Feb 4, 2021

Hydrogeological mapping for Climate Resilient WASH in Ethiopia – LOT 1

Report Phase 2 – Final BDA/ICB/GW01/2021




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Acronyms

Abbreviation	Description
BDA	Basins Development Authority
MoWIE	Ministry of Water, Irrigation and Energy
MoWE	Ministry of Water and Energy
MOU	Memorandum of Understanding
DFID	Department for International Development
SDG	Sustainable Development Goal
WDC	Water Development Commission
NGO	Non-governmental Organisation
GIS	Geographic Information System
QGIS	Quantum GIS
UTM	Universal Transverse Mercator
EPSG	European Petroleum Survey Group
WGS84	World Geodetic System 1984
TWI	Topographic Wetness Index
SRTM	Shuttle Radar Topography Mission
SRTMGL1	Shuttle Radar Topography Mission Global 1-arc second dataset
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
ESA	European Space Agency
CCI	Climate Change Initiative
Ksat	Saturated conductivity
AHP	Analytic Hierarchy Process
CI	Consistency Index
T	Transmissivity
Q	Discharge
q	Specific discharge
TDS	Total dissolved solids
CSA	Central Statistical Agency
GTP II	Growth and Transformation Plan
lpcd	Litre per Capita per Day
TOR	Terms of Reference
BOQ	Bill of Quantities
RMS	Risk Mitigation Strategy
DEM	Digital Elevation Model
LIDAR	Light Detection and Ranging
RMM	Risk Mitigation Method
O&M	Operation and Maintenance
WAPOR	Water productivity open access portal
SAR	Synthetic Aperture Radar

1 Introduction

The Ministry of Water and Energy has received funding from DFID for a three-year project entitled "Delivering Climate Resilient Water, Sanitation and Hygiene in Ethiopia". As agreed by an MOU between DFID and the Government of Ethiopia, two of the four programs are being implemented by the Ministry.

This project, which runs to 31 March 2022, is part of the UK government's aid strategy to support the poorest people in adapting to climate change, specifically on building climate resilience in water and sanitation services that contributes to achieving Sustainable Development Goal 6. The project complements DFID and Ethiopia's significant programming on water and sanitation and supports effective delivery of the Government of Ethiopia's strategy for sustainable water supply in drought affected areas. A key feature of this program involves funding for groundwater mapping and improvement of groundwater data management.

1.1 Objective

1.1.1 Overall objective

The objective of this project is to increase access to safe and sustainable water for the people in drought affected regions by producing hydrogeological maps at the Woreda level and recommend drilling sites which the Government of Ethiopia and other partners can use for developing groundwater.

1.1.2 Specific objectives

A first step of this project is the initial identification of target areas for borehole drilling. The focus of this project is:

- Create detailed groundwater potential maps for each Woreda.
- Identify one optimal drilling site and one alternative (optional) drilling site per Woreda, using the groundwater potential maps and geophysical field investigation results, and recommend the type of drilling methodology(s) to be employed.
- Build the capacity of the former Water Development Commission (WDC), former Basins Development Authority (BDA), regional governments, and NGOs to use/apply overlay analysis techniques for groundwater potential mapping and borehole siting in Ethiopia.

1.2 Project area

The overall project covers a total of 53 woredas throughout the country which is subdivided into four lots. The current project deals with the 13 woredas from Lot 1 in the Tigray, Afar and Amhara Regions (Figure 1).

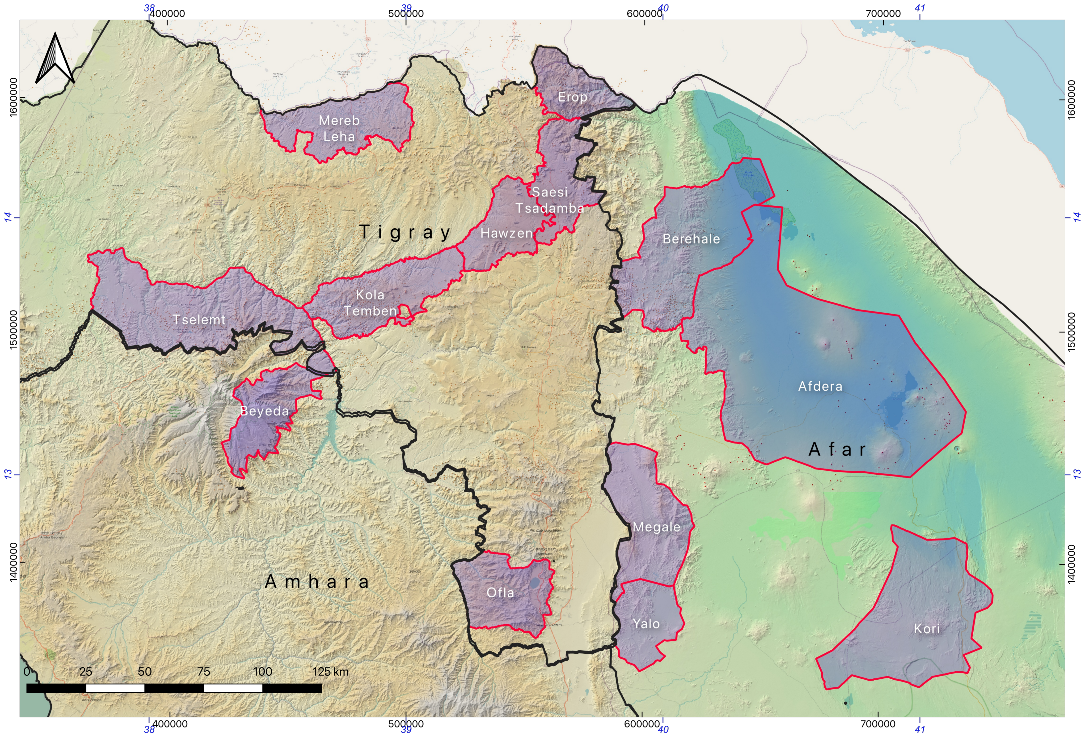

Figure 1. Location of the 13 selected woredas for Lot 1

1.3 This project

The project is designed in 3 phases:

- Phase I (Inception Phase)
- Phase II (Mapping Phase)
- Phase III (Siting Phase)

Phase I has been completed in August 2021, and this report covers the work for Phase II. The siting phase (Phase III) will start in December 2021, after the results from Phase 2 have been validated.

The main outputs of Phase II are

- Groundwater potential map for every woreda at scale 1:100,000
- Conceptual hydrogeological models for every woreda
- Ground truthing and water point inventories
- Water demand estimation in target woredas
- Selection of target areas (2 per woreda)
- Risk Mitigation Strategy Document

2 Groundwater potential maps

2.1 General

The groundwater potential maps have been constructed using an automated GIS overlay procedure in Quantum GIS using the following primary overlay layers:

Table 1. Overlay layers

Layer	Criteria	Indicators
1	Regional permeability	Rock type, Aquifer classification
2	Secondary permeability	Lineament proximity, Lineament density
3	Topographic location	Slope, Topographic wetness index
4	Recharge	Recharge rate
5	Land use	Recharge potential
6	Soil	Infiltration capacity

In the sections below the pre-processing of the six input layers is described. The final products (groundwater potential map per woreda) have been prepared on a scale of 1:100,000 with a resolution of 100 meter (1 pixel = 1 mm). The map projection for all overlay layers and the final products is UTM 37N, WGS84 (EPSG 32637). The maps are attached as Annex 1.

Lot 5 of this project deals with the dissemination of the project results (databases, maps, and reports) on a website. All maps, data and GIS layers will be uploaded to this website during phase 3.

2.2 Regional permeability

The hydrogeological map that was composed during the inception phase, contains 29 different lithological codes and 9 aquifer classes (Table 2). The aquifer classes (B1 to B9) are used as a proxy for the permeability layer, and the lithology code is used to derive the recharge layer (see section 2.5). Please note that aquifer class B3 and B8 do not occur in the project area. The aquifer classes have been converted to raster files of 100 m resolution for every woreda, with values equal to the class number (1 to 9).

Table 2. Lithology, infiltration coefficients and aquifer classes

Code	Lithology	Infiltration coefficient	Aquifer class	Class description
M12	Low grade metamorphic rocks – phyllite and slate - metavolcanics rocks - intermediate and basic lavas, tuffaceous slate, agglomerate, rhyolite and metasediments - black slate, limestone, sandstone, siltstone and greywacke	0.08	B5	Fissured aquifers, low productive
M19	Medium grade metamorphic rocks – schist - phyllitic schist, metagreywacke and metaconglomerate	0.06	B5	Fissured aquifers, low productive
M29	Amphibolite	0.05	B5	Fissured aquifers, low productive
M42	Metamorphosed carbonates	0.08	B4	Fissured aquifers, moderately productive
M43	Epimetamorphic basement, granite, basic intrusion, Mesozoic cover of Danakil Alps	0.08	B5	Fissured aquifers, low productive
M45	Gabbroic intrusive, metagabbro and metapyroxinite	0.06	B7	Non-aquifers
Q12	Alluvium	0.17	B2	Intergranular aquifers, moderately productive
Q22	Alluvial and lacustrine sediments – clay and sand with gravel, dunes and other aeolian deposits (in Afar)	0.13	B2	Intergranular aquifers, moderately productive
Q25	High fluvial terraces - gravel and low cemented sandstone	0.11	B1	Intergranular aquifers, highly productive
S12	Sandstone – Adigrat, Amba Aradom, Enticho	0.07	B4	Fissured aquifers, moderately productive
S16	Continental conglomerate and sediments of Red Series: conglomerate, sandstone, silt and clay	0.14	B1	Intergranular aquifers, highly productive
S25	Limestone – Antalo, Asem, marble, fossiliferous and sand limestone and	0.08	B4	Fissured aquifers,

	sediments of Afdera bed: lacustrine limestone and diatomite			moderately productive
S28	Agula Shale	0.08	B6	Minor aquifers
S30	Edaga Arbi Glacials/Tillite and Enticho sandstone	0.07	B6	Minor aquifers
S37	Tuff	0.11	B9	Alternating porous and fissured moderately productive aquifers
S38	Tufite of Hamsho Units	0.06	B6	Minor aquifers
S46	Gypsum with rare calcareous intercalation of Zariga formation or White Series	0.17	B6	Minor aquifers
S47	Evaporite (halite)	0.18	B6	Minor aquifers
S48	Dolomite interbedded with slate of Didikama Formation	0.06	B4	Fissured aquifers, moderately productive
S51	Equal to S30	0.07	B6	Minor aquifers
V12	Basic pyroclastic of sub aerial origin	0.15	B2	Intergranular aquifers, moderately productive
V17	Basalt with minor trachyte and upper pyroclastic	0.13	B4	Fissured aquifers, moderately productive
V21	Mekele Dolerite	0.07	B4	Fissured aquifers, moderately productive
V44	Ignimbrite	0.10	B6	Minor aquifers
V45	Rhyolite and alkaline over saturated trachyte, alkaline and peralkaline rhyolite	0.14	B6	Minor aquifers
V46	Trachyte and phonolite - Adwa Plugs	0.08	B7	Non-aquifers
V52	Intermediate and silicic lavas of Afera volcano	0.16	B6	Minor aquifers
Vh13	Granite / syenite	0.07	B5	Fissured aquifers, low productive
Vh25	Granite / syenite	0.08	B5	Fissured aquifers, low productive

2.3 Secondary permeability (lineaments)

For the lineament input layer, we have used a combination of the distance to lineaments (proximity in meter) and lineament density (length of lineaments per km2). To prepare these two indicators, we have extracted the fault lines from the 1:250,000 geological maps from the Geological Survey and enhanced the result with lineaments extracted from multispectral and radar imagery (Landsat-8 and Sentinel-1). The lineament extraction procedure is described in detail in Annexe 5.

The lineament proximity has been derived by calculating the distance in meters to main fault lines and rasterizing the result to 100 m resolution. The extracted lineaments from Sentinel-1 and Landsat-8 imagery have been used to calculate the lineament density, using a raster kernel to generate a raster density map from vector data (unit: kilometre lineament per square kilometre) with resolution of 100 m.

2.4 Topographic location

In both literature and previous work in Ethiopia, the slope of the terrain has been used for the topographic location criteria, while the topographic wetness index (TWI) has been used as a secondary criterion (Type II layer). During a meeting with BDA, DFID, Montrose, and the consultants in august 2021, it was decided to use the TWI as a primary overlay layer instead of slope. We have prepared TWI layers using algorithms provided by QGIS using SRTMGL1 (30 m resolution) as a data source. The data has been aggregated to 100 m using a median filter before calculating the TWI.

2.5 Recharge

Recharge rate has been estimated from the annual precipitation and infiltration coefficient derived from the lithology. The average annual precipitation (2000-2020) was obtained from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). The source data has a spatial resolution of 0.05 degree and was aggregated and resampled to 100 m using bicubic interpolation.

For the recharge calculations, use is made of the study by MoWIE, BCEOM, ISL and BRGM in 1999 for the Abbay River Basin Integrated Development Master Plan Project. In the study, an infiltration coefficient was assigned to all lithological units appearing on the geological map of Ethiopia. These infiltration coefficients were assigned to the lithological units of the 1:250,000 geological map (Table 2). The final recharge layer has been obtained by multiplication of the annual precipitation raster by the raster with infiltration coefficient.

2.6 Land use

The Sentinel-2 land use classification created by the Climate Change Initiative (CCI) of the European Space Agency (ESA) (2016) was used as Land Use and Land Cover layer (LULC). This dataset contains 10 land use classes on a 20 m resolution. The data has been aggregated to 100-meter resolution and reclassified to 6 land use classes for the overlay analysis (Table 3).

Table 3 .Land use reclassification

ESA Land use		Overlay	
Class	Description	Class	Description
1	trees	3	forest
2	shrubs	2	bush/range land
3	Grassland	2	bush/range land
4	cropland	1	cropland
5	vegetation aquatic or regularly flooded	6	irrigated
6	lichen and mosses / sparse vegetation	4	degraded land
7	bare	4	degraded land
8	built up	5	urban area
9	snow and/or ice	n/a	
10	open water	6	irrigated

2.7 Soil type

The recharge layer has been prepared using annual precipitation and the infiltration coefficient derived from the lithology on the geological maps. In cases where a soil has developed that limits the infiltration, the recharge may be overestimated. To correct for the overestimation, we have used the saturated conductivity (Ksat) of the soil. Ksat of the soil was derived using a pedotransfer function. Pedotransfer functions estimate soil hydraulic parameters, such as hydraulic conductivity, using soil properties that are easily measured in the field. The Rosetta pedotransfer function version 2 (Schaap et al. 2004) was applied to the soil clay, silt and sand content obtained from the SoilGrids dataset (Poggio et al. 2021). The data are available for six different depth classes up to two meters depth and have a resolution of 250 m. First, the saturated conductivity (Ksat) was derived for each depth interval. Then, it was assumed that the layer with the lowest hydraulic conductivity best represents the overall infiltration capacity. The resulting raster map has been resampled to 100 m resolution and classified using the classes from Table 4.

Table 4. Saturated conductivity classes

Ksat cm/d	Class
< 28	Low
28 – 31	Low to medium
31 – 34	Medium
34 – 37	Medium to high
> 37	High

2.8 Overlay procedure

2.8.1 Classification and scoring

The output of the overlay algorithm is a weighted combination of recoded, numerical input layers. To prepare the input layers, the source data need first to be classified and scored. To determine the class scores the Analytical Hierarchy Process (AHP) has been used (Saaty, 1977, 1982). The result of the exercise is summarized in Table 5. For every layer, the consistency index (CI) has been calculated and we verified that the index is below 0.1.

Table 5. Class scores

Permeability			
Aquifer class	Eigenvalue	Normalized weight	Relative score
B1	4.12	0.35	1.00
B2	2.06	0.18	0.50
B3	1.85	0.16	0.45
B4	1.15	0.10	0.28
B5	0.52	0.04	0.13
B6	0.33	0.03	0.08
B7	0.21	0.02	0.05
B9	1.49	0.13	0.36
		Consistency Index	0.06

Recharge			
Recharge in mm/y	Eigenvalue	Normalized weight	Relative score
<25	0.25	0.03	0.06
25 - 50	0.49	0.06	0.12
50 - 100	1.00	0.13	0.25
100 - 200	2.04	0.26	0.52
>200	3.94	0.51	1.00
		Consistency Index	0.06

Topographic location			
Slope in degrees	Eigenvalue	Normalized weight	Relative score
>15	0.34	0.05	0.12
10 - 15	0.58	0.09	0.20
5 - 10	1.00	0.15	0.34
2 - 5	1.72	0.26	0.59
<2	2.91	0.44	1.00
		Consistency Index	0.01

Topographic location (alternate)			
TWI	Eigenvalue	Normalized weight	Relative score
<2	0.25	0.03	0.06
2 - 5	0.49	0.06	0.12
5 - 10	1.00	0.13	0.25
10 - 20	2.04	0.26	0.52
>20	3.94	0.51	1.00
		Consistency Index	0.06

Land use, land cover			
Landuse	Eigenvalue	Normalized weight	Relative score
urban	0.32	0.03	0.08
bare	0.55	0.05	0.14
bush/rangelan(	1.00	0.09	0.26
forest	2.03	0.19	0.53
cropland	2.79	0.26	0.72
irrigated	3.85	0.37	1.00
		Consistency Index	0.02

Soil			
Ksat	Eigenvalue	Normalized weight	Relative score
<28	0.34	0.05	0.12
28 - 31	0.58	0.09	0.20
31 - 34	1.00	0.15	0.34
34 - 37	1.72	0.26	0.59
>37	2.91	0.44	1.00
		Consistency Index	0.01

Lineament density			
density in km/km2	Eigenvalue	Normalized weight	Relative score
<0.2	0.25	0.03	0.06
0.2 - 0.5	0.49	0.06	0.12
0.5 - 1.0	1.00	0.13	0.25
1.0 - 2.0	2.04	0.26	0.52
>2.0	3.94	0.51	1.00
		Consistency Index	0.06

Lineament proximity			
proximity in meter	Eigenvalue	Normalized weight	Relative score
>4000	0.25	0.03	0.07
2000 - 4000	0.53	0.07	0.15
1000 - 2000	1.05	0.14	0.30
500 - 1000	2.04	0.28	0.59
<500	3.47	0.47	1.00
		Consistency Index	0.03

2.8.2 Layer weights

To calculate the suitability, the scored layers are assigned a weight. Next, the layer scores are multiplied with the layer weight and added. The layer weights may vary per region/woreda and ideally, the weights are assigned by a group of experts (from the Peer review Committee) who have extended knowledge of the regional and local hydrogeological conditions. It was planned to have regional workshops with local stakeholders and experts to assign layer weights for every woreda using the AHP methodology. Because of the current security situation in the project area, the workshop could not take place. Instead, we have used the expert judgement of the team members to assign layer weights on a regional level (Table 6, Table 7 and Figure 3).

For the overlay analysis, the lineament density and lineament proximity were combined into one layer 'lineaments' with equal weight to proximity and density.

Table 6. Regional layer weights Afar

Layer weights Afar			
Layer	**Eigenvalue**	**Normalized weight**	**Relative weight**
Landuse	0.28	0.04	0.09
Soil	0.57	0.07	0.19
Recharge	1.31	0.16	0.43
Topographic location	1.99	0.25	0.66
Linaments	0.78	0.10	0.26
Permeability	3.02	0.38	1.00
		Consistency Index	0.05

Table 7. Regional layer weights Tigray and Amhara

Layer weights Tigray, Amhara			
Layer	**Eigenvalue**	**Normalized weight**	**Relative weight**
Landuse	0.28	0.04	0.11
Soil	0.53	0.07	0.21
Recharge	1.40	0.18	0.55
Topographic location	2.24	0.29	0.88
Linaments	0.83	0.11	0.33
Permeability	2.54	0.32	1.00
		Consistency Index	0.01

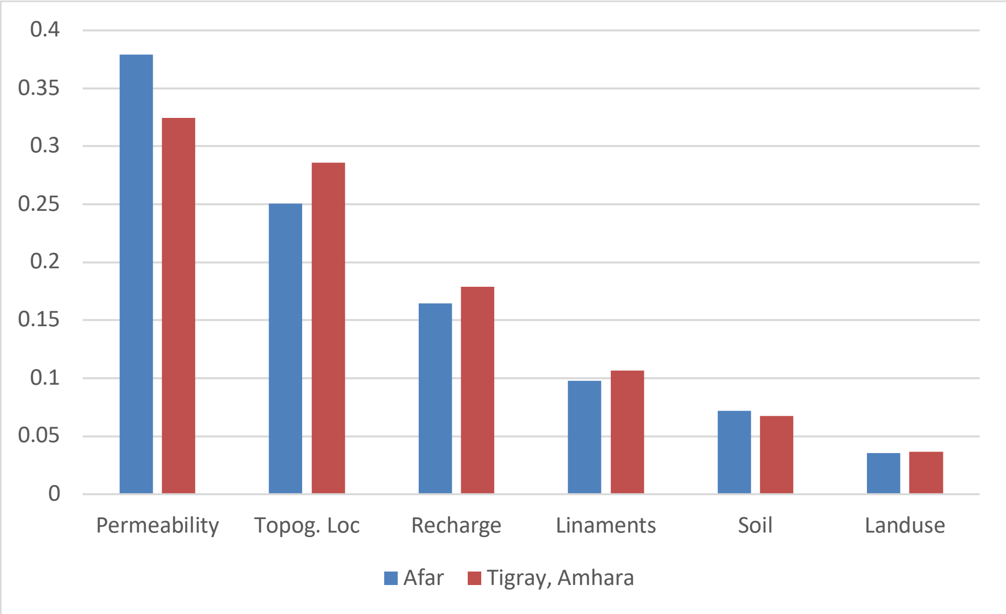

Figure 2. Layer weights per region

Permeability and topographic location (TWI) are considered most significant for all regions. In Tigray, the topographic location, recharge, and occurrence of lineaments are considered more significant than in Afar, whereas in Afar the regional permeability alone determines one third of the suitability score.

2.8.3 Results

The result of the overlay procedure is a groundwater potential map for every woreda at scale 1:100,000 (Annexe 1). The maps show the groundwater potential in terms of suitability for drilling productive water wells, and show relevant features like wells, springs, streams, roads, villages, built-up area, and administrative divisions on a backdrop of hill-shaded terrain. A sample extracted from Kola Temben woreda in Tigray is presented in Figure 4 below.

The colours on the map range from red (low potential) via yellow and green to blue (high potential). It should be noted that maps present a *relative* suitability, meaning that blue areas are more suitable than red areas. This does not mean that drilling in a blue area is a guarantee for success. Also, drilling in a red area may produce productive boreholes.

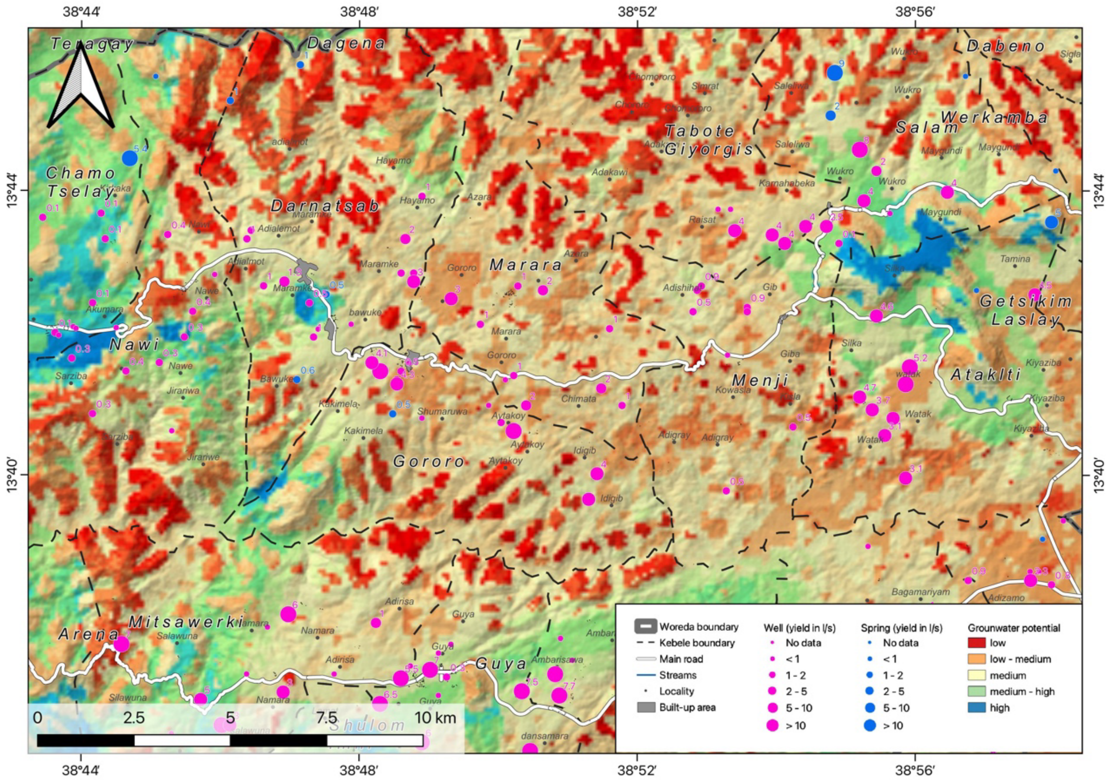

Figure 3. Sample groundwater potential map

To validate the results, the number of wells and the well yield from the inventory database was plotted against the suitability class (Figure 5 and Figure 6). Most wells plot in the medium suitability range (0.3-0.4), but no clear relation between yield and suitability is apparent. This may be caused by the fact that the wells are not randomly distributed over the potential maps and dry wells have not been included.

