Improving drilling success rate in Afar and Tigray regions

Remote Sensing Component

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Disclaimer

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The results of the remote sensing analysis are presented in map sheets, annexed to this report. We have prepared three overview maps on 1:250000 scale for all three woredas (total 9 maps): terrain morphology, topographic wetness index and potential drilling sites. Additionally, we have produced two sets of map sheets on scale 1:50000 containing the potential drilling sites and the topographic wetness index (total 66 maps).

Abbreviations

UAP	Universal Access Plan
GTP	Growth and Transformation Plan
WHO	World Health Organization
GwA	Groundwater Analysis
S-GwA	Shallow Groundwater Analysis
D-GwA	Deep Groundwater Analysis
GIS	Geographical Information System
DTM	Digital Terrain Model
TWI	Topographic Wetness Index
AMSR-E	Advanced Microwave Scanning Radiometer – EOS
EOS	Earth Orbiting System
SMOS	Soil Moisture and Ocean Salinity
ESA	European Space Agency
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
RFE2	Rainfall Estimation Algorithm version 2
GTS	Global Telecommunication System
ASAR	Advanced Synthetic Aperture Radar
NDVI	Normalized Difference Vegetation Index
MODIS	Moderate Resolution Imaging Spectroradiometer
TRMM	Tropical Rainfall Measuring Mission
SRTM	Shuttle Radar Topography Mission
ARC-2	Africa Rainfall Climatology Version 2
LPRM	Land Parameter Retrieval Model
NASA	National Aeronautics and Space Administration
TUW	Technical University of Vienna
NIR	Near Infrared
VNIR	Visible and Near Infrared

1 Introduction

1.1 Background

As stated in the International call for consultancy (2014): "Ethiopia has set ambitious targets to increase drinking water coverage as reflected in the two strategic plans: Universal Access Plan (UAP) and the Growth and Transformation Plan (GTP). These strategic plans have been used as background for the government and development partners to invest resources to contribute to the achievement of the set goals. The plans have been used to galvanize financial and technical support. Currently up to 80% of domestic water supply in Ethiopia is sourced from groundwater. Groundwater has been proven resources to support emergency water supply, urban water supply, livestock watering, and more recently shallow groundwater sources are identified as potential target for developing small holder or household irrigation.

Nevertheless Ethiopia's groundwater drilling program, particularly in arid areas of Afar, Somali, Oromia etc, faces serious challenges: a) negative wells up on drilling following poor site selection; b) yield reduction of boreholes after few years of service (generally less than 3 years) due to variety of factors (recharge decline, environmental degradation, clogging of wells due to poor maintenance, etc) c) poor design and construction of wells after drilling (lack of human capacity) and d) return of poor quality water in drilled wells. It is documented that in arid setting of Afar and Somali up to 50% of drilled wells return negative results and salinity is often in excess of WHO drinking water quality standard."

UNESCO Addis Ababa Office in collaboration with the Ministry of Water Irrigation and Energy is undertaking a groundwater exploration project in Afar Regional State. The overall goal of the project is to increase the drilling success rate both in terms of sustainability and in value for money. The current study is the second phase of the project. The objective of this phase is to conduct a detailed and integrated hydrogeological study, including the application of remote sensing over three water-insecure Woredas (districts) in Afar an d Eastern Tigray. The goal of the remote sensing application is the identification of areas where the appearance of fresh groundwater available for abstraction is most likely. The project focuses on three Woredas in Afar region and eastern Tigray, these Woredas are Elidar, Erepti and Atsbi (figure 1).

1.2 This report

This study is the second phase of a larger project. The result of the current phase will be a map for each of the three woredas indicating the most feasible areas to further investigate the existence of fresh groundwater. Please note, that to create a map specifying final drilling locations, a detailed siting study is required involving additional geophysical exploration.

In this report the approach towards groundwater potential maps is described (chapter 2) introducing the Groundwater Analysis (GwA) Methodology developed by Acacia Water in this project. Chapter 3 describes the most important building blocks including the methodology to derive them and the main results. The potential for shallow groundwater in the three woredas is discussed in chapter 4-6, and chapter 7 addresses the deep groundwater. Finally, in chapter 8 the maps that are added at high resolution to this report are introduced, and chapter 9 gives the general conclusions of the project.

The results of the remote sensing analysis are presented in map sheets, annexed to this report. We have prepared three overview maps on 1:250000 scale for all three woredas (total 9 maps): terrain morphology, topographic wetness index and potential drilling sites. Additionally, we have produced two sets of map sheets on scale 1:50000 containing the potential drilling sites and the topographic wetness index (total 66 maps). All maps and data used for this report are attached on the enclosed DVD. The DVD contains also the high resolution versions of the figures in this report, maps of the main results are provided on scale 1:250000 and 1:50000.

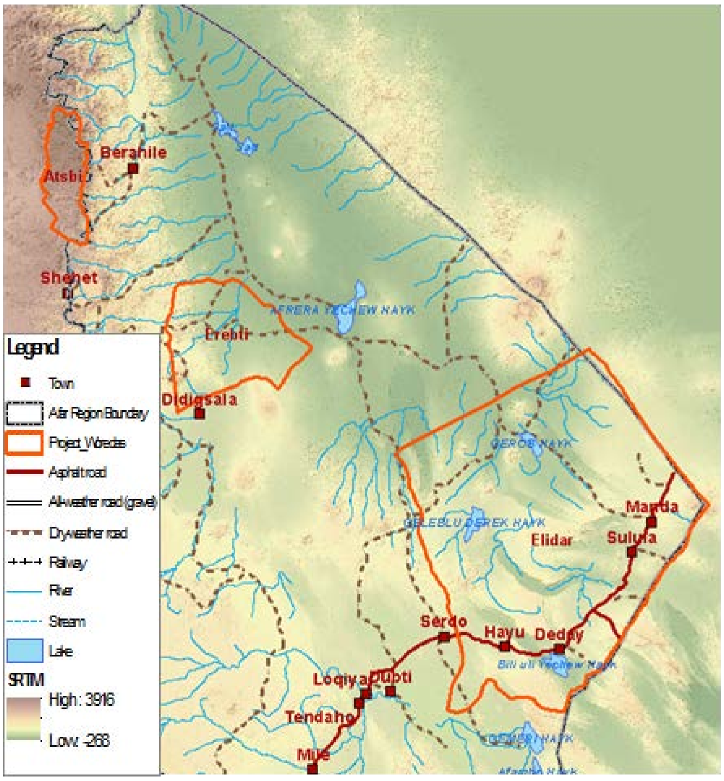


Figure 1. Locations of the three target Woredas.

2

Approach

2.1 General approach

In this project we introduce the by Acacia Water developed Groundwater Analysis (GwA) methodologies to identify the areas with the highest groundwater potential. The determination of shallow (until about 100m below surface) and deep (more than 100 m below surface) groundwater follow the same approach but require each their own analysis. We apply in this project both the Shallow Groundwater Analysis (S-GwA) and the Deep Groundwater Analysis (D-GwA), with a focus on the first in which satellite information plays a prominent role.

In the GwA a number of steps are distinguished to go from (satellite) data towards an indication of the areas with the highest potential for fresh groundwater occurrence. This is summarized in figure 2. In the first step the data sources that will provide the necessary information are determined. These include mainly satellite data, but also available data about e.g. the geology, hydrogeology, climate and existing wells. The data are processed into the building blocks that provide information about the geo-hydrological situation and the groundwater recharge for the specific region. The available information is combined with expert judgment to create a conceptual model that indicates the presence and extent of aquifers and recharge zones. The GwA interpretation with detailed analysis and upscaling of typical locations finally leads to the groundwater potential maps, which indicate the areas where the occurrence of deep and shallow fresh groundwater is most likely.

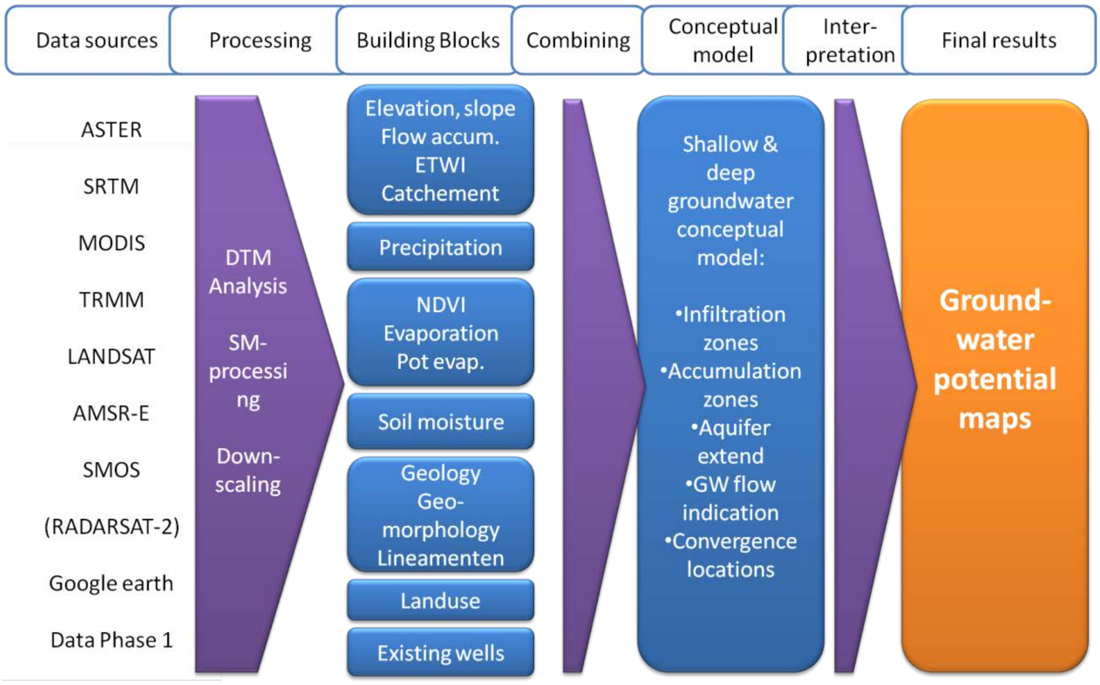


Figure 2. Overview of the Groundwater Analysis (GwA) methodology developed by Acacia Water.

The GwA comprises three levels of detail. General maps are downloaded and compiled for an area that includes all three Woredas, covering northern Afar and the eastern part of Tigray (see figure 1). This area is further referred to as the target area. The second level of detail are the three Woredas, for which the potential groundwater maps will be developed. Finally, at a third and more detailed level potential target sites are studied. The detailed study of such specific phenomena supports the indication of the locations where shallow groundwater is expected. These results are scaled up to the full Woredas using the area covering satellite data.

2.2 Building blocks

Building blocks are required that provide information about the geo-hydrological situation in the study area. This project has a main focus on satellite data and the fieldwork in the study area to compose a concept of the geo-hydrology in the area. The satellite data provide valuable information. However, the satellite penetration depth is not sufficient to show the groundwater occurrence directly, therefore different building blocks are required as well. In the GwA the available data are selected, downloaded and compiled for the specific study area, covering the full target area. All data are being georeferenced and stored in a GIS database. Some satellite data are available in a form that can directly be used in the analysis, such as the precipitation. Others are processed to obtain the required building block from the information provided by the satellite data.

For details regarding the data sources and input data we refer to chapter 3 and the baseline report (Acacia Water, 2014). The table below specifies the satellite data that are used to derived the building blocks, including their resolution.

Source	Resolution	Derived products	Resolution
LANDSAT-5,7,8	30m	Geology, Landuse, Lineaments	15-30m
ASTER VNIR	15m		
ASTER SWIR	30m		
Google Optical Images	variable		
MODIS	250m	NDVI, evapotranspiration, potential evapotranspiration, Land surface temperature	250m
ASTER	30m	DTM, Flow accumulation, Topographic wetness index	30-90m
SRTM	90m		
AMSR-E	8000m	Soil moisture	1000m
SMOS	40000m		
ENVISAT ASAR	1000m		
TRMM VIRS, PR, TMI, CERES, LIS NOAA, GMS, GOES	0,25 degree	Precipitation	0,1 degree
ARC-2 EUMETSAT-IR, GTS	0,1 degree		
Sentinel-1	90m	Examples of soil moisture (expected to be available at the end of the project)	90m
GlobCover, based on ENVISAT satellite	300m	Land cover	300m
Soil Atlas of Africa	1000m	Soil map	1000m

Table 1. Satellite data used for the analyses

2.3 Conceptual model

The creation of a conceptual model of the hydrological situation forms the core of the GwA. For this the building blocks of satellite data and additional data sources are analyzed and combined. An important aspect of the GwA is the efficient combination of automated tools and expert knowledge. In the target area (just as in most arid lands) the data are scarce and the area is complex. Therefore, expert interpretation is required to use the available information to its full extent and only part of the process can be automated. In GwA quantitative and qualitative data are combined and indirect information is used to deduce flow paths and groundwater appearance.

Here the conceptual model part of the GwA for shallow groundwater and for deep groundwater are described. Since the satellite data provide mostly information about the surface characteristics the main focus of this study is on the first.

2.3.1 Shallow groundwater conceptual model

An important notion in the S-GwA conceptual model is that the shallow groundwater potential is determined by the presence of an aquifer, the water quality and the amount of water to recharge the aquifer. Additionally, for abstraction of the water the zones are targeted where the groundwater accumulates and success rates of drilling is increased. Therefore the S-GwA aims to identify locations where sufficient recharge water accumulates in a (shallow) aquifer. It incorporates the soil moisture, vegetation, and precipitation, digital terrain model (DTM), catchment and topographic wetness index (TWI) building blocks as described below.

Soil moisture and vegetation indices

The soil moisture and vegetation data provide direct information about the presence of water at very shallow depths. Soil moisture information derived from satellite data (AMSR-E, SMOS and ASAT) provides information about the water availability in the first (tens of) centimeters of the soil. Vegetation indices like NDVI (MODIS, Landsat) can provide an indication of the water availability at the rooting depth, which may stretch to slightly larger depths, but still remains an indication of only the shallowest presence of soil moisture.

Water availability

The water availability for recharge depends amongst others on the amount of precipitation and its distribution in time and space. With satellite data (TRMM and ARC-2) a full map and the temporal variance of the precipitation over the area is obtained. Precipitation data are available for every three hours (TRMM). For the general analysis in L-GwA monthly data are used, with a further refinement when required. This information is used to provide insight in the total amount of precipitation potentially available for recharge, the differences throughout the area and to determine the driest month.

Topography analyzes to determine the accumulation of water

The accumulation of water and its (surface) flow is largely determined by the elevation and slope of the terrain. Satellite data (SRTM) provide information for the digital terrain model (DTM), which forms the base of essential analysis in the S-GwA to understand the hydrological characteristics of the area. The DTM shows the elevations and slopes of the full area. With a catchment analysis the watersheds and the catchment sizes are determined, which combined with the precipitation data for example indicate the maximal amount of accumulated water that can be expected at specific locations in the area.

