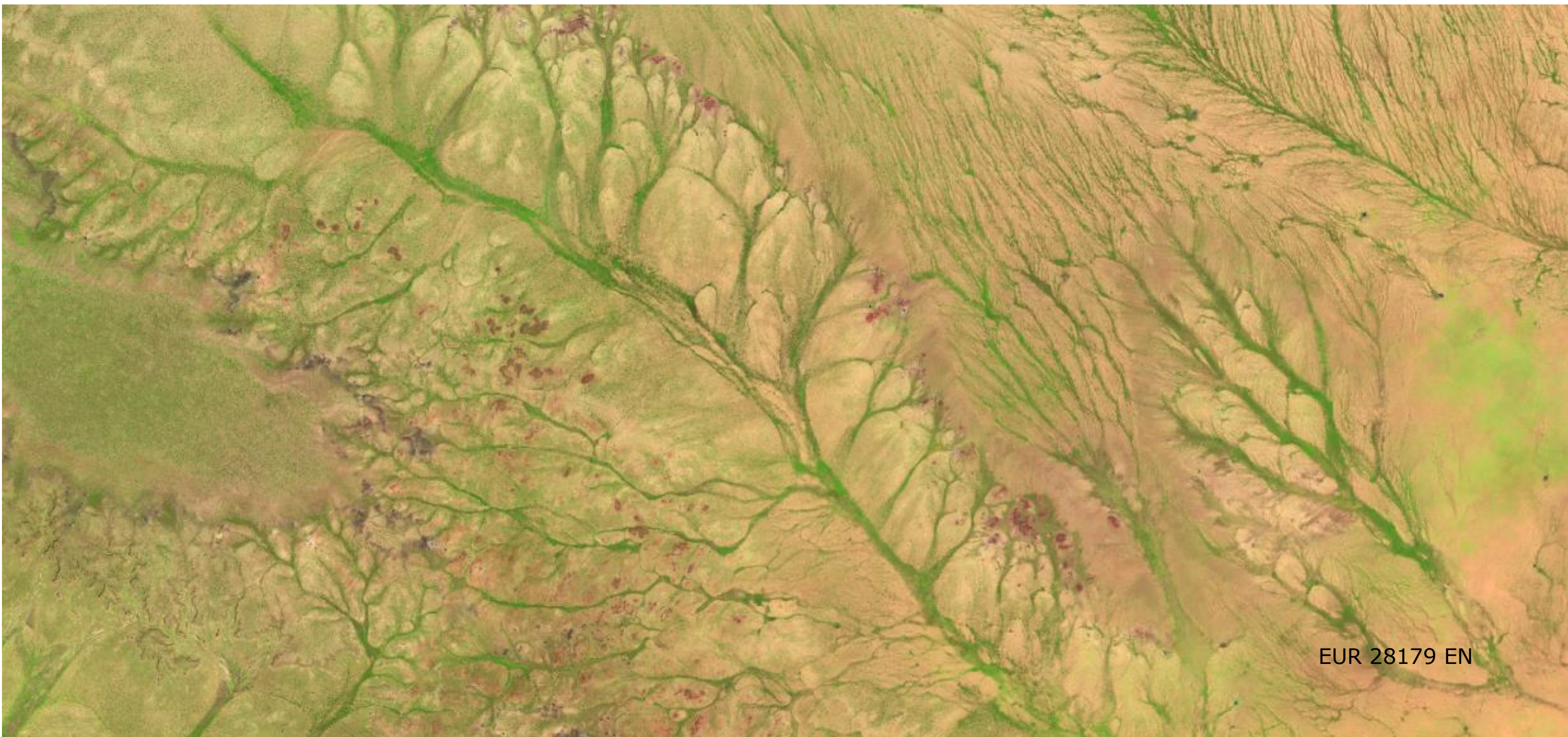
Hydrogeological study in drought affected areas of Afar, Somali, Oromia and SNNP regions in Ethiopia

Part 1: Remote sensing and overlay analysis

Abebe Ketema, Gezahegn Lemecha
Anne Schucknecht, Francois Kayitakire

2016



EUR 28179 EN

This publication is a Technical report by UNICEF and the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policy-making process. The scientific output expressed does not imply a policy position of both the European Commission and UNICEF. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use which might be made of this publication.

Affiliation of the authors
UNICEF Ethiopia: Abebe Ketema, Gezahegn Lemecha
EC JRC: Anne Schucknecht, Francois Kayitakire

Contact information
Name: Francois Kayitakire
Address: Via Fermi, 2749 / TP 266
E-mail: francois.kayitakire@jrc.ec.europa.eu
Tel.: +39 0332786580

JRC Science Hub
https://ec.europa.eu/jrc

JRC103616

EUR 28179 EN

PDF ISBN 978-92-79-63205-1 ISSN 1831-9424 doi:10.2788/050278

Luxembourg: Publications Office of the European Union, 2016

How to cite: Ketema A, Gezahegn L, Schucknecht A, Kayitakire F; Hydrogeological study in drought affected areas of Afar, Somali, Oromia and SNNP regions in Ethiopia – Part I: Remote sensing and overlay analysis; EUR 28179 EN; doi:102788/050278

Table of contents

Acknowledgements

This work has been made possible through the generous support of the EU making available their remote sensing data of Ethiopia, facilitated through a Memorandum of Understanding signed between UNICEF and the EU. We would like to acknowledge the support of colleagues from EC-JRC, Guido LEMOINE, Feyera Aga HIRPA and Peter SALAMON, and from the European Delegation to Ethiopia, David MOGOLLON and Antonio CAPONE.