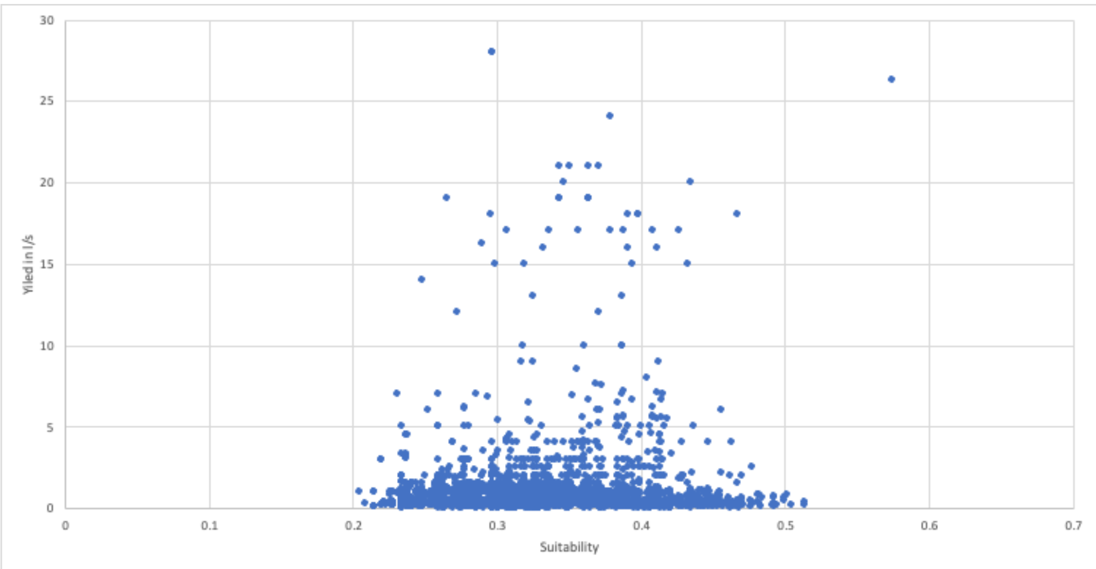

Figure 4. Relation between suitability and well yield

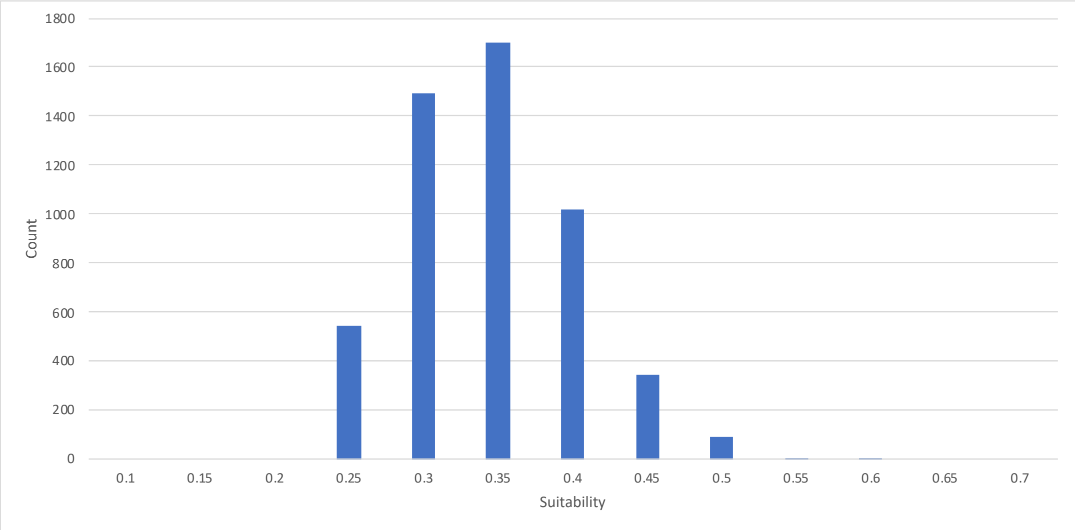

Figure 5. Relation between suitability and number of wells

3 Conceptual models

The following description of conceptual models (geology, aquifers and hydrogeological concept for each Woreda is accompanied by geological cross-sections at scale 1:100,000 (Annex 2).

3.1 Kori

The Woreda is located in the Afar Zone 1 and has an area of 2,870 km^2. The area is located at the foot of the Afar Depression and consist mainly volcanic rocks accompanied by alluvial sediments.

3.1.1 Geology

Large part of the Woreda is covered by volcanic rocks consisting mainly basalts of Afar stratoid series (Tb3) and basaltic lava flows and related spater cones (Qh1). Silicic centers of dominantly rhyolite in composition (Tr) separates basaltic rocks. The area is highly tectonized and grabens developed between volcanic ridges are filled with various alluvial sediments (Qha).

Afar stratoid series (Tb3) contains layers of different basalt flows (mainly aphanatic and vesicular basalts) showing good stratification 10 to 15 m thick basalt flows are seen often separated by intercalated rhyolitic flows, ignimbrite and sediments mainly in the upper part with tectonic discontinuities. They are grey when weathered and when fresh they have a dark grey color.

Basaltic lava flows and related spater cones (Qh1) represent fissural eruptions. They are fine-grained, dark gray and slightly weathered basalts. On outcrops they range in size from boulders to pebbles and they form dome-shape outcrops in places.

Silicic centers of dominantly rhyolite in composition (Tr) are exposed in several places of the Woreda. The major silicic centers are comprised of pumice, rhyolite and minor tuff and pyroclastic ash and obsidian lenses. The pumiceous obsidian is glassy gray rock containing intercalations of pumice with obsidian and rock fragments of tuff and pumice with a few crystals of quartz.

Alluvium (Qha) is represented by undifferentiated sediments and fluvio-lacustrine sediments. The fluvio-lacustrine sediments consist reddish brown silty to sandy soil with a few outcrops of diatomite about 1 m thick. The undifferentiated sediments covering a flat plain in the grabens. Most of the alluvial sediments occur in wide, flat, meandering valleys and the sediments are intercalated with minor salt deposits.

3.1.2 Hydrogeology

Hydrogeological units with porous permeability and moderate productivity or locally developed and highly productive aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s)***.*** The groundwater is accumulated in and flows through the pores of unconsolidated material. The Quaternary alluvium and lacustrine sediment represent the porous materials. The groundwater availability and flow are highly dependent on grain size, sorting, type of cementing material and the thickness of the aquifers.

The permeability of alluvium consisting of silt, clay and sand dunes and other aeolian sediments is very variable depending on the grain size, sorting as well as recharge conditions. Close to intermittent streams, groundwater can be found at a depth ranging from 80 to 300 m. In the majority of the area, alluvial sediments are the main source of groundwater for water supply.

Hydrogeological units with fissured permeability, high and moderate productivity. Groundwater in these units is stored in and flows through the fractured and weathered parts of volcanic rocks. Most of the Tertiary and Quaternary volcanic rocks of the area exhibit such permeability. Volcanic lava flows may have a high porosity, but an integrated combination of primary and secondary structures (fissures, joint, etc.) is necessary for good permeability. In most cases, the large amount of groundwater is stored in the fractured zones developed along some structural features.

Highly productive aquifers (T = 10.1 – 100 m^2/d, q = 1.1 – 10 l/s·m, Q = 5 – 25 l/s for wells and/or springs) developed in the Afar stratoid basalts are where recharge and topographic positions are favorable. Some boreholes drilled in the aquifer in various part of the Afar Depression yield 5 l/s for a drawdown of 0.25 m and yields 5 l/s for a drawdown of 0.7 m, respectively. In general, it would have high values, as can be inferred from the low drawdown. Most of the time, groundwater is fracture controlled rather than lithology. In case, where shallow aquifers made of alluvial deposits are covering the deep aquifers hosted in Afar stratoid basalts, the yield of the wells activating both of the aquifers can reach 10 l/s.

Moderately productive aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) in Basaltic lava flows and related spater cones and form flat topography. The occurrence of the main regional fractures with linear alignments is an important feature for groundwater movement from high to low groundwater concentration areas. The depth of hand dug wells is from 15 to 18m, and the boreholes have a depth ranging from 250 to 300 m (**281** m Kori town). These aquifers are recharged from erratic rainfall, but mainly from intermittent rivers and streams.

Formation consisting of a minor fissured aquifer with local and limited groundwater resources – Aquitards are represented by fresh massive rocks with limited fractures, shallow depth of weathering and steep slopes in rhyolitic and trachytic lava domes provide very low permeability and limited groundwater occurrence. They can store a little groundwater in the fractured and weathered parts, otherwise it acts as a barrier to the vertical movement of groundwater. Hence, if the overlying unit is permeable and thick enough, good quality water can be stored near the contact with the overlying unit.

Water quality

Groundwater is hard with TDS between 1000 and 2000 mg/l with content of fluoride above standards for drinking water.

3.1.3 Conceptual model

The characterization and prediction of flow and transport through fractured hard rock mass is extremely difficult as the geometry of the flow and path in these rocks is often very complex and heterogeneous depending upon the fracture characteristics.

From a geomorphological point of view, the groundwater may follow the surface drainage systems. The surface drainage systems are controlled by local topography. Subsurface drainage may form in sedimentary rocks like limestone and gypsum. Therefore, it is difficult to speculate on the groundwater flow system without any meaningful data. The shallow static water level of dug wells may not represent a deep flow system for the different aquifers.

Direct recharge from rainfall is limited due to low rainfall in the study area; consequently, the main source of recharge to the aquifers in the study area is recharge from intermittent rivers and aquifers of the escarpment area.

From conceptual hydrogeological point of view the Woreda area can be divided into three basic parts: A covering most of the western part, B covering eastern part and C located in central part. The parts are shown in Figure 7 which is extract from hydrogeological map presented in phase I.

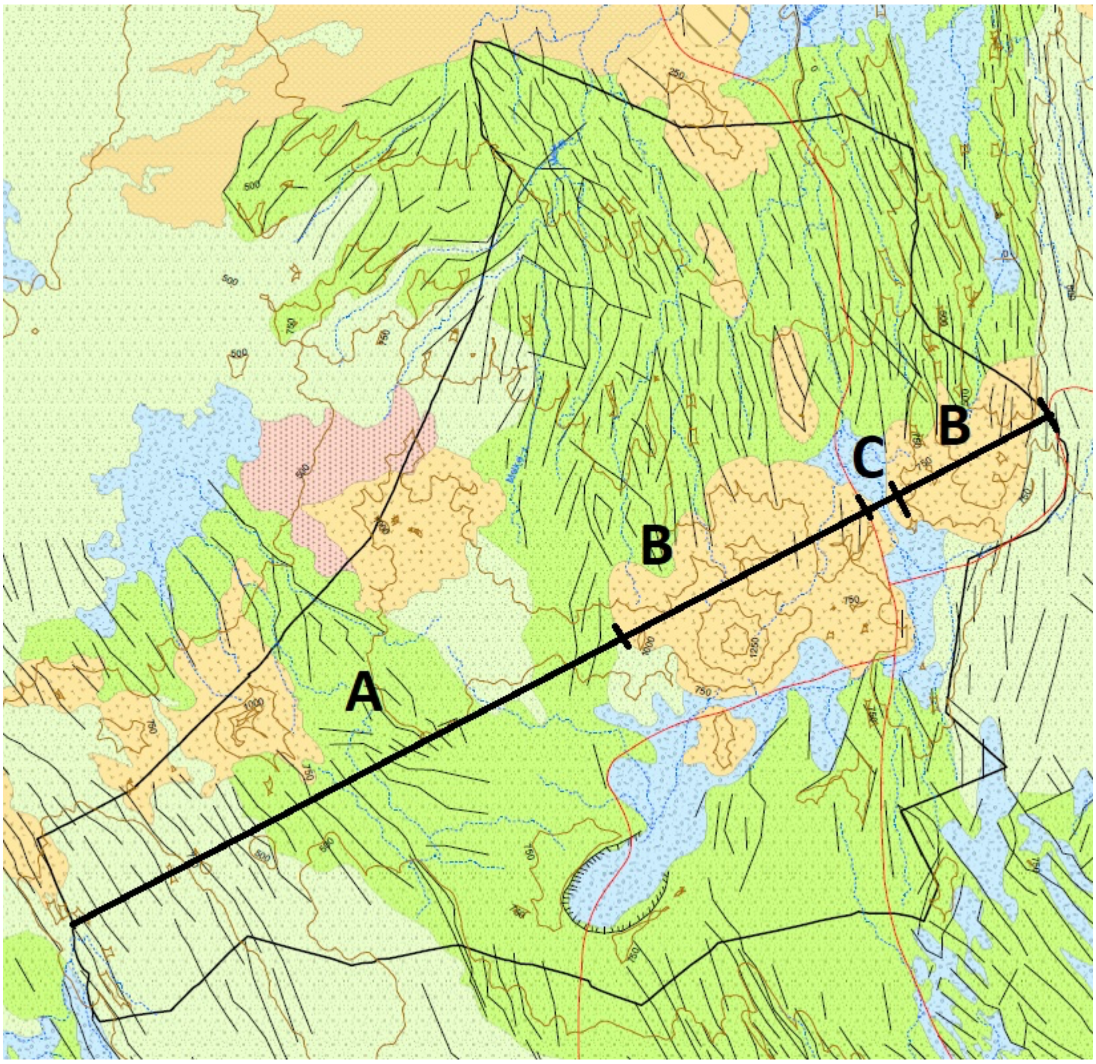

Figure 6. Hydrogeological map of Kori

A western part covering most of the Woreda area and consists of highly and moderately productive fissured aquifers developed in basaltic Tertiary and Quaternary volcanic rocks. Faults are of hydrological significance and they increase the secondary (fissured) porosity, which enhances groundwater flow. In case, where shallow aquifers made of alluvial deposits are covering the deep aquifers hosted in the yield of the wells activating both of the aquifers can reach 10 l/s. Direct recharge from rainfall is limited only to several erratic rainfall episodes; consequently, the main source of recharge to the aquifers in the study area is recharge from intermittent rivers and deep aquifers of the escarpment area. ***Deep wells drilled in basalts aquifers along faults and lineaments and shallow wells drilled in local alluvial aquifers near to deep wadis can provide water supply for population living in the area. Detailed structural geometry in and near faults and lineaments is impossible to predict without detailed hydro geophysical investigation.***

B Eastern part represented by minor aquifers with limited groundwater resources developed in silicic (rhyolite) domes.

C Central part has large aquifers developed in alluvial / lacustrine sediments. Groundwater is recharged directly from rainfall, but can be also recharged by runoff from silicic domes. It can be also recharged by deeper groundwater flow from basalts, of which northward direction is inferred. ***Groundwater can be exploited mainly using shallow wells and hand dug wells (Italian wells) located at the bank of wadi and inside of large alluvial sediments, particularly in depressions between silicic volcanic rocks.***

3.2 Afdera

The Woreda is located in the Afar Zone 2 and has an area of 7,435 km^2. The area is located at the floor of the Afar Depression, its western border is located at the foot of the western escarpment

3.2.1 Geology

Geologically, the Woreda consists mainly volcanic rocks accompanied by alluvial sediments with outcrops of blocks of sandstone and limestone.

Volcanic rocks outcrop in the central part of the Woreda forming active volcanic ridge of Erta Ale. Basic lava flows and related scatter lava cones are found over most of the central and southeastern part of the area. Dominantly, it forms ridges, hills, cliffs and grabens. In some parts, it appears on gentle and very rugged topography dissected by deeply chiseled valleys. Basaltic rocks are penetrated by intermediate and silicic lavas of Afdera volcano (south of the lake) and rhyolite accompanied by basic pyroclastic of subaerial origin (north of the lake).

Sedimentary rocks of the Afar are represented by semi-consolidated Afdera beds outcropping in depression of Afdera Lake. The exposure contains lacustrine sediments mainly limestone and diatomite, which is moderately to highly weathered. Rocks are chalk-like, very soft, very fine-grained, light, dense and friable.

Sedimentary rocks of the western escarpment outcrops in form of tectonised blocks consisting of sandstone and limestone.

Alluvial sediments and Aeolian deposits are located on both sides (eastern and western) along central volcanic block lying on desert flat topography and on flat parts of rocky areas and ridges. These are fine-grained sediments found in desert areas and are composed of sand and silt as well as shells of gastropods making up calcareous sand.

Flood sheet terrace deposits composed of gravels and sands along the foot of the escarpment and hills. **Continental conglomerate** has similar composition and is accumulated at the foot of Danakil Alps east of boundary of Woreda. Sediments are of the Pleistocene age.

3.2.2 Hydrogeology

Hydrogeological units with porous permeability where groundwater is accumulated in and flows through the porespores of unconsolidated material. The Quaternary alluvium, lacustrine sediments, and unwelded pyroclastic material represent the porous materials. The groundwater availability and flow are highly dependent on grain size, sorting, type of cementing material and thickness.
Highly productive aquifers (T = 10.1 – 100 m^2/d, q = 1.1 – 10 l/s·m, Q = 5 – 25 l/s for wells and/or springs) developed in Continental conglomerate and flood terrace deposits. Texturally, it is dominated by gravels and sands around the escarpment and the foot hill

regions. The aquifers have fractured, weathered and jointed surfaces that contribute to its high permeability and productivity and they are mainly recharged from the escarpment area.

Moderately productive aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) developed in Alluvium, silt, clay, sands and other Aeolian deposits are) and are recognized in following two types: (a) those spread out in alluvial plains, and (b) those which occur as thin strips along intermittent streams. These aquifers represents extensive and moderately productive porous aquifers.

The recharge comes from rainfall and runoff during the rainy season, however most of the recharge comes from runoff from the escarpment.

Hydrogeological units with fissured permeability where groundwater is stored in and flows through the fractured and weathered parts of volcanic rocks. Most of the Tertiary and Quaternary volcanics of the area exhibit such a type of permeability. In most cases, the volcanic lava flows may have high porosity, but in order to have a good permeability there should be an integrated combination of primary and secondary structures. Such permeability is influenced by the intensity, degree, depth and extent of fractures and joints. However, in some cases the presence of secondary infilling material decreases the permeability of such structures. In most cases, the fractured zones and the weathered mantle are the main areas of groundwater storage. In the study area shallow groundwater sources (dug wells) and deep sources (springs) serve as the main water supply for small communities.

Moderately productive aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) developed in Basic lava flows, lava fields and related scattered cones and some trachyte are. Aquifers are located in the central and southeastern parts of the Woreda mainly form ridges, hills, cliffs and grabens. These aquifers represent extensive and moderately productive fissured aquifers. Some exposures, especially those intercalated with different basaltic products (scoria and coriaceous basalt) and lake sediments, are found forming layering and bedding. These structural settings allow the movement and storage of groundwater within the units but the units have relatively low recharge.

Formation consisting of a minor fissured aquifer with local and limited groundwater resources – Aquitards. They are represented by fresh massive with very limited fractures and a shallow depth developed in rhyolite domes and intercalations of gypsum strata which has a very low permeability and limited groundwater.

Water quality
Groundwater is hard with TDS between 1000 and 2000 mg/l with content of sulphate and fluoride above standards for drinking water in the western part of Woreda (foot of escarpment). Groundwater is hard with TDS above 2000 mg/l and with content of fluoride above standards for drinking water east of Afdera Lake.

3.2.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into three basic parts: A Western part, B Central part and C eastern part. Parts are shown in Figure 8 which is extract from hydrogeological map presented in phase I.

A Western part consists mainly of highly and moderately productive porous aquifers. The main source of groundwater in the area is directly from precipitation and from surface water from intermittent streams. Much of the runoff from floods occurs from the escarpment to the depression where the water either evaporates or percolates into these porous aquifers. Western part is considered as recharge area and topographically low areas as discharge areas. Most of the infiltrated water from the escarpment travels as shallow groundwater to replenish laterally by deep groundwater flow (> 250 m) the evaporating basins of Lake Afdera in the south where it emerges in the form of springs at the lake shore. This is also supported by increasing TDS from 1,000 mg/l in the western highland to more than 2,000 mg in the area of Lake Afdera. In the majority of the area, alluvial sediments are the main source of groundwater for water supply***. Shallow and deep wells can be drilled for public water supply.***

B Central part consists mainly of moderately productive fissured aquifers developed in central ridge of the area. These aquifers are recharged directly from erratic rainfall but mainly from intermittent streams located in deep valley in highly dissected volcanic massifs. Most of the time, groundwater is fracture controlled rather than lithology. Groundwater level can be found in greater depth compering with part A and C. ***Groundwater accumulated in fractures zones along faults and lineaments and can be developed by deep wells after using Remote Sensing and geophysical location of structure, which potentially bear groundwater.***

A Eastern part consists mainly of moderately productive porous aquifers. The main source of groundwater in the area is directly from precipitation and from surface water from runoff of intermittent streams draining from Danakil Alps east of the Woreda area. This area is considered as recharge area and topographically low areas as discharge areas. Most of the groundwater travels as shallow groundwater to replenish laterally the evaporating basins of Lake Afdera in the south where it emerges in form of springs at the lake shore. Alluvial sediments are the main source of groundwater for water supply. ***Shallow and deep wells can be drilled for for groundwater development for public water supply.***

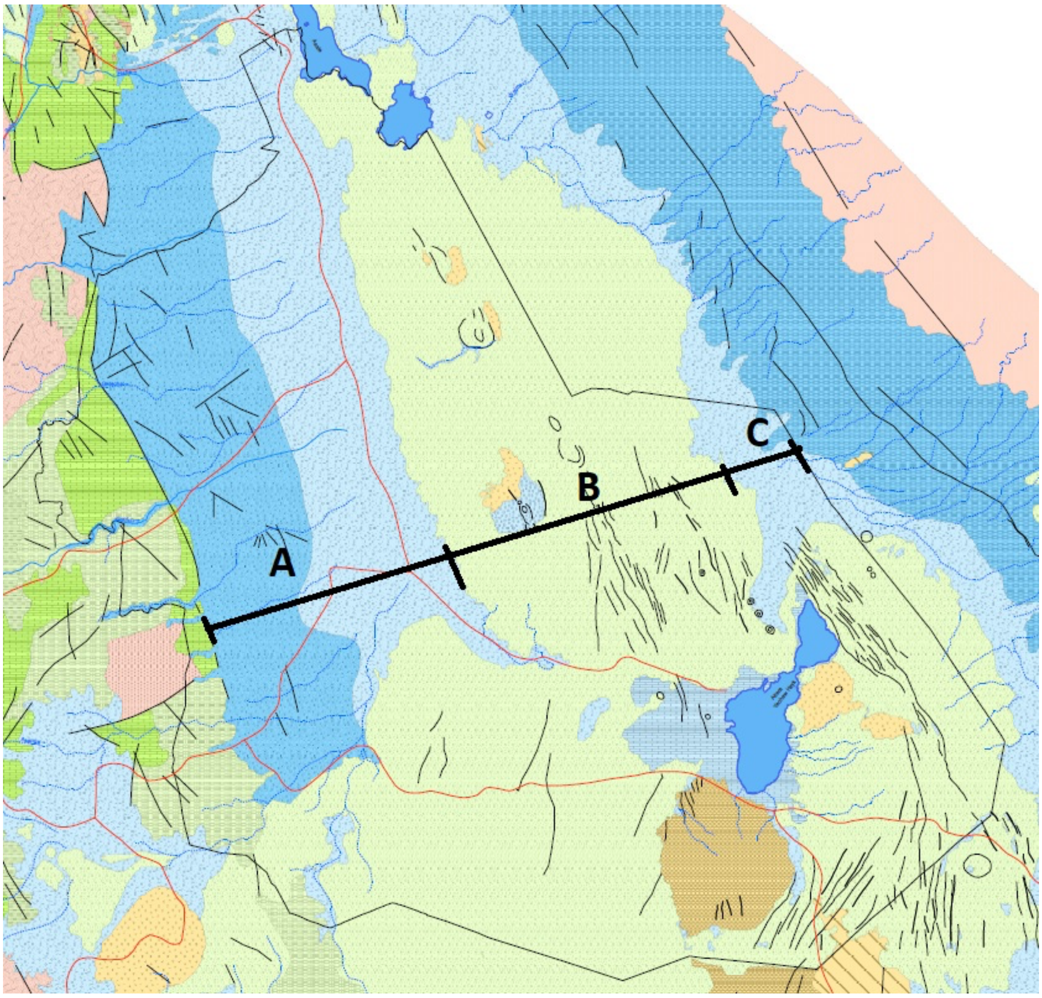

Figure 7. Hydrogeological map of Afdera

3.3 Berehale Woreda

The Woreda is located in the Afar Zone 2 and has an area of 2,509 km². The area is located at the western escarpment, Bikilal (Balakia) horst and foot of the Afar Depression and consist mainly low grade metamorphic and alluvial sediments.

Large part of Woreda is covered by basement represented by low grade metamorphic rocks – phyllite and slate consisting metavolcanics and of the Main intrusive. Central part is represented by sedimentary rocks (mainly limestone) of Bikilal (Balakia) horst in its northern part and by high terraces fluvial deposits and “Red Beds” in its southern part. These units are followed to the east by alluvial sediments of the Afar depression. The eastern part is occupied by northern limit of the ridge consisting of volcanic rocks of the Erta Ale ridge.

3.3.1 Geology

Low grade metamorphic rocks – phyllite and slate of Tambien group consisting of slate and phyllite with some black limestone, detritic dolomite interbedded with slate, greywacke, limestone and some calcareous slate and metavolcanics.