With a flow accumulation analysis for each pixel the direction of the surface water flow is calculated based on the elevations, using ArcHydro Tools in ArcGIS. This results in a flow pattern, indicating the locations of streams and rivers, the stream orders, and the size of the catchment behind each pixel within the area. To determine runoff from the catchment areas the curve number method was used which indicates the amount of rainfall which will come to run-off (developed by the Soil Conservation Service. For each separate catchment the total catchment curve number was derived, using classifications for the slope complemented with land use and soil, and precipitation data.

Finally, the Topographic Wetness Index (TWI) is calculated from the elevation, flow accumulation and terrain slope (Sørensen et al., 2006). In the TWI the flow accumulation is combined with the slope, indicating areas where water accumulates from the upstream catchment and where water slows down due to a reduced slope. Generally, TWI is an indicator for depth of column, and potentially soil moisture and shallow groundwater occurrence.

Drainage or infiltration

In the determination of locations with infiltration and with accumulation or convergence of the water an analysis of the geology, lithography and morphology are important. The geology indicates for example the expected infiltration rates related to the different geological formations, e.g. scoria basalts are porous and are expected to have a high infiltration rate, while the older basalt have a lower infiltration rate. The available geological maps are used as a base and where necessary refined with the use of satellite data. In particular LANDSAT-8 band 7, 5, 3 are used for the lithology mapping, which provide the best resolution. The identification of infiltration or drainage areas is checked by an analysis of the presence or absence of drainage patterns that indicates areas with high or low drainage respectively, river and wadi morphology and the presence of river sedimentation and alluvial fans. Finally, a lineament analysis is made based on the SRTM, LANDSAT-8 and Google imagery. The automated lineament analysis (ArcGIS) is further refined with a manual interpretation to connect the longer lineaments based on the existing information.

Combined these different elements provide the information to determine the most important geohydrological features and to select locations where the highest groundwater potential is expected.

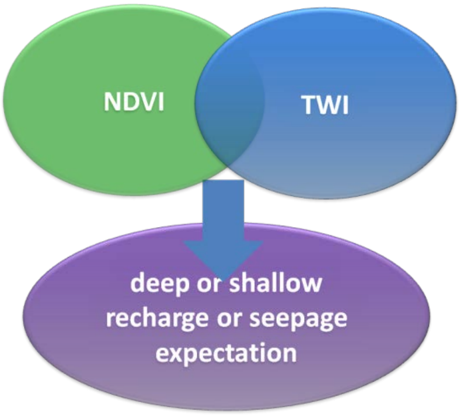


Figure 3, example of combination of building blocks into information about the groundwater system

2.3.2 Deep groundwater conceptual model

As an addition also a link to the deep groundwater is made in the D-GwA. For this a large scale analysis is made of the full project area. Of the deep groundwater only very limited observations are available. Therefore D-GwA attempts to construct a conceptual model based on the combination of the indirect information from the building blocks. The main focus of the current project was on shallow groundwater (i.e. up to about 100m below surface). Therefore, the D-GwA is only applied to provide a first impression, and could be applied with more detail in a future study.

Elevation and geological analysis

Based on the elevation information from the satellite data (SRTM) processed into the DTM building block, a large scale profile is made indicating the high and low zones in the area. This forms the basis for the conceptual model of the deep groundwater recharge and occurrence. Additionally the information about the geology, from which a general image about the porosity of the different geological formation is deduced. The geological map (see annex B) formed a starting point for this analysis, and is refined with satellite data (LANDSAT) and with observations that were made during the field visit. This provides an indication about where infiltration and seepage could be expected based on elevation differences and the geology.

Evaporation as an indicator

In D-GwA evaporation (derived from MODIS products) is used as an indicator of locations where seepage may occur. Additionally, the presence of open water is analyzed (field observations, secondary data and LANDSAT). A calculation of the amount of evaporation that can be expected from the open water bodies indicates how much water is required as supply to sustain this open water occurrence. This amount is compared with the results of calculations with the catchment runoff model, which indicate how much water supply could be expected from the surrounding catchments directly draining towards the open water location. Where the water supply required for the observed evaporation exceeds the direct catchment supply, this supports the notion of seepage zones in the conceptual model.

Combination into a hydro-geological image

Finally, in the conceptual model, the analyzed infiltration zones and seepage zones are confronted with the other building block, like NDVI, drainage patterns, presence of deep wells etcetera. Based on this a hydro-geological image is formed, providing an indication of the most likely flow paths linking the infiltration and seepage zones. Currently this provides only a first indication, detailing could be done in a follow-up study with D-GwA, including additional data and observations next to the satellite data.

3

Building blocks

3.1 Water availability

3.1.1 Methodology

The satellite data provide information about the precipitation at 0,25 degree (TRMM) and 0,1 degree (ARC-2) resolution. These data are used to prepare area covering, detailed maps and time series of precipitation. The data from the satellites are complemented with ground data, from phase 1 monthly data is available for 25 stations in Afar. The number of stations in Afar are limited, especially North-Eastern Afar and the data series are often incomplete, with a number of stations in Afar for which no data is available and no data was found in the database for any of the stations in Atsbi (see Annex B: Rainfall data and availability). Therefore, the use of satellite data provides a useful method to provide a temporal and spatial dataset, and to fill the gaps in the ground data.

The TRMM system uses Precipitation Radar (PR), Microwave Imager (TMI) and Visible and Infrared Scanner (VIRS), Clouds and the Earth's Radiant Energy Sensor (CERES) and a Lightning Imaging Sensor (LIS) to estimate the precipitation. This estimate is merged with NOAA, GMS, GOES and Meteosat data to produce merged 3-hourly precipitation datasets in a 0.25 x 0.25 degree grid (dataset 3B42)

The ARC-2 system uses inputs from two sources: 1) 3-hourly geostationary infrared (IR) data centered over Africa from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and 2) quality-controlled Global Telecommunication System (GTS) gauge observations reporting 24-h rainfall accumulations over Africa. The algorithm is consistent with the operational Rainfall Estimation, version 2, algorithm (RFE2). Daily ARC-2 data are available on a 0.1 x 0.1 degree grid from 1983 onwards.

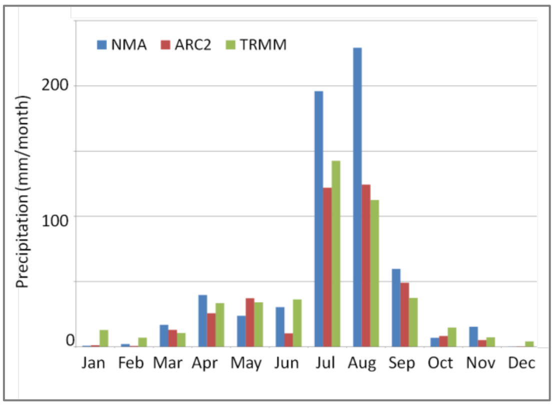


Figure 4, Comparison of monthly rainfall in Atsbi, averaged over 2007-2011. Sources: TRMM, ARC2, NMA

The data from both remote sensing sources are comparable but differ from the rainfall measurements from the National Meteorological Agency (NMA). The differences may be caused by many factors such as the number of observations, point data (NMA) versus spatial aggregates (TRMM, ARC), algorithm, accuracy etc. Because of the limited availability of NMA data and excellent spatial and temporal resolution of ARC-2 data we have used ARC2 as a source for precipitation in the rainfall/runoff and recharge estimates. TRMM data is used in the soil moisture algorithms.

3.1.2 Results

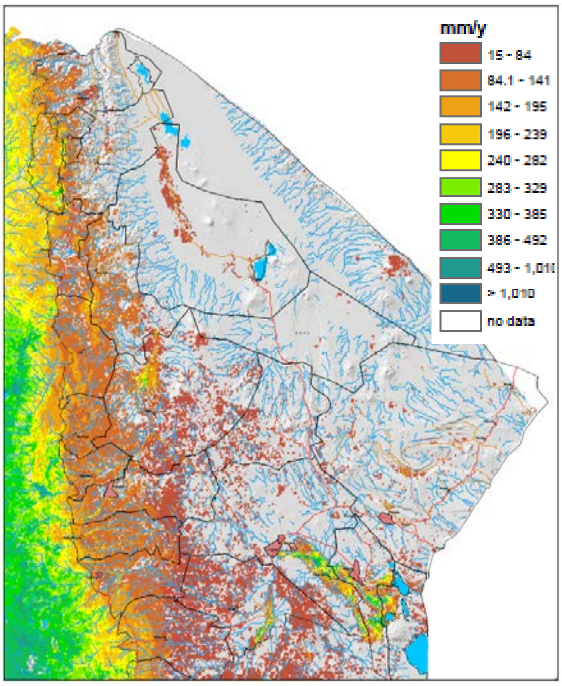


Figure 5 MODIS MOD16 average yearly evapotranspiration for 2000-2013 (Afar region)

Based on the rainfall statistics (figure 6) January is selected as driest months, since this is at the end of the dry season. February can also be seen as part of the dry period, but as the rainfall statistics indicate some mm of precipitations can be expected in this month, which could lead to some small scale, short term vegetation growth that would hamper the vegetation indicator analysis described below.

The evapotranspiration data available from the satellites (MODIS) is very limited in the Afar region (figure 5). This relates to the absence of vegetation which is required for the MODIS algorithm to calculate the evapotranspiration. This algorithm is based on the Penman-Monteith equation and incorporates surface stomatal resistance and vegetation information derived from MODIS land products. Therefore, only at locations with vegetation MODIS evaporation data are available. In Atsbi data are available from the MODIS database for almost the full Woreda and in the other Woredas only for the locations with vegetation.

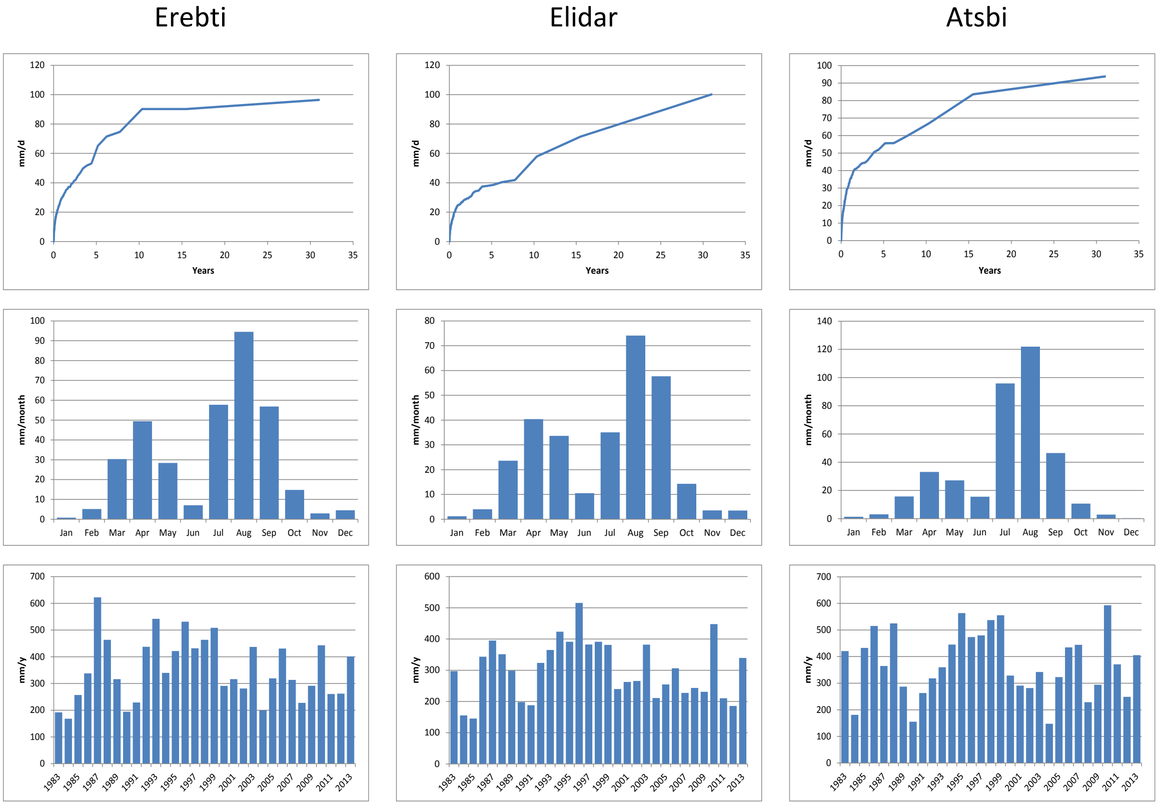


Figure 1 Rainfall statistics (ARC2) for Elidar, Erepti and Atsbi woredas. Period: 1983 - 2013

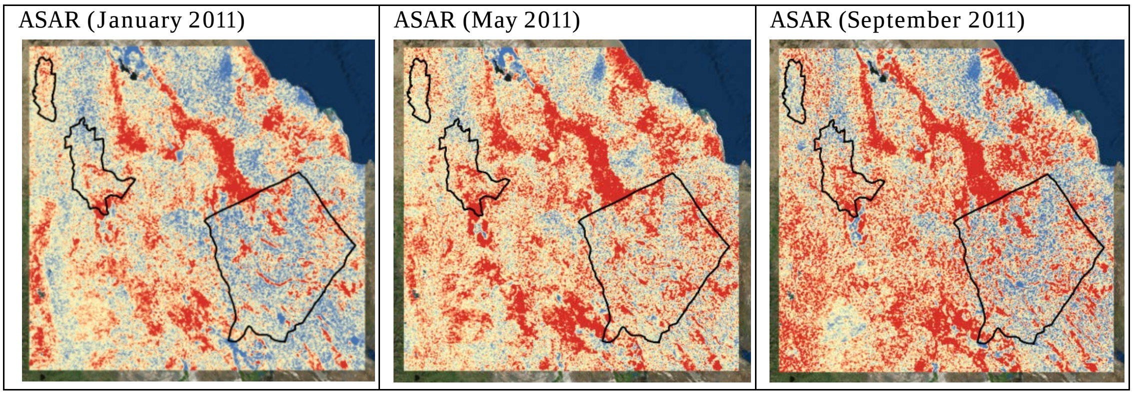
3.2 Soil moisture

3.2.1 Methodology

Within this project 2 different soil moisture products are used. The first one is based on passive microwave brightness temperatures from the AMSR-E satellite sensor. This product describes volumetric soil moisture (Vol %) of the first centimeter of the soil at a coarse scale resolution. The soil Moisture has been derived from level 2a V12 AQUA - AMSR-E passive microwave brightness temperatures (Ascroft and Wentz, 2013). The retrieval methodology is based on the Land Parameter Retrieval Model (LPRM). The LPRM was developed jointly by researchers from the VU University Amsterdam and NASA Goddard Space Flight Center and uses a simple radiative transfer to convert low frequency brightness temperatures from the satellite microwave radiometers to soil moisture (Owe et al., 2001; Owe et al., 2008) and has been considered to be very accurate over semi-arid regions with an accuracy of about 5-6 Vol.% (Parinussa et al., 2012; Gruhier et al., 2010). This accuracy degrades when the vegetation cover becomes more dense. The original spatial resolution of this dataset is about 50 km, which is often too coarse for regional hydrological studies. Therefore the data has been downscaled using a smooth modulation filter technique (De Jeu et al., 2014). The data (both original and downscaled) is available through several NASA data portals including NASA Reverb (http://reverb.echo.nasa.gov/). For this project we made use monthly composites from daily night-time (~observation time is about 01:30 AM solar time) observations for the period 2007-2011.

