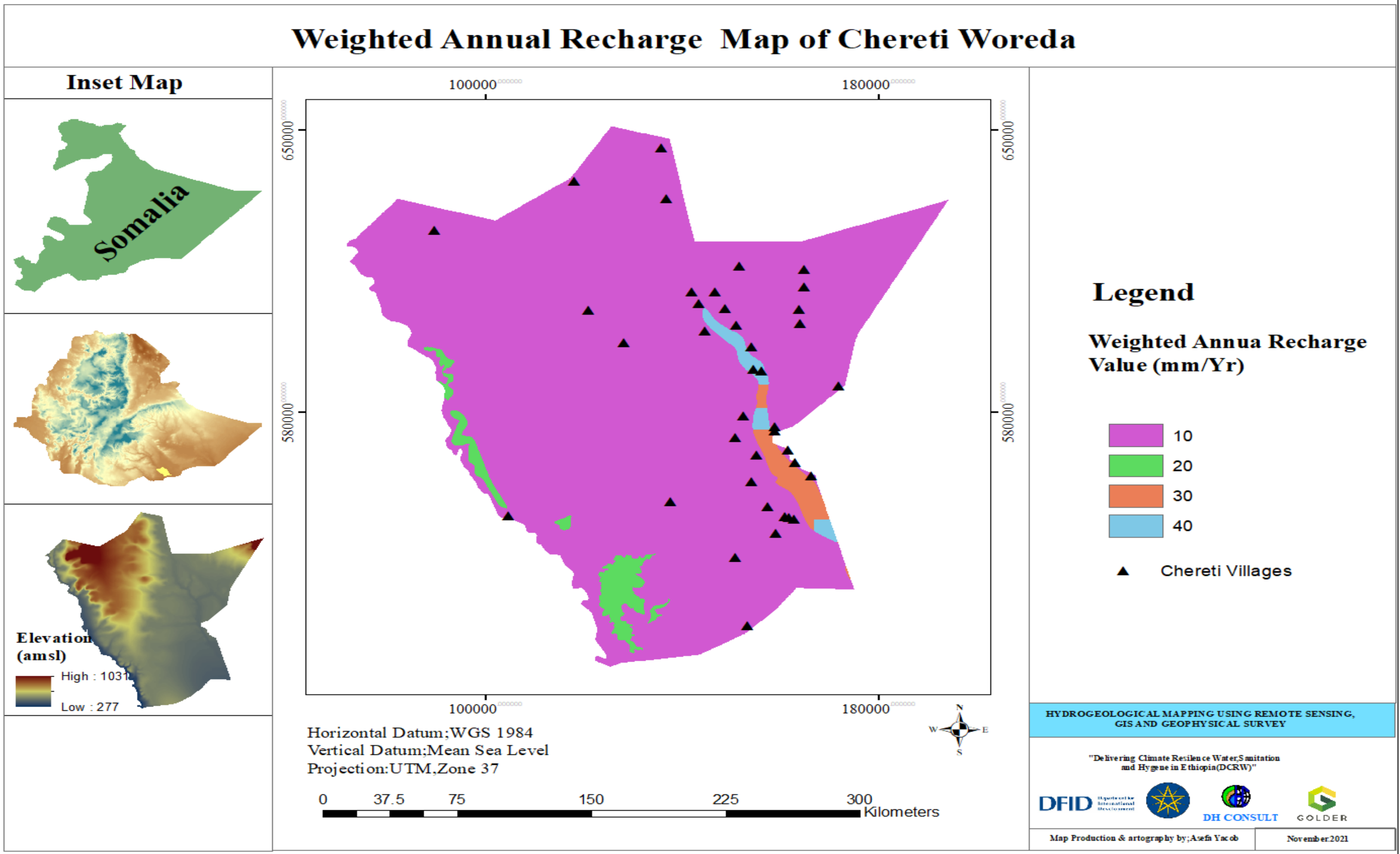

Figure 5-158. Weighted Annual Recharge classes' map of the Chereti woreda

5.14.3. Classification of Groundwater Potential Zones

The hydrogeological system of Chereti woreda is comprised of four main lithological units as Baslat and Fluvial sand silt (Stream channel deposit), Limestone locally cherty (Korahe Belet Uen) with Sandstone, siltstone intercalations with local limestone (Korahe Ambaradom), Shale mudstone limetone intercalations (Gabradarre) and Gypsum, anhahydrite and potash intercalations with marl, shaly mudstone and siltstone (Korahe Middle). At regional scale, Baslat and Fluvial sand silt (Stream channel deposit) form extensive and highly productive aquifers. Within the domain of Chereti Woreda, theses, Baslat and quaternary deposits form aquifers with high groundwater potential.