Limestone of Bikilal Horst consisting tectonized blocks of dominantly Antalo limestone with Adigrat sandstone (Jtz)

High terraces fluvial deposits and Gasrat Formation "Red Beds" consisting of gravel and sandstone, conglomerate, silt, clay, marlstone and associated volcanic material at foot of escarpment and the foot hills.

Alluvial deposits are located at the south-western part of Woreda covering depression along the (Darakatna River) in metamorphic rocks (Qha) and in Afar following high terrace sediments and basaltic volcanic rocks of the Erta Ale ridge (Qpa).

Basaltic to intermediate volcanic rocks and associated cinder cones of the Erta Ale ridge. Dominantly, it forms ridges, hills, cliffs and grabens. In some parts, it appears on gentle and very rugged topography dissected by deeply chiseled valleys.

Phonolite and Edaga Arbi glacials form small outcrops in the northeastern part of Woreda

3.3.2 Hydrogeology

Hydrogeological units with porous permeability where groundwater is accumulated in and flows through the porespores of unconsolidated material. The Quaternary alluvium along rivers and at floor of Afar Depression, lacustrine sediments, and some volcanic material (in Red Beds) represent the porous aquifers. The groundwater availability and flow are highly dependent on grain size, sorting, type of cementing material and thickness.

Highly productive aquifers (T = 10.1 – 100 m^2/d, q = 1.1 – 10 l/s·m, Q = 5 – 25 l/s for wells and/or springs) developed in Red Beds and flood terrace deposits. Texturally, it is dominated by gravels and sands around the escarpment and the foot hill regions. The aquifers have fractured, weathered and jointed surfaces that contribute to its high permeability and productivity and they are mainly recharged from the escarpment area.

Moderately productive aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) in alluvial deposits along rivers and in intermountain depression of the plateau and part of escarpment consist of unconsolidated beds of gravel, sand, silt and clay. They are the youngest deposits of the area, and are generally less than 10 m thick. Alluvium, silt, clay, sands and other Aeolian deposits are recognized in following two types: (a) those spread out in alluvial plains, and (b) those which occur as thin strips along intermittent streams. These aquifers represents extensive and moderately productive porous aquifers. The recharge comes from rainfall and runoff during the rainy season, however most of the recharge comes from runoff from the escarpment.

Hydrogeological units with fissured permeability where groundwater is stored in and flows through the fractured and weathered parts of volcanic and sedimentary rocks.

Highly productive aquifers (T = 10.1 – 100 m^2/d, q = 1.1 – 10 l/s·m, Q = 5 – 25 l/s for wells and/or springs) in sedimentary rocks consisting tectonized blocks of dominantly Antalo limestone with Adigrat sandstone (Jtz). Adigrat sandstone forms a regional aquifer and according to Tesfay Chernet and Gebretsadik Eshete (1978) assessed the hydraulic conductivity of Adigrat sandstone ranges from 0.18 to 8.3 m/d. Antalo limestone is coarse-grained, thick bedded to massive in places, the coarse-grained limestone beds contain mud flakes and possible algal fragments. Karstification is highly variable, but some karst features can significantly increase productivity of this unit.

Moderately productive aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) in recent volcanic rocks. Lava flows near the top of the Erta Ale Range in the extreme northeast are vesicular basalts with no intervesicular connections, but with some fracture permeability, though fracture permeability is reduced where the joints are filled with minor volcanic ashes. Some vegetation grows where the lava is covered with ashes, which have better water retention capacity and serve as soil. Generally, the central volcanic range is barrier to groundwater flow especially at depth. Lava flows are scoriaceous and permeable further away from the centers of the eruption, like at the foot of the Erta Ale Range.

Low productive fissured aquifers (T = 0.11 - 1 m^2/d, q = 0.0011 - 0,01 l/sm, Q = 0.051 -0.5 l/s for wells and/or springs) in Precambrian basement complex consisting of low grade metamorphic rocks. Practically all of the groundwater in the basement is stored in the fractured zones and the weathered mantle called regolith. The weathered thickness ranges from 10 to 50 meters, the greater thickness being located along streams, fault zones and topographic lows. The shallow depth fracture system (usually to the depth of 70 m) develops shallow aquifer zones. The fractures tend to close at depth. The greatest permeability is found in the sub-soil zone within the partly decomposed rock. This aquifers occupy the central part of the Woreda. Higher recharge and yield of wells can be expected from outcrops (lenses) of limestone and detritic dolomite.

Formation consisting of a minor fissured aquifer with local and limited groundwater resources – Aquitards are represented by phonolite plugs and Edaga Arbi glacials, which form small outcrops in the northeastern part of Woreda.

Water quality
Groundwater is hard with TDS between 1000 and 2000 mg/l with content of sulphate and fluoride above standards for drinking water in the eastern part of Woreda (foot of escarpment). Groundwater TDS below 1000 mg/l and content of suplphate of fluoride exceeding standards for drinking water occurs only in few water points in the western part of Woreda (escarpment).

3.3.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into four basic parts: A Western escarpment, B Bikilal (Balakia) horst, C foot of escarpment and Afar floor and D volcanic ridge. Parts are shown in Figure 9 which is extract from hydrogeological map presented in phase I.

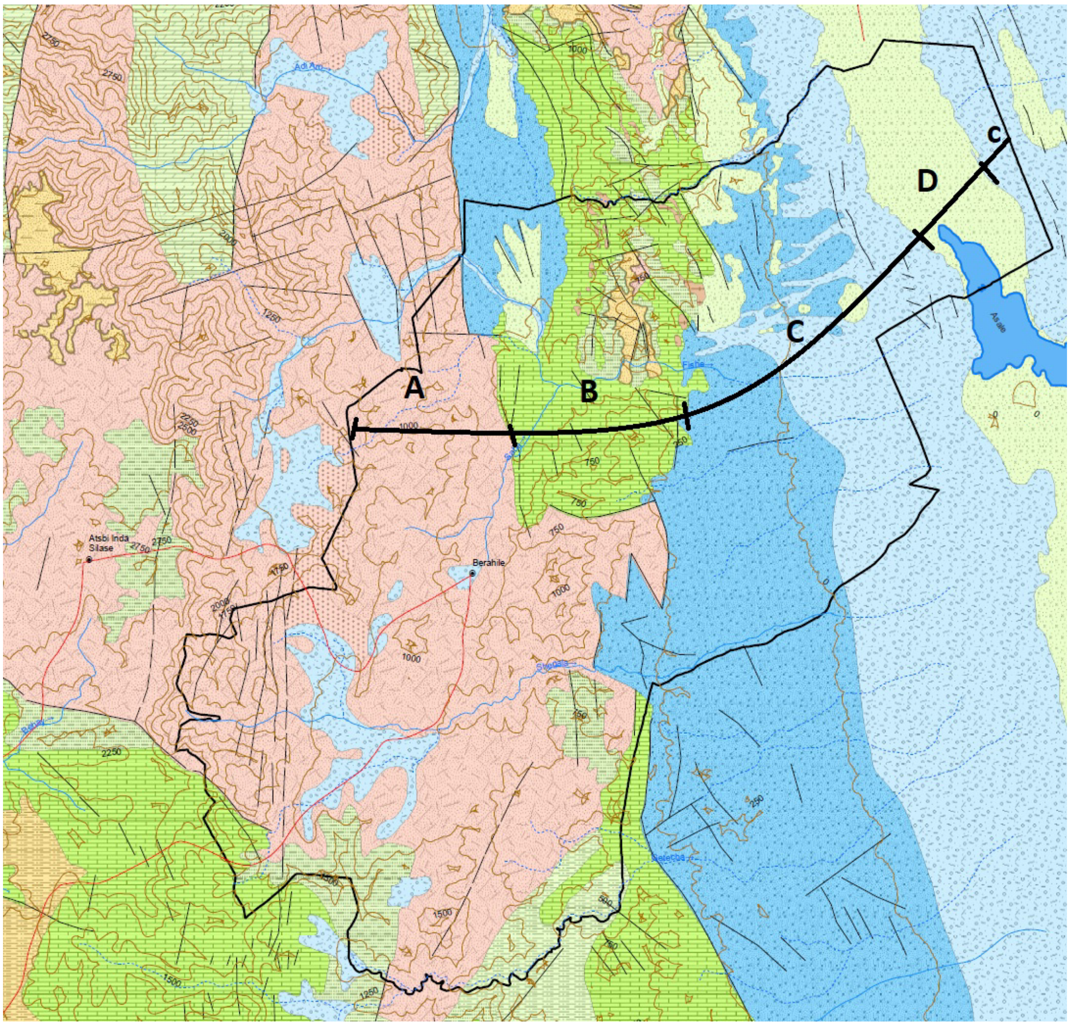

Figure 8. Hydrogeological map of Berehale

A Western escarpment consists mainly of low productive fissured aquifers developed in basement rocks with some alluvial sediments in intermountain depressions. Groundwater is stored in weathered mantle and relatively shallow fractured zones. Direct infiltration from rainfall dominate in the area and groundwater table follow the slope of the terrain. ***Groundwater resources can be developed by shallow wells drilled into fissured zones which should be located by combination of Remote Sensing and geophysical data and spring development.***

B Bikilal (Balakia) horst consist of block of Mesozoic sediments underlined by basement. Rainwater is infiltrating into fissured aquifers and form shallow groundwater flow to both western and eastern edge of the horst. Groundwater forma also deep groundwater flow and is recharging laterally aquifers at the western part of Afar floor. I emerge finally as springs at Lake Asale***. Groundwater can be developed mainly as springs in deeper valleys.***

C foot of escarpment, small marginal graben and Afar floor part consists mainly of highly and moderately productive porous aquifers. The main source of groundwater in the area is directly from precipitation and from surface water from permanent and intermittent streams. Much of the runoff from floods occurs from the escarpment to the depression where the water either evaporates or percolates into these porous aquifers.

Western part is considered as recharge area and topographically low areas as discharge areas. Groundwater flowing to the east direction is accumulated in alluvial sediments in between of basement outcrops in structure similar to marginal grabens. Most of the infiltrated water from the escarpment travels as shallow groundwater to be combined laterally with deep groundwater flow (> 250 m) at the evaporating basins of Lake Asale in the south where it emerges in the form of springs at the lake shore. This is also supported by increasing TDS from less than 1,000 mg/l in the Berehale area to more than 2,000 mg/l in the area of Lake Asale. In the majority of the area, alluvial sediments are the main source of groundwater for water supply***. Shallow and deep wells can be drilled for public water supply.***

D volcanic ridge area consists mainly of moderately productive fissured aquifers developed in volcanic ridge of the area. Generally, this volcanic range is barrier to groundwater flow especially at depth to the east. These aquifers are recharged directly from erratic rainfall but mainly from intermittent streams located in deep valley in highly dissected volcanic massifs. Most of the time, groundwater is fracture controlled rather than lithology. Groundwater level can be found in greater depth compering with parts of Woreda. ***Groundwater accumulated in fractures (lineaments) can provide some water for water supply and can be developed by deep wells after using Remote Sensing and geophysical location of structure, which potentially bear groundwater.***

3.4 Megale

The Woreda is located in the Afar Zone 2 and has an area of 1,548 km^2. The area is mainly located at the Western Afar margin.

3.4.1 Geology

The Woreda consist dominantly low grade metamorphic rocks, volcanic rocks accompanied by alluvial sediments and some outcrops of sedimentary rocks from geological point of view.

Alluvial sediments in intermountain (N-S) elongated depression (Qha) consisting of alluvial and colluvial sediments.

Limestone and sandstone dividing sediments of plateau (Jtz / Ja) and Afar. Sediments are represented detritic dolomite of the Tambien group and undifferentiated Jurasic sandstone and limestone. Disconnected outcrops of Amba Aradam Formation consisting of variable sediments of clay, silt, pebble conglomerate with common laterite surface

The Trap Basalts at the escarpment/plateau area are represented by olivine basalts with minor interbedded lacustrine deposits

Low grade metamorphic rocks mainly detritic dolomite interbedded with slate, greywacke, limestone and some calcareous slate and metavolcanics.

3.4.2 Hydrogeology

Hydrogeological units with porous permeability and moderate productivity (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) where groundwater is accumulated in and flows through the pores of unconsolidated material. The Quaternary alluvium and colluvium in intermountain (N-S) elongated depression (Qha) most probably structurally based (marginal graben). The River Ago is flowing through this graben and will be also contributing to infiltration (in dry period) additional to direct infiltration from rainfall.

Hydrogeological units with fissured permeability where groundwater is stored in and flows through the fractured and weathered parts of volcanic and sedimentary rocks.

Highly productive aquifers (T = 10.1 – 100 m^2/d, q = 1.1 – 10 l/s·m, Q = 5 – 25 l/s for wells and/or springs) in sedimentary rocks consisting highly tectonized blocks of dominantly Antalo limestone with Adigrat sandstone (Jtz). Adigrat sandstone forms a regional aquifer and according to Tesfay Chernet and Gebretsadik Eshete (1978) assessed the hydraulic conductivity of Adigrat sandstone ranges from 0.18 to 8.3 m/d. Karstification is highly variable, but some karst features can significantly increase productivity of this unit.

Moderately productive aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) in sedimentary rocks consisting outcrops of Antalo limestone with Adigrat sandstone (Jtz) and Amba Aradom sandstone (Upper sandstone) n the northwestern part of the Woreda. Productivity of these outcrops is highly variable. Large outcrops of olivine basalts with minor interbedded lacustrine deposits represent fissured aquifer developed in Trap volcanics in west - central part of Woreda. Thera are many springs with a wide variation in yield due to the topographic set up, degree of fracture, level of weathering and recharge condition. The discharge of spring varies from 0.5 l/s 6 l/s. On rugged terrain and mountains with steep slopes, the recharge to the groundwater is very limited.

Low productive fissured aquifers (T = 0.11 - 1 m^2/d, q = 0.0011 - 0,01 l/sm, Q = 0.051 -0.5 l/s for wells and/or springs) in Precambrian basement complex consisting of low grade metamorphic rocks. Practically all of the groundwater in the basement is stored in the fractured zones and the weathered mantle called regolith. The weathered thickness ranges from 10 to 50 meters, the greater thickness being located along streams, fault zones and topographic lows. The shallow depth fracture system (usually to the depth of 70 m) develops shallow aquifer zones. The fractures tend to close at depth. The greatest permeability is found in the sub-soil zone within the partly decomposed rock. This aquifers occupy the south central part of the Woreda. Higher recharge and yield of wells can be expected from outcrops (lenses) of limestone and detritic dolomite.

Water quality
Groundwater TDS below 1000 mg/l and no ions exceeding standards for drinking.

3.4.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into three basic parts: A Western Afar margin – volcanic and sedimentary rocks, B Valley (marginal graben) of the River Ago, C Western Afar margin - low grade metamorphic rocks. Parts are shown in Figure 10 which is extract from hydrogeological map presented in phase I.

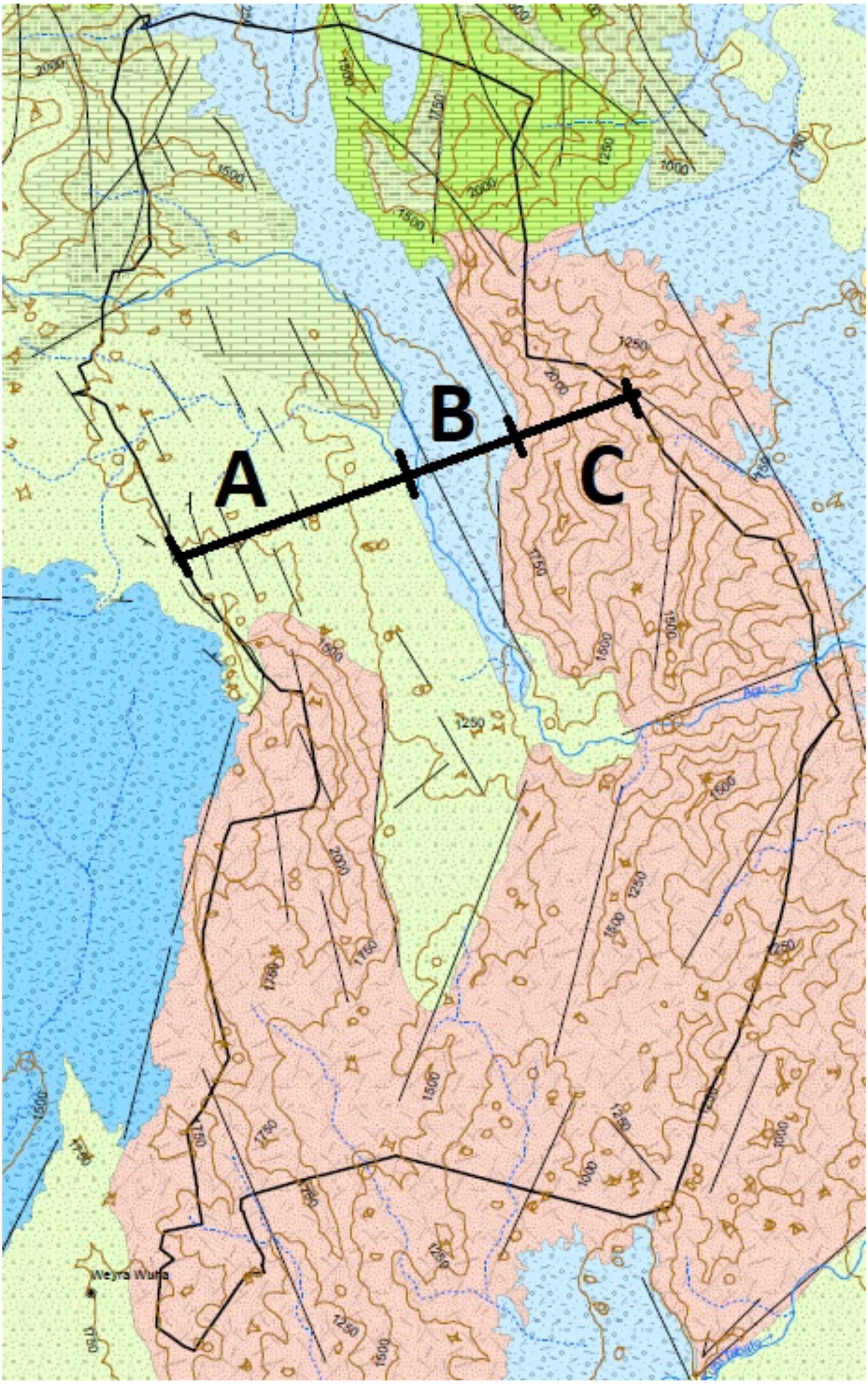

Figure 9. Hydrogeological map of Megale

A Western Afar margin – volcanic and sedimentary rocks. The uppermost aquifers is developed in fissured aquifers developed in trap basalts, these aquifers are underlined by Mesozoic sandstone and limestone. Rainfall is the main source of recharge in these aquifers. The groundwater lateral flow direction is dependent on the inclination, steepness or slope of the topography in the area. Outcropping aquifers can also recharge deeper located aquifers and form deep groundwater flow to the east direction which can later laterally recharge aquifers in the Afar plain and this groundwater can be discharge in form (hot) springs at the Afar lakes. ***Groundwater resources can be developed mainly by deep wells drilled into fissured zones (faults and lineaments) which should be located by combination of Remote Sensing and geophysical data and by spring development.***

B Valley (marginal graben) of the River Ago with accumulation of alluvial sediments. The aquifers is directly recharge by rainfall and is also recharged by lateral flows of shallow and deeper groundwater from volcanic and sedimentary rocks as well as from basement. The River Argo can also recharge and/or discharge aquifer depending on rainy or dry season. ***Groundwater resources can be developed in depression (shallow marginal graben) between volcanic basement rocks by shallow wells drilled near perennial rivers.***

C Western Afar margin - low grade metamorphic rocks where rainfall is the main source of recharge in basement rocks and form shallow groundwater. The shallow groundwater movement and flow direction are dependent on the inclination, steepness or slope of the topography in the area. In most parts of the Woreda, the direction of flow and existence of springs is controlled by topographic breaks. The groundwater flows from the western part of Woreda with the higher elevation to east and southeast and laterally recharge aquifers located in lower elevation. Deeper groundwater circulation and drainage to the east to Afar plain can occurs along deep faults of W-E direction of which existence is indicated by direction of flow of perennial rivers (Ago, Kubi Tabato, Golina). ***Groundwater resources can be developed by shallow wells drilled into fissured zones which should be located by combination of Remote Sensing and geophysical data and by spring development.***

3.5 Yalo

The Woreda is in the Afar Zone 4 and has an area of 823 km^2. The area is mainly located at the Western Afar margin - hilly terrain (escarpment) and the Afar floor.

3.5.1 Geology

The Woreda consist dominantly by volcanic rocks accompanied by alluvial sediments and some outcrops of sedimentary rocks from geological point of view.

Alluvial sediments (Qa) fluvial and terraces (colluvial deposits)) of lacustrine sediments. The lacustrine sediment is 1 m thick weathered gray to yellowish clour, horizontally thinly to thickly laminated and bedded diatomite exposed along the Afar rift floor in the south-eastern part.

Basalts (Qbvr) covers most of the Afar plains, include porphyritic, amygdaloidal, vesicular and aphyritic basalt and scoria cones, forming isolated hills of conical to elliptical morphology. It exposed within stream cut and on flat plain. In some places it shows columnar jointing. The rock is black and dark gray fresh sample weathered to gray and brownish color. ***Silicic centers – rhyolite*** (Qavr) are common in the rift plain, it is white and pink in color, fine to coarse grained. Rhyolitic flow banding dome forming morphology

3.5.2 Hydrogeology

Hydrogeological units with porous permeability and moderate productivity (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) where groundwater is accumulated in and flows through the pores of unconsolidated material. Extensive and moderately productive porous aquifers consisting of fluvio-lacustrine sediments (Qa). These aquifers filling the Afar rift floor and forming the flat morphology. These thick aquifers on the western Afar escarpment become thinner towards the east, far from the rift escarpment. The permeability of these sediments is very variable depending on the grain size and sorting as well as the value of rainfall and its distribution. Those with grain size of silt and sand have better permeability and productivity, whereas those with very fine ash and massive tuff interbreeding layers of sediments have low permeability and productivity. The aquifers are mainly recharged by lateral flow from the surrounding highlands and along some rivers. They are also recharged from direct precipitation, but the meteorological data analysis shows that the rainfall is low and evaporation is high on the Afar rift floor.

***Hydrogeological units with fissured* permeability and moderate productivity** (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) where groundwater is stored in and flows through the fractured and weathered parts of volcanic rocks. Basalts at the Rift floor are moderate to highly jointed and vesicular. The vesicles are interconnected but are mostly filled with calcite reducing their hydrogeological importance. They are recharged by streams and occupy relatively moderate to gentle topography on the Rift floor. Wells drilled in Quaternary basic volcanic rocks have a yield in the range of 05-5 l/s. In general, in basalt aquifers as the depth of wells increases, the discharge also increases because of the multi layered character of the aquifers.

Formation consisting of a minor fissured aquifer with local and limited groundwater resources – Aquitards. They are represented by rhyolite, which is slightly jointed and occupies steep solitary hills (domes). The recharge, permeability and storage are minimal. Most of the precipitation in the area does not have time to percolate and runs off.

Water quality
Groundwater TDS below 1000 mg/l and no ions exceeding standards for drinking.

3.5.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into three basic parts: A North-western part represented by Western Afar margin, B Foot of escarpment along River Kubi Tabato, C The Afar plain. Parts are shown in Figure 11 which is extract from hydrogeological map presented in phase I.

A North-western part of the Western Afar margin and associated grabens, where recharge from rainfall is minimal and the main source of groundwater is from regional flows. Groundwater movement and flow direction are dependent on the inclination, steepness, or slope of the topography in the area. In most parts of the Woreda, the direction of flow and existence of springs is controlled by topographic breaks. This is an area of Transitional slope with step faults and Graben-Horst structures with moderately productive fissured and karst aquifers (T =1-10m 2/d, Q =0.5-5l/s for wells). Local recharge from rainfall is minimal because of low rainfall and high runoff. Occurrence of groundwater is mainly related to the regional groundwater flow from the western mountains.

The groundwater flows from the western part of Woreda with the higher elevation to east and southeast and laterally recharge alluvial (along River Kubi Tabato) and volcanic aquifers of the rift floor (Afar plain). Deeper groundwater circulation can occur along deep faults of W-E direction of which existence is indicated by direction of flow of perennial rivers (, Kubi Tabato and Ago and Golina rivers located out of the Woreda area). ***Groundwater resources can be developed by shallow wells drilled into fissured zones which should be located by combination of Remote Sensing and geophysical data and by spring development.***

B Foot of escarpment along River Kubi Tabato and adjacent areas, these are typically featured by accumulation of alluvial sediments over the marginal depression areas characterized by groundwater discharge into wadies and lakes. The alluvial sediments are underlain by volcanic rocks and Mesozoic Sedimentary rocks which are moderately productive porous and fracture aquifers (T =1-10m2/d). Groundwater occurs because of local recharge from flush floods from the mountains, rainfall, and regional groundwater flow.