The second product used in this project is the Envisat ASAR 1 km Radar surface soil moisture product. This product has been developed by the Technical University of Vienna and is based on a change detection algorithm (Wagner et al.,1999) to convert the backscatter coefficients into soil moisture values . The data has been processed for Australia, the African continent and South America. For this project we made use of a 1 km dataset based on the Global Monitoring (GM) mode (Dostálová et al., 2014) and represents the soil moisture of the first centimeters. This product is slightly different as the passive microwave products because the soil moisture values are produced in degrees of saturation (0-100 %) instead of volumetric soil moisture. However several studies have revealed a strong similarity between the active and passive microwave products (e.g. De Jeu et al., 2008; Dostálová et al., 2014; Dorigo et al., 2010). For this study we made use of monthly composites for a 3 year period (2009-2011). The dataset is free available upon request through TU Wien (see https://rs.geo.tuwien.ac.at/products/98a2808e-d550-5bdb-9cc5-edcaf16f4f97/2595/).

There are several additional radar soil moisture products available from different satellite sensors (e.g. products from Palsar, ERS, ALOS, and Radarsat). However, these data products often lack a sound documentation and are not applied at different climate regimes. Both the AMSR LPRM soil moisture and the ASAR TU Wien soil moisture data products are based on proven scientific technologies and have been described and used in many peer reviewed publications including Nature (e.g. Jung et al., 2010; Taylor et al., 2012) and these satellite products have been heavily validated by the scientific community over different vegetation conditions (e.g. Dostálová et al., 2014). These two methods have now also been selected by ESA as the baseline algorithms for the development of a long term soil moisture climate record (see http://www.esa-soilmoisture-cci.org/). Therefore, we focus on the high quality AMSR LPRM and the Envisat ASAR radar soil moisture products.



ASAR (January 2011) ASAR (May 2011) ASAR (September 2011)

Figure 7. Three different ASAR soil moisture images (January, May and September 2011) of a large part of the study area including Erepti, Astbi en Elidar. Note a similar color legend as indicated in figure 8 is used

3.2.2 Results

Soil Moisture from the active (ASAR) and passive (AMSR-E) microwave observations have been analyzed for the application of groundwater exploration in Afar. The ASAR radar image gives more detailed information about the soil moisture fields than the AMSR-E data, which makes this data product more useful for groundwater exploration in this study area.

Figure 7 gives an overview of the larger area for three different months in 2011, including a large part of the Afar and the three study areas Erepti, Atsbi and Elidar. This image shows both the dynamics and the patchy characteristics of surface soil moisture. Some areas are continuously dry, some continuously wet, while others switch between wet and dry. By analyzing these dynamics in space and time one can zoom in and detect preferential regions.

To illustrate this two areas within the Erepti woreda are selected in order to explain the potential of satellite soil moisture for the use of groundwater exploration. This case is an example of how radar soil moisture from ASAR can be used in combination with a vegetation map to refine the search area for shallow groundwater explorations.

Generally, both soil moisture products (figure 8) showed in the north of Erepti a higher soil moisture signal than the south of the woreda. Nonetheless, the ASAR soil moisture product revealed in the south of the woreda an area with higher soil moisture (figure 8, area A), which coincides with an area with a strong vegetation signal. Area A is located at a large alluvial fan with a distinct vegetation zone at the edge of the fan, which is also detected by the NDVI images. The wet patches in this region are most likely too small for AMSR-E, because this sensor does not see a wet region in this area. By analyzing the ASAR images over time (figure 9) it can be seen that several parts within this area are continuously wet with the highest values in September. This information is important for groundwater exploration because it provides the direction where wet regions can be found.

The area in the north of the Erepti woreda is indicated as area B (figure 8). In this area both AMSR and ASAR provide high soil moisture values, while no strong vegetation signals are found. This region is dominated by a braided ephemeral river system and the wet patches of ASAR appear to follow most of these (dry) river beds. By localizing these wet regions (both wetness and size), an indication of potential shallow groundwater areas could be obtained. The maps are however too coarse to pinpoint precise locations or to determine smaller groundwater potential areas. Therefore, this information is combined with more detailed satellite information as described in the adjacent sections.

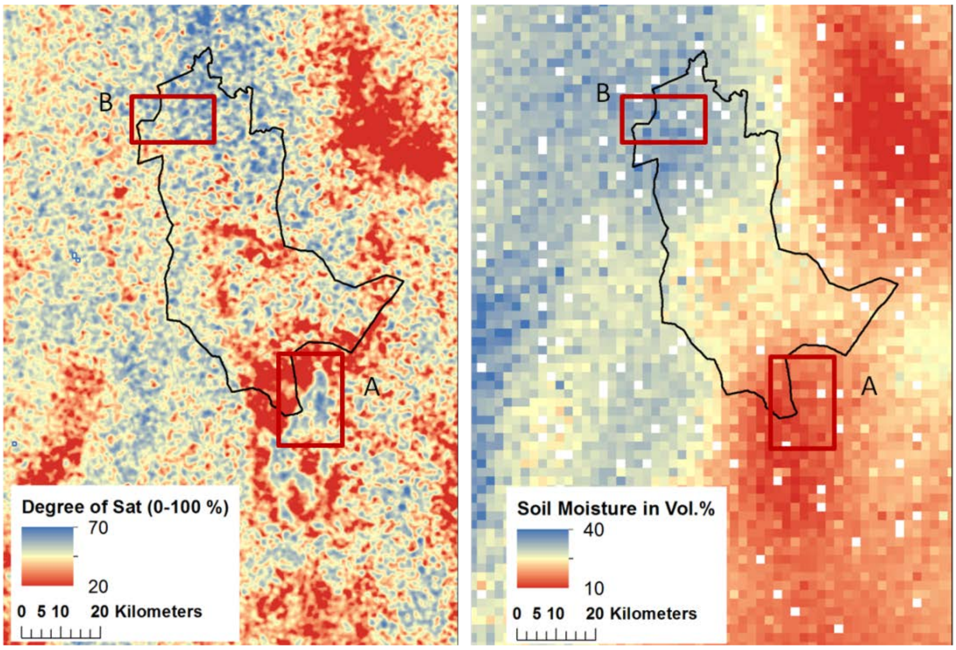


Figure 8 Soil moisture composite for January based on 1 km ASAR surface soil moisture observations (left) and (right) the downscaled AMSR-E soil moisture from the Land Parameter Retrieval Model.

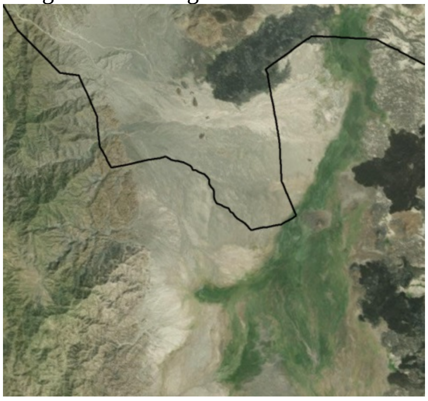
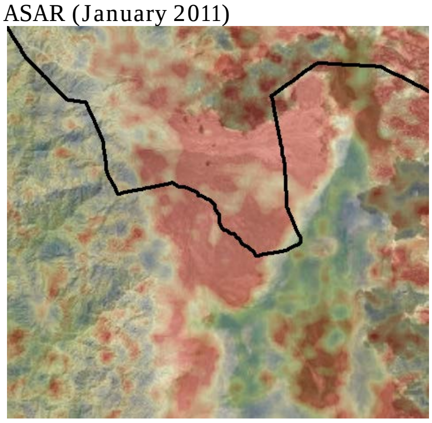
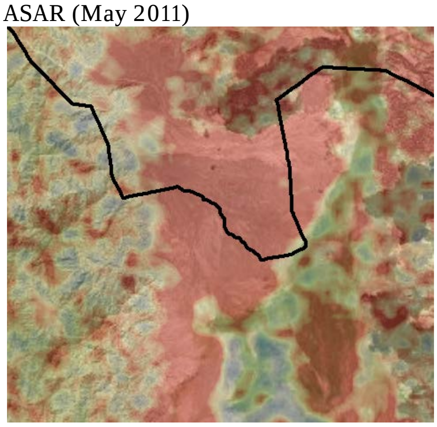
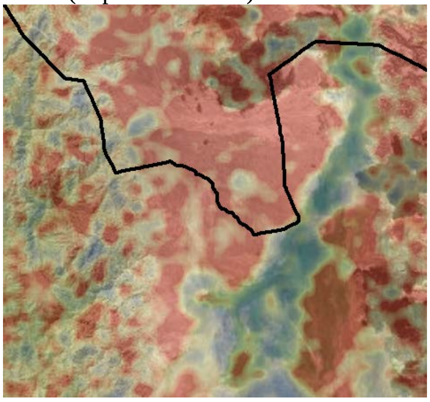
Google Earth Image of the Alluvial Fan	ASAR (January 2011)
	
ASAR (May 2011)	ASAR (September 2011)
	

Figure 9 A Google Earth image and three different ASAR soil moisture images (January, May and September) of the alluvial Fan (Area A, See Figure 3.x). Note a similar color legend as indicated in figure 6 is used.

3.3 Vegetation indices

3.3.1 Methodology

For the analysis of the vegetation we used both MODIS and LANDSAT-8 data. From both datasets we used the NDVI (normalized vegetation index) as indication of the greenness. For MODIS this was directly available, while for LANDSAT this had to be calculated from the Thermal and Near Infrared bands. MODIS provided long term data, from which we used the years 2000-2013 to calculate the minimum and variance of the NDVI at 250m resolution. Additionally, we used LANDSAT-8 from which we could generate NDVI maps with a much higher resolution (30 m). This is used for the analyses at a detailed level for the Woredas. Since LANDSAT-8 is only available for the last year, we selected from this dataset specific periods for the analyses, of which the most important is January 2014 to represent the driest period.

3.3.2 Results

The NDVI in the project area is generally very low, and the occurrence of vegetation is limited to only some specific locations. On the plateau in the western part of the project area, i.e. in Atsbi, the vegetation is most abundant, with vegetation all year round (see figure 10). This relates to the precipitation patterns (see section 3.2).

In this dry environment with little precipitation and high evaporation, abundance of vegetation at the end of the dry season indicates areas with perennial water addition, either through surface water or through groundwater seepage. In Afar region, groundwater seepage is illustrated by the presence of permanent vegetation at the foot of alluvial fans and or depressions (e.g. figure 11).

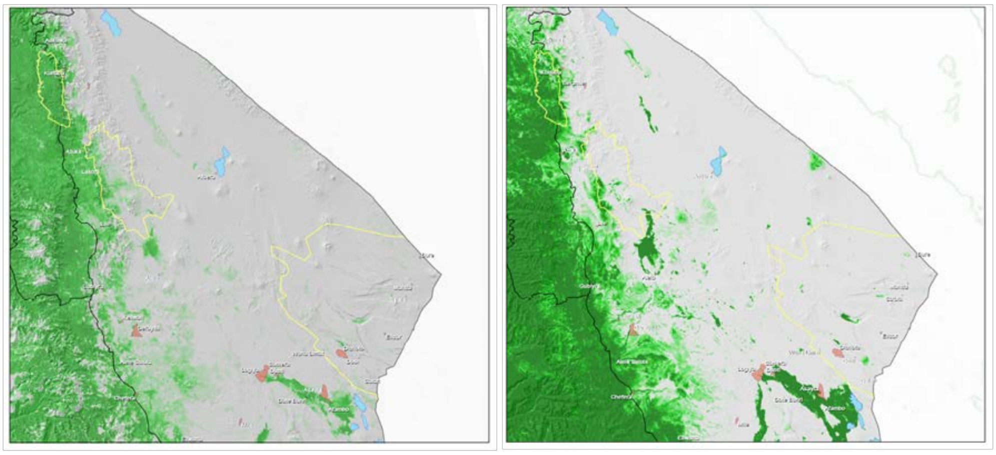


Figure 10 MODIS NDVI minimum (left) and variance (right) over the period 2000-2013

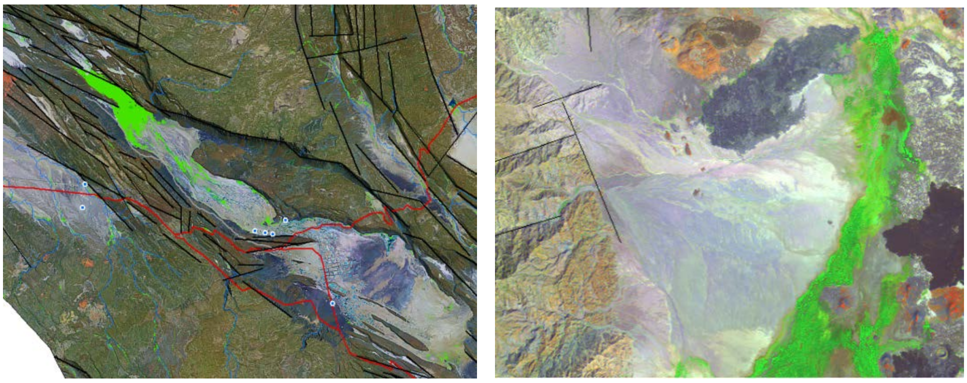


Figure 2 NDVI calculated from LANDSAT-8, showing Permanent vegetatio in depressions (Dobi graben) (left) and permanent vegetation at foot of alluvial fan (Erepti/Teru) (right)

3.4 Accumulation and runoff

3.4.1 Methodology

We processed both the traditional 90 meter resolution from the Shuttle Radar Topography Mission (SRTM) and the recently released 1 arc second (30 meter) data to create a Digital Terrain Model (DTM). Watersheds were determined for each river system, up to its outflow into a depression or sink (figure 16). The streams and basins are computed using ArcHydro Tools in ArcGIS. In addition, each catchment was analyzed on soil, land cover and slope. These parameters were divided into classes and the area for each class was determined per catchment area with ArcGIS. Based on these analysis maps with slope, flow accumulation, wetness index and catchment delineation were derived.

The Topographic Wetness Index (TWI), also called Compound Topographic Index (CTI), is an important building block in the S-GwA methodology. It uses a DTM as raster data source and involves calculation of the upslope contributing area and terrain slope.

Runoff characteristics depend on a combination of physical, climatological and hydrological conditions. A conceptual rainfall-runoff modelling approach was used for the watersheds of the ephemeral rivers in Afar. Parameters used for the model are rainfall (Arc-2 satellite imagery), catchment area (SRTM DEM, 30 m), soil type (Soil Atlas of Africa), land cover (GlobCover) and slope (SRTM DEM, 30 m). Time series with 30 year daily rainfall were generated for each of the catchments, based on ArcII satellite imagery (see section 3.1). Rainfall data from meteorological stations was used for comparison, but not for the development of mean daily rainfall time series per catchment, because of the limited availability of rainfall stations in Afar and the incomplete rainfall data series available from these stations.