At regional scale, the Limestone Formation and lower sandstone form extensive and moderately productive aquifers having high hydraulic conductivity. However, at local scale, within the domain of Dolobay Woreda, due to the geomorphic setup, the Limestone Formation and the underlying units do not form high potential aquifer as revealed from existing borehole information rather the Weathered and slightly fractured sedimentary rocks with overlying Quaternary deposit form major potential aquifer with moderate productivity within the domain of Dolobay Woreda along lineament lines and associated plains. Hydrogeological data from water point inventory, hydro-chemical data and geophysical investigation outcome of the next phase will help to improve the understanding of hydrogeological frame work of the area.

On the basis of the assignment and normalized weighting of the individual features of the thematic layers, a potential groundwater index map was produced (Figure 5-159). The potential groundwater zones (PGZ) of the Dolobay Woreda revealed four distinct zones, namely very low,low, moderate and high zones whose distribution and extents are 3,498.14 km2 (90 %), 268.75 km2 (7 %), 105.35 km2 (2%) and141.34 km2 (1 %), respectively as presented in Table 5-69.

The potential map, as presented in Figure 5-159, gives a quick assessment of the occurrence of groundwater resources in the study area. The groundwater potential map revealed that most elevated areas around the peripheries and central parts of the CheretiWoreda generally have low potentials with area coverage of about 90 %, while limited areas at central regions generally exhibits moderateto low potentials representing about 2 % and 1 % of the study area, respectively. The generally high to moderate groundwater potentiality of the study area as reflected by 3 % coverage is a confirmation of generally moderate to high productive aquifers of recent alluvial and sedimentary deposits, whereas low to very low groundwater potential areas have an indication of limited aquifers capabilities of gypsum and shale with marl intercalation.

Furthermore, a closer assessment of the groundwater potential map revealed that the distribution is more or less a reflection of the geology and lineament density in addition to the topographic wetness index control. In addition, areas underlain by recent quaternary deposits especially in the central and southern sections of the study area which are characterized by relatively plain land with flat slope and higher recharge amount due to the presence of dense lineaments and apparently deep fracturing and weathering have high and moderate groundwater potential on the one hand. On the other hand, areas underlain by sedimentary rocks of limestone and gypsum in the majority of the woreda areas are characterized by small ridges and steep slopes, lower recharge and lineament densities, exhibit low groundwater potential while areas underlain by sedimentary rocks associated with sediments have medium potential. Moreover, high drainage densities and predominance of limestone rock outcrops can be attributed to the observed low groundwater potentials at the most part of the study area. However, predominance of recent sediments and sedimentary rock outcrops, low drainage density, high recharge and low slope which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential exhibited at central and western portions of the study area. Summary of the groundwater potential zones identified in the Dolobay Woreda is presented in the table below (Table 5-69).

a) *Table 5-69.Classification of groundwater potential zones and coverage areas alongside the respective yield and transmissivity categories*

Woreda Name	GWP Zones	Area (km^2)	Area (%)	Major Aquifer Units	Borehole Yield Classification (l/s) Q (Range)
Chereti	High	1	6.6	Tertiary volcanics and quaternary Sediments	>5
	Moderate	2	11.8	Sedimentary Rocks limestone	2-5
	Low	7	33.2	Sedimentary Rocks Gypsum	0.5-2
	Very Low	90	48.4	Shale and marl	0.05-0.5

5.14.4. Validation with Borehole Yield Data

In order to validate the classification of the groundwater potential zones as revealed by the GIS based groundwater potential map, data on existing wells (yield) were collated for boreholes in and around the study woreda area.