We would like to thank the local groundwater experts in Ethiopia for the valuable technical discussions and contributions in reviewing and setting of the overlay analysis criteria - in particular Dr Seifu Kebede and Professor Tenalem Ayenew of Addis Ababa University and Ato Tesfaye Tadesse of the Ministry of Water, Irrigation and Electricity.

In UNICEF Ethiopia we are grateful to the support of Dr Samuel Godfrey, Dr Jane Bevan and Ali Regah for their close follow-up and guidance of the activities, and to Jane for editing this report. Thanks are also due to the UNICEF staff in the sub-national offices of Afar, Oromia, Somali and SNNPR and the regional, zonal and woreda local government water offices and the communities around the project areas for providing data/information relevant to the project and their cooperation.

Executive Summary

Ethiopia was hit by an El Nino induced drought during 2015/2016 that left millions across the country without access to adequate water supply. More than 220 districts throughout the country faced water supply emergencies. These areas are characterized by frequent shortage/shifting of rainy season and resulting water supply problems. During normal rainy years, the communities in these areas rely on rainwater harvesting, traditional ponds, hand dug wells excavated along wadis and a few shallow groundwater wells.

The United Nations Children's Fund (UNICEF) has a programme of rural water supply and is also the Emergency WASH cluster lead in Ethiopia. Hence it supports the government and other partners in the rehabilitation, maintenance and construction of new water supply systems in response to the drought.

This report presents the first part of a joint hydrogeological study of UNICEF and the European Commission Joint Research Centre (JRC) in nine selected *woredas* in the lowland areas of Afar, Somali, SNNPR, and Oromia regions in Ethiopia. The study aims to improve groundwater sector knowledge and the access to safe water in these *woredas*. Specifically, the main goal of the project is to locate drilling sites with a substantial increase in drilling success rate.

In order to improve the success rate, it is vital to undertake reliable groundwater investigations. However, conventional methods to generate detailed hydrogeological maps require a huge amount of time, manpower, logistical and financial resources. Besides hydrogeological field studies, remote sensing (RS) based analysis can be carried out to identify the most feasible sites for drilling. The advantage of using RS data is their large spatial coverage and homogeneous data acquisition. Although there is no satellite-based sensor to measure the occurrence and amount of groundwater directly, different RS-based parameters (e.g., elevation, precipitation, evapotranspiration, vegetation) can be utilized in the assessment of groundwater potential as several studies have demonstrated that spatial variability in groundwater levels is controlled by surface and subsurface topography, vegetation, soil- and bedrock properties. The use of RS data does not eliminate or exclude the in situ data collection, which is needed to verify the accuracy of RS data and to aid their interpretation, but RS data helps to minimize field data collection.

A combined approach was therefore applied in this study aiming to use all available information to increase the rate of successful drilling. The approach consists of three phases: 1) Remote sensing and overlay analysis, 2) Hydrogeological and geophysical field surveys, and 3) Drilling of productive test wells. The present report covers the first phase that comprised two main steps: a) data acquisition, processing & RS analysis, and b) overlay analysis. The RS analysis aims to generate thematic maps from RS-based products that are potentially relevant for the assessment of groundwater occurrence. Different RS datasets have been used to generate maps of the study *woredas* related to topography, geological structures (lineaments), climate (precipitation and evapotranspiration), vegetation, and hydrology. Information derived from these RS-based maps and other sources (e.g. geological maps) are then combined in a weighted overlay analysis to derive maps indicating the probability of groundwater occurrence (groundwater potential).

Parameters assumed to be related to the main factors for the occurrence of groundwater (namely permeability of the geological unit, lineament density, slope, and recharge) were directly integrated in the overlay analysis that resulted in the generation of a groundwater potential map. Senior professionals from the Ethiopian groundwater sector were consulted for the weighting process. Other parameters (like NDVI, TWI, river network) and existing water point information were then utilised to check the plausibility of the map and to determine target areas for further analysis. Since the interest was also in deep groundwater exploration, the groundwater potential maps were adapted for deep groundwater using conceptual models and deep well data wherever the information was available. Afterwards, ground-truthing work, including the identification and prioritization of permanent settlements and villages with critical water supply problems and the collection of additional local hydrogeological information was undertaken in the target areas and the surroundings to check the results of the overlay analysis. The results of the ground-truthing revealed that the selected target areas for further analysis were appropriate.

In the next steps, detailed hydrogeological and geophysical investigations will be conducted for the siting of drilling spots over the selected target areas. Similarly, based on the evaluation of the drilling results, the methodology will be up-scaled for further application to other areas.

A precursor methodology was previously applied in selected *woredas* of Afar and Tigray. The results from this and actual drilling results obtained, as well as the present field verifications indicate that the method can certainly add value to the conventional hydrogeological investigation methods to improve drilling success rates. The applied approach allowed us with relatively low cost to identify areas with a high groundwater potential and therefore reduced the expenses for field work. Drilling results of about seven boreholes drilled within Afar and Tigray have been productive. Therefore, we recommend this approach should be encouraged and expanded to a larger scale over the country, continuing the successful partnership between UNICEF and JRC.