A conceptual model of the Soil Conservation Service (SCS), the Curve Number (CN) method was used to determine runoff from the catchment areas. For each separate catchment feature the CN was determined using classifications for land use, slope and soil, from which the total catchment CN was derived. No gauging data is available for the rivers in Afar and therefor the results could not be calibrated on actual measurements. The field survey and interviews have provided some information about the discharge characteristics of the rivers. This information has been used for the development of the model.

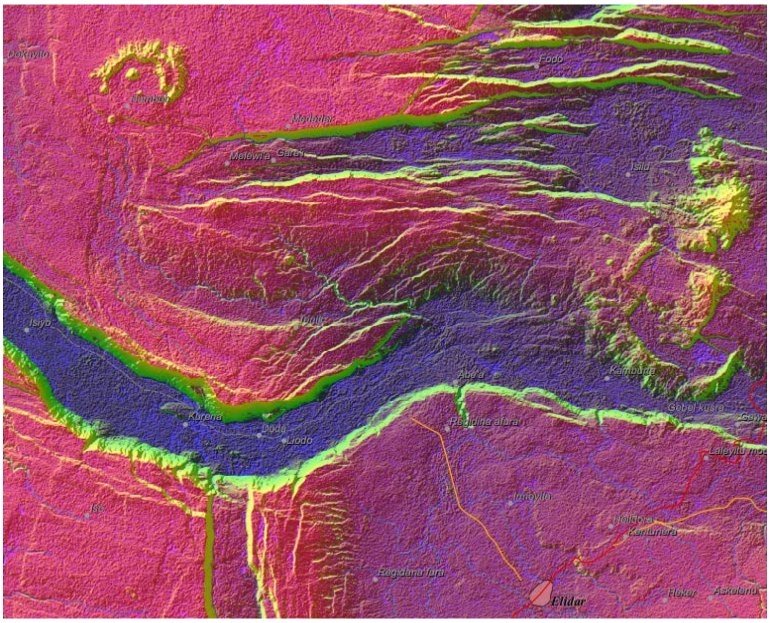


Figure 12 False colour composite of elevation (red), slope (green) and TWI (blue) in Elidar Woreda

3.4.2 Results

The results of the TWI analysis are presented in attached 1:250000 maps for all three woredas. The accompanying DVD contains also detailed 1:50000 TWI maps.

The rivers in Afar discharge into different depressions or sink areas where the river flow disappears, these are generally low altitude flat areas. There are rivers with dendritic drainage patterns, but also Radial and Deranged patterns, and especially in Elidar there are Trellis drainage patterns, related to the geological structures. Some of the depressions are (currently) permanently dry, while others have stagnant water during part of the year or permanently. The latter form permanent salt lakes. Where the ephemeral rivers enter the depressions the river spreads out and forms an alluvial fan from where the water disappears. The results of the catchment delineation and drainage pattern is shown in figure 16.

The results of the rainfall-runoff modelling for the three target woredas showed an average runoff of 8 to 10% of the annual precipitation. Moreover, the rainfall-runoff relation for some selected catchments (figure 14) shows that substantial runoff is only generated after rainfall of more than 20 mm per day.

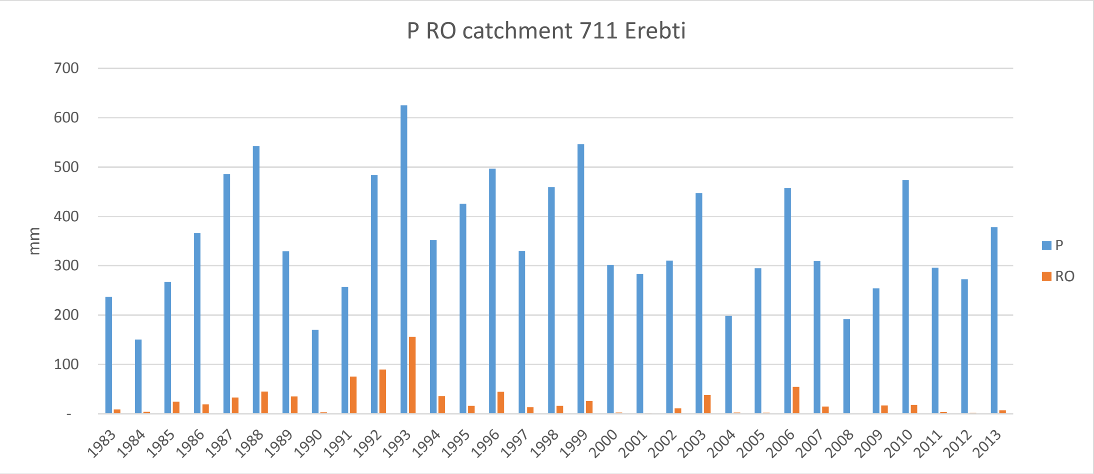


Figure 33 Precipitation (P) and modelled runoff (RO) for catchment 711 in Erepti

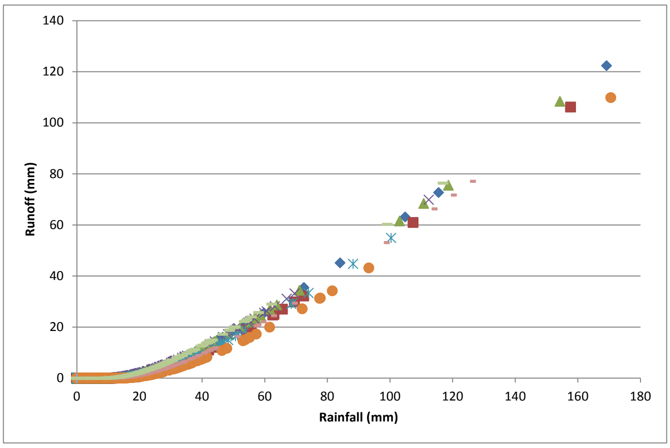
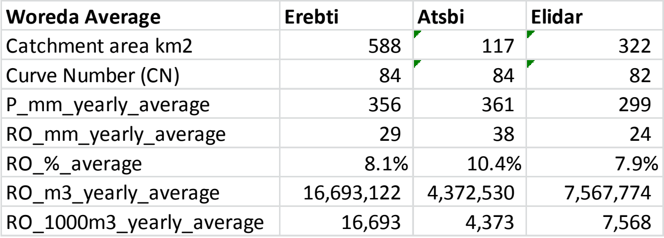


Figure 14 Rainfall-runoff relation for selected catchments



Woreda Average	Erebti	Atsbi	Elidar
Catchment area km2	588	117	322
Curve Number (CN)	84	84	82
P_mm_yearly_average	356	361	299
RO_mm_yearly_average	29	38	24
RO_%_average	8.1%	10.4%	7.9%
RO_m3_yearly_average	16,693,122	4,372,530	7,567,774
RO_1000m3_yearly_average	16,693	4,373	7,568

Figure 15 Results of the rainfall-runoff model for the three target woredas

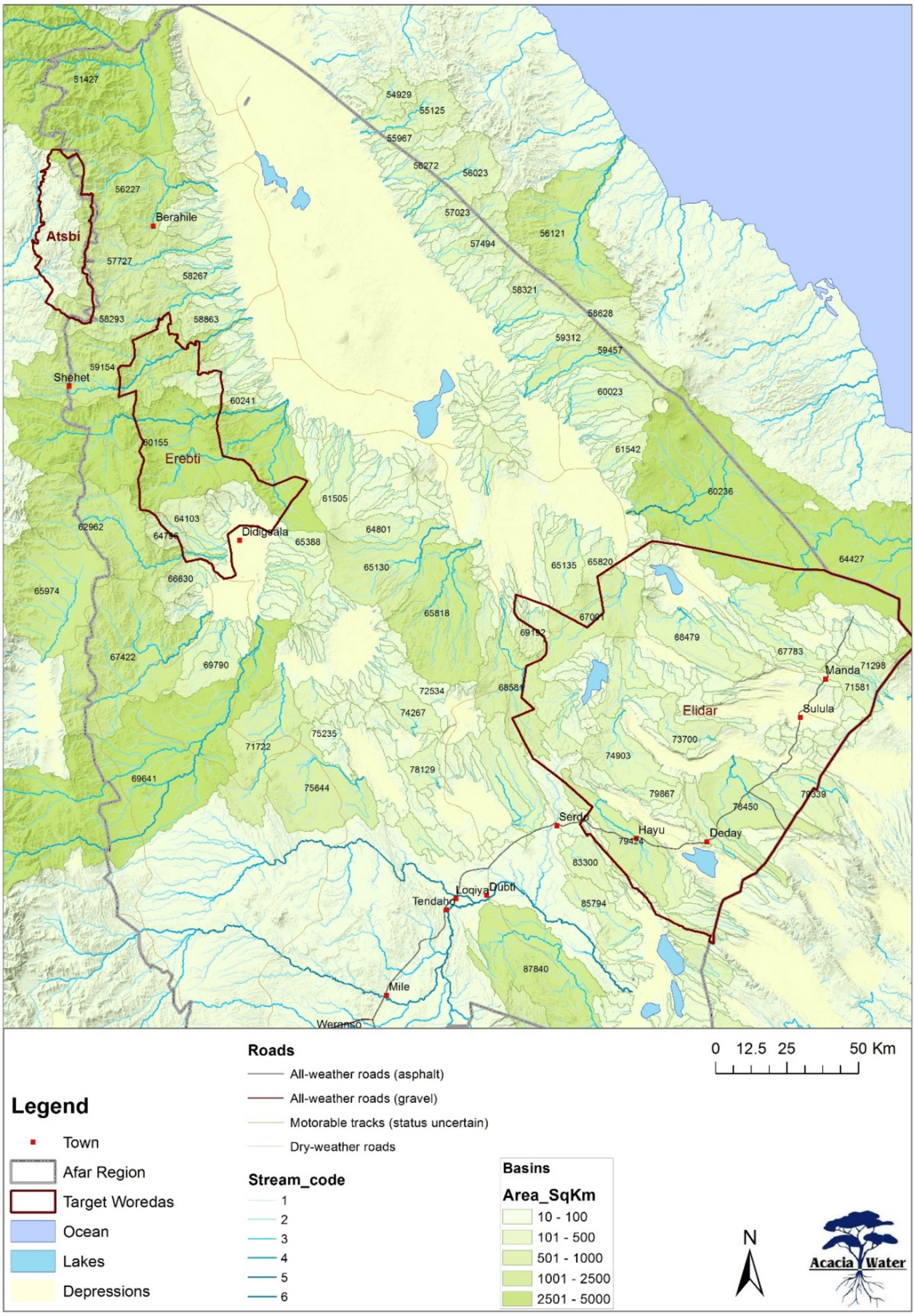


Figure 46 Catchment delineation and drainage

3.5 Geology and morphology

3.5.1 Methodology

The GIS database from phase 1 includes a generalized geological and aquifer map of entire Afar (Annex B), in which the aquifer map is based on the main geological units and provides a limited description of general aquifer characteristics. Additionally, we used the soil map from the African Soil Atlas. At relevant locations, at interesting locations for the three target Woredas, these maps are refined based on LANDSAT-8. The different bands provide various information about amongst others the morphology and geology. LANDSAT-8 thermal infrared, near infrared and green or blue bands are combined to create maps which provide a clear visual indication of the lineaments, the morphological features like alluvial fans and flood plains, and at which some geological formations can be distinguished. With the use of panchromatic LANDSAT-8 band 8 (15 m), this is further refined to sharpen the picture. In addition to the Landsat-8 false color composites, specific band ratios for lithological mapping have been used to enhance lithological differences (Sultan (1987), Gad and Kusky (2006)).

Lineament mapping was done in a two-step approach. First an automatic method is used, then the lineament maps were refined manually using the DEM, Landsat and optical imagery (Google). Tri-Decadal Global Landsat Orthorectified Thematic Mapper (TM) Mosaics were used for automatic lineament delineation, several bands were tested, but a combination of all bands provided the best result. The automatic lineament extraction process was carried out with the LINE module of PCI Geomatica, based on automatic detection algorithms (canny algorithms).

The permeability of the surface determines the ease with which the water can infiltrate. The permeability of the different layers of the subsurface plays an important role in the formation of either shallow or deep groundwater. Roughly the options can be summarize in four categories. The first is the situation where the layer at or near the surface has a low permeability (figure 17a). In that case the water will not or hardly infiltrate and remain on the surface, where it will evaporate or run further as overland flow.

The second category are soils that contain an impermeable layer at some depth beneath the surface, for example a clay layer or the top of the bedrock. In that case the infiltrated water can form a shallow groundwater layer in the perched aquifer on top of the impermeable surface (figure 17b).

Also in the third category shallow groundwater is formed. In this category an impermeable layer is absent or located very deep below the surface. If shallow groundwater exists in such a situation it is in the form a thick water layer in the unconfined aquifer (figure 17c). The shallow groundwater may in this case be in contact with the deep groundwater, shallow recharge can then also be regarded as recharge to the deep groundwater.

Finally, in the fourth category shallow groundwater and a shallow impermeable layer are both absent, while deep groundwater may be present. When in this case water infiltrates into the soil it will either be evaporated or transported through the soil to the deep groundwater (figure 17d). A limited amount of water may in this case remain available in the upper subsurface in the form of soil moisture.

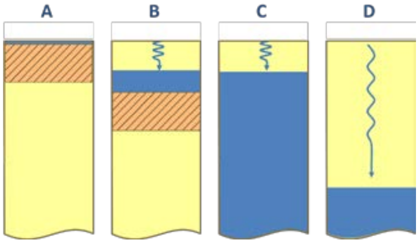


Figure 17. categories of groundwater expectation related to (im)permeable layers

3.5.2 Results

The available geological maps have been compiled using extensive fieldwork and image processing techniques and we found that the quality of the existing maps to be very high (figure). With high resolution satellite imagery that is available today, the maps could be improved but this needs additional fieldwork that is beyond the scope of this project. Figures 18 and 19 below show part of Atsbi woreda with Enticho sandstone, Precambrian limestones and phyllites.