Deeper groundwater circulation can occur along deep faults of W-E direction. The River Kubi Tabata can also recharge and/or discharge aquifer depending on rainy or dry season. ***Groundwater resources accumulated in alluvial sediments and volcanic rocks along the Kubi Tabato River can be developed by shallow wells located preferable along the river.***

C The Afar plain with local high grounds, where the source of groundwater recharge to fissured aquifer developed in basalt is mainly direct precipitation. The potential evapotranspiration on the Afar rift floor is higher than the annual rainfall, which make infiltration relatively low. The groundwater flows from escarpment in the western part of Woreda can also laterally recharge volcanic aquifers of the rift floor (Afar plain). Deeper groundwater flow can that occurs along deep faults of W-E direction can also contribute to recharge of this aquifers. General direction of groundwater is to northeast. ***Groundwater resources can be developed by deep wells drilled into preferably in regional lineaments which should be located by combination of Remote Sensing and geophysical data.***

The Volcanic rocks (Rhyolite) mountain characterized by rugged terrain and steep slopes, which is slightly jointed and occupies steep solitary hills (domes) has minimal recharge, permeability and storage and locally act as water divide. Most of the erratic precipitation in the area does not have time to percolate and runs off. Rainwater harvesting is practiced as optimal water management structure in some of rhyolite domes in the Afar area.

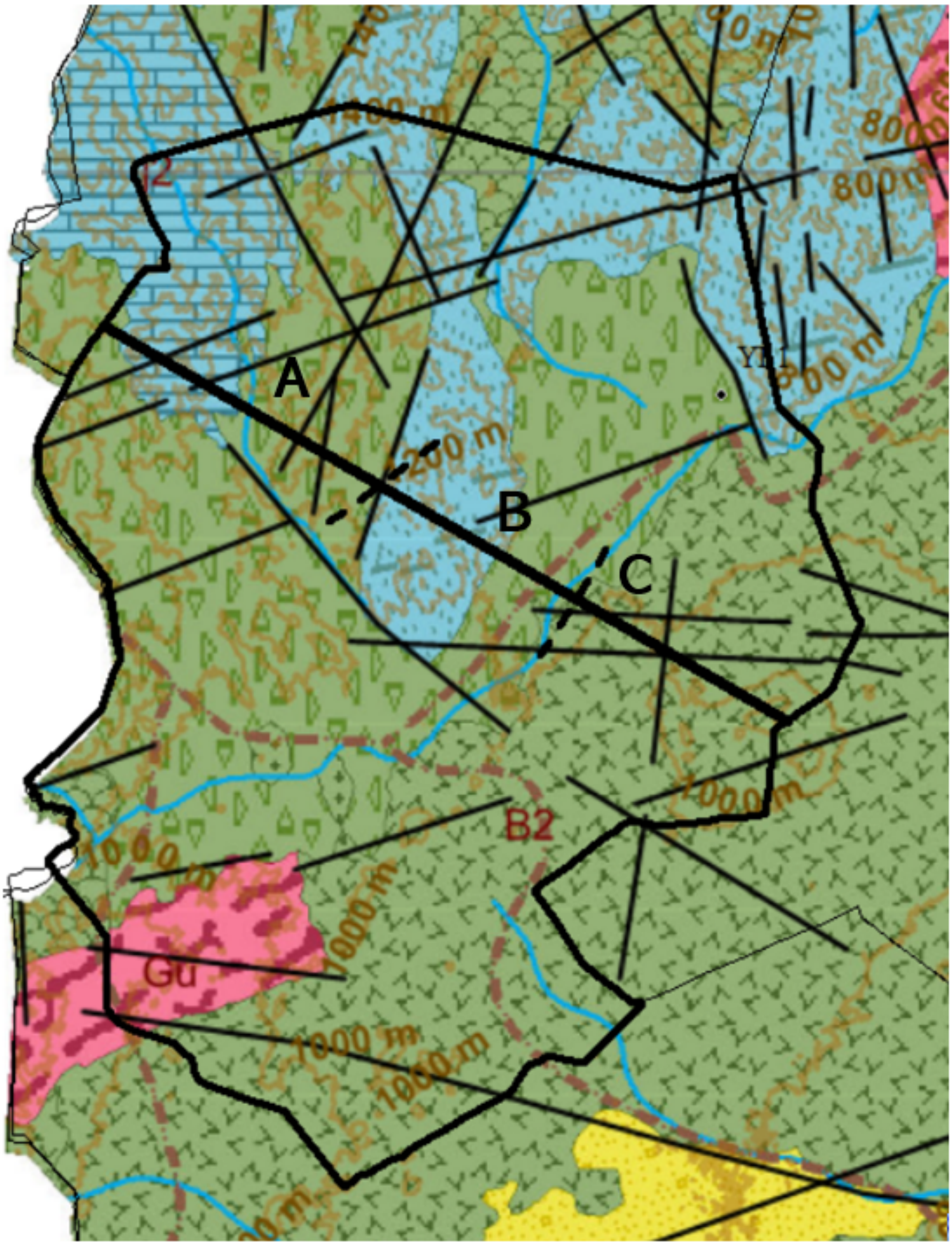

Figure 10. Hydrogeological map of Yalo

3.6 Beyeda

The Woreda is located in the North Gonder zone of the Amhara Region and has an area of 973 km^2. The area is mainly located at the Western plateau (highlands) at the eastern flank of Ras Dashan Mountain.

3.6.1 Geology

Majority of the Woreda area is covered by shield volcanic rocks and Tertiary trap volcanic rocks consisting of basalts with minor trachyte and upper pyroclastic of the massif of Ras Dashan. Basement rock outcrop in the northern limit of the area in deep valleys formed by tributary of the Tekeze River.

Shield volcanic rocks and Trap basalts of the Ras Dashan massive form the majority of Woreda area is a black olivine alkali basalt with clinopyroxene plagioclase groundmass, of which thickness is up to 2,500 m. The Simian Mountains are bounded in the north and west by imposing cliffs, up to 2,000 m high, forming the southern wall of the deep Tekeze gorge and are cut by steep gorges formed by tributaries of the Tekeze River. Numerous flows with well-developed columnar jointing, which has concentrations of white zeolite and inter-flow fossil soils in many places. Interbedded lacustrine deposits of off-white silicified limestone and diatomite with gastropods occur at several levels.

Adigrat sandstone is underlying Trap basalts in the north-eastern corner of the Woreda. Lithologically, the Adigrat sandstone is yellow to red sandstone, fine to medium-grained; interbedded with variegated siltstone and clay. White sandstone, medium to coarse-grained: friable, cross-bedded, shows turbidity structures and contains well-distributed lenses of ferruginous silt.

Low grade metamorphosed rock of basement (Tambien Group) in the north – eastern corner of the Woreda underlying Adigrat sandstone are represented by various slates and sugary dolomite with blue – ribboned slates.

3.6.2 Hydrogeology

The hydrogeological characteristics and groundwater potential of the Woreda are highly affected by the complexity of geology, physiography, climate and geological structures. There are two prominent topographic features, an extensive highland plateau and the deeply dissected wide canyon or gorge along the Tekeze River and its tributaries. The aquifers developed in sandstone and volcanic rocks are the most important aquifers of Tekeze river basin.

Hydrogeological units with fissured permeability and moderate productivity (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) where groundwater is stored in and flows through the fractured and weathered parts of volcanic and sedimentary rocks. Structurally affected Tertiary trap volcanics are one of the major water bearing formations of the area. Structures and vertical fissures/fractures facilitate direct recharge from rainfall as well as vertical flow of groundwater into great depth. The Tertiary trap volcanics represent usually aquifers with a confined groundwater table caused by inter-bedded rocks. There are a lot of productive deep and shallow wells drilled in this aquifer for town and rural water supply. Relatively large springs are known at the foot of shield volcanic massif of Ras Dashan Mountain, showing deep circulation of groundwater from shield volcanic material to underlying Trap basalts.

Adigrat sandstone is exposed in highly dissected valleys and forms cliffs. The sandstone is exposed particularly along the Tekeze river section and has a maximum thickness of 650 to 670 m. Adigrat sandstone is unconformably overlain by Tertiary trap volcanics and their contacts are usually marked by a sharp topographic break. The sandstone fractures increase groundwater storage and hydraulic conductivity. The permeability of the sandstone is increased by weathering in addition to closely spaced vertical fissures and horizontal bedding. This aquifer is recharged from the overlaying aquifers in Tertiary trap basalts and from direct rainfall infiltration. Recharge and permeability of this sandstone aquifer are relatively high but due to the steep topographic setting development of its potential is difficult.

Low productive fissured aquifers (T = 0.11 - 1 m^2/d, q = 0.0011 - 0,01 l/sm, Q = 0.051 -0.5 l/s for wells and/or springs) in Precambrian basement complex consisting of low grade metamorphic rocks represented by various slates and sugary dolomite. These aquifers are recharged from rainfall and recharge can be enhanced by vertical flow of groundwater from overlying aquifers. The upper weathered surface of metamorphic rocks supplies small amounts of water in some shallow wells along the main rivers.

Water quality
Groundwater is soft with TDS between 400 and 500 mg/l and no ions exceeding standards for drinking.

3.6.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into three basic parts: A Ras Dashan shield volcano, B Deep valley with sandstone and C Deep valley with basement. Parts are shown in Figure 12 which is extract from hydrogeological map presented in phase I.

A Ras Dashan shield volcano is the highest volcanic plateau in Ethiopia. The area receives large volume of rainfall of which part is infiltrating into fissures of Trap basalts. It forms shallow as well as deep circulation and groundwater accumulation in various layers of Trap basalts. Deep circulation and vertical groundwater flow can also recharge underlying aquifers developed in Adigrat sandstone, particularly near to the contact between these two aquifers. The groundwater flow direction is to the east to valley of the Tekeze River. In the shield volcanoes, the interlayer of acidic lava and ash components with fractured basaltic layers create a dual feature for groundwater storage in movement. Highly permeable rubbly and/or fractured lavas form high potential part of aquifer. Vertical structures enable deep circulation of groundwater from shield volcanic material to underlying Trap basalts. ***Groundwater resources can be developed deep wells drilled into preferably in regional lineaments which should be located by combination of Remote Sensing and geophysical data to locate depth of highly productive units. Spring development is an additional option of groundwater development.***

B Deep valley with sandstone overlain by Trap basalt. Rainfall and vertical flow from Trap basalts are the main source of recharge in these aquifers. The groundwater lateral flow direction is dependent on the inclination, steepness or slope of the topography in the area. Groundwater resources can be developed mainly by deep wells drilled into fissured zones which should be located by combination of Remote Sensing and geophysical data and by spring development.

Groundwater resources can be developed by deep wells drilled into preferably near contact of volcanic rocks and sandstone. Combination of Remote Sensing and geophysical data to site the wells is recommended.

C Deep valley with basement where rainfall is the main source of recharge in basement rocks and form shallow groundwater. The shallow groundwater movement and flow direction are dependent on the inclination, steepness or slope of the topography in the area. In most parts of the Woreda, the direction of flow and existence of springs is controlled by topographic breaks and by river.). ***Groundwater resources can be developed by springs development and by shallow wells drilled into fissured zones along faults and lineaments (preferably near to the river) which should be located by combination of Remote Sensing and geophysical data.***

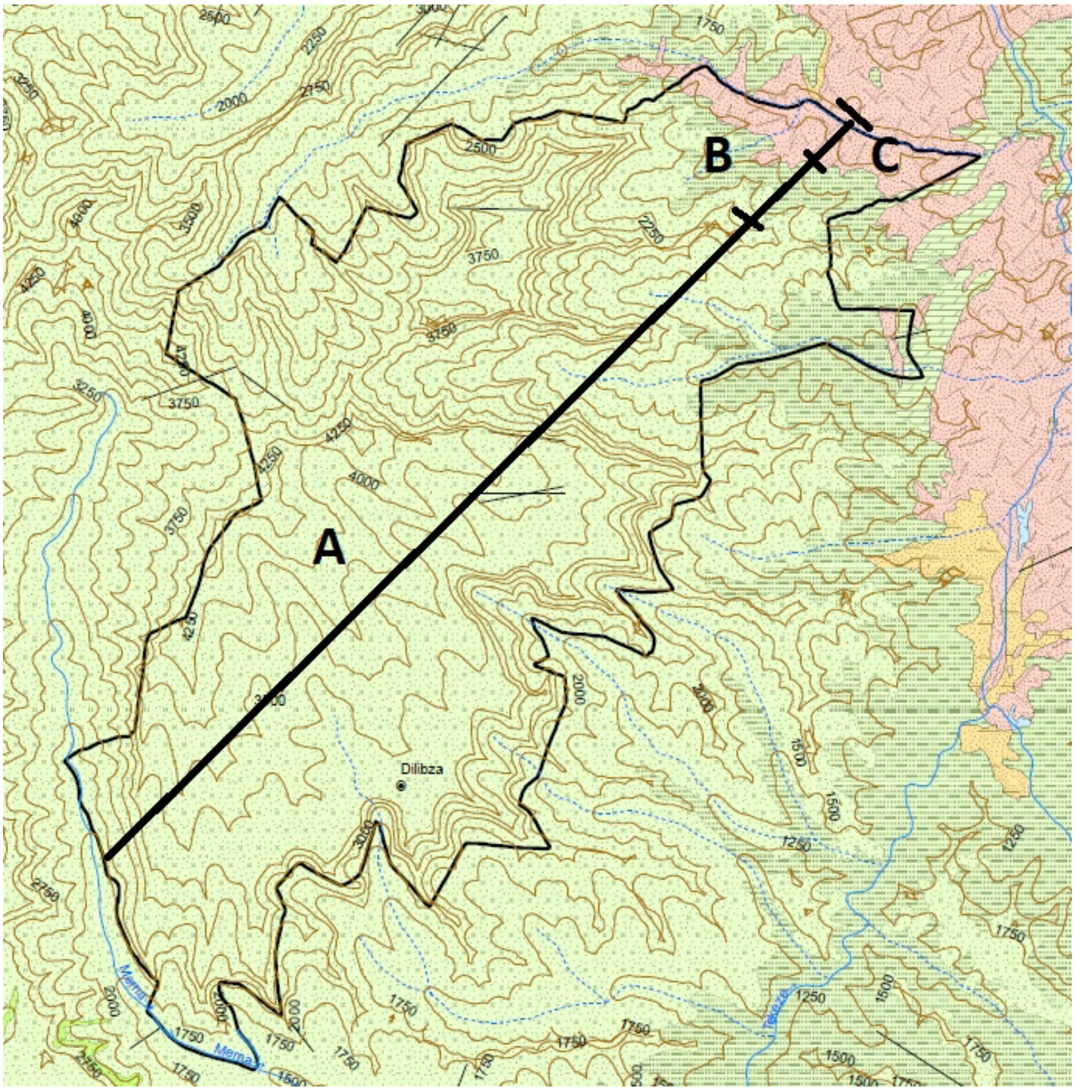

Figure 11. Hydrogeological map of Beyeda

3.7 Kola Temben

The Woreda is located Central zone of the Tigray Region and has an area of 1,365 km^2. The area is located at the Western plateau (highlands).

3.7.1 Geology

The Woreda consist mainly basement rocks (metavolcanics), sandstones and minor glacial sediments and volcanic rocks from geological point of view.

The Precambrian rocks of the area comprise mainly rocks of Tsaliet metavolcanics. The unit is composed of green schist, which was originally volcanic rocks and is therefore named metavolcanics and can be more than 1,500 m thick. Stratigraphically, Tsaliet is unconformably overlain by the Tambien group. Lithologically, Tsaliet metavolcanics are composed of green to purple schist containing quartz, epidote and calcite, interbedded with black, white, green and pink quartzite, pink to light-green gneiss, and minor black limestone and light-green marble. The green schist is originally rhyolitic volcanic

The Paleozoic-Mesozoic sediments outcropped next to the Late Precambrian basement units (Tambain groups). They are exposed in highly dissected valleys and form cliffs. They are mainly comprised of Edaga Arbi glacials (Pzd) and Adigrat sandstone (Ja).

Paleozoic Edaga Arbi tillite has a thickness of 0 to 180 m. The section of the Edaga Arbi glacials was measured near Edaga Arbi where the unit is composed of four members as follows: 15-20 m of dark grey tillite at the base, then 27 m of massive dark greenish-grey shale, then 60 m of finely laminated greenish-grey shale and at the top 56 m of red and green shale.

Adigrat sandstone is of Triassic to upper Jurassic age and is exposed along the Tekeze river section. Adigrat sandstone is unconformably overlain by trap volcanics (central part of the Woreda). The Adigrat sandstone formation has a maximum thickness of 650 meters. To the west of Abi Adi the Adigrat sandstone forms ridges and buttes. Lithologically, the Adigrat sandstone is yellow to red sandstone, fine to medium-grained; interbedded with variegated siltstone and clay. White sandstone, medium to coarse-grained: friable, cross-bedded, shows turbidity structures and contains well-distributed lenses of ferruginous silt. Red sandstone, medium to coarse-grained poorly sorted, well cross-bedded: contains quartz pebble and ferruginous fossil wood fragments. White, yellow to brown sandstone, fine to medium-grained, well sorted in beds of 1-15 m containing quartz pebbles and minor cross bedding.

Tertiary black olivine alkali basalt with a coarse, subophitic to intergranular texture create small outcrop on the highest point of the Woreda.

3.7.2 Hydrogeology

Hydrogeological units fissured permeability and moderate productivity and (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) where groundwater is stored in and flows through the fractured and weathered parts of Paleozoic-Mesozoic sediments. These sediments usually form gentle to steep slope topography. The Paleozoic-Mesozoic sediments unconformably overlay the Precambrian metavolcanics and metasediments. They are unconformably overlain by Tertiary trap volcanics forming mall outcrop on the highest point of the Woreda. Fractures in Edaga Arbi glacials and Adigrat sandstone increase percolation, groundwater storage and hydraulic conductivity.

Permeability of Paleozoic-Mesozoic sediments is increased by weathering in addition to closely spaced vertical joints and horizontally bedding. The impact of textural variation, compaction (cementation), thickness and inclined bedding may cause local changes in discharge or other hydrogeological properties. Small outcrop of the Assem limestone in western part of Woreda has similar hydrogeological character.

Low productive fissured aquifers (T = 0.11 - 1 m^2/d, q = 0.0011 - 0,01 l/sm, Q = 0.051 -0.5 l/s for wells and/or springs) in Precambrian basement complex consisting of low grade metamorphic rocks penetrated by intrusive. Practically all of the groundwater in the basement is stored in the fractured zones and the weathered mantle called regolith. The shallow depth fracture system (usually to the depth of 70 m) develops shallow aquifer zones. The fractures tend to close at depth. The greatest permeability is found in the sub-soil zone within the partly decomposed rock. This aquifers occupy the central part of the Woreda.

Water quality
Groundwater is soft with TDS about 500 mg/l in several shallow wells nitrate ion exceeding standards for drinking reflecting lack of sanitation.

3.7.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into three basic parts: A Western part, B Central part and C Eastern part. Parts are shown in Figure 13 which is extract from hydrogeological map presented in phase I.

A Western part consists mainly of moderately productive fissured aquifers developed in sandstone and limited limestone. Direct infiltration from rainfall dominate in the area and groundwater table follow the general slope of the terrain. ***Groundwater resources can be developed by medium deep and deep wells located mainly along perennial rivers (Beles, Weret, Tekeze).***

B central part consists mainly of low productive fissured aquifers developed in basement rocks with some sandstone and basalt at the top hills of the area. Groundwater is stored in weathered mantle and relatively shallow fractured zones. Direct infiltration from rainfall dominate in the area and groundwater table follow the slope of the terrain. ***Groundwater resources can be developed by shallow wells drilled into fissured zones which should be located by combination of Remote Sensing and geophysical data and spring development.***

C Eastern part consists mainly of moderately productive fissured aquifers developed in sandstone and accompanied by impermeable glacials. Direct infiltration from rainfall dominate in the area and groundwater table follow the slope of the terrain. ***Groundwater resources can be developed by deep and medium deep wells located in sandstone along perennial rivers.***

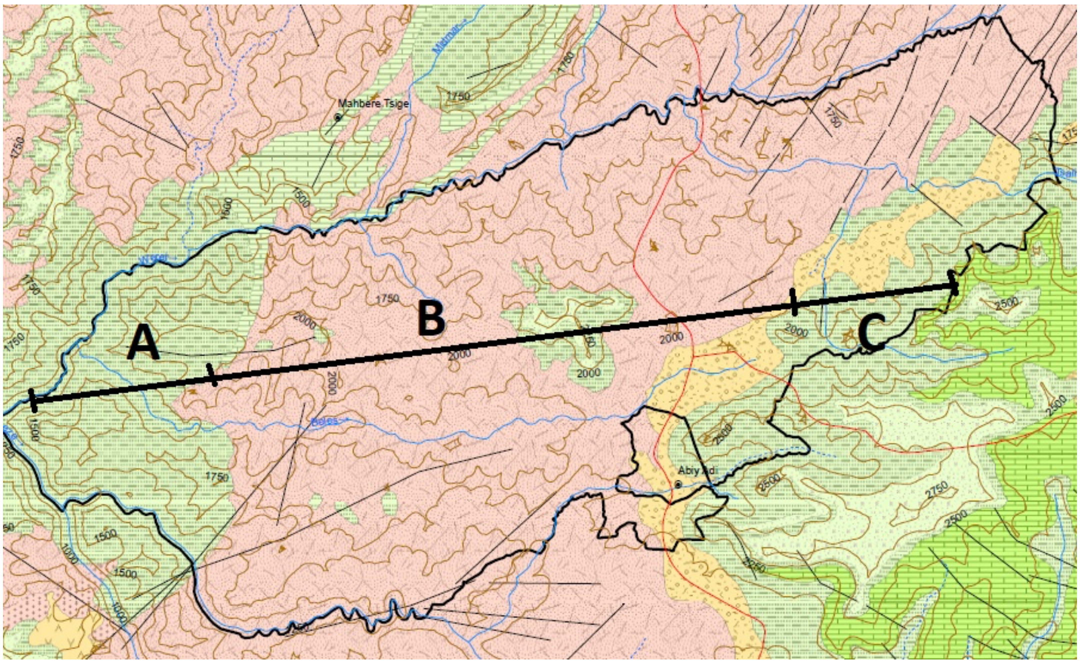

Figure 12. Hydrogeological map of Kola Temben

3.8 Mereb Leke

The Woreda is located Central zone of the Tigray Region and has an area of 1,259 km^2. The area is located at the Western plateau (highlands). The Mereb River in the most northwest limit of the area form its north border, which conform to Ethiopia and Eritrea border.

3.8.1 Geology

Practically whole area of the Woreda is located in the Chila block and is covered by basement rocks where low and medium grade metamorphosed rocks and massifs of granodiorite accompanied by two large strips of gabroic intrusive (metagabro, metapyroxenite) dominate. The basement is covered by small outcrops of sandstone and basalt. Phonolite plugs of different size penetrate the southeastern part of the area. There is a small accumulation of alluvial sediment along the Mereb River in the most northwest limit of the area

Metamorphosed rocks are represented by Low grade metamorphic rocks consisting of phyllite and quartzite with calcareous bands graphitic phyllite and quartzite (Papg). Medium grade metamorphic rocks consist of amphibolite schist with marble (Paam).

Precambrian intrusive are represented by Gabroic (Puu) intrusive consist of metagabro, metapyroxenite. Granodiorite (Gt2, Gt3) coarse grained xenolitic granite, granodiorite, diorite and tonalite, distinct marginal foliation and zone of

Alluvial sediments consist of sand gravel and silt.

Phonolite plugs, basalts (Tkv) and sandstone (Mas) form small and discontinuous outcrops.

3.8.2 Hydrogeology

The geology of the study area mainly determines the quantity and quality of the groundwater resources. Practically all of the groundwater in basement rocks is stored in tectonically affected areas, in fractured zones and in the weathered mantel, the so-called regolith.

Low productive fissured aquifers (T = 0.11 - 1 m^2/d, q = 0.0011 - 0,01 l/sm, Q = 0.051 -0.5 l/s for wells and/or springs) in Precambrian basement complex consisting of low grade metamorphic rocks penetrated by intrusive. Practically all of the groundwater in the basement is stored in the fractured zones and the weathered mantle called regolith. The shallow depth fracture system (usually to the depth of 70 m) develops shallow aquifer zones. The fractures tend to close at depth. The greatest permeability is found in the sub-soil zone within the partly decomposed rock. This aquifers occupy 97% of the Woreda area.

Hydrogeological properties in metamorphic rocks is relatively low. Transmissivity values in this groundwater body can be expected to be quite low, except in localized areas in the vicinity of fault zones where there has been a high degree of fracturing. Granite intrusions preserve only shallow joints in most cases and form boulders at their top part but after about 10 m, as seen in some river sections, the rocks become massive or the open shallow fractures either close or narrow. Gabroic intrusive rocks are very massive and hard with very slight weathering. In some places, it has very shallow fractures that play no role in groundwater occurrence or flow. Instead they act as groundwater barriers. Yield of most of the boreholes is very low, however, borehole drilled in gabbro in Idaga Hamus health center with depth of 45 m has yield 0.5 l/s.

Water quality
Groundwater is soft with TDS between 600 and 700 mg/l and no ions exceeding standards for drinking.

3.8.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area is formed by uniform geology as well as hydrogeology. The Woreda area is shown in Figure 14 which is extracted from the hydrogeological map presented in phase I.

The characterization and prediction of flow and transport through a fractured hard rock mass is extremely difficult as the geometry of the flow path in these rocks is often very complex and heterogeneous depending upon the fracture characteristics. From a geomorphological point of view, the groundwater may follow the surface drainage system. The topography of the Woreda area generally slopes towards the north (northwest) to the Mereb River. Groundwater is mainly recharged from rainfall and runoff. Rainfall entering the soil at the surface (infiltration) replenishes the soil moisture deficiency and excess water moves downwards (percolation) and reaches the groundwater table. Groundwater is discharged by springs, boreholes, dug wells and areas where the water table is exposed at the surface.