1. Introduction

1.1 Background

Ethiopia is highly vulnerable to climatic hazards like droughts and floods. The El Niño of 2015-2016 heavily affected the country through an associated severe drought. The Meher harvest for the main June-September rainy season of 2015 showed very poor outcome. March through September rainfall totals in 2015 were the lowest in more than 50 years for central and eastern Ethiopia. Impacted areas experienced a crop production decrease by 25 to 70 per cent below average (GEWCM 2016). Besides the devastating effects on crop production, millions of people across the country were left without access to adequate water supply. More than 220 districts throughout the country faced water supply emergencies.

Several studies (e.g., Cumming & Cairncross 2016 and references therein; Demissie & Worku 2013; Fenn et al. 2012) indicate that poor access to water, sanitation and hygiene (WASH) is an important factor contributing to childhood stunting (low height for age). Poor WASH affects stunting via various direct biological and multiple social and economic mechanisms. Besides the reduction of stunting, better access to safe and sustainable WASH leads to a broad range of health and non-health benefits (Cumming & Cairncross 2016 and references therein).

In Ethiopia, the percentage of population with improved drinking water sources and improved sanitation facilities increased considerably since 1990. However, still 43 per cent of the total population (and 51 per cent of the rural population) relied on unimproved drinking water sources and 72 per cent of the population used unimproved sanitation facilities in 2015 (UNICEF & WHO 2015). The situational analysis of the nutrition sector in Ethiopia for 2000–2015 revealed that poor water supply and sanitation are risk factors for child stunting whereby the effect of poor water supply is greater among children aged 24 to 59 months while poor sanitation has a greater effect among children less than 24 months old (FMoH et al. 2016). The type of water source is an important factor in the association of water supply with stunting, as child stunting does not decrease until public tap or piped water supply is achieved. Furthermore, maternal education modifies the effect of improved water supply and sanitation. Children of mothers with some education benefit more from an improvement in these two areas than those without, indicating the need for an education/behaviour change component in water supply and sanitation improvement programs (FMoH et al. 2016).

The access to water and types of water source differ geographically within Ethiopia. Water access is critically low in the lowlands of Ethiopia, where it is difficult to have sustainable water sources. Here, people rely on temporary solutions such as water from *birkas* (underground water storage tanks stocking rain water) and in times of emergency water trucking is the only alternative. Groundwater is the main source of rural and urban water supply in the arid lowlands of Ethiopia that are characterized by complex geology, low rainfall and highly variable topography. These environmental settings represent challenging conditions for groundwater supply as drilling success rates are controlled by various factors including the geological conditions (bedrock versus sediment), climatic situation (humid versus arid), level and depth of baseline hydrogeological knowledge, and the expertise of the hydrogeologists and the drillers involved.

In recent years, the number of drilled water wells has dramatically increased through the intervention of various international and local initiatives. However, the success rate of productive wells in the arid lowlands is still very low (30-50 per cent), even by sub-Saharan African standards. The failure in pinpointing productive sites is primarily attributed to the complexity of hydrogeology in the region that requires adequate scientific information to precisely explore the availability of groundwater.

Limited investigations have been carried out with regard to the identification of groundwater resources and possible interventions for community water supply in the lowland areas of Ethiopia. Data availability is very poor and little is known about boreholes drilled or hydrogeological and geophysical investigations carried out so far to map the geological formations and/or structures which are potentially water bearing. The drastic lack of data is the major difficulty in understanding and managing groundwater resources. Even where the information is available, it is incomplete, uneven and often of poor quality, which further complicates the problem.

In order to improve success rates, it is vital to undertake reliable groundwater investigations. However, conventional methods to generate detailed hydrogeological maps require a huge amount of time, manpower, logistical and financial resources. Besides hydrogeological field studies, remote sensing (RS) based analysis can be carried out to identify feasible sites for drilling. The advantage of using RS data is their large spatial coverage and homogeneous data acquisition. Although there is no satellite-based sensor to measure the occurrence and amount of groundwater directly, different RS-based parameters (e.g. elevation, precipitation, evapotranspiration, vegetation) can be utilized in the assessment of groundwater potential. Several studies have demonstrated that spatial variability in groundwater levels is reflected by surface and subsurface topography, vegetation, soil and bedrock properties (Rinderer et al. 2014). However the use of RS data does not eliminate the in situ data collection needed to verify the accuracy of RS data and to aid their interpretation, but RS data helps to minimize field data collection (Jha et al. 2007). Previous studies utilized different RS data for the exploration and assessment of groundwater resources, for example aerial photographs and Landsat TM images (Salaman et al. 1994), Landsat TM (Teeuw 1995), Landsat TM, SPOT, and infrared aerial photographs (Sander et al. 1996), Landsat TM and SPOT (Leblanc et al. 2007), radar imagery and aerial photographs (Edet et al. 1998), IRS LISS-II or -III (Shahid & Nath 2002; Kumar et al. 2007; Chowdhury et al. 2009), IRS ID LISS-III and Landsat TM (Rao & Jugran 2003), Landsat 7 ETM, SPOT and aerial photos (Shaban et al. 2006), Meteosat, AVHRR, SRTM, MODIS, Landsat TM, and MODIS (Leblanc et al. 2007).