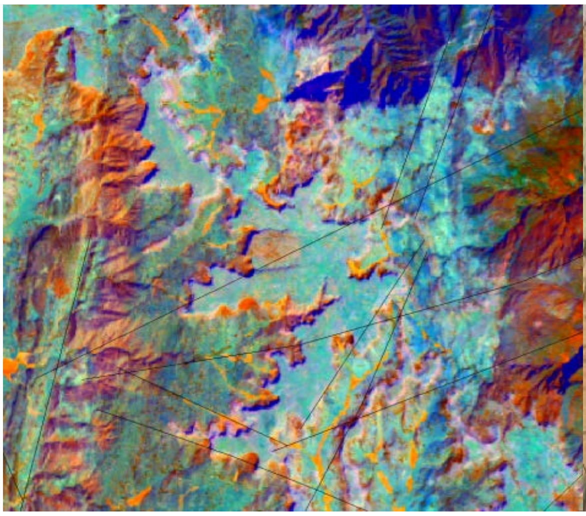


Figure 6 Landsat false color composite (Sultan)

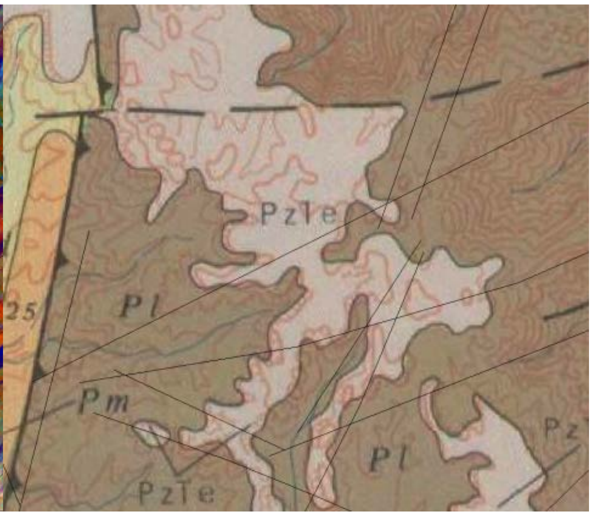


Figure 7 Geological map 1:250000 (ND37-7)

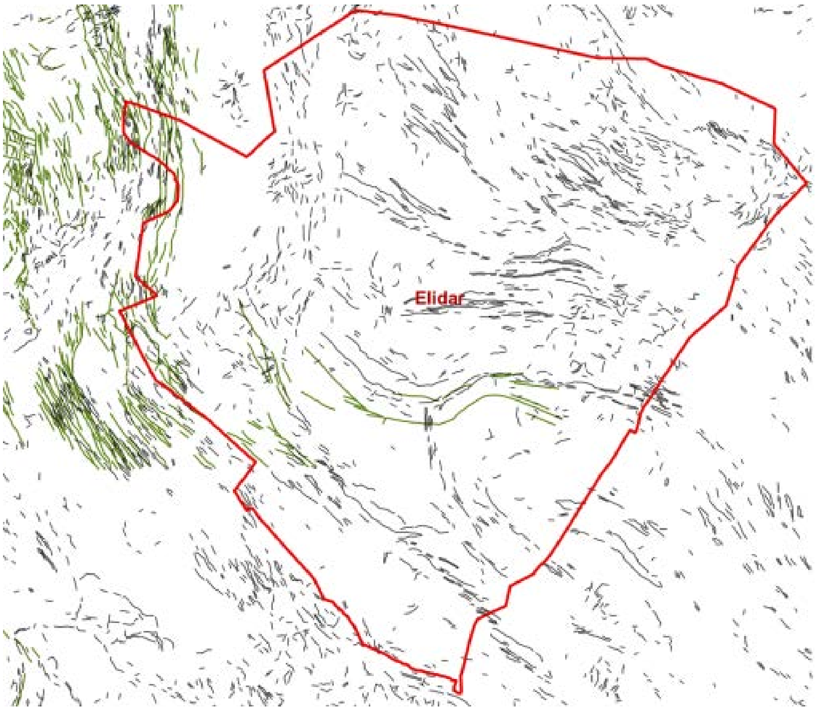


Figure 8 Lineaments in Elidar woreda

4 Shallow groundwater in Erepti

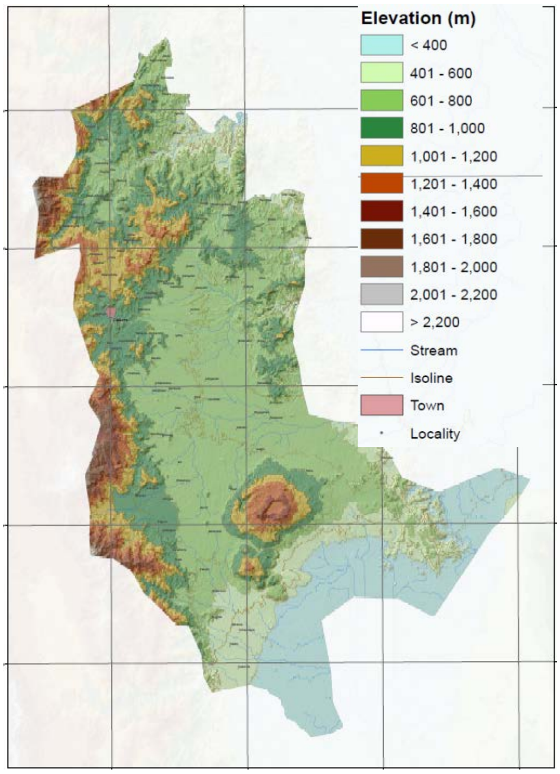


Figure 9 Erepti woreda elevation in m above sealevel

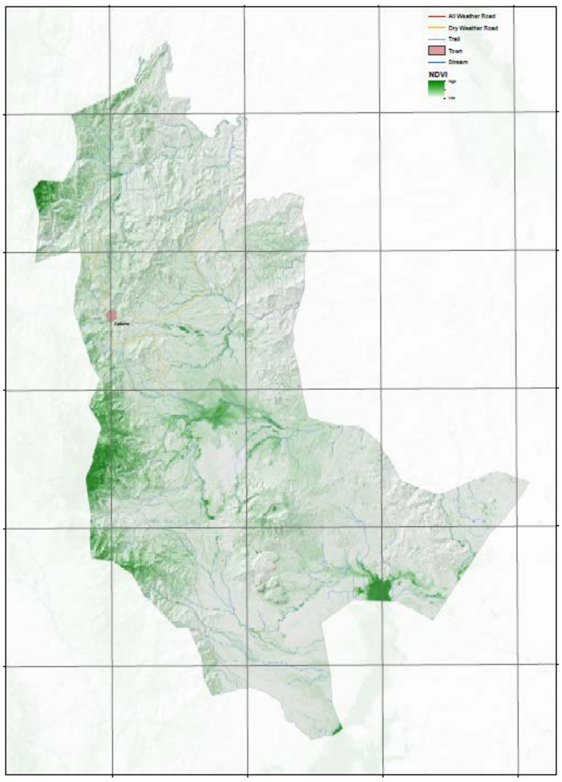


Figure 22 Vegetation appearance in the Erepti woreda indicated by the NDVI (derived from LANDSAT8, January 2014)

Erepti is located at the base of the plateau. At the western border and in the north of the woreda elevations of over 1000m are found, while the remainder of the woreda is less elevated (figure 21). The vegetation, indicated by the NDVI is limited to specific locations and scarce in most of the woreda (figure 22 and 23). Most vegetation is found at the edges of the plateau, in or near the (seasonal) streams and at the base of alluvial fans, where even at the end of the dry period vegetation is present.

Erepti contains three catchments of importance (figure 23), where the two large catchments extend outside the borders of the woreda. Two major streams originate from the plateau west of the woreda, transit through the woreda and drain towards the east. The catchment and flow accumulation analyzes combined with the precipitation data indicated a relatively large discharge through these catchments, because of the high amounts of precipitation at the plateau and the large catchment sizes.

The flow accumulation analysis showed that the streams are also fed by water that accumulates from within the woreda. Based on the geology, porous formation are identified in the northern part of the woreda, which can supply the streambeds with a subsurface recharge. The TWI analysis was used to identify locations in the stream beds with a high potential for infiltration. These locations are confirmed with the geomorphology derived from LANDSAT 8, at the potential recharge locations the streambeds were wider and sediment appeared to accumulate.

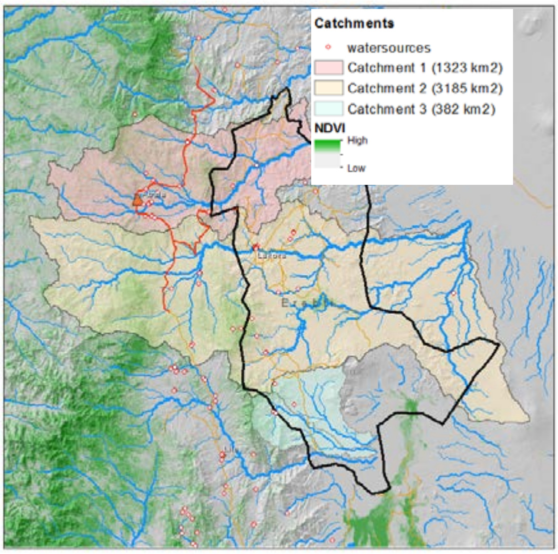


Figure 10. Streams and catchments in the Erepti woreda, and the vegetation presence indicated by the NDVI (derived from MODIS)

Other hydrological important features are the alluvial fans where young sediments have accumulated in the south of the woreda. The southern edge of the woreda covers a small part of a large alluvial fan that extends towards the Teru plain. At the base of this fan a large stretch of vegetation is found that remains green throughout the full year, of which only the northern tip is located in Erepti (figure 23). More towards the middle of the woreda also a small alluvial fan is found.

4.1 Determination of potential drilling locations

Based on the geo-hydrological characteristics a number of zones where the occurrence of shallow groundwater is expected are identified. In these zones in more detail specific locations are identified. The five zones with the associated site points can be found at the map in figure 24 and the separate high resolution pdf map, they are characterized as follows:

A. Zone A is located at the north of the Erepti woreda along the stream bed from the large northern catchment. This area consists of limestone and sandstones, in which water is expected to infiltrate and recharge the shallow groundwater. Towards the eastern border of the woreda low permeable schists and phylites occur. The probable flow path of the shallow groundwater is along the streambed towards the north east. At the streambed water accumulation is expected both from the discharge of the plateau, and from the porous formations within the woreda. Specific site points (10-13) with a high potential for shallow groundwater are situated at locations where the streambed intersects with lineaments and/or at locations with a high TWI.

B. Zone B is located in the center of the woreda along the streambeds east of Erepti town (Lakora). Also here water accumulates from the plateau. Therefore, comparable to zone A specific site points with high potential for groundwater are situated at the intersection of streambeds with lineaments. However, the salinity of the river discharge at this location is relatively high due to dissolution of gypsum. This may also indicate quality problems in the shallow groundwater (site points 5-7). These quality problems may be less in the streambeds where only water from within the woreda accumulates, but the expected amount of recharge is less here because of the smaller recharge catchment (site points 8-9)

C. More towards the south of the woreda is zone C located. This is the base of the little alluvial fan, where permanent vegetation is found. Therefore, moisture must be present in the rootzone, which expected to be seepage that is recharged with water flowing through the alluvial fan and it may have groundwater recharge from two directions (see blue arrows in figure 24). The site points (0-4) with a high potential for shallow groundwater are situated at the intersection of lineaments where groundwater is expected to converge.

D. In the southwest of the woreda zone D is located at the top of the large alluvial fan that extends towards the Teru plain. Potential sites are situated at the top of the alluvial fan where the sediment is expected to be coarse and water is expected to infiltrate. However, the amount of recharge may be limited. The potential is expected to increase further southeast (along the blue arrow in figure 24), there deeper groundwater (>200m) may be present. The quality iof the shallow groundwater at the toe of the alluvial fan may show higher salinity due to high evaporation.

E. Zone E is located in the south east (Haiten plain) at the northern tip of the depression that extends to the Teru plain. The area is recharged from the adjacent volcano and basalt/lava plateaus. Shallow groundwater (depth up to 100 meter) is expected at the fringe of the depression..Further to the south the vegetation density increases, indicating the presence of shallow groundwater in lacustrine deposits.

Figure 24 Areas (A-E) and site points (pink dots) where a high potential for groundwater is expected. For a more detailed map we refer to the separate high resolution pdf map.

5 Shallow groundwater in Atsbi

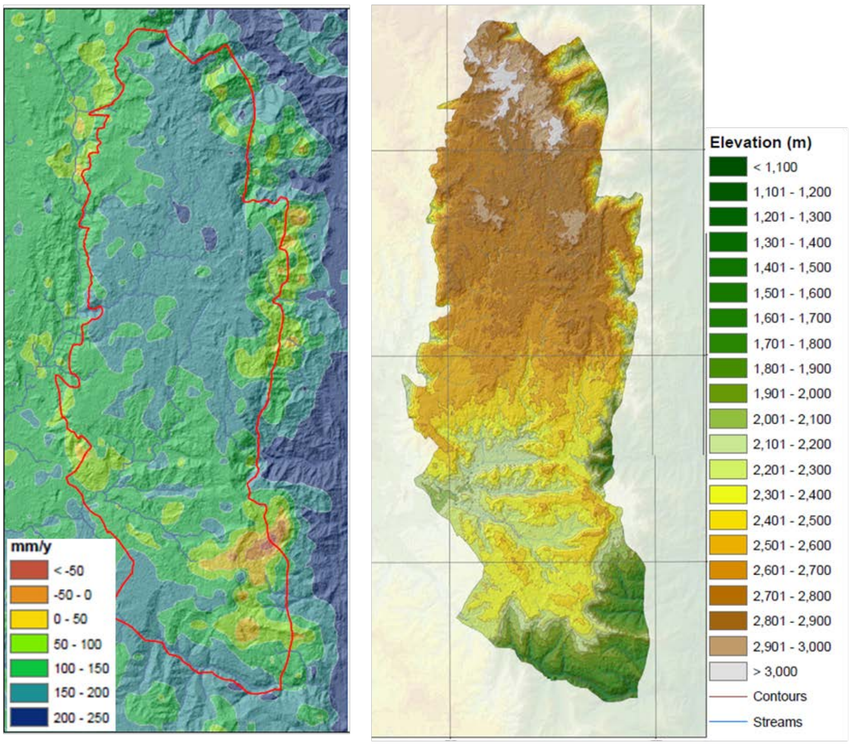


Figure 11. Atsbi woreda net yearly precipitation and elevation

The Atsbi woreda is located at the plateau in east Tigray. The northern part of the woreda has elevations over 2000m above sea level, and locally above 3000m (figure 25). In the south elevations are lower and deep valleys are found. Also geologically the north and south can be seen as two separate parts, with in the north sandstone and conglomerates on top of the Paleozoic basement consisting of schists and phyllites, and in the south tilted Mesosoic sedimentary formations (Antalo limestone, Adrigat sandstone).

On the plateau the amount of precipitation is higher than in the lower lying woredas. Also the vegetation cover is clearly different from the other two woredas, as in most of Atsbi permanent vegetation is found, with a high NDVI throughout the year. Therefore, in Atsbi also evapotranspiration data are available from MODIS, which are only calculated for vegetated areas. The precipitation data (ARC-2) and evaporation data (MODIS) were combined to obtain the yearly net precipitation (figure 25). Generally Atsbi has a precipitation surplus of about 150-200 mm/year in the north and 0-100 mm/year in the south. This indicates that water from the Atsbi woreda is available for recharge and run-off.