Development of aquifers in basement rocks (low and medium grade metamorphic rocks). Despite to the fact that aquifers developed in basement rock have limited groundwater resources, it is possible to recommend drilling 30 – 70 m deep wells. Greater yield of wells can be achieved when siting wells along faults and lineaments using Remote Sensing structural analysis and geophysical exploration, which seems to be indispensable for basement rocks.

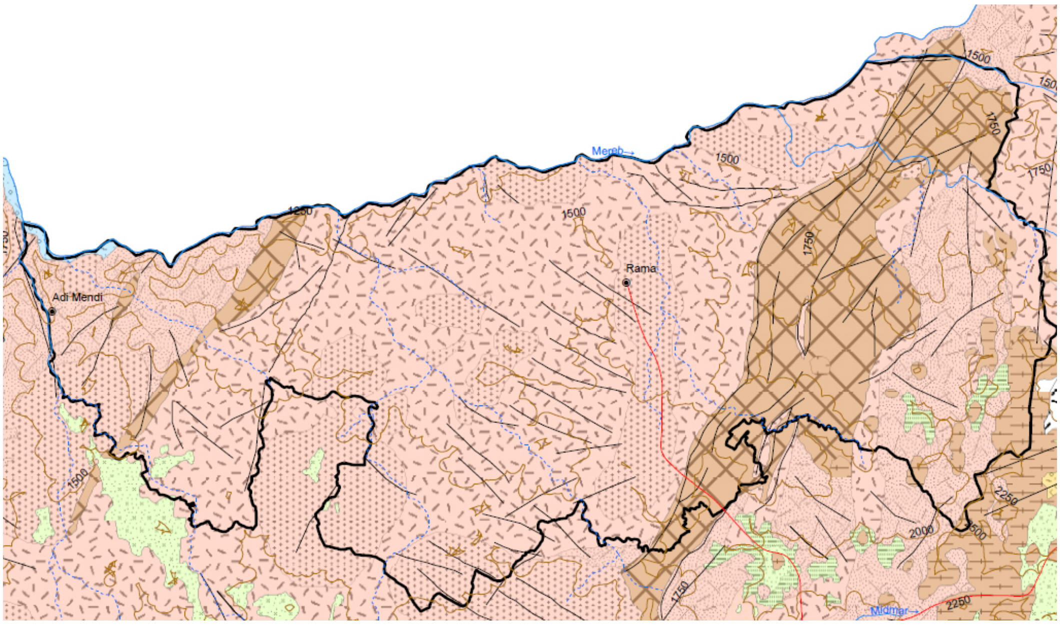

Figure 13. Hydrogeological map of Mereb Leke

3.9 Erob

The Woreda is located Eastern zone of the Tigray Region and has an area of 773 km^2. The area is located at the Western plateau (highlands). Its north border is conform to Ethiopia and Eritrea border.

3.9.1 Geology

A dominant part of the Woreda is covered by basement represented by low grade metamorphic rocks – phyllite and slate with some intrusive rocks. Dolomite interbedded with slate of Didikama Formation and limestone, undifferentiated slates, calcareous sediments, marble and fossiliferous and sand limestone form central part of the Woreda. High fluvial terraces, consisting gravel and low cemented sandstone, followed by alluvium make small outcrop in the eastern limit of the area.

Metamorphosed rocks consist of low grade metamorphic rocks phyllite and slate with some intrusive rocks of the Tsaliet group and carbonate rocks of (Pd) Didikama (dolomite interbedded with slate) and (Pta) Arequa (slates, phyllites, calcareous sediments and limestone) Formations.

Precambrian intrusive are represented by granite (Pg2) of the Asimba Mountain and some quartz porphyry sills in the upper part of Tsalient group.

High fluvial terraces and alluvial sediments consisting gravel and low cemented sandstone and undifferentiated gravel sand and clay in the eastern limit of the area.

3.9.2 Hydrogeology

The geology and structural settings of the study area mainly determines the quantity and quality of the groundwater resources. Practically all of the groundwater in basement rocks is stored in tectonically affected areas, in fractured zones and in the weathered mantel, the so-called regolith. Additional groundwater is stored in fissures of mainly calcareous low metamorphosed rocks.

Hydrogeological units with porous permeability and high to moderate productivity where groundwater is accumulated in and flows through the pores of unconsolidated material. These aquifers consisting gravel and low cemented sandstone of High fluvial terraces and undifferentiated gravel sand and clay in the eastern limit of the area of alluvial sediments. These aquifers outcrop in the eastern limit of the area and have small extent.

Hydrogeological units with fissured permeability and moderate productivity (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) in calcareous rocks of Didikama and Arequa Formations are the main lithological unit of these aquifers. The ridge forming nature, fine lamination (foliated) have a negative impact on the groundwater storage properties of the rocks. However, localized accumulations close to young and penetrative fractures and at deeply seated fracture pattern zones within the group rocks are expected. Perennial springs of low discharge are expected on the top or middle portions of the ridges. The spring discharge can partly be influenced by the hydraulic property of the overlying unit in addition to the role of open and young fractures and the proportion of dolomite. Groundwater flow direction as well as groundwater level in the aquifers can be approximate based on perennial rivers of the Woreda flowing from west to east (Berbere Gado, Berber).

Low productive fissured aquifers (T = 0.11 - 1 m^2/d, q = 0.0011 - 0,01 l/sm, Q = 0.051 -0.5 l/s for wells and/or springs) in Precambrian basement complex consisting of low grade metamorphic rocks penetrated by intrusive. Practically all of the groundwater in this part of basement is stored in the fractured zones and the weathered mantle called regolith. The shallow depth fracture system (usually to the depth of 70 m) develops shallow aquifer zones. The fractures tend to close at depth. The greatest permeability is found in the sub-soil zone within the partly decomposed rock. This aquifers occupy 50% of the Woreda area.

Water quality

Groundwater is medium hard with TDS above 1,000 mg/l and no ions exceeding standards for drinking.

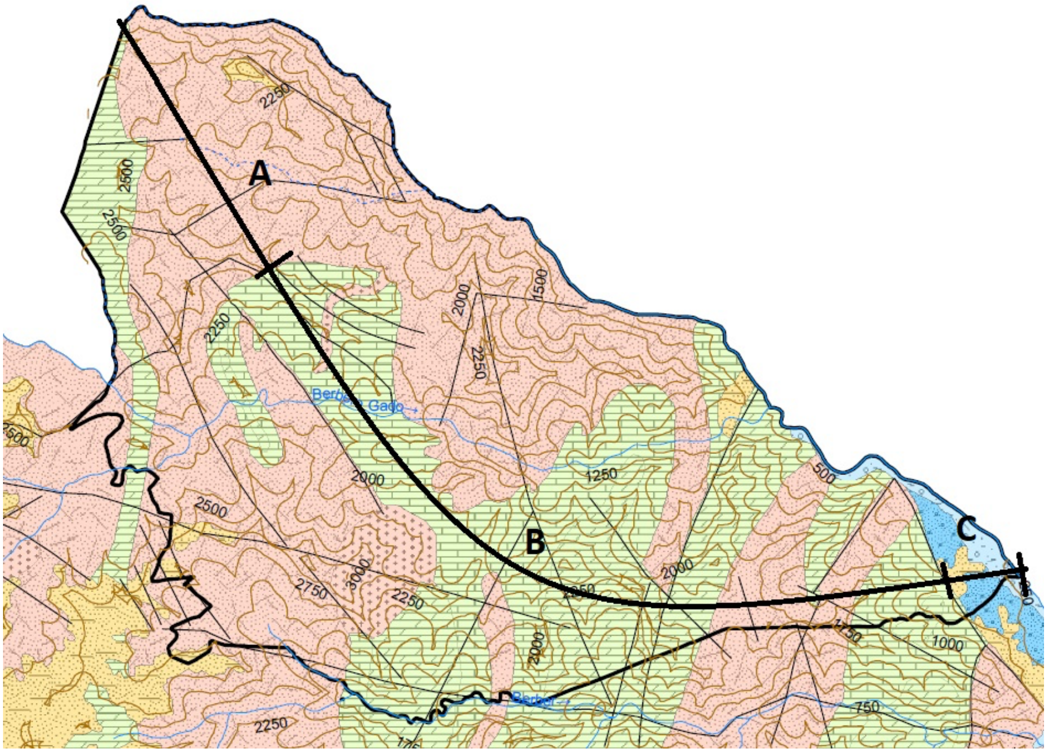

Figure 14. Hydrogeological map of Erob

3.9.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into three basic parts: A North western part, B Central part and C southeastern part. Parts are shown in Figure 15 which is extract from hydrogeological map presented in phase I.

A North western part where the characterization and prediction of flow through a fractured basement is extremely difficult as the geometry of the flow path in these rocks is often very complex and heterogeneous depending upon the fracture characteristics. From a geomorphological point of view, the groundwater may follow the surface drainage system. The topography of the Woreda area generally slopes towards the east to the center of Woreda where rivers Berbere Gado and Berber are flowing. Groundwater is mainly recharged from rainfall and from interaction with rivers. Groundwater is discharged by springs and by rivers. *Development of aquifers in basement rocks is by drilling mainly 30 to 70 m deep shallow wells. Greater yield of wells can be achieved when siting wells using Remote Sensing structural analysis and geophysical exploration, which seems to be indispensable for basement rocks.*

B Central part where the uppermost aquifers are developed in fissures of dolomite and limestone. Rainfall is the main source of recharge in these aquifers. The groundwater lateral flow direction is dependent on the inclination, steepness or slope of the topography in the area and is generally to the east. Outcropping aquifers can also recharge / discharge be perennial rivers flowing throughout the Woreda. *Groundwater resources can be developed mainly by shallow wells with depth of about 100m drilled into fissured zones (faults and lineaments) near to these perennial rivers which should be located by combination of Remote Sensing and geophysical data and by spring development.*

C southeastern part is formed by small outcrops of highly and moderately productive porous aquifers consisting gravel and low cemented sandstone of consisting composing of High fluvial terraces and undifferentiated gravel sand and clay in the eastern limit of the area of alluvial sediments. Sediments of High terraces are highly porous and can easily accumulate large volume of groundwater. *Groundwater resources can be developed mainly by shallow and deep wells drilled at the foot of High terraces and in alluvial sediments.*

3.10 Hawzen

The Woreda is located Eastern zone of the Tigray Region and has an area of 869 km^2. The area is located at the Western plateau (highlands). Its southern and western borders are formed by Tsaliet and Werei rivers (the Tekeze River tributaries).

3.10.1 Geology

The Woreda area is composed of various lithological units. The northwest part consists mainly basement build by low grade metamorphic rocks penetrated by intrusive rocks, the northeast part consist mainly Edaga Arbi glacial. The southern part consists of Enticho sandstone additional to large strip of Edaga Arbi glacial and noncontiguous outcrops of Antalo limestone.

Low grade metamorphic rocks penetrated by intrusive rocks outcrop in the northwest part of the Woreda. The outcrop is composed by Werii slate and phyllite with some black limestone, Tsalient metavolcanics in form of green schists, which were originally agglomerate and tufaceous sediments, rhyolitic lava, black limestone, dolerite and diorite. Metamorphic rocks are penetrated by porhyrite and granite cut by aplite dykes and pegmatite veins.

Edaga Arbi glacial are located mainly at the north east part and in small strips in southern part of the Woreda. It is a tillite sediments, containing granite boulders up to 6 m in diameter. Where it is transiting to calcareous Enticho sandstone there are also lenses of polymictic conglomerate, clay and sand.

Adigrat Sandstone is outcropping in the southern part of the Woreda and is composed by siltstone and fine to coarse grained sandstone, minor calcareous sandstone and ferruginous silt and clay at the surface.

Antalo limestone outcrops in southern part of the Woreda and is composed from several layers. These layers contain finely crystalline limestone, coquina, oolitic limestone and marl, sandy limestone, marl interbedded with coquina and fine grained limestone.

Small outcrop of basalt overlay Adigrat sandstone at the northern part of the Woreda

3.10.2 Hydrogeology

Hydrogeological units with fissured permeability where groundwater is stored in and flows through the fractured (karstified) parts of sedimentary rocks.

Highly productive aquifers (T = 10.1 – 100 m^2/d, q = 1.1 – 10 l/s·m, Q = 5 – 25 l/s for wells and/or springs) where groundwater is stored in and flows through the fractured and weathered parts of limestone and where the productivity can be enhanced by karstification along some fissures.

Antalo limestone forms a regional aquifer and according to Tesfay Chernet and Gebretsadik Eshete (1978) assessed the transmissivity of Antalo limestone ranges from 2.5 to 14.6 m^2/d. Antalo limestone is coarse-grained, thick bedded to massive in places, the coarse-grained limestone beds contain mud flakes and possible algal fragments. Karstification is highly variable, but some karst features can significantly increase productivity of this unit. Because of intense jointing and lower marl proportions some parts of sequence have greater permeability than. There is an east-west facies change being from marly formations in the east to more sandy formations in the west.

Moderately productive aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) where groundwater is stored in and flows through the fractured and weathered parts of Adigrat sandstone. These sediments usually form gentle to steep slope topography. Permeability of Adigrat sandstone is increased by weathering in addition to closely spaced vertical joints and horizontally bedding. The impact of textural variation, compaction (cementation), thickness and inclined bedding may cause local changes in discharge or other hydrogeological properties. There is less infiltration where sandstone is covered ferruginous silt and clay at the surface.

Low productive fissured aquifers (T = 0.11 - 1 m^2/d, q = 0.0011 - 0,01 l/sm, Q = 0.051 -0.5 l/s for wells and/or springs) in Precambrian basement complex consisting of low grade metamorphic rocks penetrated by intrusive. Practically all of the groundwater in the basement is stored in the fractured zones and the weathered mantle called regolith. The shallow depth fracture system (usually to the depth of 70 m) develops shallow aquifer zones. The fractures tend to close at depth. The greatest permeability is found in the sub-soil zone within the partly decomposed rock. This aquifers occupy the central part of the Woreda.

Formation consisting of a minor fissured aquifer with local and limited groundwater resources – Aquitards are represented by Edaga Arbi glacials, which form large outcrops in the northwestern part of Woreda and small outcrops in the southwestern part of the Woreda.

Water quality
Groundwater is soft with TDS between 400 and 500 mg/l and no ions exceeding standards for drinking.

3.10.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into three basic parts: A Northeastern part, B Northwestern part and C southern part. Parts are shown in Figure 16 which is extract from hydrogeological map presented in phase I.

A Northeastern part is covered by Edaga Arbi glacials which represents hydrogeological units with an impermeable character and with limited groundwater resources in unit without regional groundwater body. ***Shallow groundwater using dug wells may be developed under geologically favorable condition.***

B Northwestern part where the characterization and prediction of flow through a fractured basement is extremely difficult as the geometry of the flow path in these rocks is often very complex and heterogeneous depending upon the fracture characteristics. From a geomorphological point of view, the groundwater may follow the surface drainage system. The topography of the Woreda area generally slopes towards the south (Gereb Rivar) and west where Tsaliet River makes southern boundary of the Woreda. Groundwater is mainly recharged from rainfall and from interaction with rivers.

Groundwater is discharged by springs and by rivers***. Development of aquifers in basement rocks is by drilling mainly 30 to 70 m deep shallow wells. Greater yield of wells can be achieved when siting wells using Remote Sensing structural analysis and geophysical exploration, which seems to be indispensable for basement rocks.***

C southern part is formed by moderately and highly productive fissured aquifers developed in sandstone and limestone, which represent regional aquifers with regional groundwater bodies of the area. Groundwater recharge is from rainfall and can be also supported by bank infiltration the Tsaliet River after rainy season. The river is also forming discharge of groundwater from aquifers in form of baseflow. An altitude of the river course is in conformity (controlled) with groundwater level particularly in aquifers hosted in limestone. Regional groundwater flow direction will be into southwest direction.
Groundwater resources can be developed mainly by deep wells drilled into fissured zones of sandstone and limestone near to the Tsaliet perennial river by spring development. Location of drilling sites near lineaments and faults using combination of Remote Sensing and geophysical investigation can help in drilling high yielding wells.

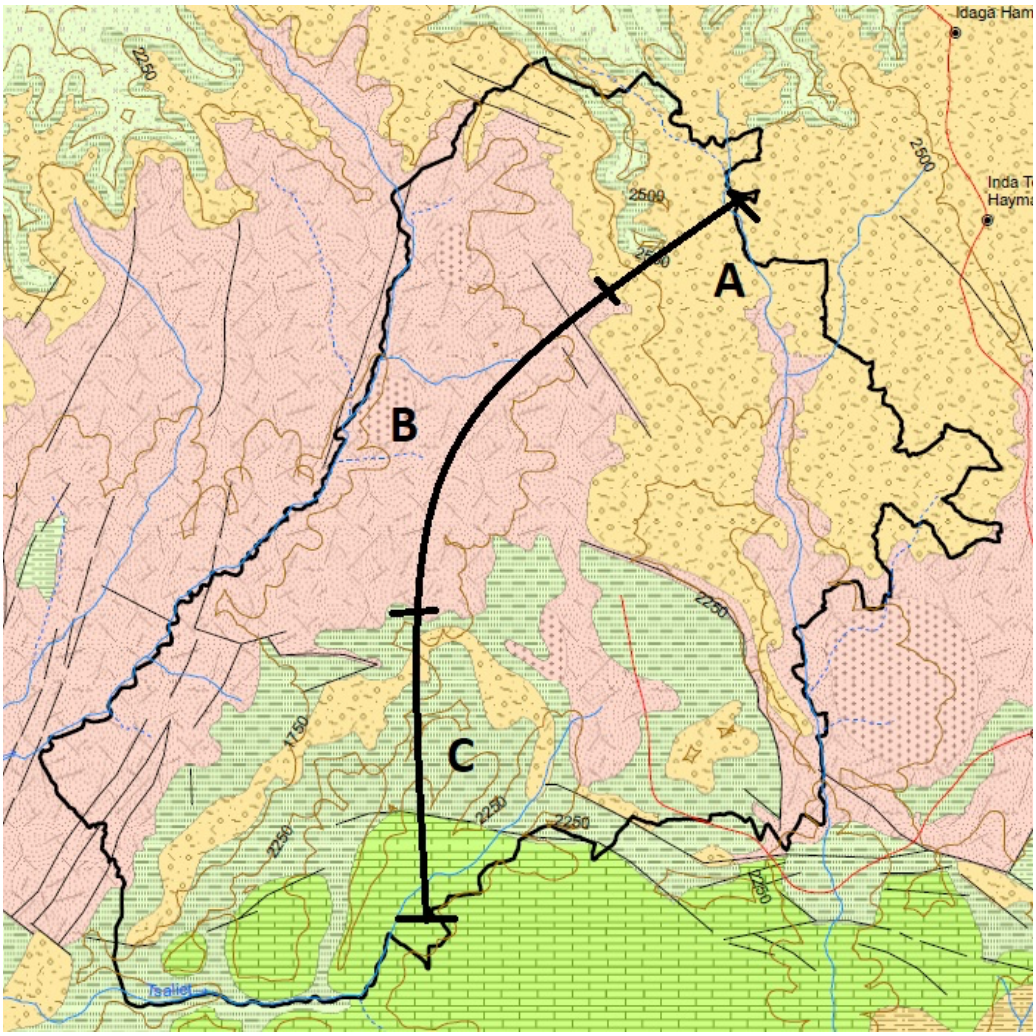

Figure 15. Hydrogeological map of Hawzen

3.11 Saesie Tsaedaemba

The Woreda is located Eastern zone of the Tigray Region and has an area of 963 km^2. The area is located at the Western plateau (highlands) at the surface water divide between Tekeze basin (southern part of Woreda) and Danakil basin (northern part of Woreda).

3.11.1 Geology

The western part of the Woreda is mainly covered by Edaga Arbi glacial and Enticho sandstone where sandstone is not mapped separately. The eastern part of the Woreda is mainly covered by sandstone, dolomite and limited outcrops of limestone. The southern part is represented by basement consisting of low grade metamorphosed rocks and massif of granodiorite.

Low grade metamorphic rocks penetrated by intrusive rocks cover eastern and southern part of the Woreda area. They consist metavolcanics of Tsaliet group with low grade metamorphosed intermediate and basic lava, greywacke, tuffaceous slate, phyllite, agglomerate and rhyolite and metasediments of Didicama Formation composed of dolomite interbedded with slate and Arequa Formation composed of limestone, calcareous sediments, slate and phyllite. The units are penetrated by Foliated granite.

Paleozoic and Mesozoic sedimentary rocks covers eastern part of the Woreda. They consist of Enticho sandstone, which is coarse grained and cross-bedded sandstone with calcareous lenses in the upper part and mainly Edaga Arbi glacials consisting dark shales with erratic boulders and thin beds of silty limestone and tillite. Adigrat sandstone locally cross bedded with subordinate siltstone and shale make small outcrop west of Edaga Hamus town.

Outcrops of Adigrat sandstone are overlain by amygdaloidal basalts of the lower unit.

3.11.2 Hydrogeology

Hydrogeological units with fissured permeability and moderate productivity (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) where groundwater is stored in and flows through the fractured and weathered parts of Adigrat sandstone, which form only small outcrop) and mainly through metasediments of Didicama and Arequa formations (dolomite and limestone). These sediments usually form gentle to steep slope topography. The impact of textural and material variation, thickness and inclined bedding may cause local changes in discharge or other hydrogeological properties in metasediments. There is direct infiltration of rainfall into these aquifers. These aquifers occupy the eastern part of the Woreda.

There is direct infiltration of rainfall into basalts covering Adigrat sandstone and vertical jointing can support of indirect infiltration of groundwater by vertical flow from aquifer in basalt to undelaying aquifer in sandstone.

Low productive fissured aquifers (T = 0.11 - 1 m^2/d, q = 0.0011 - 0,01 l/sm, Q = 0.051 -0.5 l/s for wells and/or springs) in Precambrian basement complex consisting of low grade metamorphic rocks (dominantly metavolcanics) penetrated by intrusive (foliated granite). Practically all of the groundwater in the basement is stored in the fractured zones and the weathered mantle called regolith. The shallow depth fracture system (usually to the depth of 70 m) develops shallow aquifer zones. The fractures tend to close at depth. The greatest permeability is found in the sub-soil zone within the partly decomposed rock.

Groundwater flow direction is in conformity with slope of terrain. These aquifers occupy the eastern and southern parts of the Woreda.

Formation consisting of a minor fissured aquifer with local and limited groundwater resources – Aquitards are represented by Edaga Arbi glacials with Enticho sandstone, which form a large outcrops in the western part of Woreda and small outcrops in the eastern part of the Woreda.

Water quality
Groundwater is soft with TDS between 500 and 1,000 mg/l in several shallow wells nitrate ion exceeding standards for drinking reflecting lack of sanitation.

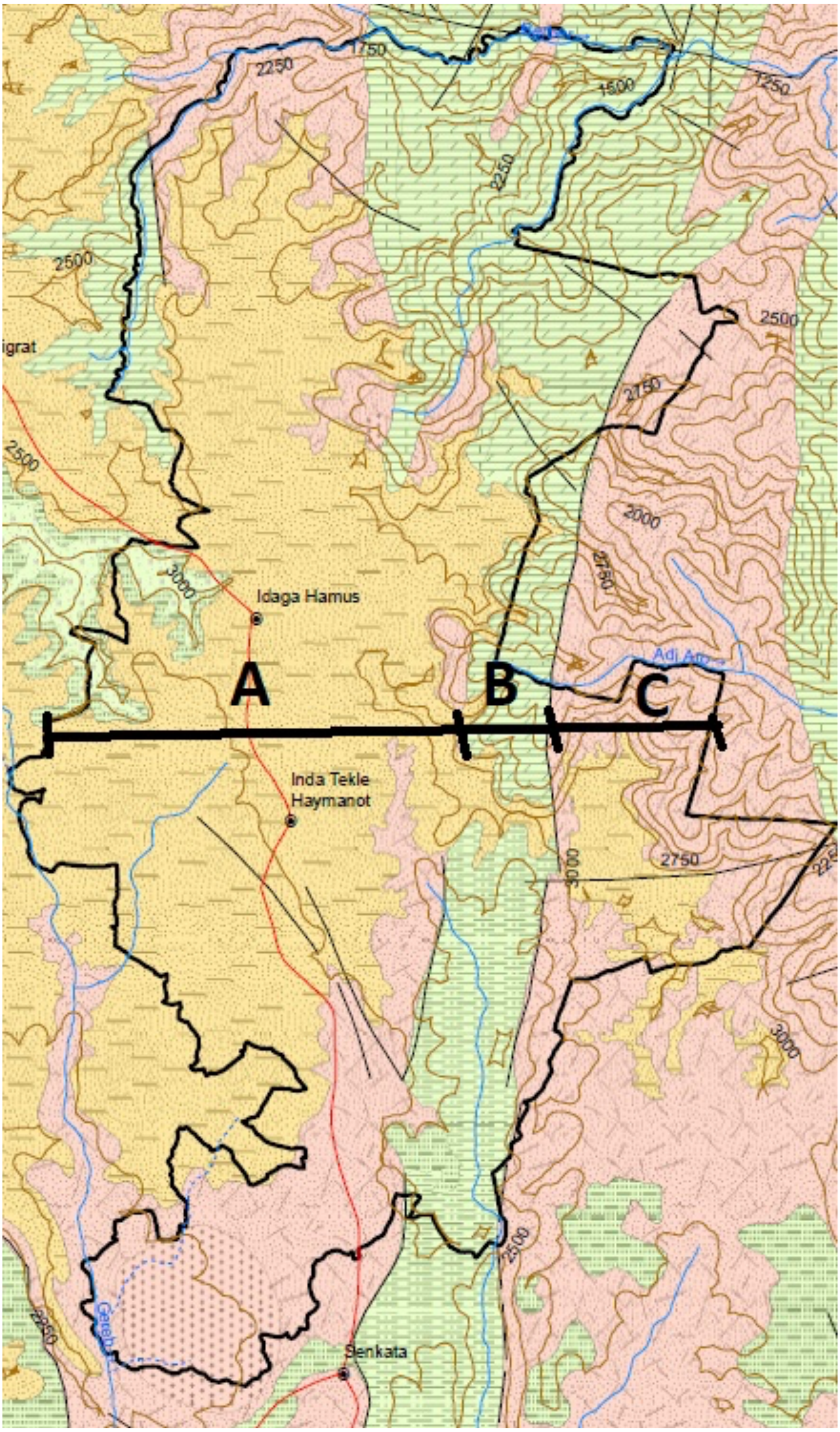

Figure 16. Hydrogeological map of Saesie Tsaedaemba

3.11.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into three basic parts: A Western, B Central and C Eastern parts.