In Ethiopia, limited groundwater investigations that use RS data have been undertaken due to accessibility constraints and processing costs of satellite imagery. Although high resolution images (spatial resolution of about tens of meters; suitable for mapping in the scale range 1:25,000 to 1:100,000) are freely available (e.g. Landsat and Sentinel 2 data), access is often problematic for example due to low internet speed, lack of data processing tools and skills, etc. On the other hand, many conventional hydrogeological field investigations (e.g. resistivity and conductivity analysis) are suitable for local scale assessment (but still require combination with other information like geology, precipitation, etc. to understand groundwater recharge and flow), but they are not appropriate for larger scale studies to locate groundwater resources (e.g. too expensive). Therefore, methodologies combining satellite imagery, hydrogeological (field) studies and geophysical surveys are required for a more precise location of deep groundwater occurrences.

UNICEF is active in the WASH sector of Ethiopia, supporting the Government of Ethiopia and other partners in the rehabilitation, maintenance and construction of new water supply systems, provision of water purification and treatment chemicals, scaling up of water trucking activities, and provision of sanitation and hygiene facilities in schools. In addition, UNICEF is exploring innovative ways to use satellite data to detect deep groundwater for large scale, multiple-village water supply systems. As part of the overall drought emergency response, UNICEF supports programmes in child protection, education, health and nutrition.

In 2015, UNICEF had implemented a project that combines the different kinds of groundwater analysis to locate areas with a high potential of groundwater occurrence in three Ethiopian *woredas* in Afar and Tigray regions through UNESCO contracted international and local experts (Acacia Water 2015; AYJEF Water Woks and Business

Service PLC 2015). This former groundwater feasibility study was conducted in three different phases (1) Remote sensing analysis, (2) hydrogeological and geophysical investigations in areas identified from the remote sensing analysis, and (3) test drilling of selected sites identified, having a success rate of over 80 per cent. The third phase is currently ongoing in five selected drilling sites in Afar region whereby the first four boreholes were successfully drilled and one is in progress.

1.2 Context of this report

The United Nations Children's Fund (UNICEF) and the European Union (EU) agreed in a Memorandum of Understanding in February 2016 (MoU, UNICEF and EU) to collaborate in a hydrogeological study in selected *woredas* in the lowland areas of Afar, Somali, SNNPR, and Oromia regions in Ethiopia. The study aims to improve groundwater sector knowledge and the access to safe water in these *woredas*. Specifically, the main goal of the project is to locate drilling sites with a substantial increase in drilling success rate.

Similar to the previous study on groundwater in Ethiopia, the joint UNICEF-EU study consists of three phases:

1.) Remote sensing and overlay analysis,
2.) Hydrogeological and geophysical field surveys, and
3.) Drilling of productive test wells.

The methodology and results of the first phase will be covered in this report, while a second report will be dedicated to phases two and three.

Within the first phase of the study, the main responsibility of the EU through the European Commission Joint Research Centre (JRC) was the acquisition, processing, and analysis of RS-based data, while UNICEF was responsible for the overlay analysis and the acquisition, processing, and analysis of geological and field data. The aim of the RS analysis is the generation of thematic maps that are potentially relevant for the assessment of groundwater occurrence (e.g. for elevation and derived parameters, climate parameters and vegetation). These RS-based maps are then combined with other information (e.g. geology) in an overlay analysis (applying expert weighting) to produce a groundwater occurrence probability map. Based on the results of the overlay analysis, site specific detailed hydrogeological and geophysical field surveys are conducted in the areas with the highest groundwater occurrence potential to verify potential drilling sites for productive deep wells. Currently selected areas are based on the survey of critical water problem areas in combination with the evaluation of groundwater resources. Hydrogeological and geophysical surveys have already been conducted on the first batch of sites at the time of writing of this report. Similar investigations will be conducted on other potential areas in the future as required.

2. Study area

The study areas were determined by UNICEF in consultation with the regional water bureaus and the Ministry of Water, Irrigation and Electricity (MoWIE) and cover the following districts (*woredas*):

- Afdera, Bidu, Dalul, and Kori in the Afar region
- Kumbi and Meyu Muluke in the Oromia region
- Alaba in the SNNPR region
- Gashamo and Shinile in the Somali region

The study *woredas* (Figure 1) are located in the arid lowland areas (except Alaba) characterized by a lower water supply coverage, a higher number of non-functional wells and a chronic drought vulnerability. Apart from areas adjacent to perennial rivers like the Awash River (not flowing through the study *woredas*), groundwater is the only sustainable water source for the local population. It is often difficult to strike productive wells with a reasonable amount of water and an acceptable quality.