The borehole data were superimposed on the groundwater potential map and numbers of wells with different yield ranges for different groundwater potential zones were evaluated. Generally, the yields of the boreholes in the study area vary from >5 lit/sec in high potential zones and varying 2- 5 lit/sec in moderate potential zones, 0.5 lit/sec to 2 lit/sec in the low and from 0.05-0.5 lit/sec in the very low potential zones (Fig.18). As shown in the Figure 5-159, the occurrence of number of wells with yield of in the range 2- 5 lit/sec (moderate yield) and of >5 lit/sec (high yield) cut across mainly the recent quaternary deposits and sedimentary rocks. However, the less frequency of wells within gypsum and shale rock in the low and very low yield category signifies the generally low potential of these rocks as highlighted by the GIS-based potential map. In addition, the moderate-yield (2- 5 lit/sec) and high-yield (>5 lit/sec) categories are associated also with wells in the Mesozoic sedimentary rocks and quaternary alluvial deposits along river channel. This is also consistent with the low, moderate, high and very high groundwater potential classification of the GIS map for these rocks unit.

The validation clearly highlights the efficiency of the integrated RS and GIS methods employed in this study as useful modern approach for proper groundwater resource evaluation and sustainable groundwater development. Nonetheless, the groundwater potential zonation presented here can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration and exploitation in such basement and sedimentary settings, while individual site selection for groundwater development should take into consideration other site-specific conventional ground-truthing methods.