5.1 Determination of potential drilling locations

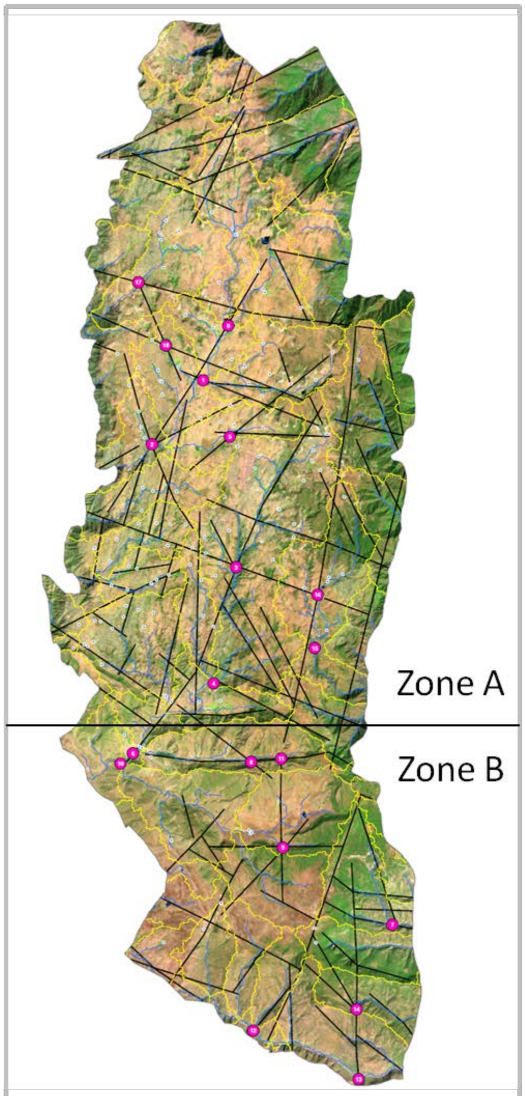


Figure 12. Atsbi Woreda, the black lines indicate the lineaments and yellow the catchments boundaries. The pink dots indicate location with groundwater potential. For a more detailed map we refer to the separate high resolution pdf map

Based on the geo-hydrological characteristics Atsbi is devided in two zones which each a different groundwater potential. In these zones specific locations are identified in more detail. The associated site points can be found at the map in figure 26 and 27, they are characterized as follows:

A1. Zone A comprises the northern part of the woreda. Here two important features support the appearance of groundwater. The first are the plateaus consisting of sandstone and conglomerate (A1) and the second lineaments (A2). The plateaus are porous formations that store groundwater, which support the springs at the intersection of the sandstone plateaus with the underlying basement. These springs are the sources for the wetlands found at the Atsbi plateau. Already many wells tap into the drainage of the sandstone plateau. This groundwater source is therefore assumed to be known and used already, and is not further specified here.

A2. We identified in zone A locations that have a potential for shallow groundwater, but where currently no wells exist. The basement of the Atsbi plateau only allows for infiltration at specific locations. Therefore, the lineament analysis is essential to determine the groundwater potential in this area. Specific site points with a high potential for shallow groundwater are situated at locations where lineaments intersect with (seasonal) streams and/or at locations where lineaments lead to groundwater convergence and where deep weathering is expected. Only locations where sufficient recharge can be expected based on the catchment size and the precipitation are selected as high potential site points.

B. In the southern part of the woreda zone B is located. This area is consists of tilted Mesozoic limestone and sandstone. Potential for groundwater is here only expected at deeper locations at probably about 300m depth. The high potential site points are situated where the recharge is relatively large (based on the catchment size, the net precipitation and location of wadis) and where large lineaments intersect.

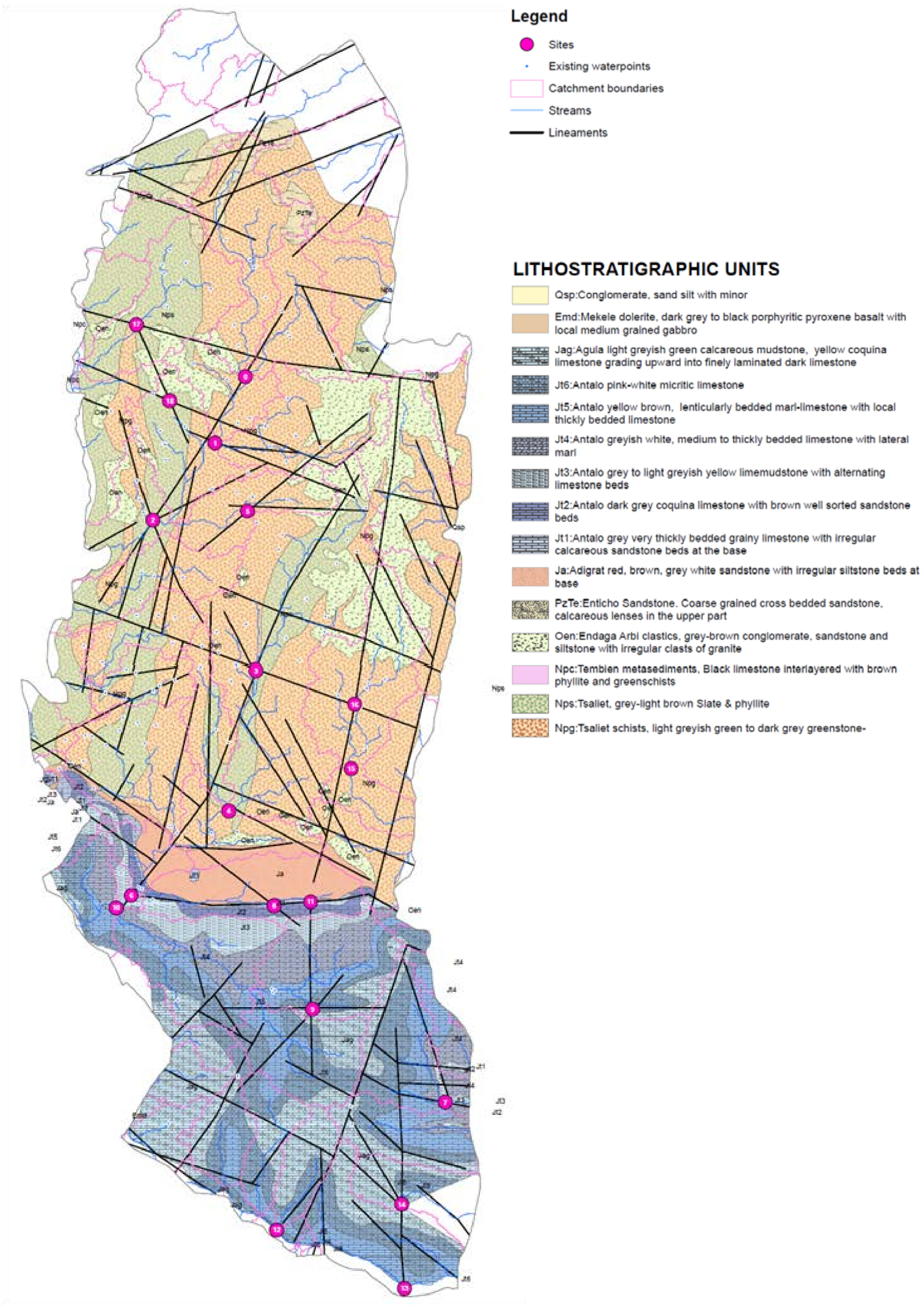


Figure 13 Lithostratigraphic units in the Atsbi Woreda. The black lines indicate the lineaments and pink the catchments boundaries. The pink dots indicate location with groundwater potential. For a more detailed map we refer to the separate high resolution pdf map

6 Shallow groundwater in Elidar

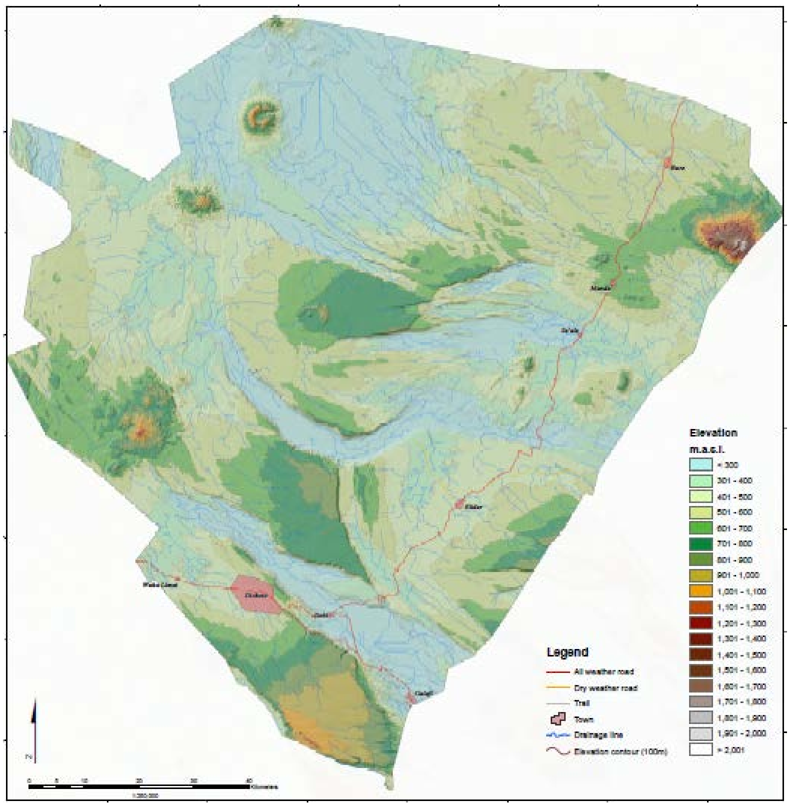


Figure 14. Elidar woreda elevations and drainage patterns

Elidar is characterized by the presence of horsts and grabens. This results in distinct elevation differences within the woreda (figure 28). The grabens are below 300m above sealevel, while the higher parts of the horsts have elevations of more than 700m above sealevel. At several places in the woreda the elevation was increased to over 1000m above sea level due to volcanic activity.

The woreda is generally very dry, and vegetation is scarce. At the bottom of the grabens some permanent vegetation is found, indicated by a higher NDVI throughout the year (figure 30). However, even in this low areas the vegetation is limited to specific locations. This indicates that only locally soil moisture is present in the root zone.

The catchment analysis indicated that many small catchments exist in this woreda (figure 29) that discharge into the grabens. Each of these catchment is only a limited source of water, because of the relative small catchment sizes and the limited amount of rainfall. Nonetheless, locations can be found where water accumulates, for example where multiple little catchments drain into the same part of a graben (figure 30). The catchment and flow accumulation analysis also revealed clearly the flow paths and drain direction. At some locations this provided new insights. For example the depression connecting the two southern grabens discharges towards the south, while the two alluvial fans at its north have only a very small catchment behind them.

6.1 Determination of potential drilling locations

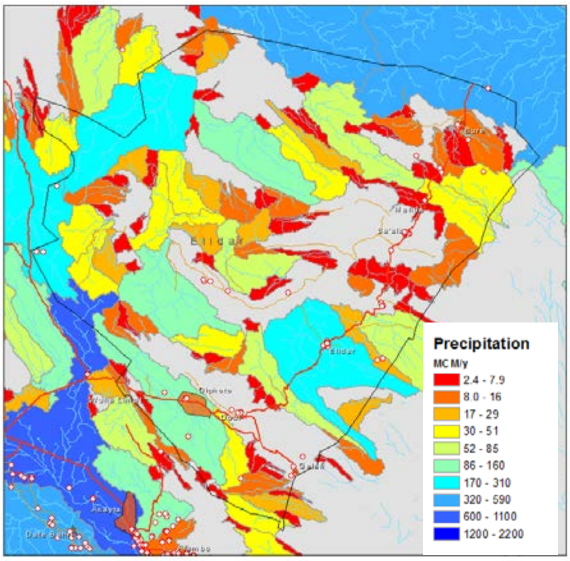


Figure 15. Cumulative amount of precipitation per catchment in Elidar

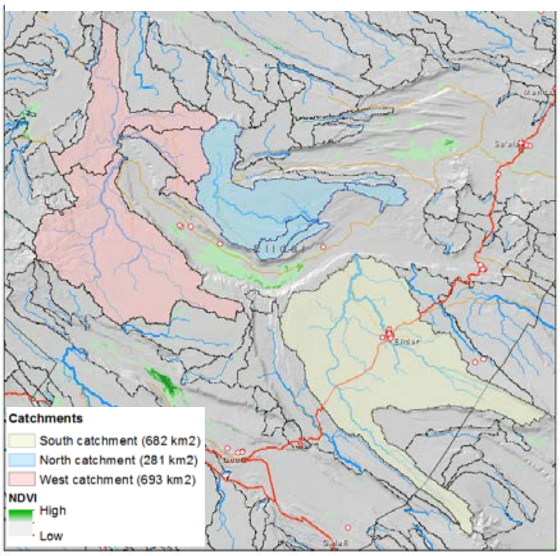


Figure 16. Aaggregation of the catchments that discharge into the same part of the graben in the middle of Elidar woreda. Green indicates the NDVI

Based on the geo-hydrological characteristics a number of zones where the occurrence of shallow groundwater is expected are identified and in more detail specific locations are identified. Generally the next zones can be disguised (figure 31). Additionally site specific information is included in table 2, for the detailed site numbers we refer to the map sheet annexed to this report.

A. Zone A comprises the northern part of the woreda. Here the presence of the horsts and grabens is less distinct than in the south of the woreda. Lineaments in different directions are present, which provides locations where groundwater may be expected. Site points are situated at the junction of lineaments at the edge of depressions and/or where at locations with possibilities of local recharge and seepage (site points 1-8).

B. Zone B comprises the eastern side of the middle graben of the Elidar woreda. Specific site points with a high potential for shallow groundwater are situated near the locations where the basalt plain drains into the graben. Locate shallow well at the top of the alluvial fan (site point 9), near the escarpement to avoid water quality problems, or at the crossing of a lineament and a wadi (site points 10-11).

C. Zone C indicates the crossing of regional large scale structures, i.e. grabens (site points 13-14). Basalts are expected to be very well fractured and the deep groundwater should be targeted here. Shallow groundwater may exist, but its quality may be questionable. This is the deepest part of the graben.

D. Zone D comprises the Dobi graben. Drill deep well to find fractured basalts and scoria with regional groundwater.

E. In the woreda also some very specific locations are identified where a specific formation or depth should be targeted for groundwater potential (see table 2).