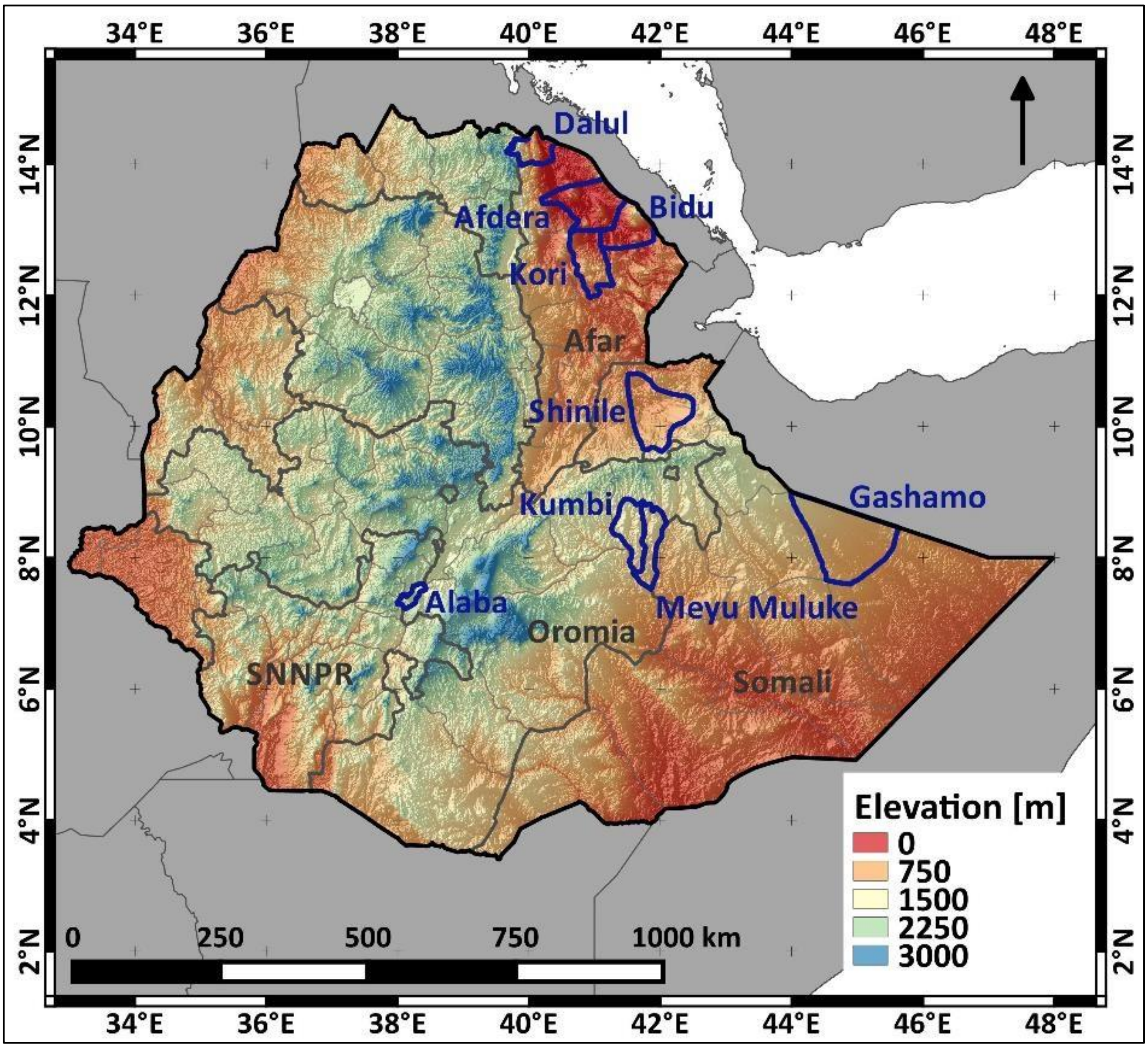


Figure 1. Location of the selected study woredas (in blue) in Ethiopia and corresponding region (administrative boundaries: Gaul 014) as well as elevation with hillshade (from HydroSHEDS)

Geology

Most of the selected *woredas* are situated within the east African rift system which is the largest structural feature of the Earth's crust. The geology of the project *woredas* in Afar and SNNP regions is dominated by rift related volcanic rocks. The Afar rift floor mainly consists of upper Miocene to recent volcanic rocks, which are predominantly basic. Fissural basaltic lava flows, silicic domes and lavas, and thick pyroclastic deposits constitute the main petrographic units of the rift floor and the Afar lowlands. The depression areas are covered by alluvial sediments. Project *woredas* in Somali and Oromia regions are covered by consolidated Mesozoic sediments and unconsolidated Quaternary sediments.

The oldest rocks in the study *woredas* are the metamorphic units mapped in the Dalul *woreda*. A sedimentary unit deposited during the Mesozoic era by transgression and regression processes is overlying the basement rocks. Hamaneli limestones mapped in Meyu Muluke and Kumbi, and Jessoma sandstones in Gashamo are among the rock units deposited by this process of transgression and regression. Overlying the Mesozoic sedimentary succession are the rift volcanics. The plateau basalt is the oldest among the group. Quaternary units are the youngest rock in the study area.

In the project area all types of rocks i.e. basement, sedimentary, volcanic and unconsolidated sediments have been mapped. Except for the basement rock, sedimentary volcanic and unconsolidated rocks have primary geologic structures which make them important from a groundwater movement and storage point of view.

In limestone environments karst structures are important for groundwater storage and movement. The karst structures also follow tectonic trends and joints.