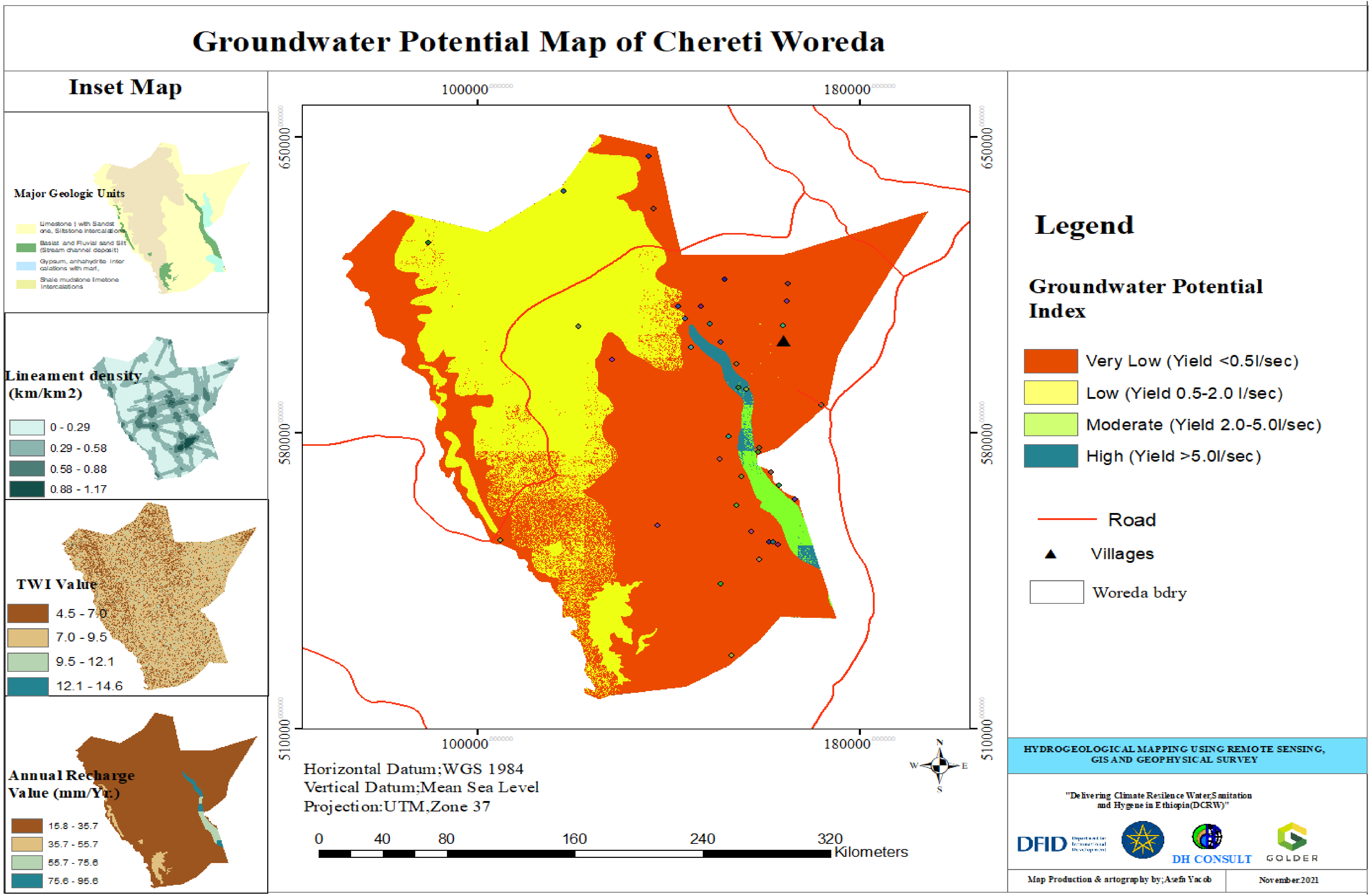

Figure 5-159. Groundwater Potential Zones Map of Chereti woreda

5.14.5. Population projection and Water Demand

5.14.5.1. *Population*

It is essential that the water supply system is designed to meet the requirements of the population expected to be living in the community at the end of design period by taking into account the design period and annual growth rate. Hence in order to avoid or minimize the aforementioned population related risks, efforts are made to review & justify the credibility of the available population data and growth rate figures.

Population projection is made making use of the geometric growth rate method by using the base population figure estimated by the central statistical Authority. The CSA has set average growth rates for urban and rural areas of the country varying at different times during the design period as shown in the table below. Accordingly, these values are adopted in forecasting future population of the town.

Table 5-70 CSA Rural Population Growth Rates

Rural Population Projection Growth Rate of Regions: 2008-2037						
YEAR / Growth Rate % (Rural)	2008-2012	2013-2017	2018-2022	2023-2027	2028-2032	2033-2037
Oromia Region	2.74	2.54	2.29	2.03	1.8	1.56
SNNP Region	2.49	2.37	2.31	2.03	1.82	1.57
Somali Region	2.75	2.63	2.35	2.05	1.89	1.83
Gambela Region	3.52	3.1	3.13	2.76	2.46	2.31

Source: CSA Population Projection for Ethiopia 2007-2037, Addis Ababa July 2013

Geometric method forecasting formula

$$P = Po\,(1 + r)^{n}$$

Where P – projected population
Po – current population
n – Number of years for projection
r – Population growth rate

The population of Chereti Woreda has been projected forward until 2036 using the growth rate of Somali Regional State. The minimum and maximum population in the Woreda is 1,090 and 36,023 respectively. The total population of the Chereti Woreda in 2036 is going to be 247,043.

5.14.5.2. *Water Demand Projection*

Projected Water Demand

Estimating water demands mainly depends on the size of the population to be served, their standard of living and activities. To make the demand projection reliable and suitable for rural areas it is better to classify in details as domestic and non-domestic demands.

Domestic Water Demand

Domestic water demand is the amount of water needed for drinking, food preparation, washing, cleaning, bathing and other miscellaneous domestic purposes. The amount of water used for domestic

purposesgreatly depends on the lifestyle, living standard, and climate, mode of service and affordability of the users.

Domestic water demand service can be categorized according to the level of service to be provided and amount of per capita water required satisfying the demand served by the level of service. Modes of services used for our projection are classified into four categories, namely: -

- Traditional Source users (TSU)
- Public tap users (PTU)
- Yard connections and Neighborhood (shared) connections (YCO)& (YCS)
- House tap connections (HTU)

In projecting the domestic water demand, the following procedures were followed:

- Determining population percentage distribution by mode of service and its future projection
- Establishment of per capita water demand by purpose for each mode of service;
- Projected consumption by mode of service;
- Adjustment for climate;
- Adjustment due to socio-economic conditions.

After considering the necessary mode of services, per-capita demand and applying the adjustment factors the domestic demand for the corresponding year and population has been calculated.

Non-Domestic Water Demand

Non-domestic water demand was also determined systematically. We have classified it into three major categories based on our projection:

- Institutional water demands (Public and governmental);
- Commercial water demand;
- Livestock water demand

N.B: - The use of a reliable base population figure is very important for optimizing the water sources but adopting 2007 CSA data as a base population has real impact on the projection so to compensate some unforeseen situation like migration and unplanned rural town growth. To compensate for such

- To estimate the demand of public institutions and commercial services we have adopted 15% - 20% of the domestic demand for our consumption.
- The demand for livestock watering adopted in the projection is 10% -15% of the domestic demand.

Total Average daily day demand

The average daily day demand is taken to be the sum of domestic demands and non-domestic demand. The water demand in a day varies with time according to the consumer’s life style. It is the total sum of adjusted domestic, public and livestock demand.