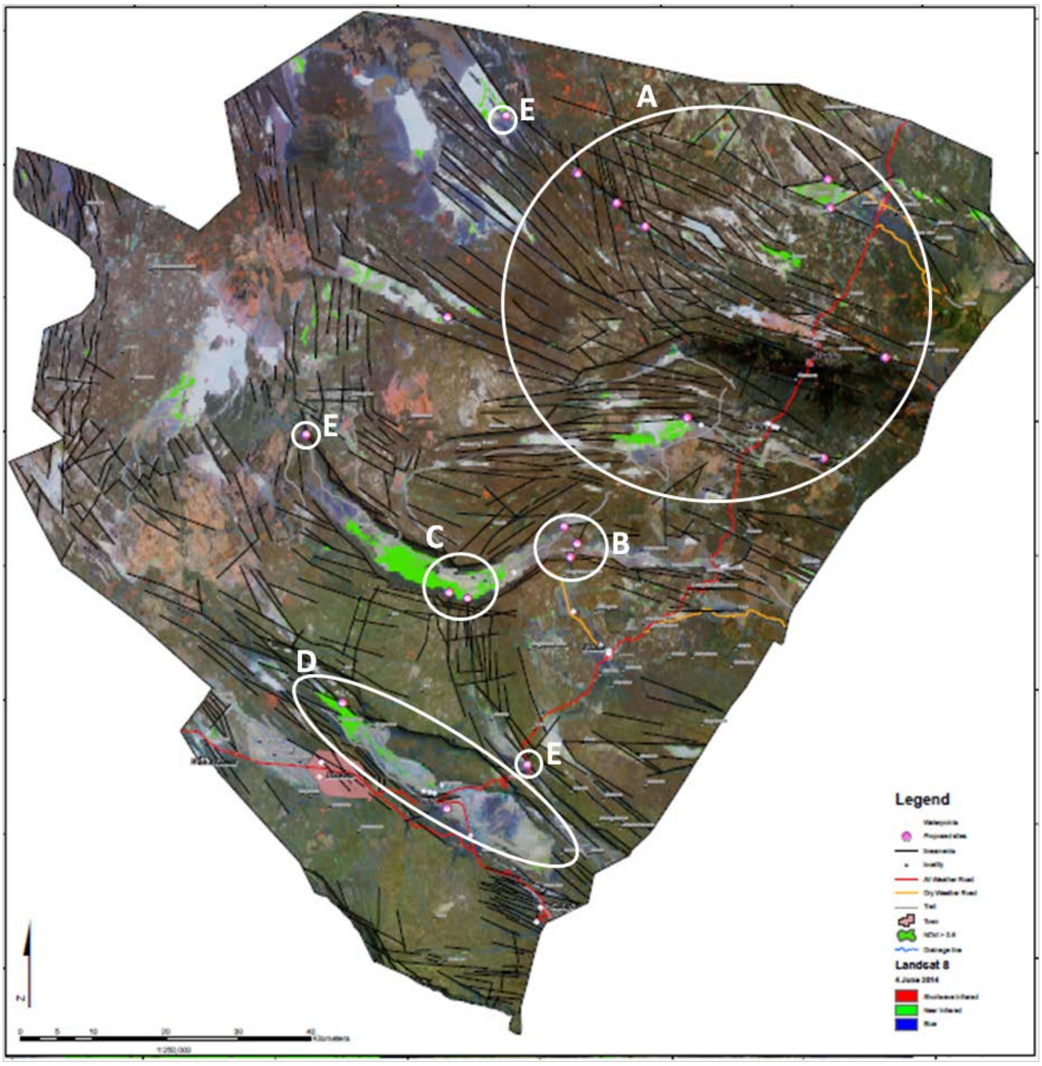


Figure 31. Areas (A-E) and site points (pink dots) where a high potential for groundwater is expected. For a more detailed map we refer to the separate high resolution pdf map

Id	Remarks
1	Depression west of Bure. Locate site on junction of lineaments at northern boundary of depression. Avoid center (salinity)
2	Depression west of Bure. Locate site on junction of lineaments at southern boundary of depression. Avoid center (salinity)
3	Junction of regional northwest-southeast llineament with local NNW-SSW lineaments. Possibility of local recharge and seepage. See also 4,5,19
4	Junction of regional northwest-southeast llineament with local NNW-SSW lineaments. Possibility of local recharge and seepage. Relatively large See also 3,5,19. Area surface catchment = 370 km2
5	Junction of regional northwest-southeast llineament with local NNW-SSW lineaments. Possibility of local recharge and seepage. See also 3,4,19
6	10 klm northeast of Mandi on junction between two regional WNW-ESE lineaments where alluvial deposits have accumulated. At the foot of recent lava flows of Mandi-Inakia range
7	About 9 km southeast of Sa'ala at southern border of recent Mandi lava flows. Located on lineament crossings on wadi bed, near locality Daho
8	Northern border of foodplain west of Sa'ala, 2 km west of existing borehole on crossing of lineaments. Depth and discharge of existing borehole unknown.
9	15 km northwest of Elidar, where basalt plain drains into the graben. Permanent water seepage along the escarpement. Locate shallow well at the top of the alluvial fan, near the escarpement to avoid water qaulity problems. Deeper drilling may result in higher yield.
10	2 km north of site 9 on the toe of the fan at crossing of lineament and wadi. Anticipating considerable recharge from northern and southern drainage basins. Deeper drilling may result in higher yield.
11	3 km northwest of site 10 on crossing of lineament and wadi. Anticipating intercepting subsurface drainage from northern catchements.
12	On crossing of regional large scale structures (grabens). Basalts are expected to be very well fractured and the deep groundwater should be targeted here. Shallow groundwater may exist, but its quality may be questionable. This is the deepest part of the graben.
13	On crossing of regional large scale structures (grabens). Basalts are expected to be very well fractured and the deep groundwater should be targeted here. Shallow groundwater may exist, but its quality may be questionable. This is the deepest part of the graben.
14	At the far end of the graben (west) where large rhyolitic area drains into the depression. Shallow well only. Avoid rhyolite, target basalt and alluvial deposits
15	Dobi graben. Drill deep well to find fractured basalts and scoria with regional groundwater
16	Dobi graben. Drill deep well to find fractured basalts and scoria with regional groundwater
17	On the road between Dobi and Elidar. Possibility for shallow groundwater in mini graben. Locate the site at the northern escarpement near the damaged bridge on the main nw-se lineament.
18	Located in a remote area on the southeastern edge of a graben where surface water runoff accumulates and infiltrates or evaporates. The site should be located on the northern fault line where surface water infiltration is maximized and evaporation is minimized. Drainage area is around 600 km2. Suitable for both shallow and deep groundwater
19	Very low elevation. Possibility to capture deep aquifer within 200 m. Extensive Norhwest - Southeast lineament, Permanent vegetation on sandy deposits. Locate site at the southern edge of the sandy patch for shallow recharge, or right at the northeastern escarpement on the main lineament for deep, regional groundwater. See also 3, 4, 5

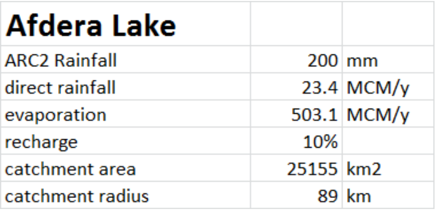
Table 2. Proposed sites in Elidar (for the site numbers on the map see the separate high resolution pdf map)

7 Deep Groundwater

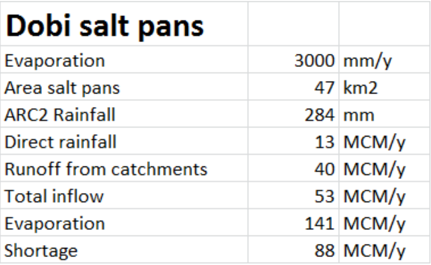
7.1 Seepage zones

Although Remote Sensing does not give direct answers to questions on the occurrence of deep groundwater, the conceptual model that was developed using the D-GwA methodology indicates that deep groundwater exists in Afar (figure 32). We used satellite precipitation data, rainfall-runoff characteristics, evaporation and evapotranspiration data to calculate water balances for two areas with permanent surface water: Afdera Lake and the salt pans in Dobi graben.

For Afdera lake we estimate that a recharge area of 25,500 km2 is required to maintain the water level in the lake. Such a large drainage area does not exist (it would extend up to Eritrea and the Ethiopian highlands). Therefore seepage of deep groundwater could be a plausible explanation. For the salt pans in the Dobi graben (Elidar woreda) we estimated a shortage on the water balance of 88 million m3/y. Also here the seepage of deep groundwater could account for this shortage.



Afdera Lake		
ARC2 Rainfall	200	mm
direct rainfall	23.4	MCM/y
evaporation	503.1	MCM/y
recharge	10%	
catchment area	25155	km2
catchment radius	89	km



Dobi salt pans		
Evaporation	3000	mm/y
Area salt pans	47	km2
ARC2 Rainfall	284	mm
Direct rainfall	13	MCM/y
Runoff from catchments	40	MCM/y
Total inflow	53	MCM/y
Evaporation	141	MCM/y
Shortage	88	MCM/y

7.1 Potential drilling locations

Potential drilling location are in the low lying areas near the depressions, where the deep groundwater is within reach of conventional drilling machines. Examples of such wells are Semara and Teru plain where 600 m deep wells have been drilled yielding up to 90 lps. Additional field verifications are required to site successful wells.

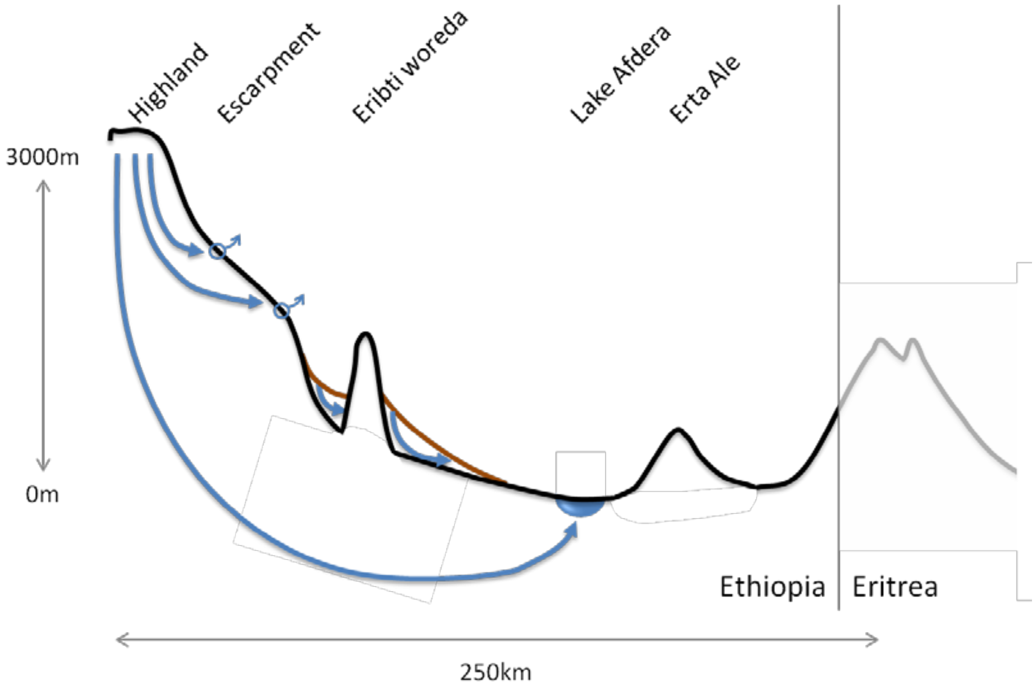


Figure 172 Conceptual flow paths of deep groundwater

8 Maps

The results of the remote sensing analysis are presented in map sheets, annexed to this report. We have prepared three overview maps on 1:250000 scale for all three woredas (total 9 maps): terrain morphology, topographic wetness index and potential drilling sites. Additionally, we have produced two sets of map sheets on scale 1:50000 containing the potential drilling sites and the topographic wetness index (total 66 maps).

8.1 Potential drilling sites

The 1:50000 maps with potential drilling sites use a Landsat-8 false colour composite as background (bands: thermal infrared, near infrared and blue or green). This band combination makes it possible to make a distinction between different lithologies and emphasizes vegetation. Areas with permanent vegetation are enhanced (bright green) using the NDVI values, computed from red and near infrared bands. Moreover, the drainage pattern and lineaments are shown on these maps. Please note that only a selection of potential sites has been indicated on the maps and the sites have been numbered randomly.

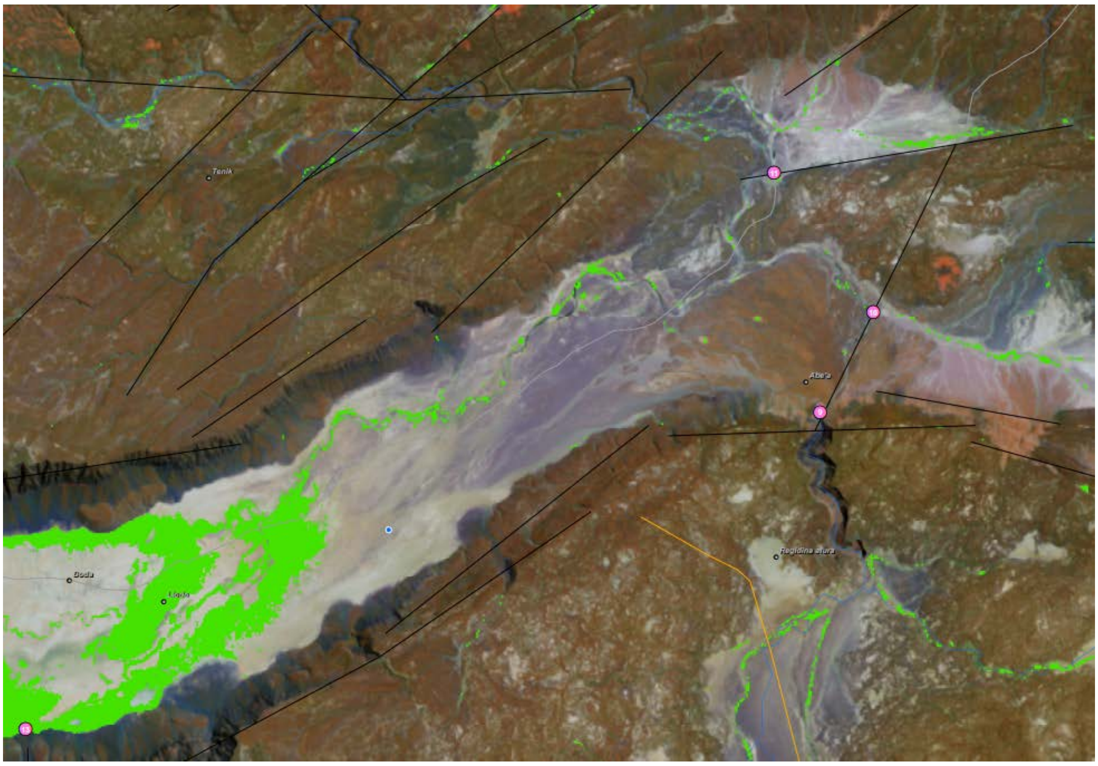


Figure 183 Sample map with potential drilling sites (Elidar woreda)

8.2 Topographic wetness index

The TWI maps are used to analyse the drainage pattern and flow accumulation to locate sites with favourable conditions for shallow groundwater. An example map is shown below. The maps are colour composites using three sets of information: elevation (red), slope (green) and wetness index (blue). Areas that are bright red have high elevation, low slope and low wetness index. Similarly, blue colour represents areas with high wetness index. Combinations of the three variables are reflected as colour combinations. Example: high elevation and high slope is represented as yellow (mix of red and green), high wetness index and high elevation is shown as purple (red + blue) (for an example see figure 12).