The Jessoma sandstone is a highly permeable rock unit, and the thickness of the unit is huge. However a lower confining bed cannot be found within economic depths which makes the unit insignificant as groundwater storage media.

The rift valley is known to be a geologically active zone which as a result complicates the occurrence and movement of groundwater systems. It is characterized by complex faults aligned mainly in NE-SW direction, which is parallel to the general trend of the axis of the rift. Fractures due to faulting play a very important role in the movement and occurrence of groundwater in the Cenozoic volcanics, particularly in the rift valley and adjacent escarpments.

Most of the rocks have a high permeability. The common presence of aquiclude intercalations in the volcanic and sedimentary units generally cause the availability of shallow/deep groundwater as well as a stack of aquifers interconnected by large faults and fractures, Water quality issues are a well-known problem in the rift valley. Thermal groundwaters of high salinity occur frequently in the rift lowlands especially at large depths. In some areas, the fluoride content or the salinity of the groundwater is too high for human consumption, such as in the Alaba *woreda*. High salinity caused by low recharge and high evapotranspiration as well as salt contribution through groundwater movement occurs in the lowlands such as in the Afdera *woreda*.

Better quality groundwater can be found at the foot of the escarpments of the rift valley within the alluvial fans such as in the Afdera and Dallol *woredas*.

3. Data and methods

The occurrence, movement and storage of groundwater depend on multiple factors. The controlling parameters are not uniform for all geographic areas. An aggregation of the controlling parameters is needed in order to find suitable locations for siting groundwater exploitation wells. Weighted overlay analysis is a technique for the digital aggregation of diverse inputs to create an integrated result in a GIS environment.

There are various approaches to perform an overlay analysis, but the general steps involve (*http://resources.arcgis.com/en/help/previous-help/*):

- Problem definition
- Breaking the problem into sub models
- Determining the significant layers
- Reclassifying or transforming the data within a layer
- Weighting the input layers
- Adding or combining the layers
- Analysing the result

In the present study, the applied methodology comprised two main steps: 1) data acquisition, processing & RS analysis, and 2) overlay analysis (Figure 2). The RS analysis aims to generate thematic maps from RS-based products that are potentially relevant for the assessment of groundwater occurrence. Different RS datasets have been used to generate maps of the study *woredas* related to topography, geological structures (lineaments), climate (precipitation and evapotranspiration), vegetation, and hydrology. Information derived from these RS-based maps and other sources (e.g. geological maps) are then combined in a weighted overlay analysis to derive maps indicating the probability of groundwater occurrence (hereafter called "groundwater potential maps"). The two main steps of the methodology are presented in more detail in the following sub-chapters.

We applied the open source QGIS software (version 2.14.1; http://www.qgis.org/en/site/) as well as ArcGIS (version 10.3.1 for Desktop; Esri Inc.; http://www.esri.com) to build Geographic Information System (GIS) databases for this project, to process data (e.g., georeferencing, digitization, reprojection) and to perform different geospatial analyses.

As well as using the two GIS programmes, we applied the following software:

- SPIRITS Software for the Processing and Interpretation of Remotely sensed Image Time Series (version 1.3.1; http://spirits.jrc.ec.europa.eu/) for the processing and analysis of time series
- ENVI (version 5.0.3 [classic]; Exelis Visual Information Solutions, Inc.; www.exelisvis.com) for image processing and analysis
- Google Earth Engine (https://earthengine.google.com/) to compute and extract products (NDVI, colour composites) from Landsat 8 images
- Geomatica 2016 (Trial Version; PCI Geomatics; www.pcigeomatics.com) for the lineament analysis
- SAGA System for Automated Geoscientific Analysis (version 2.1.2; http://www.saga-gis.org) for the computation of the topographic wetness index (TWI)