Maximum Day Demand

The maximum day demand is the highest demand of any one 24 hour period over any specific year. It represents the change in demand with season. This demand is used to design source capacity. The deviation of consumption from the average day demand is taken care of as per the maximum daily coefficient figures. Usually a value from1.1 to 1.3 is adopted as maximum day factor. A constant value of 1.3 is adopted as maximum day factor for all of the villages.

Figure 3-18 shows the distribution of water demand in each Kebeles of the Woreda. Towfiq kebele water demand is the minimum 585 M3/day and maximum water demand is required for Jarati-1Kebele with 2,809 M3/day respectively. The overall water demand for the projected population in the Charati Woreda is 19,194 M3/day.

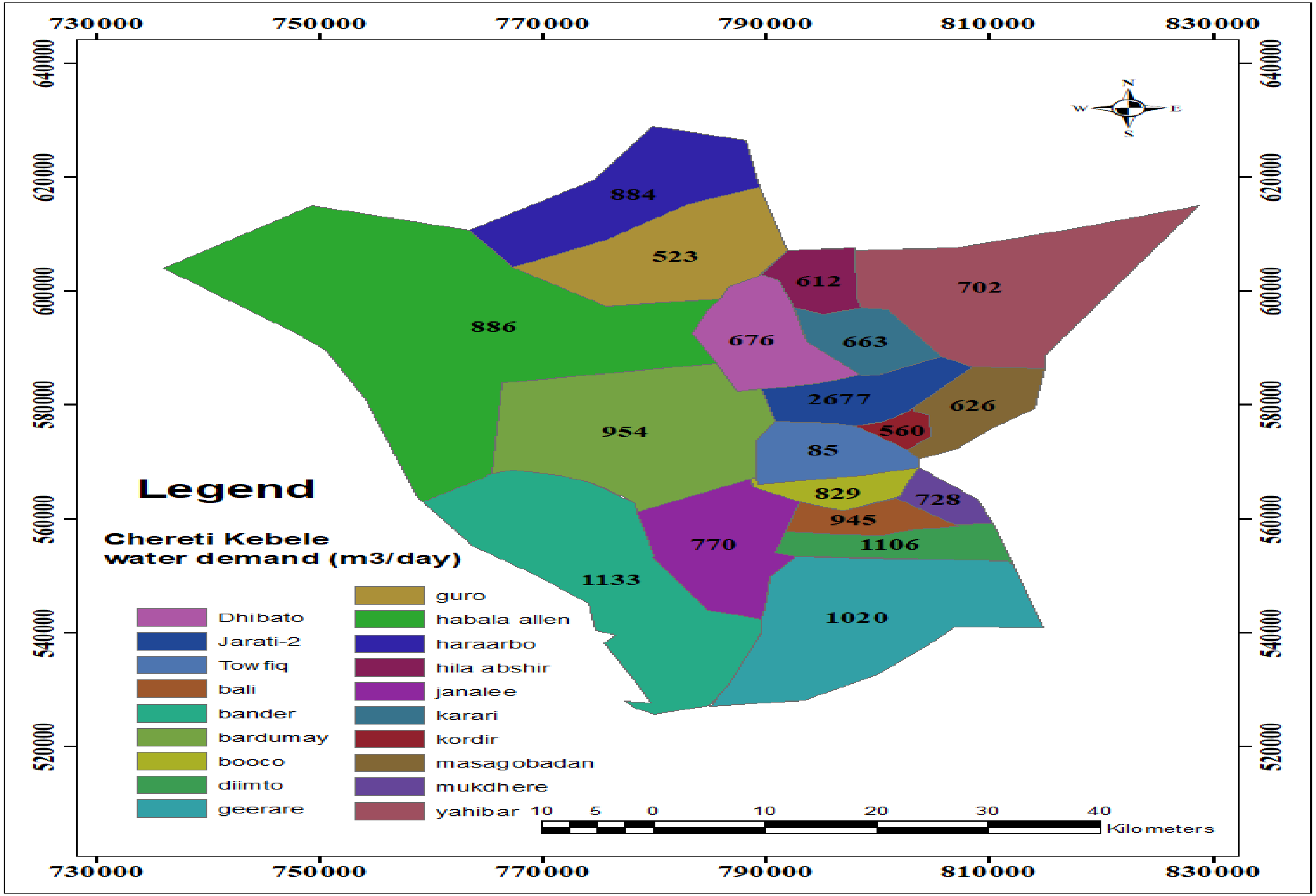

Figure 5-160:-Demand map of Chereti woreda

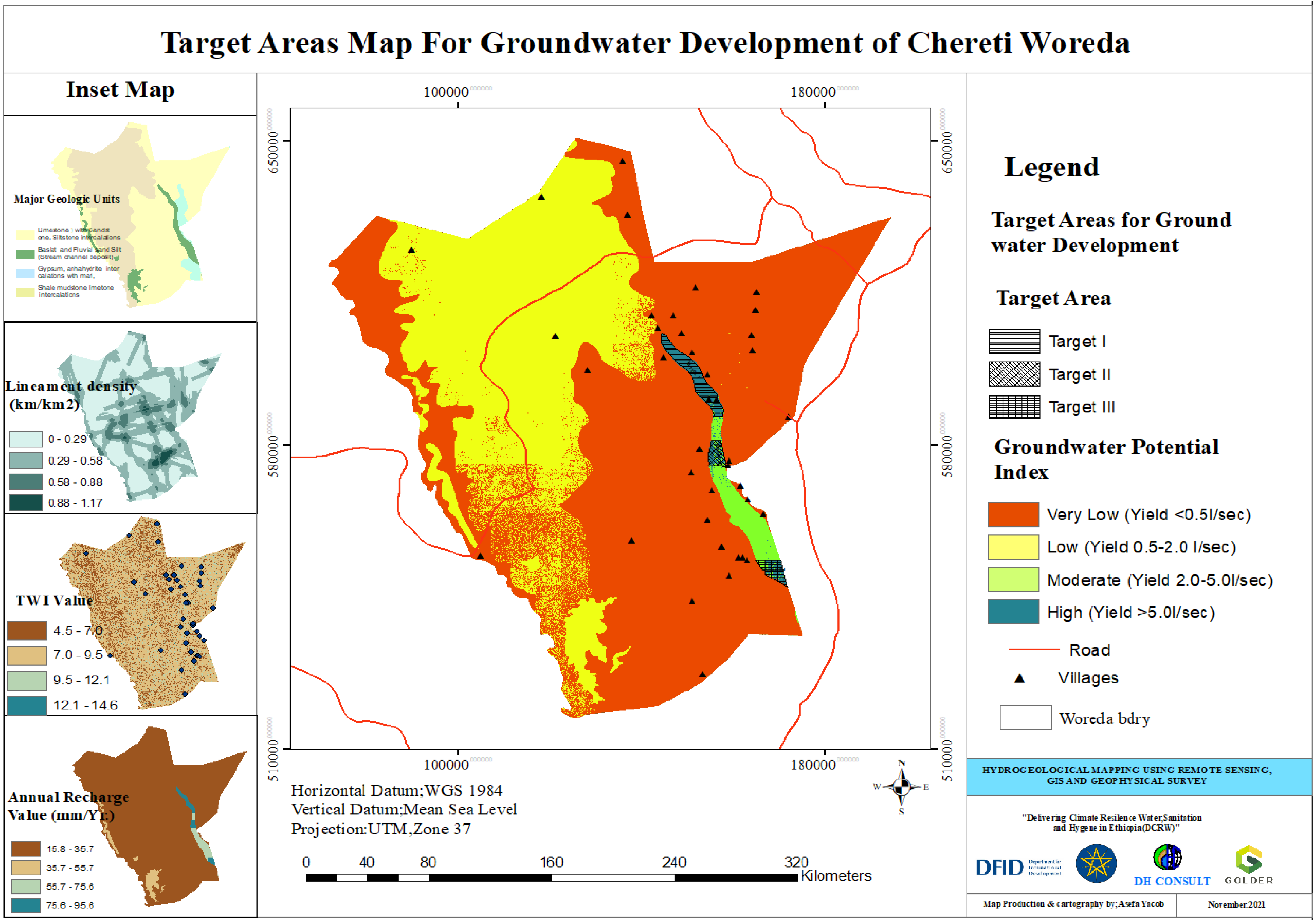

Figure 5-161:-Target Areas Map of Chereti woreda

5.14.6. Propsed Target Sites

Proposed target sites are identified, prioritized and selected within the woreda based on the identified groundwater potential zones, the productivity of the hydrostratigraphic units with their expected optimum borehole yield, proximity to beneficieries, population density and discussion made with the woreda's stakeholders so that to understand and identify kebeles with sever water shortage in particular. Accordingly, four priority target sites were selected and delineated within the Chereti woreda for detail studies to be carried out in order to verify further and locate appropriate borehole drilling sites.