A Western part consists of Edaga Arbi glacials and Enticho sandstone, which is hydrogeological units with an impermeable character and some shallow groundwater can be found only in case of favorable condition Lenses of sandy material). Regional groundwater table and groundwater body is not existing.

B Central part have a form of graben and is represented by fissured aquifers hosted by Adigrat sandstone and Didikama limestone. Rainfall is the main source of recharge in these aquifers. The groundwater lateral flow direction is dependent on the inclination, steepness or slope of the topography in the area and, which is generally to the north and souths. Outcropping aquifers can also recharge / discharge by perennial rivers flowing to the north and to the south throughout the Woreda. *Groundwater resources can be developed mainly by medium deep wells drilled into fractured aquifer into some fissured zones (faults and lineaments) near to perennial rivers which should be located by combination of Remote Sensing and geophysical methods. Better chance for groundwater accumulation is in the northern and southern part of the central part than in its middle part B.*

C Eastern part consists of basement rocks, where the characterization and prediction of flow through a fractured basement is extremely difficult as the geometry of the flow path in these rocks is often very complex and heterogeneous depending upon the fracture characteristics. From a geomorphological point of view, the groundwater may follow the surface drainage system. The topography of this part generally slopes towards the east, where the River Adi Ato is flowing. Groundwater is mainly recharged from rainfall and from interaction with river. Groundwater is discharged by springs and by rivers. *Development of aquifers in basement rocks is by drilling mainly 30 to 70 m deep shallow wells into fissured zones (lineaments and faults) . Greater yield of wells can be achieved when siting wells using Remote Sensing structural analysis and geophysical exploration, which seems to be indispensable for basement rocks. The area along the river can be also preferable for well siting.*

3.12 Tselemt

The Woreda is located Northwestern zone of the Tigray Region and has an area of 2,656 km^2. The Woreda area is located at the Western Plateau (highlands) and slopes to the north where it is bounded by the Tekeze River.

3.12.1 Geology

Basement rocks outcrops along the Tekeze River at the North and are overlain by Adigrat sandstone and Tertiary basalts to southern border of Woreda.

Low grade metamorphic rocks penetrated by intrusive rocks of Tsalient metavolcanics consisting of tuffaceous sediments, massive green and purple metavolcanics with interdbeds of sediments and lenticular limestone and green schists outcrop in the valley of the Tekeze River. The metamorphic rocks are intruded by porphyritic granite usually with microcline porphyries.

Hamsho Unit is a part of Tambien group and makes small outcrops in the eastern part of the Woreda. The unit is composed of tuffaceous sediments, quartzite, arkose and agglomerate.

Adigrat sandstone is exposed along the Tekeze river section. Adigrat sandstone is unconformably overlain by trap volcanics. The Adigrat sandstone formation has a maximum thickness of 650 meters. Lithologically, the Adigrat sandstone is yellow to red sandstone, fine to medium-grained; interbedded with variegated siltstone and clay. White sandstone, medium to coarse-grained: friable, cross-bedded, shows turbidity structures and contains well-distributed lenses of ferruginous silt.

Tertiary black olivine alkali basalt flows cover southern part of the Woreda. The black olivine alkali basalt flows are generally stratified and cover extensive areas. Lithologically, the trap volcanics are black olivine basalt with a coarse, subophitic to intergranular texture. Numerous flows with well-developed columnar jointing, which has concentrations of white zeolite and inter-flow fossil soils in many places. Interbedded lacustrine deposits of off-white silicified limestone and diatomite with gastropods occur at several levels.

3.12.2 Hydrogeology

Hydrogeological units with fissured permeability and moderate productivity (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5l/s) consist of Adigrat sandstone overlain by Tertiary basalts**.** Adigrat sandstone overlies the Late Precambrian basement units is unconformably overlain by trap volcanics. It is exposed usually in highly dissected valleys and forms cliffs. The sandstone fractures increase groundwater storage and hydraulic conductivity. The permeability of the sandstone is increased by weathering in addition to closely spaced vertical fissures and horizontal bedding. This aquifer is recharged from the overlaying aquifers in Tertiary trap basalts, from perennial rivers and from direct rainfall infiltration. Recharge and permeability of this sandstone aquifer are relative high but can be decreased in some places due to the steep topographic setting.

Structures and vertical fissures/fractures in basalts facilitate recharge. Faults trending NE-SW and SE-NW mostly occur in the basalts. The lower basalts are mostly massive, but the top layers are highly columnar jointed. Thus, this unit forms a non-homogeneous hydrogeological environment. This is a reason that aquifers with confined groundwater table caused by inter-bedded rocks can be find in some places. This aquifer is recharged directly by infiltration of rainfall. The formation is also recharged and/or drained by perennial and seasonal rivers. Vertical flow in fissures and joints can contribute to groundwater of underlying sandstone. There are a lot of productive wells drilled in this aquifer for town and rural water supply. Most of the springs are located at the local depressions as topographic breaks. The impact of topography is significant for aquifer productivity in the highly tectonized and irregular geomorphic terrains of the study area.

Low productive fissured aquifers (T = 0.11 - 1 m^2/d, q = 0.0011 - 0,01 l/sm, Q = 0.051 -0.5 l/s for wells and/or springs) in Precambrian basement complex consisting of low grade metamorphic rocks (dominantly metavolcanics) penetrated by intrusive (granite). Practically all of the groundwater in the basement is stored in the fractured zones and the weathered mantle called regolith. The shallow depth fracture system (usually to the depth of 70 m) develops shallow aquifer zones. The fractures tend to close at depth. The greatest permeability is found in the sub-soil zone within the partly decomposed rock. Shallow groundwater is recharge mainly by rain and flow direction is in conformity with slope of terrain. This groundwater is discharged by small springs and small rivers that form left tributaries of the Tekeze River.
Hamesho units is small and has an impermeable character.

Water quality

Groundwater is soft with TDS between 300 and 500 mg/l and no ions exceeding standards for drinking.

3.12.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into three basic parts: A Northern part, B Central part and C Southern part. Parts are shown in Figure 18, which is extract from hydrogeological map presented in phase I.

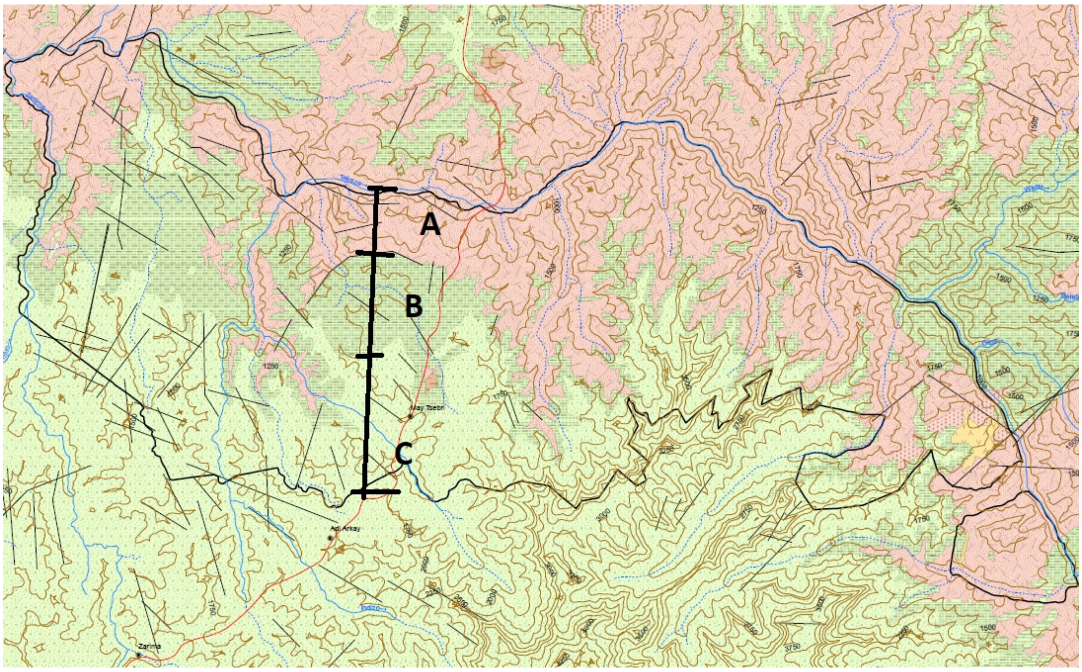

Figure 17. Hydrogeological map of Tselemt

A Northern part consists of basement rocks, where the characterization and prediction of flow through fractured basement is extremely difficult as the geometry of the flow path in these rocks is often very complex and heterogeneous depending upon the fracture characteristics. From a geomorphological point of view, the shallow groundwater may follow the surface drainage system. The topography of this part generally slopes towards the north, where the River Tekeze is flowing. Groundwater is mainly recharged from rainfall and from interaction with river. Groundwater is discharged by springs and by rivers. ***Development of aquifers in basement rocks is by spring development and by drilling mainly 30 to 70 m deep shallow wells. Greater yield of wells can be achieved when siting wells using Remote Sensing structural analysis (identification of faults and lineaments) and geophysical exploration, which seems to be indispensable for basement rocks. The area along the river can be also preferable for well siting.***

B Central part is represented by fissured aquifers hosted by Adigrat sandstone. Rainfall is the main source of recharge in these aquifers additional to contribution of groundwater by vertical flow from overlying basalts. The groundwater lateral flow direction is dependent on the inclination, steepness or slope of the topography in the area and, which is generally to the north to the Takeze River. Outcropping aquifers can also recharge / discharge be perennial rivers flowing throughout the Woreda. ***Groundwater resources can be developed mainly by springs and deep wells drilled into fractured aquifer and some fissured zones (faults and lineaments) near to perennial rivers and near contact of sandstone with basement. These structures should be located by combination of Remote Sensing and***

geophysical. Better chance for groundwater accumulation is near contact of sandstone with underlying basement rocks.

C Southern part is represented by fissured aquifers hosted by Trap basalts. Rainfall is the main source of recharge. The groundwater lateral flow direction is dependent on the inclination, steepness or slope of the topography in the area and, which is generally to the north. Outcropping aquifers can also recharge / discharge to perennial rivers flowing throughout the Woreda. Part of groundwater is drained by vertical flow and is recharging undelaying sandstone***. Groundwater resources can be developed mainly by springs and deep wells drilled into fractured aquifer and some fissured zones near to perennial rivers. These structures should be located by combination of Remote Sensing and geophysical***.

3.13 Ofla

The Woreda is located Southern zone of the Tigray Region and has an area of 1,085 km^2. The area is located at the Western plateau (highlands) west of the surface water divide between Tekeze and Danakil basins. Lake Ashange is located in northeastern part of the Woreda.

3.13.1 Geology

The area is covered by volcanic (Ashangi basalts) and sedimentary (Upper sandstone) rocks.

Upper sandstone (Amba Aradom) (Ka) This unit occurs in the western part of the Woreda on the dissected plateau. It is exposed as a discontinuous hill with gentle and steep slope topography, and also as a tectonic block. In the northwestern part on the plateau, it covers an extensive area exposed within the valleys, and forms continuous ridges and hills. The sandstone has a light, pink color, weathered to yellowish gray and is medium to coarse-grained and characterized by upward coarsening sequences. The sandstone strata is observed tectonically interleaved with the Ashangi formation. Along zones of deformation, the sandstone is steeply inclined and strongly faulted and sheared

Ashangi basalt (Tab) is exposed within the dissected valleys and gorges of the plateau. It represents the earliest volcanism in the area, which unconformably underlies the Aiba basalt. The unconformity contact of Ashangi and Alaje is commonly marked by paleosoils and/or sediments (coal seams). The Ashangi formation in the mapped area is dominantly composed of basalt with varying proportions of aphanitic basalt, vesicular basalt, and phyric basalt. Characteristically, the exposures of the Ashangi formation are strongly weathered, intensely fractured and jointed. The flows are horizontally bedded and doleritic dikes commonly inject it.

Alaje basalt (Talb) occupies the plateau and forms a long ridge with gentle and rolling slope topography. The basalt is horizontally layered. Lithologically, it is comprised of dominantly aphanitic, vesicular and phyric (pyroxene and olivine) basalts. Towards the lower part of the succession, the basalts are interlayered with pyroclastic rocks.

3.13.2 Hydrogeology

Hydrogeological units with porous permeability and moderate and locally high productivity (T = 1.1-10 m^2/d, q = 0.011-0.1 l/s.m, with spring and well yield Q = 0.51-5l/s) consisting of basalts and sandstone.

Aiba basalt (Taib) forms plateaus, flat undulating surfaces, as well as rugged terrains. Recharge and groundwater circulation vary due to these variations in topography. Shallow to deep Eutric cambisols cover the basalt outcrops. A relatively high permeability and good water storage capacity are reflected by spring discharge varying from 2 l/s to more than 5 l/s. The aquifers are recharged directly from precipitation, surface flow and runoff from mountains and rivers.

Ashangi formation (Tab) is exposed within the dissected valleys and gorges of the plateau. Like other volcanic rocks in the area, the main water bearing zone is within these weathered parts, fractures, and joints which increase the permeability of the rock. The soil cover is shallow to very deep. There are many springs with a wide variation in yield due to the topographic set up, degree of fracture, level of weathering and recharge condition. The Ashangi formation has transmissivity ranging between 0.5 and 85 m^2/day. The discharge of spring varies from 0.5 l/s to 6 l/s with the average yield of the springs is 3.25 l/s. On rugged terrain and mountains with steep slopes, the recharge to the groundwater is very limited.

Amba Aradom sandstone (Ka) is steeply inclined, strongly faulted, sheared and less fractured, faulted and slightly to moderately weathered. The sandstone in the study area is light pink, medium to coarse grained, not well sorted and friable. A weathered bed is seen at the bottom of this unit. A conglomeratic layer is seen towards the base, as well as sandy and crystalline limestone layers. Springs yield vary from 0.5 to 6.0 l/s.

Aquifer are recharged directly by rainfall, but can also be recharged by lateral flow from aquifer located in higher topographical position and by vertical flow from overlying aquifers.

Water quality
Groundwater is soft with TDS between 400 and 500 mg/l and no ions exceeding standards for drinking.

3.13.3 Conceptual model

From conceptual hydrogeological point of view the Woreda area can be divided into two basic parts: A Eastern part, B Western part. Parts are shown in Figure 19 which is extract from hydrogeological map presented in phase I.

A Eastern part is formed mainly by Ashangi basalts with fissured permeability, where rainfall is the main source of recharge. The groundwater lateral flow direction is dependent on the inclination, steepness or slope of the topography in the area and, which is generally to the northwest. Groundwater is mainly drained by perennial rivers (Gibiya, Tiare) but part of groundwater is drained by vertical flow and is recharging undelaying sandstone. ***Groundwater resources can be developed mainly by springs and deep wells and located along perennial river where it cross some faults and lineaments. These structures should be located by combination of Remote Sensing and geophysical investigation.***

B Western part consists of represented by fissured aquifers hosted by Amba Aradam sandstone. Rainfall is the main source of recharge in these aquifers additional to contribution of groundwater by vertical flow from overlying basalts. The groundwater lateral flow direction is dependent on the inclination, steepness or slope of the topography in the area and, which is generally to the northwest. Outcropping aquifers can also recharge / discharge be the Tiare River, which is perennial river of the area. ***Groundwater resources can be developed mainly by springs and deep wells drilled into fractured aquifer mainly along contact of sandstone with basement and into some fissured zones (faults and lineaments) near to perennial rivers. These structures should be located by combination of Remote Sensing and geophysical.***

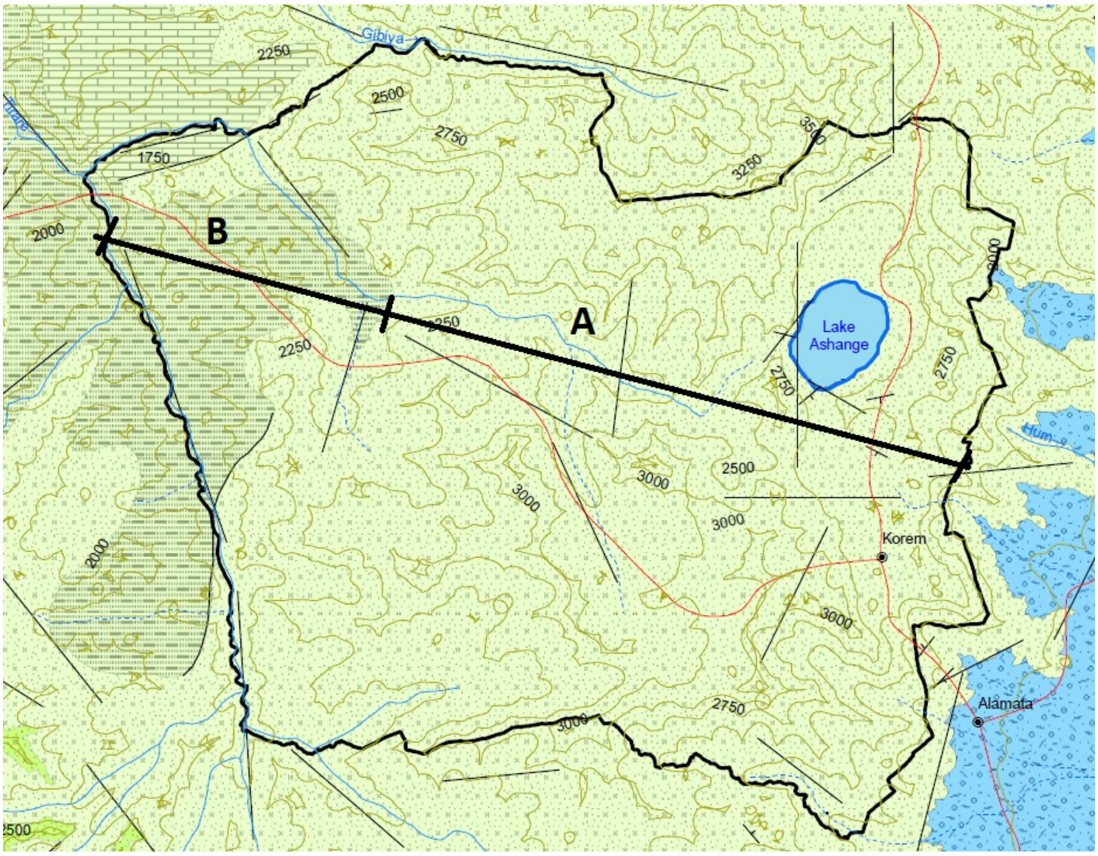

Figure 18. Hydrogeological map of Ofla

4 Water demand

Planned field visits for ground truthing and inventory work could not take place due to the security situation. Instead, we had to rely on secondary data from the Regional Water Bureaus of Tigray and Afar obtained at the initial stages of this project. We are also grateful to the Ministry of Water and Energy for providing water point and water quality data. We have compiled a database consisting of 4600 water points and 531 water samples located within the administrative boundaries of the 13 selected woredas. The springs and wells are indicated on the groundwater potential maps in Annex 1 and are mostly located in Tigray region.

S/N	Woreda	Region	Springs	Wells	Water samples
1	Tselemt	Tigray	96	169	172
2	Mereb Leha	Tigray	4	375	152
3	Kola Temben	Tigray	56	258	2
4	Erop	Tigray	38	261	
5	Saesi Tsadamba	Tigray	76	1272	193
6	Hawzen	Tigray	96	1119	12
7	Ofla	Tigray	139	407	
8	Beyeda	Amhara	89	51	
9	Kori	Afar	0	1	
10	Megale	Afar	2	3	
11	Berehale	Afar	16	19	
12	Afdera	Afar	9	26	
13	Yalo	Afar	10	9	
Total			631	3970	531

Information on socio-economic aspects and water demand relevant for decision making on water supply have been supplied by the Central Statistical Agency of Ethiopia.

It should be noted that the water demand figures are the quantities of water that population should access to according to national policy criteria. They do not present the actual water scarcity. This depends more on the degree to which the present facilities meet these required quantities and would require an inventory of the facilities and their state of operation and capacity. Ideally, these insights should be provided by representatives of water bureaus, woreda offices, local NGO's and other stakeholders during regional consultation meetings. Unfortunately, the regional meetings could not take place due to security issues.

The existing information comprises:

- Administrative boundaries of kebeles and woredas
- Population densities of kebeles
- Livestock data at zonal level
- Villages and towns (localities)
- Schools
- Health facilities
- Water facilities
- Roads
- Rivers

The socio-economic and water demand maps for the 13 woredas of this Lot are attached in two maps, one for Tigray and Amhara woredas and one for the 5 woredas in Afar region. (Annex 3 and 4)

4.1 Domestic water demand

Population density of the kebeles is expressed as the number of total inhabitants in 2030 per square kilometre. The population data is based on the census 2007 data (CSA, 2017, 2019) and is corrected for an average population growth of 2.46 % (CSA, 2013, 2017).

The domestic water demand in m3 per day per kebele is based on number of inhabitants and daily per capita demand as defined in the GTP II (National Planning Commission, 2016). According to the GTP II water demand in rural areas is 25 litres per capita per day (lpcd). In urban areas water demand varies from 40 to 100 lpcd but has been defined here as 50 lpcd for urban kebeles. Where urban or rural conditions are not clear 30 lpcd has been used.

4.2 Livestock water demand

Because actual data on livestock could not be obtained from the woredas, an attempt has been made to estimate the livestock population from existing data provided by CSA (2021). We made use of the data available at zonal level (Table 8) and calculated the livestock ratio per capita for 9 livestock classes (Table 9). Assuming the ratio per capita remains constant between 2021 and 2030, the expected livestock population per woreda and kebele has been estimated using the projected population in 2030 in the kebeles as a reference. Table 11 lists the water demand in 2030 for the 13 project woredas using daily water requirements from Sileshi et al (2002) (Table 10). The total demand per kebele is presented in Annexes 3 and 4.

Table 8 Livestock population in thousands by zone (CSA, 2021)

Region	Zone	Population	Cattle	Sheep	Goats	Horses	Mules	Donkeys	Camels	Poultry	Beehives
Afar	Zone 1	392	917	2182	3924	0	0	125	472	0	0
Afar	Zone 2	401	62	413	1377	0	0	59	123	62	19
Afar	Zone 3	199	621	1090	1872	0	0	61	432	0	0
Afar	Zone 4	314	101	338	588	0	0	24	66	0	0
Afar	Zone 5	241	258	454	1083	0	0	39	165	0	0
Amhara	N Gondar	91	779	507	645	35	9	187	0	1304	96

Tigray	NW Tigray	1255	726	549	1110	0	0	179	11	1390	74
Tigray	E Tigray	658	467	615	195	0	0	146	0	971	79
Tigray	NW Tigray	769	1954	411	2357	0	0	268	18	2592	85
Tigray	S Tigray	1053	391	186	162	0	4	70	0	406	28
Tigray	W Tigray	333	848	101	679	0	0	73	7	871	39

Table 9 Distribution of livestock ratios per capita per zone for 2021

Region	Zone	Cattle	Sheep	Goats	Horses	Mules	Donkeys	Camels	Poultry	Beehives
Afar	Zone 1	2.34	5.56	10.00	0.00	0.00	0.32	1.20	0.00	0.00
Afar	Zone 2	0.16	1.03	3.43	0.00	0.00	0.15	0.31	0.15	0.05
Afar	Zone 3	3.11	5.46	9.38	0.00	0.00	0.31	2.17	0.00	0.00
Afar	Zone 4	0.32	1.08	1.87	0.00	0.00	0.08	0.21	0.00	0.00
Afar	Zone 5	1.07	1.88	4.49	0.00	0.00	0.16	0.68	0.00	0.00
Amhara	N Gondar	0.27	0.17	0.22	0.01	0.00	0.06	0.00	0.45	0.03
Tigray	C Tigray	0.58	0.44	0.88	0.00	0.00	0.14	0.01	1.11	0.06
Tigray	E Tigray	0.71	0.93	0.30	0.00	0.00	0.22	0.00	1.48	0.12
Tigray	NW Tigray	2.54	0.53	3.07	0.00	0.00	0.35	0.02	3.37	0.11
Tigray	S Tigray	0.37	0.18	0.15	0.00	0.00	0.07	0.00	0.39	0.03
Tigray	W Tigray	2.55	0.30	2.04	0.00	0.00	0.22	0.02	2.62	0.12

Table 10 Daily water requirement per livestock class in litres per day

Class	Requirement
Cattle	27.0
Sheep	5.0
Goats	5.0
Horses	20.0
Mules	16.0
Donkeys	16.0
Camels	45.0
Poultry	1.5
Beehives	1.8

Table 11 Water demand per woreda in 2030 (m3/d)

Woreda	Drinking	Livestock	Total
Afdera	1,503	2,166	3,669
Berehale	3,819	5,504	9,322
Beyeda	4,699	1,768	6,467
Erop	1,049	1,094	2,143
Hawzen	4,900	5,113	10,013
Kola Temben	5,789	5,149	10,938
Kori	1,292	8,655	9,947

Megale	1,437	2,071	3,508
Mereb Leha	4,855	4,319	9,174
Ofla	5,741	2,570	8,312
Saesi Tsadamba	5,282	5,512	10,793
Tselemt	5,890	19,359	25,249
Yalo	2,449	2,798	5,247

5 Target areas

Using the groundwater potential maps, socio-economic maps, conceptual models and cross sections, target areas have been selected in every woreda for further study during phase 3. The selection of target areas should have been done in consultation with local experts and stakeholders. Due to the security constraints, this could not be realized. Instead, the project team has prepared a prioritized list of 2 to 4 target areas per woreda where both groundwater potential, and water demand has been considered. It should be noted here that the water demand is derived from secondary data from CSA census, projected population growth, locations of schools, health centres and existing water point inventories. We propose to do the final selection of two target areas per woreda in consultation with the review committee during the validation workshop of phase II.