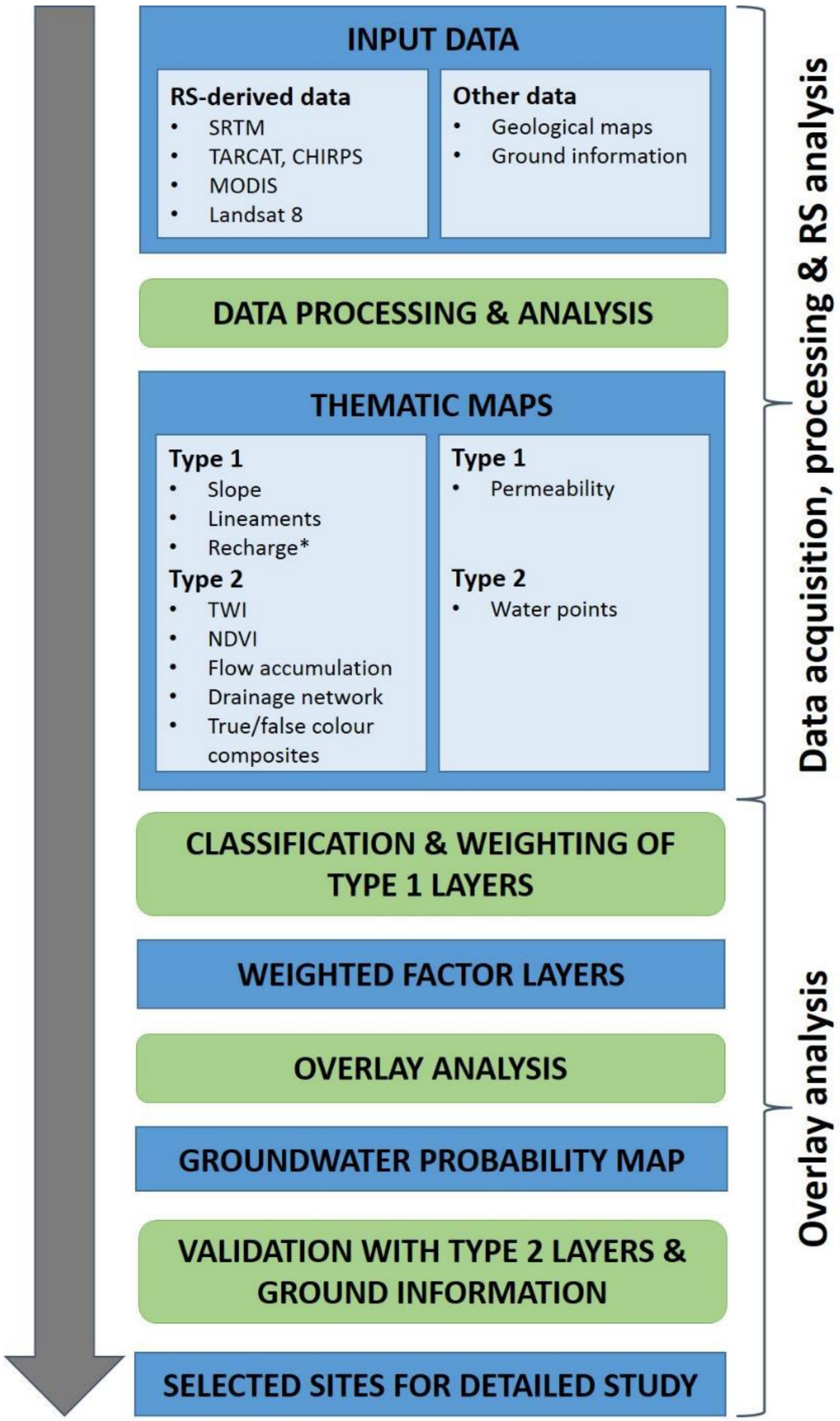

INPUT DATA
RS-derived data
SRTM
TARCAT, CHIRPS
MODIS
Landsat 8
Other data
Geological maps
Ground information
DATA PROCESSING & ANALYSIS
THEMATIC MAPS
Type 1
Slope
Lineaments
Recharge*
Type 2
TWI
NDVI
Flow accumulation
Drainage network
True/false colour composites
Type 1
Permeability
Type 2
Water points
CLASSIFICATION & WEIGHTING OF TYPE 1 LAYERS
WEIGHTED FACTOR LAYERS
OVERLAY ANALYSIS
GROUNDWATER PROBABILITY MAP
VALIDATION WITH TYPE 2 LAYERS & GROUND INFORMATION
SELECTED SITES FOR DETAILED STUDY
Data acquisition, processing & RS analysis
Overlay analysis

Figure 2. Flow chart of applied methodology. blue = (intermediate) products, green = action, process

3.1 Data acquisition, processing and remote sensing analysis

Different satellite imagery (Table 1) and other data sources were utilized to generate thematic maps. The methodology of the RS analysis partly followed the methodology applied in the recent UNICEF-UNESCO groundwater feasibility study described in the Acacia Water Report (2015). This section shortly describes the different products, processing steps and performed analyses. More detailed information are provided in Appendix 1.

Table 1. Overview of parameters derived from RS data

Parameter	Source product	Spatial resolution	Remarks
Slope	SRTM	30 m	
Lineaments	SRTM	30 m	
Topographic Wetness Index	SRTM	30 m	
River network, drainage direction, flow accumulation	HydroSHEDS	500 m	derived from hydrologically conditioned SRTM
Precipitation	TARCAT CHIRPS	0.04° 0.05°	TARCAT data used for generation of groundwater recharge map
Evapotranspiration	MODIS (MOD16A3)	1000 m	
NDVI	MODIS Landsat 8	250 m 30 m	
True and false colour composites	Landsat 8	30 m	Used for visual validation

3.1.1 Digital Elevation Model and derived products

Based on a digital elevation model, different parameters can be derived that can affect the occurrence of groundwater. The regional and local relief settings give an indication about the general groundwater flow direction and its influence on groundwater discharge and recharge (Jha et al. 2007). The slope affects the groundwater potential in a sense that lower slopes show in general a higher groundwater potential (Jha et al. 2007). In rocky terrains, lineaments (linear geological features in a landscape) may point to underground fractures and faults indicating groundwater occurrence (Jha et al. 2007). Open lineaments significantly enhance the permeability of rock formation by inducing secondary porosity. In the presence of interconnected fractures, cracks, joints, fault or shear zones or solution cavities, rainwater can easily percolate through them and contribute to groundwater recharge.

Data. A Shuttle Radar Topography Mission (SRTM) product (available from the U.S. Geological Survey, e.g. via the USGS EarthExplorer: http://earthexplorer.usgs.gov/) was used as a source for elevation data. The utilized product offers worldwide coverage of void filled elevation data with a spatial resolution of 1 arc second (~30 meters).