Target Site-I:

This target site is located in the central part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 5.0 l/s. This target site is mainly underlain by Tertiary volcanics and quaternary recent deposits of alluvial sediments.

Target Site-II:

This target site is located in the central part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 5.0 l/s. This target site is mainly underlain by Tertiary volcanics and quaternary recent deposits of alluvial sediments.

Target Site-III:

This target site is located in the central part of the woreda. It is situated in the identified high potential zones with expected optimum borehole discharge of about 5.0 l/s. This target site is mainly underlain by Tertiary volcanics and quaternary recent deposits of alluvial sediments.

5.15. Conceptual Hydrogeological Model

Hydrogeological conceptual models are collections of hypotheses based on geological structural and geomorphological evidences and existing wells lithologic logs to describe and understand the groundwater occurrence, localization and movement beneath the ground surface. The purpose of the hydrogeological model across inferred groundwater flow direction is to reflect the prototype of regional groundwater flow system into the two priority sites selected for further study in phase III. In the conceptual model, groundwater head represents the regional groundwater table along with major geological section which marks most important aquifers and physical boundaries.

Development of the hydrogeological conceptual models of the target Woredas shall be prepared based on the converging evidence of secondary data including digital elevation model (DEM), geological and hydrogeological maps and structures, lithological well logs

The conceptual hydrogeological models for target woredas to be constructed along/across groundwater flow path will be produced after stake holder consultation work shop to select priority target sites for further hydrogeological characterization. This conceptual hydrogeological model summarizes what is known about the hydrogeological system and thereby provides a framework for hydrogeological system of the target woreda at broad scale including the following.

- ✓ Major groundwater flow zone (inflow, groundwater flow paths, inferred depth, and outflow).
- ✓ Groundwater condition of target woreda area such as delineate inferred groundwater table from existing data (spring, river and boreholes).

CHAPTER 6 : - CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

Multidisciplinary integrated approach has been employed to characterize the areas for groundwater occurrence, localization and flow dynamics. Four thematic layers (Geology/lithology, Lineaments/ lineament density, Topographic Wetness index and groundwater recharge) were produced to be integrated into groundwater potential zones. Integration and overlay analysis of thematic layers by assigning weights depending on their hydrogeological significance helps to identify four to five groundwater potential zones:

- Very high groundwater potential zones,
- High groundwater potential zones,
- Moderate groundwater potential zones,
- Low groundwater potential zones and
- Very low groundwater potential zones.

From the general overview of mapping the groundwater potential zones geological units, structures, geomorphology play significant role in groundwater occurrence, localization and flow characteristics. The target sites selected based on the overlay analysis have groundwater at different depths depending on the litho-stratgraphic set-up of the sub-surface.

Three to four target sites were selected for further discussion with stake holders at woreda level to prioritize two for further study in phase III. Conceptual hydrogeological model lines orientation for the two target sites will be determined ones the target sites are determined. Conceptual models will be produced at woreda and target site scale.

6.2 Recommendations

Based on the groundwater potential zones mapping result the following recommendations are given:

- Two to Four priority target sites are proposed given consideration to better groundwater potential and proximity to the target community. In consultation with stakeholders, two sites will be selected out of the proposed sites for further hydrogeological study in phase III. Conceptual hydrogeological model summarizes what is known about the hydrogeological system and thereby provides a framework for hydrogeological system of the area, hence the conceptual models will be constructed along/across groundwater flow path ones the stake holder consultation work shop conducted and priority sites identified,
- Detail field based hydrogeological study that include water point inventory and hydrogeological mapping is recommended including water quality assessment,
- The overlay analysis methods employed in this study are recommended as a preliminary approach to identify the most suitable priority sites or areas for further geophysical and hydrogeological studies.
- Geophysical investigation using Vertical Electrical Sounding approach is recommended to be conducted at two identified target sites where the lateral electrode spread depends on the nature of the aquifer material identified in this phase and AB/2 will be determined based on the actual data obtained during the survey

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ANNEX- POTENTIAL AND TARGET AREA MAPS OF 14 WOREDAS (A0 & A1 Sizes)