In the process of selecting potential target areas, several factors have been considered which includes both technical and socio-economic aspects of the areas. These includes evaluations on geology and geomorphological settings, general hydrogeological conditions and suitability for groundwater development, access, water demand and presence of social infrastructures in the area with lack of water supply to get priority in selections, etc.

The groundwater potential map used as a basis to select the target areas has been prepared using the overlay analysis methodology which applies the rating and scoring of hydrogeological parameters that controls the occurrence and movement of groundwater in the areas, which considers parameters such as: lithology, lineament and lineament density, drainage, and drainage density, inferred permeability, geomorphology and slope, precipitation, and recharge rate.

Specific drilling site within the selected target area, will be fixed during the actual planning for drilling with additional geophysical survey works to support the present analysis to further detail to determine expected depth of drilling to intercept the inferred potential aquifer formation and indications on the water quality conditions, define drilling methods and preparations of TOR for drilling.

In this phase, the target areas are presented as polygons with reference coordinates to their centres to support in ground control during the geophysical survey and pinpointing the actual drilling sites which will be depicted on the 1:50,000 operational hydrogeological maps during phase III.

As a result of these evaluations potential target areas have been selected for each Kebeles with alternative options for prioritization during the actual field verifications and geophysical surveys. A total of 44 target areas have been selected with the three regions (Afar, Amhara and Tigray).

Figure 19 and Table 8 show the proposed target areas together with basic information about groundwater characteristics.

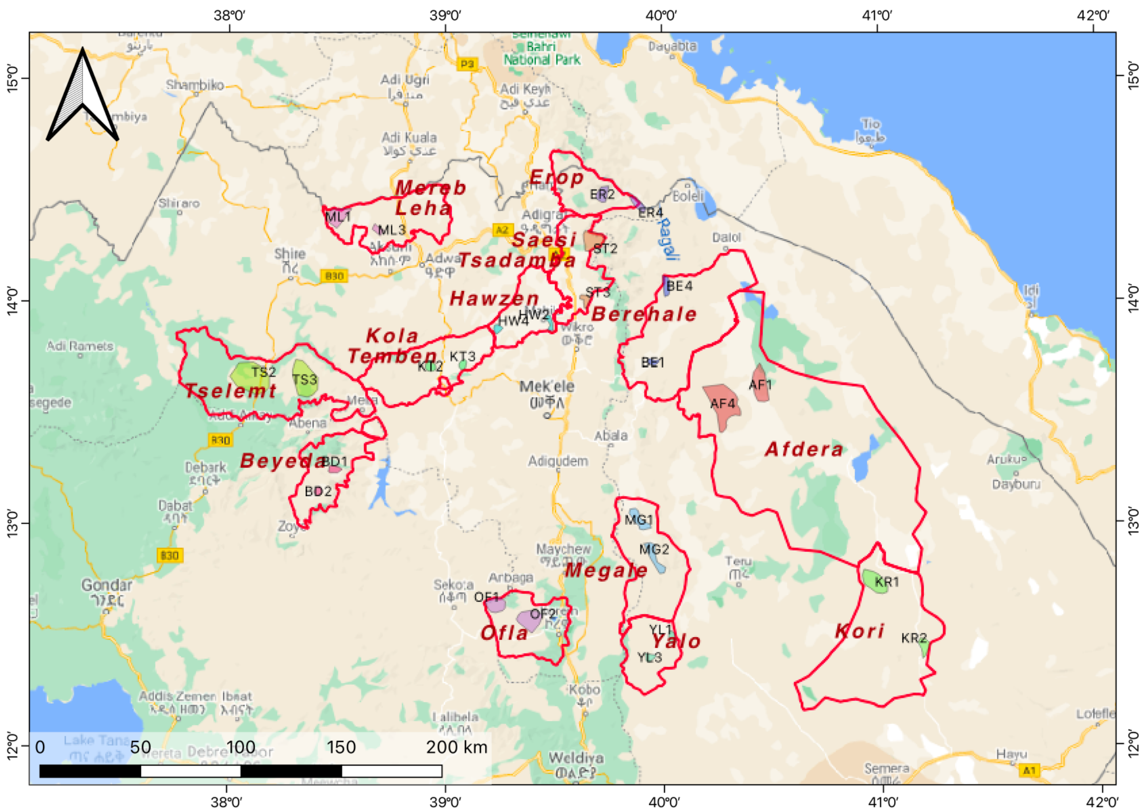

Figure 19. Proposed target areas

Table 12. Target areas

SN	Target Area code	Region	Zone	Woreda	Kebele	centerX	centerY	Area (km²)
1	AF1	Afar	Zone 02	Afdera	Ayitura	656516	1506757	104
	Moderately productive porous aquifers where groundwater flowing to the northeast is accumulated by barrier of central massif of Erta Ale and can be developed by shallow and deep wells. Groundwater is hard with TDS between 1000 and 2000 mg/l, however content of sulphate and fluoride can be above standards for drinking water.							
2	AF4	Afar	Zone 02	Afdera	Debure	638272	1497458	228
	Highly productive porous aquifers (high terraces) where surface and groundwater flowing from the escarpment to the east is infiltrating into aquifers and can be developed by deep wells. Groundwater is hard with TDS between 1000 and 2000 mg/l, however content of sulphate and fluoride can be above standards for drinking water.							
3	BD1	Amhara	North Gondar	Beyeda	Liwaer	444830	1464676	18
	Moderately productive fissured aquifers in basalts with high rainfall and good infiltration. Groundwater resources can be developed by deep wells drilled into faults and lineaments (higher discharge) and by spring development. Groundwater is soft with TDS between 400 and 500 mg/l and no ions exceeding standards for drinking.							
4	BD2	Amhara	North Gondar	Beyeda	Abare	436821	1453824	13
	Moderately productive fissured aquifers in basalts with high rainfall and good infiltration. Groundwater resources can be developed by deep wells drilled into faults and lineaments (higher discharge) and by spring development. Groundwater is soft with TDS between 400 and 500 mg/l and no ions exceeding standards for drinking.							
5	BE1	Afar	Zone 02	Berehale	Lela Ala	603389	1517777	12
	Moderately productive porous aquifers where groundwater flowing to the east direction is accumulated in alluvial sediments in between of basement outcrops and can be developed by shallow wells. Groundwater TDS below 1000 mg/l, content of sulphate of fluoride exceeding standards for drinking water occurs only in few water points.							
6	BE4	Afar	Zone 02	Berehale	Sebana Demale	610083	1555670	28
	Moderately productive porous aquifers where groundwater flowing from southeast and from northwest and accumulated in alluvial sediments between volcanic ridges and can be developed by shallow wells. Groundwater TDS below 1000 mg/l, content of sulphate of fluoride exceeding standards for drinking water occurs only in few water points.							
7	ER2	Tigray	Eastern Tigray	Erop	Ara	578324	1601243	35
	Moderately productive fissured aquifers developed in carbonate rocks of basement along perennial rivers and faults and lineaments. Development of aquifers can be done by drilling mainly shallow wells with depth about 100 m. Groundwater is medium hard with TDS above 1,000 mg/l and no ions exceeding standards for drinking.							
8	ER4	Tigray	Eastern Tigray	Erop	Ara	596043	1596140	27
	Highly productive porous aquifers (high terraces) where surface and groundwater flowing from the basement to the east form a secondary resource of infiltration (additional to rainfall) to aquifers and can be developed by deep wells. Groundwater is medium hard with TDS above 1,000 mg/l and no ions exceeding standards for drinking.							

9	HW2	Tigray	Eastern Tigray	Hawzen	Digum	552061	1537350	16
	Moderately productive fissured aquifers developed in Adigrat sandstone. Groundwater is flowing to southern direction and can be developed by deep and shallow wells. Groundwater is soft with TDS between 400 and 500 mg/l and no ions exceeding standards for drinking.							
10	HW4	Tigray	Eastern Tigray	Hawzen	Koraro	526113	1534284	14
	Moderately productive fissured aquifers developed in Adigrat sandstone. Groundwater is flowing to southwestern direction and can be developed by deep and shallow wells. Groundwater is soft with TDS between 400 and 500 mg/l and no ions exceeding standards for drinking.							
11	KR1	Afar	Zone 01	Kori	Meto Ariba	713504	1408732	96
	Highly productive fissured aquifers developed in Stratoid basalt. Groundwater can be developed by deep wells drilled in basalt aquifers particularly along faults and lineaments and shallow wells drilled in local alluvial aquifers near to deep wadi. Groundwater is hard with TDS between 1000 and 2000 mg/l, however content of fluoride can be above standards for drinking water.							
12	KR2	Afar	Zone 01	Kori	Silisa	738108	1376779	32
	Moderately productive porous aquifers where groundwater is accumulated in alluvial and eluvial sediments in depression between silicic volcanic rocks and can be developed by shallow wells. Groundwater is hard with TDS between 1000 and 2000 mg/l, however content of fluoride can be above standards for drinking water.							
13	KT2	Tigray	Central Tigray	Kola Temben	Ataklti	492686	1515890	20
	Moderately productive fissured aquifers developed in Adigrat sandstone covered by basalt. Groundwater is flowing to all direction and can be developed by medium deep wells located along contact of sandstone with basement and by spring development. Groundwater is soft with TDS about 500 mg/l in several shallow wells nitrate ion exceeding standards for drinking reflecting lack of sanitation.							
14	KT3	Tigray	Central Tigray	Kola Temben	Adiha	508790	1516604	13
	Moderately productive fissured aquifers developed in Adigrat sandstone. Groundwater is flowing to northwestern direction and can be developed by medium deep and deep wells located mainly along perennial river. Groundwater is soft with TDS about 500 mg/l in several shallow wells nitrate ion exceeding standards for drinking reflecting lack of sanitation.							
15	MG1	Afar	Zone 02	Megale	Faro	596458	1439622	49
	Highly productive fissured aquifers (potentially karstic) developed in blocks of limestone and sandstone of horst structure. Groundwater is flowing to eastern direction and can be developed by deep wells. Groundwater TDS below 1000 mg/l and no ions exceeding standards for drinking.							
16	MG2	Afar	Zone 02	Megale	Adu	604143	1420995	55
	Moderately productive porous aquifers where groundwater is accumulated in alluvial and eluvial sediments in depression (shallow marginal graben) between volcanic basement rocks and can be developed by shallow wells. Groundwater TDS below 1000 mg/l and no ions exceeding standards for drinking.							
17	ML1	Tigray	Central Tigray	Mereb Leha	Adigebat	446627	1590155	65

	Low productive fissured aquifer in low grade metamorphic rocks where groundwater can be developed by drilling 30 – 70 m deep wells. Greater yield of wells can be achieved when siting wells along faults and lineaments using Remote Sensing structural analysis and geophysical exploration. Groundwater is soft with TDS between 600 and 700 mg/l and no ions exceeding standards for drinking.							
18	ML3	Tigray	Central Tigray	Mereb Leha	Awet	466467	1583516	16
	Low productive fissured aquifer in medium grade metamorphic rocks where groundwater can be developed by drilling 30 – 70 m deep wells. Greater yield of wells can be achieved when siting wells along faults and lineaments using Remote Sensing structural analysis and geophysical exploration. Groundwater is soft with TDS between 600 and 700 mg/l and no ions exceeding standards for drinking.							
19	OF1	Tigray	South Tigray	Ofla	Denka Ashena	525230	1397204	56
	Moderately productive fissured aquifers developed in Ambaaradom sandstone. Groundwater is flowing to western direction and can be developed by medium deep and deep wells located mainly along contact of sandstone with basement. Groundwater is soft with TDS between 400 and 500 mg/l and no ions exceeding standards for drinking.							
20	OF2	Tigray	South Tigray	Ofla	Adisham Bereket	542137	1389793	93
	Moderately productive fissured aquifers developed in Ashangi basalt. Groundwater is flowing to western direction and can be developed by deep wells located along perennial river where it cross some faults and lineaments and by springs. Groundwater is soft with TDS between 400 and 500 mg/l and no ions exceeding standards for drinking.							
21	ST2	Tigray	Eastern Tigray	Saesi Tsadamba	Sewin	573595	1578176	80
	Moderately productive fissured aquifers developed in dolomite interbedded with slate of Didikama Formation. Surface and groundwater is flowing to the south. Groundwater can be developed by medium deep wells drilled along faults and lineaments near to perennial river. Groundwater is soft with TDS between 500 and 1,000 mg/l in several shallow wells nitrate ion exceeding standards for drinking reflecting lack of sanitation.							
22	ST3	Tigray	Eastern Tigray	Saesi Tsadamba	Gula Abina	569816	1548520	19
	Moderately productive fissured aquifers developed in dolomite interbedded with slate of Didikama Formation. Surface and groundwater is flowing to the north. Groundwater can be developed by medium deep wells drilled along faults and lineaments near to perennial river. Groundwater is soft with TDS between 500 and 1,000 mg/l in several shallow wells nitrate ion exceeding standards for drinking reflecting lack of sanitation.							
23	TS2	Tigray	North Western Tigray	Tselemt	May Ayene	403352	1510137	220
	Moderately productive fissured aquifers hosted by Adigrat sandstone. Surface and groundwater is flowing to the north to the Tekeze River. Groundwater resources can be developed mainly by springs and deep wells drilled into fractured aquifer along faults and lineaments near to perennial rivers and near contact with basement. Groundwater is soft with TDS between 500 and 1,000 mg/l in several shallow wells nitrate ion exceeding standards for drinking reflecting lack of sanitation.							
24	TS3	Tigray	North Western Tigray	Tselemt	Dima	430032	1509368	165

	Moderately productive fissured aquifers hosted by Adigrat sandstone. Surface and groundwater is flowing to the north to the Tekeze River. Groundwater resources can be developed mainly by springs and deep wells drilled into fractured aquifer along faults and lineaments near to perennial rivers and near contact with basement. Groundwater is soft with TDS between 500 and 1,000 mg/l in several shallow wells nitrate ion exceeding standards for drinking reflecting lack of sanitation.							
25	YL1	Afar	Zone 04	Yalo	Gidaelana Mudalelina Dirma	612913	1380998	18
	Moderately productive porous aquifers at the foot of escarpment where groundwater is accumulated in alluvial sediments in depression between volcanic basement rocks along the Kubi Tabato River and can be developed by shallow wells located preferable along the river. Groundwater TDS below 1000 mg/l and no ions exceeding standards for drinking.							
26	YL3	Afar	Zone 04	Yalo	Udeyle	601840	1371106	15
	Moderately productive porous aquifers at the foot of escarpment where groundwater is accumulated in alluvial sediments in depression between volcanic basement rocks along the Kubi Tabato River and can be developed by shallow wells located preferable along the river. Groundwater TDS below 1000 mg/l and no ions exceeding standards for drinking.							

6 Risk Mitigation Strategy

The Risk Mitigation Strategy (RMS) will primarily focus on the steps and processes required to evaluate and mitigate risks to borehole functionality. This will entail assessing current and future risk levels/probabilities and developing mitigation strategies to reduce risk. The first step in the process will be to develop a ranking matrix and develop an analysis/probability of current risk levels for each Woreda. Step 2 will entail the development of risk mitigation strategies for various levels/probabilities of risk that can be implemented in the field. Steps 3 - 5 are focused on maximizing sustainable borehole yields and minimizing both water quality and borehole functionality risks.

The main focus area is to outline strategies to make boreholes/water sources climate resilient. As a starting point the following "Mapping Products" can be used to develop cross-cutting strategies:

1. Precipitation map
2. Recharge map
3. Aquifer mapping
4. Topographic maps, versions updated with DEM and/or LIDAR data
5. Lineaments/siting overlay mapping

The major technical areas associated with the provision of a sustainable long-term groundwater supply sources include: (a) borehole yield (initial tested yield and borehole-yield maintenance over time); (b) borehole water quality (natural and anthropogenic); and (c) borehole operational functionality.

Borehole yield is the parameter which is directly linked to and can be most affected by climate change. Resiliency, with respect to climate, is based on the strengths and vulnerabilities of the groundwater systems (aquifers) under current conditions. If these conditions can be assessed, this analysis can lead to an evaluation of the degree of risk associated with the groundwater resource, its' sensitivities to climate changes, and strategies for climate-risk mitigation. With this in mind, the focus of the effort will be to outline a methodology and approach to make boreholes "climate resilient".

Step 1: Risk (Vulnerability) Identification and Ranking

The focus of this initial effort will be to outline a methodology and approach to make boreholes "climate resilient". To this end, **Step 1** entails the development of a ranking matrix to synthesize the baseline risk factors including:

1. Aquifer Type: Productive to Marginal (unconfined/confined)
2. Aquifer Static Reserve: High to Low
3. Groundwater Recharge: High to Negligible (0)
4. Current/Future Groundwater Use Comparison to Groundwater Recharge (Analysis of Inputs – Outputs).

A ranking matrix will provide an initial analysis of low to high risk Woredas and differentiate approaches to risk mitigation. The following Table 9 is a matrix framework, which can be filled out in specific detail to evaluate each woreda/location of interest.

Table 13. Risk Ranking Matrix Framework

Category	Low Risk	Medium Risk	High Risk
(1). Aquifer Type - Productive to Marginal	B1/2	B4	B5/6
(2). Static Reserve -High to Low	B1/2	B4	B5/6
(3). Annual Recharge – High to Negligible (0)	>150mm/year	50- 150 mm/year	<50 mm/year
(4). Inputs vs. Outputs - Ratio of inputs/outputs	High Ratio – say 5	GW use < or in balance with Recharge	GW use > recharge

1. The Main Aquifer Types in Lot 1 can be broken out into four (4) broad categories including:
   a. B1/2 – sediments/alluvium
   b. B4 – carbonate, sedimentary, basalts, and metamorphic rocks
   c. B5 - basement rocks
   d. B6 - minor aquifers – shale, gypsum, ignimbrite, rhyolite, etc.

In general, the sediment/alluvium aquifers are more productive (i.e., higher yielding) than the carbonate, sedimentary, basalts and metamorphic rock aquifers, that in turn are more productive than the basement rock and minor aquifers, as shown on the matrix. However, the specific conditions in a woreda/locale should be studied for existing and potential borehole yields.

2. Aquifer Static Reserve: This analysis will entail an estimate of groundwater held in storage per km^2 using the units m^3/km^2. This storage (static reserve) can be compared to the annual available groundwater recharge (dynamic reserve) to ascertain a “Drought Resiliency Quotient” (Figure 20). The amount of groundwater held in storage can also be compared to the annual water supply demand to evaluate the magnitude of drought buffer inherent in the respective aquifer systems.

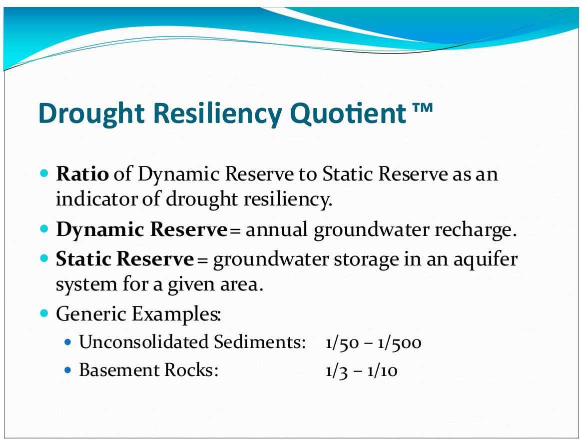

Figure 20. Drought Resiliency Quotient

3. Annual Recharge: The analysis will be derived from the Phase 2 work for Lot 1 and will provide estimates of annual recharge in mm/yr. during years of normal and drought precipitation. Annual recharge in the <50mm/year range will be considered as low and with a corresponding high risk in terms of aquifer replenishment.

4. Inputs – Outputs (Groundwater Balance): A simple accounting excel spreadsheet approach can be applied as outlined on the attached Annex 6. This balance will indicate whether the renewable groundwater resource (available groundwater recharge) is in surplus to, balanced with, or in deficit with existing and projected groundwater usage, and magnitude of the surplus or deficit.

Related questions to be directly considered in the identification and qualification of risk factors for a specific woreda include:

1. Are there concerns with low borehole yields, declining yields, boreholes going dry?
2. Are there concerns with over-pumping of groundwater?
3. Are there concerns with limited freshwater areas?
4. Are there concerns with present or future competing water uses?
5. Have ecological water needs in the area been identified?

Step 2: Risk Mitigation Strategies

Based on the development of risk levels in Step 1, "Risk Mitigation Strategies" may be developed and applied. Some preliminary examples of identified risks and mitigation strategies are outlined below.

(1) High Existing Risk: examples would include:

- 0 to negligible recharge (<50mm/yr.)
- Groundwater use > recharge

Potential mitigation measures might include:

- Water rationing/use restrictions.
- Brackish water resource evaluation and desal applications.
- Wastewater reuse for certain applications such as irrigation.

(2) Medium Existing Risk:

- Ground use and recharge are in balance.
- Static reserve provides a good drought buffer, i.e. say 30 years for groundwater storage to meet current/future demands.

Example mitigation measures:

- Water use restrictions
- Groundwater recharge enhancement (MAR)
- Installation of deeper boreholes in certain aquifer units where fresh groundwater occurrence at depth has been proven out.

(3) Low Existing Risk:

- Productive aquifer systems with large static reserve
- Groundwater recharge much > groundwater use
- Groundwater management systems in place and working.

Step 3: Maximizing Borehole Yields

Key 'Risk Mitigation Measures (RMM)' that will be applied to maximize boreholes yields and make them sustainable in the long run and through wet and extended dry periods are outlined below.

- Borehole siting in areas where focused recharge takes place by reliance on technical tools (i.e., fractured areas in the basement rock and volcanic areas).

- Optimizing borehole depths to account for water-level fluctuations – seasonal, long term, and induced by climate change.

- Optimizing borehole designs by:
    - Developing detailed borehole drilling and construction specifications for the drilling contractor and professional drilling/construction oversight.
    - Using materials (casings, borehole screens, filter packs, grout) that meet applicable standards.
    - Scientifically designing borehole screen slot size openings and filter pack sizing to prevent sand pumping.

- Borehole testing to analyze data for long-term sustained borehole yields for both current and future populations.

Step 4: Minimizing Water Quality Risks:

- Borehole siting that takes into account nearby land use and establishing protective distances to potential groundwater contamination sources.

- Wellhead drainage works, land use control, and housekeeping in a protection area around the borehole.

- Proper borehole construction with sanitary protection against artificial pathways for contaminant migration, e.g. casing annulus infiltration, by installing a protective column of grout (15 m minimum) in the borehole-casing annulus.

- Fuel storage and spill control plans for fuels.

Step 5: Borehole Functionality Risk Mitigation:

- Contracting professional firms for borehole and pumping system construction.
- Training borehole operators by means of on-the-job training and workshops.
- Instituting formal O&M procedures.
- Developing Wellhead Protection Programs using a tiered approach:
  - Tier 1 (within ~25m radius of the borehole):
    - Security fencing.
    - Daily Wellhead Inspection.
    - Housekeeping.
    - Avoiding unauthorized system intrusions.

  - Tier 2 (within ~100 to 500m radius of the borehole):
    - Review and input to proposed land-use changes.
    - Creation and operation of water reserves or conservation districts
    - Emergency response to spills, releases or leaks.
    - Education of the community regarding wellhead protection

7 Workplan phase 3

The Inception Report mentions the following activities to be carried out in Phase III:

- Conduct detail geological and hydrogeological study in target areas
- Conduct water balance study in the target areas
- Determine impact of climate change on groundwater resources in the target areas
- Develop hydrogeological conceptual model of the target areas
  Prepare map hydrogeological maps of target areas (1:50,000)
- Conduct geophysical survey and prepare drilling site maps (1:5,000)
- Select borehole sites and possible climatic sensitivities requiring resilience measures
- Produce well design, technical specifications and select appropriate drilling technology
- Prepare Terms of Reference and Bill of Quantities to drill climate resilient boreholes
- Prepare and submit draft report
- Organize validation workshop of draft report
- Prepare and submit final report

Phase III

Figure 21. Activities planned in Phase III

The following deliverables are expected from this project phase:

- A more detailed geological unit distribution, including structural details in appropriate scale, based on higher resolution images
- Hydrogeological operational maps (1:50,000)
- Detailed geological, hydrogeological, and geophysical (including existing data and satellite geophysics) study in each target area
- Determination of target drilling sites in the target areas, including drilling sites maps (1:5,000) and geophysical profiles
- Phase III final report per target area, including climate resilience
- Capitalisation report and knowledge dissemination activities in a workshop provided by the project team towards the end of the project
- Minutes of the training on Groundwater Mapping Methodology provided by the project team
- Inclusion water of water quality maps will be taken into account for final target area selection

Due to the security constrains in the project area, the workplan for phase 3 has been revised. The project team cannot travel to the field to carry out hydrogeological or geophysical studies. Instead, we must rely on existing data and remote sensing products. Because fieldwork is essential for updates on the actual water demand and gap analysis, geological and hydrogeological conditions, and geophysical surveys, we can only propose target sites with a certain tolerance radius, not exact drilling sites.