8.3 Terrain morphology

The terrain morphology maps are based on the recently released SRTM 30 m digital elevation model. The maps show the terrain morphology as well as the derived drainage pattern on a shaded relief background with basic topographical features.

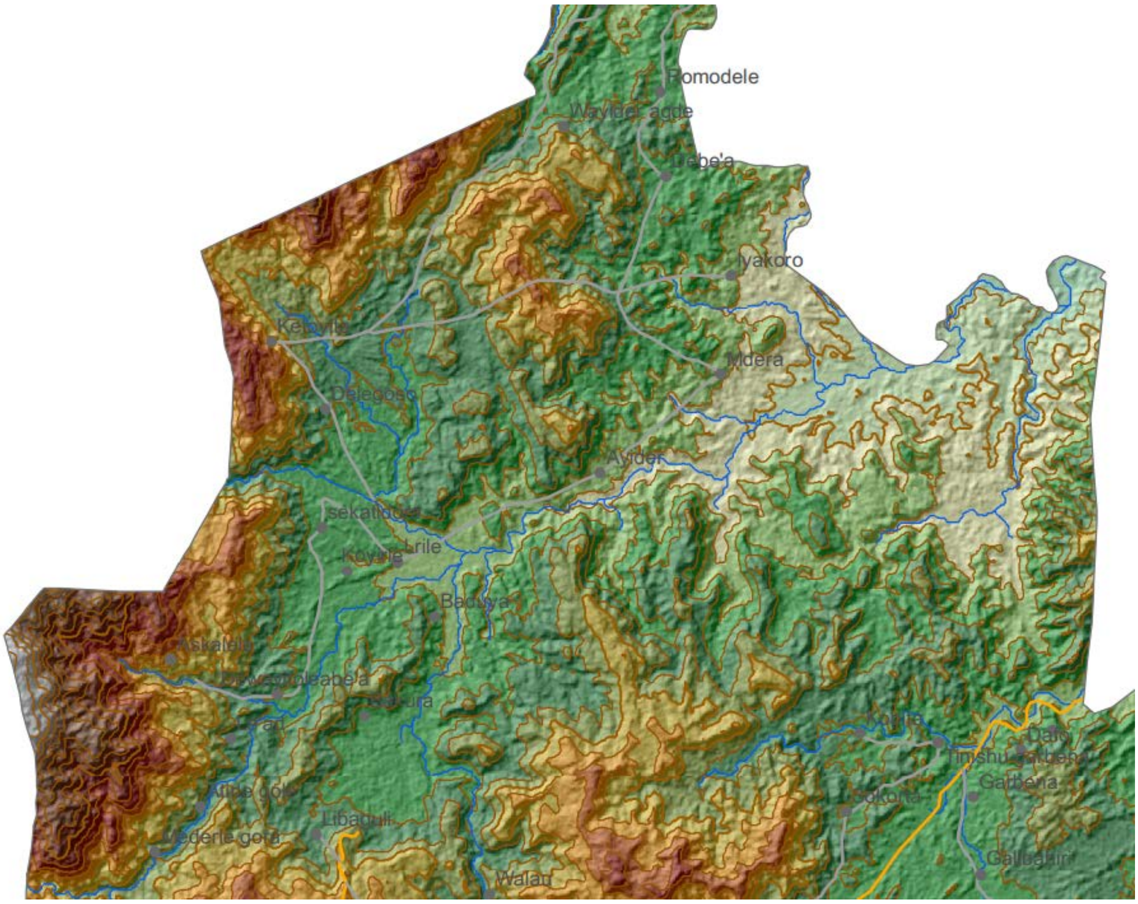


Figure 194 Sample terrain morphology map (Erepti woreda)

9

Conclusions and recommendations

The GwA methodology showed to be a useful approach to determine potential drilling locations. Satellite data provide a powerful source of information, and prove especial valuable in areas that are relatively scarce like the Afar and East Tigray target region. The satellite data provide valuable information when combined with various data sources into a conceptual model of the area. However, the satellite penetration depth is not sufficient to show the groundwater occurrence directly (see baseline report), therefore a good conceptual model is required to determine potential drilling locations.

For the creation of a conceptual model, the building blocks are analyzed. None of the building blocks provides the full information over the area, therefore the information has to be combined. This can only partly be automated. Because the area is complex and data scarce an important part of the conceptual model requires expert knowledge and interpretation. In this analysis quantitative and qualitative data are combined and indirect information is used to deduce flow paths and groundwater occurrence.

In the three target Woredas Elidar, Erepti and Atsbi the satellite data are analyzed in more detail and complemented with information from the field. Here potential drilling locations are indicated based on the available information. For this the analyzes based on the digital terrain model from the SRTM-satellite and the morphological information from LANDSAT-8 proved especially valuable. These indicated the locations where sufficient water could be expected for groundwater recharge to support a sustainable groundwater abstraction, based on the catchment and flow accumulation analysis, that clearly indicated the flow direction, which was sometimes counterintuitive. The morphology that became visual after an effective combination of the bands from the LANDSAT satellite clearly indicated drainage patterns and alluvial fans.

Summarizing the results, we found as the most potential drilling locations in the three target Woredas:

- The alluvial fans where water from a relatively large contributing surface water catchment accumulates. Depending on the specific characteristics of the fan, drilling is advised at the top of the alluvial fan where coarse material is expected to support relatively concentrated groundwater recharge (e.g. in Elidar), or at the foot of the alluvial fan where groundwater is expected to accumulate at the edge of a barrier (e.g. in Erepti).
- In the wadi beds where (during the wet period) fresh water flows. The most potential areas are locations where water accumulates from a relative large catchment, and where the slope is relatively small, i.e. at locations with a high TWI, complemented with extensive wadi beds. This is for example found in Erepti.
- At the transition between porous and less porous rocks and where the porous formation is large enough to sustain water throughout the full dry period. This is for example found in Atsbi, where shallow groundwater accumulates at the base of the porous sand stones on top of the basement.

- At the junction of lineaments or lineaments and wadis.
- For deep, regional groundwater wells it is advised to make use of the large elevation differences and to place the wells in depressions (Elidar). The conceptual deep groundwater model suggests that a deep groundwater flow can be expected.

These locations are identified as the areas with the highest potential for sustainable groundwater abstraction. Please note that detailed geophysical studies are essential for successful siting of wells on lineaments. The studies should include not only resistivity, but also magnetic and electromagnetic surveys. For exploration of deep groundwater it is recommended to use TDEM and audio magneto telluric (ATM) methods.

Annex A
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Annex B

Rainfall data availability

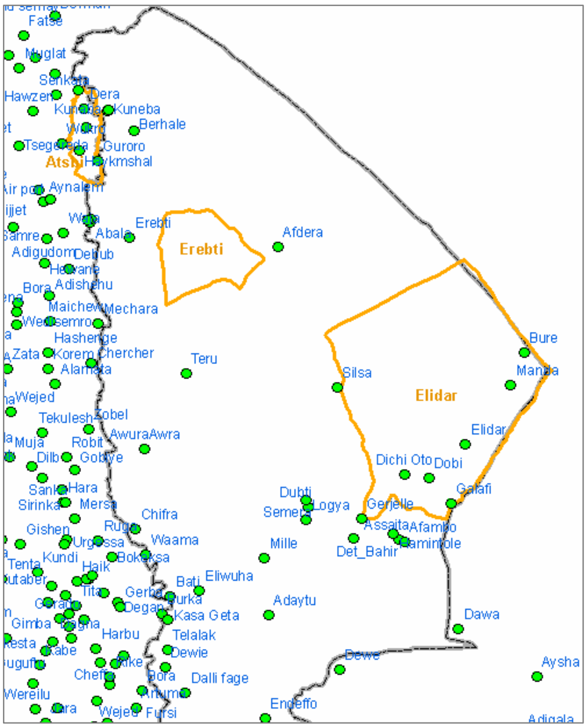

Figure B.1: Rainfall station

Stations	Zone
Guroro	Zone 2
Teru	Zone 4 (central)
Silsa	Zone 1 (north)
Det_Bahir	Zone 1
Haminitole	Zone 1
Galafi	Zone 1 (East)
Bati	Zone 5
Telalak	Zone 5
Dewie	Zone 5
Dewe	Zone1
Dawa	Zone 1 / Djibouti
Endeffo	Zone 3
Kasa Geta	Zone 5/Oromia Zone
Atsbi	Eastern Tigray
Mechara	Southern Tigray

Table B.1: Stations no data available

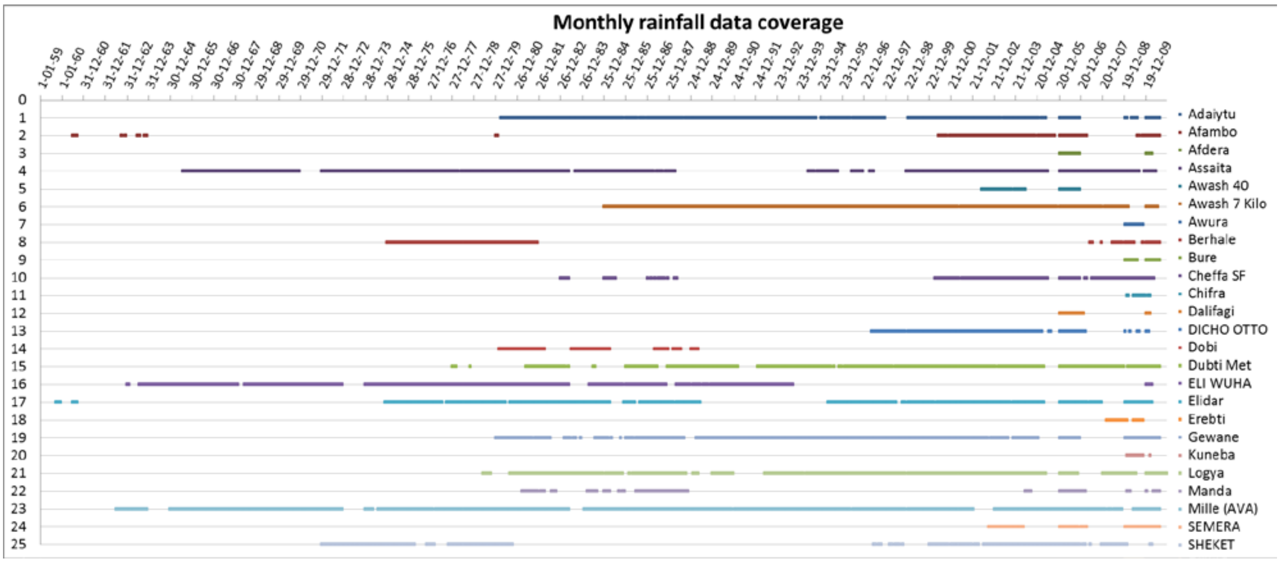

Figure B.2 Data coverage of rainfall stations in Afar (data: phase 1)

Annex C

Geology and hydrogeology

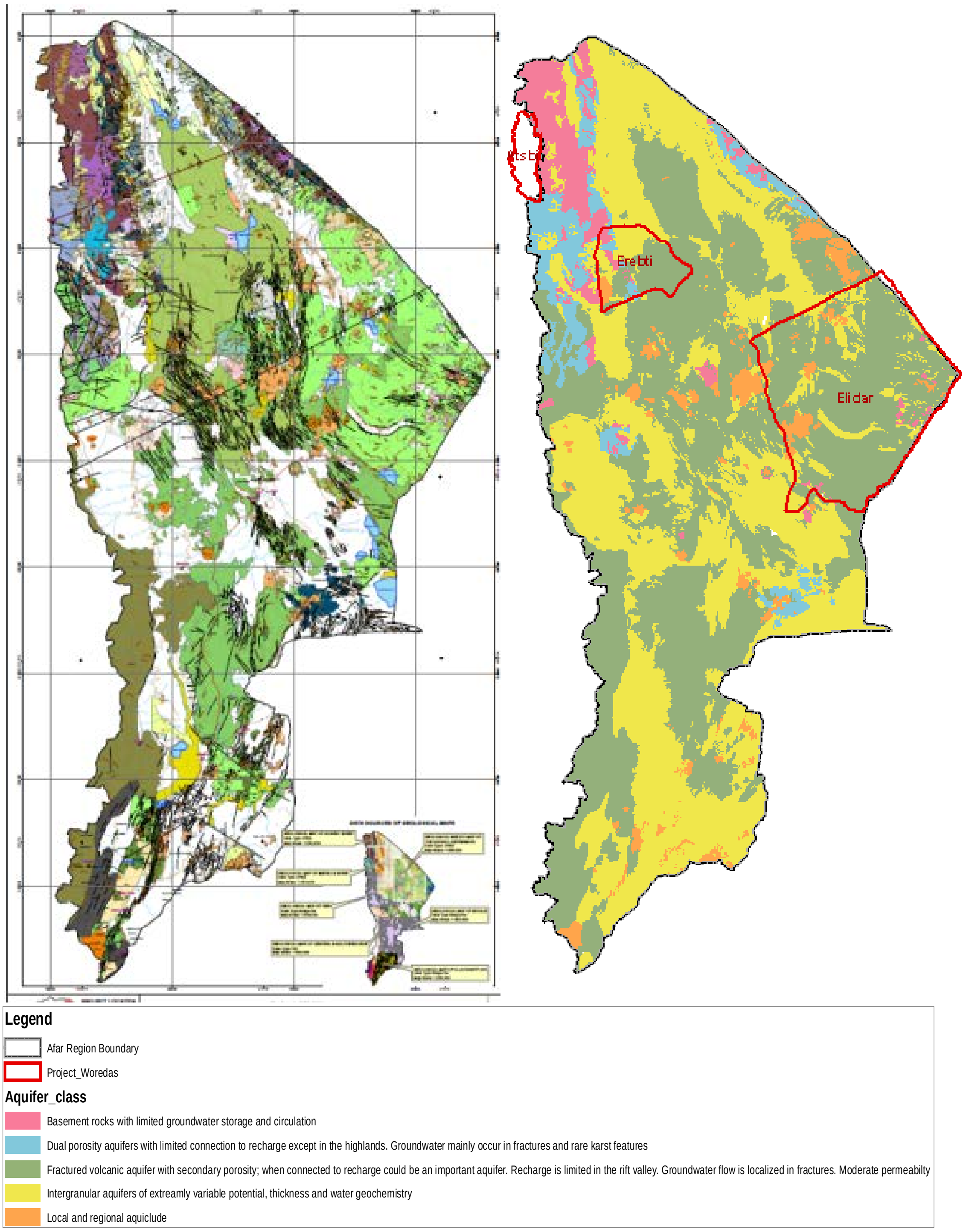

Figure C-1 Left: geological map and right: aquifer classes. Results from phase 1. Source:UNESCO and UNICEF, 2013.

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