7.1 Water balance studies and recharge estimation

Establishing groundwater recharge rates is perhaps the most elusive parameter to estimate in arid and semi-arid setting. This is because of the episodic nature of recharge, lack of monitoring data and the fact that many (some) recharge models account parametrization that would work mainly in humid environments.

In this project, multiple recharge estimation methods will be utilized, and a hybrid recharge map will be produced. The following recharge estimation methods will be considered initially, and a subset applied in the final analysis, depending on the suitability of the method and availability of data:

- Recharge estimation based on assumed percentage of rainfall
- Recharge estimation based on infiltration coefficient
- Recharge estimation based on chloride mass balance
- Recharge estimation based on hydrology models (such as WETSPSS) for selected areas
- Recharge estimation based on baseflow separation method (Chernet, 1982)
- Recharge estimation from literature surveys (e.g., Scanlon et al, 2006; Healy 2010 for global picture and a fair number of recharge studies by Ethiopia scientists).
- Recharge estimation from Remote Sensing data (WAPOR)

The hybrid recharge estimation shall be used as the basis of aquifer sustainability assessment.

7.2 Improving existing geological maps

Geology forms the basis of the hydrogeological and water potential maps. During phase III of this project, detailed hydrogeological maps (1:50,000) will be prepared of the 26 target areas. The available 1:250,000 geological maps need to be updated and refined to the 1:50,000 scale. We will harmonize the existing geological maps and studies in terms of stratigraphy and nomenclature, and refined assessment of remote sensing data using supervised classification multispectral satellite imagery.

The lineaments that were extracted using Sentinel-1 and Landsat-8 imagery will be manually refined using high resolution imagery and classified according to their hydrogeological properties as far as possible without field visits.

7.3 Remote sensing products

We propose to use high resolution satellite imagery and remote sensing products to try to compensate for the lack of field evidence. The following products are considered:

- Worldview (Panchromatic: 0.3 m, Near Infrared: 1.2m)
- Triplesat (pan: 0.8 m, nir: 3.2 m)
- IKONOS (pan: 1 m, nir: 4m)
- Spot 6 (pan: 1 m, nir: 6 m)
- Sentinel-2 (multispectral, 10 m)
- Sentinel-1 SAR (3.5 - 10 m)
- Wapor (30 – 100m)
- Vandersat (100 m)
- Aerial photographs
- Google Earth

7.4 Conceptual models and hydrogeological maps

The studies in the target areas in phase III will produce hydrogeological maps at the scale of 1:50,000 including proposed target sites. These maps display the same features as the phase II maps but in more detail and new information acquired, such as high-resolution lineaments, and water quality. An important feature of these maps is information on the demand side, like location and perimeter of the villages, zone(s) with maximum distance to new waterpoints, population, village facilities like schools and medical posts, livestock. Finally, proposed sites will be presented on these maps. Because final well siting requires field visits, the proposed sites will be represented as locations with a certain radius, or as polygons, but not as exact GPS coordinates.

7.5 Geophysics

The core function is to collate all possible existing geophysical and geospatial data. Then the main task shall be compilation and organization of existing Ground, Airborne, and Satellite geophysical data; drilled hole log and other related information.

Such information may be available locally from national & regional water bureaus, private companies/consultants and Universities; and also at the international level, from the UN, NGOs, geological research institutions & centers and open source geoscientific compilations. There are also possibilities to obtain useful geophysical data from mineral exploration company and government which was acquired in the past few decades.

Data from the following geophysical methods will be anticipated:

- Ground, Airborne, and Satellite potential field (Gravity and Magnetic);
- Ground and Airborne Electrical and Electromagnetic Methods:
- DC Resistivity (Vertical Electrical Sounding – VES)
- Induces Polarization (IP)
- Transient EM (TEM)
- Magnetotelluics (MT/AMT/CSAMT)

The data may be obtained in readily usable form, by digitizing from archived scanned maps, extracted from geological reports, and can be supplemented with borehole data Topographical and geological information shall be used to identify the main characteristics of the zone under study at the regional level, even if their scales allow, to give a detailed picture.

The drilling information of the existing pumping and observation wells can be used to constrain the interpretation of the obtained geophysical data.

7.6 Time frame

Phase III has started on December 1, 2021 and is to be completed by March 31, 2022. In this 4-months period the following activities will take place:

Activity	December					January				February				March			
	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12
Acquisition of imagery and geophysical data																	
Detailed studies of each target area																	
Updates of geological maps of the 26 target areas																	
Preparation of hydrogeological operational maps																	
Determination of target sites																	
Phase III final report per target area (1 report per woreda)																	
Training on Remote Sensing and GIS for overlay analaysis																	
Final report																	

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Annex I.
Groundwater potential maps

Annex II.

Cross sections

Annex III.

Water demand map Tigray and Amhara

Annex IV.

Water demand map Afar

Annex V.

Lineament extraction procedure

Lineament extraction procedure

Objective

The objective of this section is to identify and improve on existing lineaments analysis in the project area woredas. This was accomplished by: (a) utilizing RADAR, elevation, and Landsat data; (b) processing remote sensing data to extract lineaments from RADAR and Digital Elevation Model (DEM) images; and (c) develop maps showing the lineaments identified. Lineaments are linear geological features that can represent subsurface geological structures such as fractures and fault lines. On aerial photographs or remote sensing imageries (RADAR, DEM, Landsat) lineaments can be readily identified by tonal variations, alignment of geological structures, and stream patterns. Identifying lineaments for an extensive area is undertaken with a combination of manual identification techniques and computer aided algorithms.

As a part the ongoing work in Phase II, the improvement of mapping of lineaments in the thirteen (13) project Woreda's **(Figure I)** was accomplished using the remote sensing data outlined in the following sections.

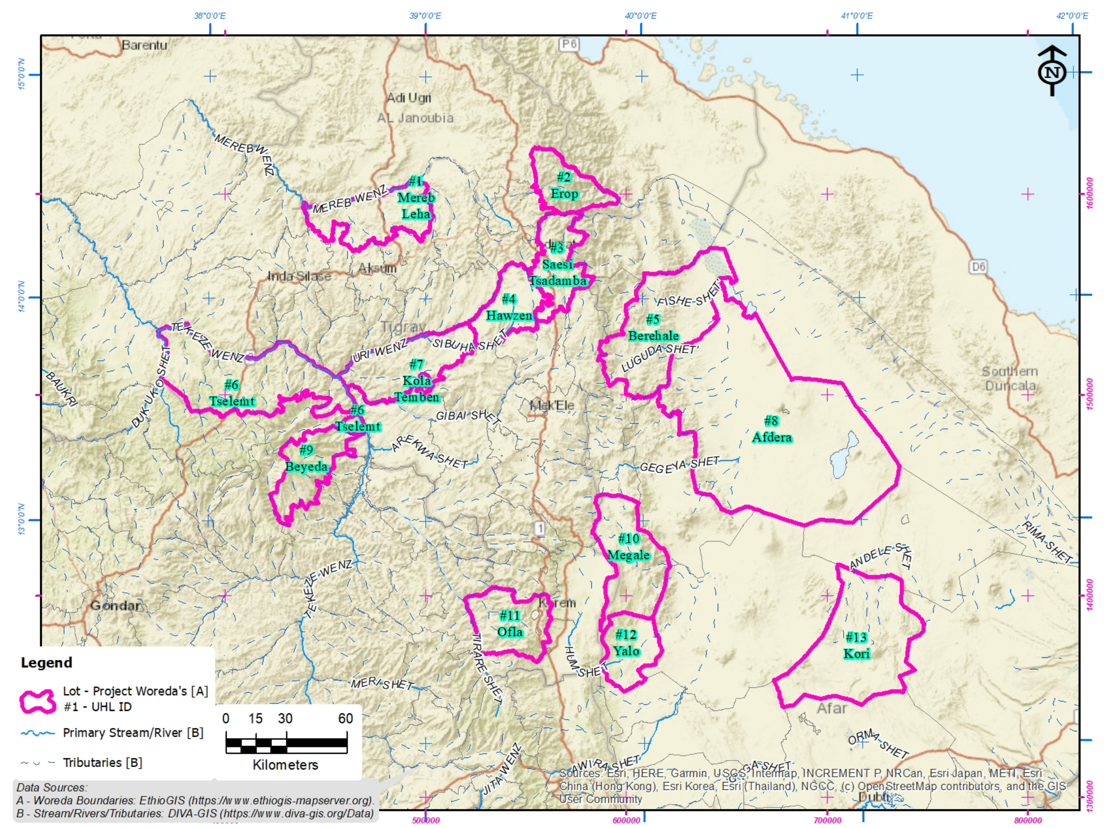


Figure I: Location Map for 13 Project Woredas

Data Sets

Remote sensing data from three imaging platforms were acquired and downloaded representing the project area as outlined below:

Sentinel 1 Synthetic Aperture (SAR) Data.

The Sentinel-1 mission is part of the Copernicus joint initiative of the European Commission (EC) and European Space Agency (ESA) to implement information services dealing with environment and security. The Sentinel-1 mission includes C-band imaging hardware operating in four imaging modes with resolutions as low as 5-meters and coverage up to 400 kilometers (km). The mission is composed of two constellation satellites Sentinel-1A and Sentinel-1B that share the same orbital plane.
Details of the Sentinel-1A data that were downloaded and processed for lineament extraction are provided below **(Figure II)**:

Level-1 Sentinel-1 SAR Data downloaded from ASF Data Search (alaska.edu)
Six data tiles were downloaded, three tiles from July 30, 2021 and three tiles from August 4, 2021.

Datasets acquired in Interferometric Wide (IW) Swath mode and downloaded as Level-1 Ground Range Detect (GRD), High Resolution tiles.
The datasets contained both vertical-vertical (vertical send and vertical receive - VV) and vertical-horizontal (vertical send and horizontal receive – VH) images.

Shuttle Radar Topography Mission (SRTM) Data

The Shuttle Radar Topographic Mission (SRTM) was flown on the Endeavor space shuttle from February 11-22, 2000. Digital Terrain Elevation Data (DTED) from the onboard C-band hardware were acquired, processed and distributed by NASA and the USGS as 1-arc second (~30 meter) images, globally. Details of the void filled SRTM data downloaded and processed for lineament extraction are provided below:
Void filled Data downloaded from EarthExplorer (usgs.gov)
Fifteen Digital Terrain Elevation Data (DTED) tiles were downloaded.
Datasets acquired and processed from C-Band Spaceborne Image Radar hardware, February, 2000.

Landsat 8 OLI/TIRS Data

The Landsat missions began in July 1972 and Landsat 8 was launched in 2013 orbiting the earth in a sun synchronous orbit. The satellite completes an orbit every 99 minutes with a temporal resolution of 16-days.
Landsat 8 data for this project was primarily used for visualization and with no significant image processing. Details of the Landsat 8 OLI/TRIS data are provided below:
Data downloaded from EarthExplorer (usgs.gov)
Eleven scenes acquired between April and May 2021 were downloaded.

Datasets acquired, processed, and downloaded as Collection-2, Level-1, Tier-1 Data tiles.

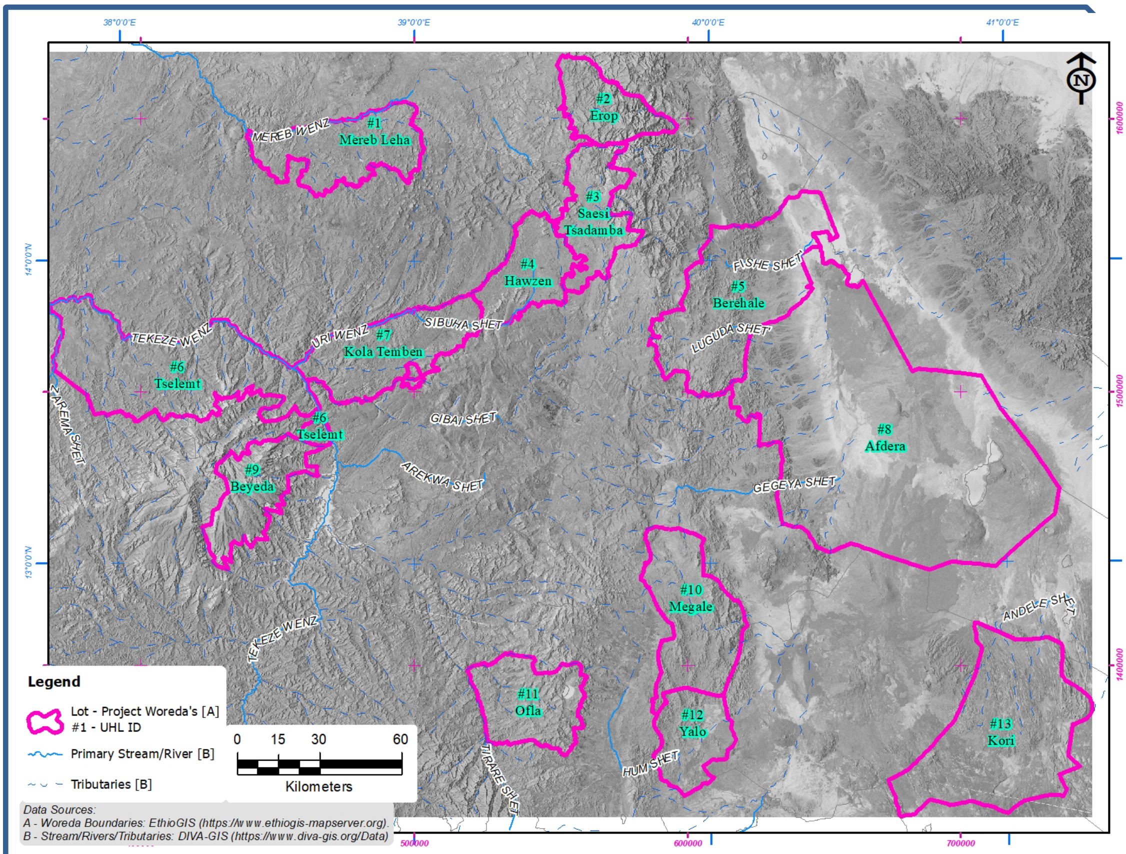


Figure II: Mosaiced Sentinel 1A dataset, July 30 and August 4, 2021

Image Processing

Image pre-processing and image processing were primarily completed using the Catalyst Earth Software (formerly PCI Geomatics). Automated lineament extraction was completed using the LINE Module Algorithm and applied on the Sentinel-1 and SRTM datasets. The Landsat 8 dataset was used for visualization and visual confirmation of larger regional lineaments. Final mapping products were viewed and finalized in ESRI Arcmap.

Pre-Processing

Prior to automated lineament extraction from the Sentinel-1 and SRTM datasets, the following steps were implemented:

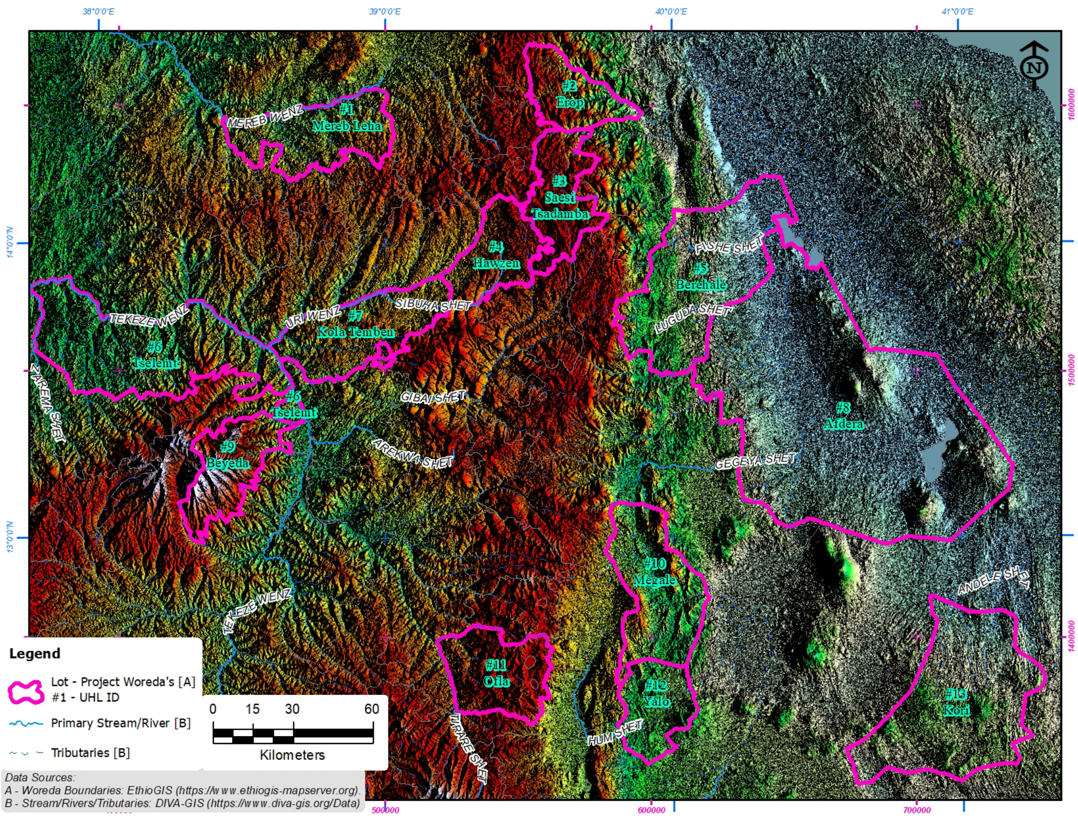
Mosaicking: Mosaicking was an important pre-processing step as it produced a seamless dataset of the project area.

Sentinel-1 Data: Six sigma-naught calibrated, VV/VH tiles were mosaiced using the mosaic tool in Catalyst Earth. **(Figure 2)**

SRTM Data: Fifteen DTED SRTM images were mosaiced in a similar fashion to the Sentinel-1 dataset.

Landsat 8: Eleven Landsat OLI/TIRS images were mosaiced.
Clipping: Mosaicked scenes were clipped to the extents of the project area defined by the Lot 1 Woreda boundaries. Clipping was an important step as not all Woreda boundaries are contiguous, and a clipped scene focused the lineament extraction to the project area.
Hillshade Complex: The mosaicked and clipped SRTM scenes were further processed to develop multiple hillshade complexes **(Figure III)**. Hillshade complex enabled viewing the DTED scenes under different illuminations and assisted with visual confirmation and Hillshade complex images were developed in Arcmap.

Figure III: Hillshade Complex



LINE Module Algorithm

Automated lineament extraction from the Sentinel-1 and SRTM data was accomplished using the LINE Module algorithm in the Catalyst Earth software. The algorithm was run on the pre-processed scenes as defined above. LINE is an algorithm designed to extract linear features from RADAR images, however, it can also be used on optical remote sensing images.
The algorithm consist of three stages:

- Stage 1 – Edge detection: Edge detection is accomplished by first filtering the input image with a Gaussian function, followed by the Canny edge detection algorithm. The radius of the Gaussian function filter is controlled by the Filter Radius Parameter that is input by the user. Stage 1 produces an edge strength image.
- Stage 2 – Binary image: The edge strength image produced in Stage 1 is thresholded to obtain a binary image. The Edge Gradient Threshold Parameter is input by the user. Stage 2 produces a binary image.
- Stage 3 – Curve extraction: The final stage of the LINE algorithm is the extraction of curves from the binary image and involves multiple sub-steps. After a thinning algorithm is applied to the binary image, the following user defined parameters are used to extract the final vector segments:

Curve Length Threshold Parameter: Any curve/line with a number of pixels less than the input value are discarded.

Line Fitting Threshold Parameter: The line fitting threshold parameter defines the tolerance for fitting line segments to a curved lineament. Lower input values result in shorter segments, a large input reduces noise and provides longer, straighter lineaments.
Angular Difference Threshold Parameter: The angular difference threshold parameter defines the maximum angle (in degrees) between two curves/lines to be linked. A smaller angle would result in straighter segments.

Linking Distance Threshold Parameter: The linking distance threshold parameter determines the maximum distance (in pixels) between two curves/lines to be linked.
The final extracted curves/lines are saved as a vector file.

Data Results

After the pre-processing steps, several LINE runs were completed on the mosaiced and clipped Sentinel-1 datasets. For the SRTM datasets, the LINE algorithm was applied on the various Hillshade Complex images. Input parameters to the LINE algorithm (defined above) were varied until suitable results were obtained.

Vector data developed after each run was exported to Arcmap and overlayed on existing geological maps and pre-processed Landsat 8 OLI/TIRS imagery. Based on the LINE runs, outputs from the Sentinel-1 dataset were used to further develop lineament density maps and used in the overlay analysis. The SRTM Hillshade complex dataset were not used the overlay analysis.

Figure IV is an output of the LINE algorithm showing identified lineament traces for Beyeda and surrounding Woreda's. Prior to completing the overlay analysis outputs show in Figure IV were clipped to the project woreda boundaries.

Final LINE Module parameters applied on the Sentinel-1 dataset are summarized below:

Filter Radius	Edge Gradient Threshold (GTHR)	Curve Length Threshold (LTHR)	Line Fitting Error Threshold (FTHR)	Angular Difference Threshold (ATHR)	Linking Distance Threshold (DTHR)
60	225	75	7	10	100

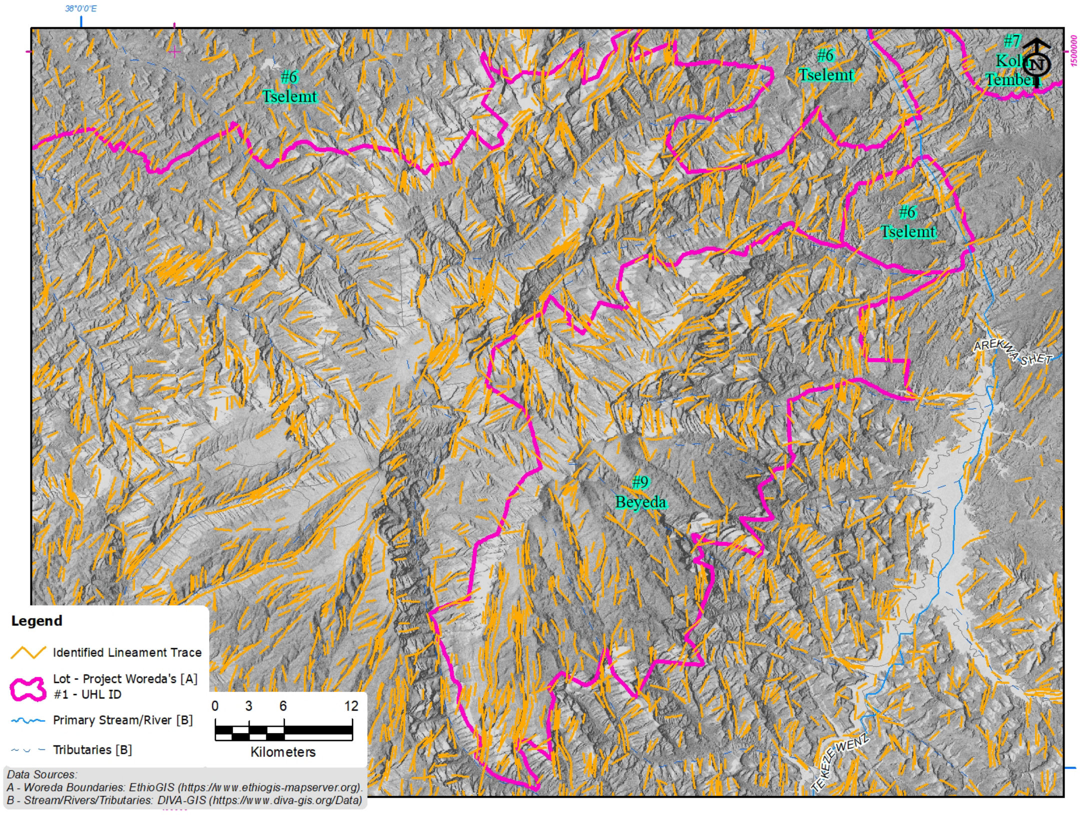


Figure IV: Identified Lineament Trace for Beyeda and Surrounding Woredas

Discussion

Lineament analysis considers all sets equal. However, structures can be flow blocking or may act as conduit. While the strike of faults may be evidently apparent (parallel to the rift trend) and dip values are of normal fault (steep to vertical) all forming step fault towards the rift, local antithetic faults dipping opposite and producing localized grabens are present in some of the section. This being the case, the dips and strikes of metamorphic fabric are not clearly provided in the existing maps. These together with the dip of rotated bedding planes in sedimentary strata due to faulting will also be verified with the help of satellite image interpretation. It is however, clear that most, if not all, faults and lineaments appear to be open conduits for ground water flow as they are most likely to have not been filled by secondary materials including veins. Although, it is possible that such faults may be filled by crushed fault zone materials and soil near to the surface exposure, that would not characterize the entire fault length and depth. Therefore, it is suggested that it is safe to take faults and lineaments as open. What we are not certain at this stage is the role of metamorphic foliations in the ground water flow.

Annex VI.

Groundwater Balance Spreadsheet

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