Processing. The tiles covering the study *woredas* were mosaicked and bad pixel values were replaced. Subsequently, several analyses were performed based on these processed elevation layers:

Terrain analyses were performed to generate layers for slope, aspect (the compass direction that a slope faces) and hillshade.

The **lineament analysis** is based on the methodology for automatic extraction of lineaments proposed by Muhammad & Awdal (2012). Hillshades with different azimuth angles were calculated from the SRTM elevation layer and used as an input for the automatic lineament extraction module (LINE) of Geomatica.

The **Topographic Wetness Index (TWI)** is a measure of the topographic control on hydrological processes and is used to calculate the likelihood for soil saturation. The TWI is defined as

$$\mathrm{TWI} = \ln(a/\tan(\beta)),$$

where a is the local upslope area draining through a certain point per unit contour length and β is the local slope (Beven & Kirkby 1979; Sørensen et al. 2006). Several studies reported groundwater levels to be correlated to TWI (the higher the TWI, the higher the groundwater level) although correlation strengths vary (Rinderer et al. 2014 and references therein). High TWI values indicate recharge areas and occur in places with high flow accumulation values and flat slopes.

The TWI can be computed in many different ways, depending on how the upslope area and the local slope are calculated. We followed an approach for SAGA GIS described in a Geographic Information Systems Forum.[1]

3.1.2 Hydrological information

For hydrological applications, DEMs often need a further processing to provide useful results. The **Hydro**logical data and maps based on **SH**uttle **E**levation **D**erivatives at multiple **S**cales (HydroSHEDS; Lehner et al., 2006) is such a further processed product derived from hydrologically conditioned SRTM data. HydroSHEDS provide hydrographic information for regional and global-scale applications in a consistent format. In this study we used the HydroSHEDS product for **drainage direction**, **flow accumulation** (in a number of cells), **river network** (stream lines), and **drainage basins** (watershed boundaries) which all have a spatial resolution of 15 arc-seconds (approximately 500 m at the equator).

The river (drainage) network of a certain region provides a good indication of the permeability of the underlying soil/rock formation. A high drainage density develops on surfaces with low permeability because surface runoff exceeds infiltration and a low drainage density develops on permeable bed rocks where infiltration exceeds surface runoff. In highly porous formations, the drainage network is less developed or completely missing. Thus, drainage density has a close relationship to the groundwater availability of an area.

[1] See http://gis.stackexchange.com/questions/90064/calculating-topographic-wetness-index-choosing-from-different-algorithms [last access: 14/06/2016]

3.1.3 Climate data

Climate parameters (e.g., precipitation, temperature, evapotranspiration, wind speed) are important factors in the groundwater potential assessment as they control (besides other factors) the amount of water that infiltrates in the ground and may contribute to groundwater recharge. In this study, precipitation and evapotranspiration (the sum of evaporation and plant transpiration from the Earth's land and ocean surface to the atmosphere) were integrated in the analysis assuming they are the most important climate parameters for groundwater potential in the study region.

Precipitation. Two different data sets were used for the precipitation analysis: the TAMSAT (Tropical Applications of Meteorology using SATellite data and round-based observations) African Rainfall Climatology And Time-series (**TARCAT**) version 2.0 dataset (Maidment et al, 2014; Tarnavsky et al., 2014) with a spatial resolution of 0.04° and the **CHIRPS** version 2.0 dataset (Climate Hazards Group InfraRed Precipitation with Station data; Funk et al. 2015) with a spatial resolution of 0.05°. Both datasets incorporate satellite imagery with in-situ station data, but differ in their data sources and algorithms resulting in different final products.

For both datasets the dekadal data (10-day sums) was cumulated to annual precipitation sums. Then, the mean and the standard deviation (SD) of annual precipitation sums were calculated for a 30 years period (1986–2015) and a short-term period (2000–2014 to match the evapotranspiration data).

Evapotranspiration. Annual evapotranspiration (ET) and potential ET (PET) data were obtained from the Moderate-resolution imaging spectroradiometer (MODIS) **MOD16A3** product (Mu et al. 2011). The product with a spatial resolution of 1 km covers the period 2000–2014. Mean and SD for annual ET and PET were calculated.

3.1.4 Vegetation and land cover

In (semi-)arid regions with seasonal and erratic rainfall, vegetation patterns can indicate near-surface water availability and movement (Greenbaum et al. 1993). Among others, vegetation patterns are related to the ability of plants to get water through their root systems. During the dry season, photosynthetically active (green) vegetation indicates the availability of soil moisture or shallow groundwater whereby plants with tap roots may give a hint for deeper moisture (Greenbaum et al. 1993). Hence, active vegetation during the dry season and/or a relatively low seasonal variability of vegetation greenness represents a surface indicator for groundwater discharge areas (Leblanc 2003; Tweed et al. 2006). Additionally, the inter-annual variability of vegetation activity can also provide helpful information for groundwater discharge mapping (Tweed et al. 2006).

The Normalized Difference Vegetation Index (NDVI) is a useful measure to monitor light-dependent physiological processes like photosynthesis and therefore indicating vegetation activity, amount of (green) vegetation, and health status. NDVI values theoretically range from -1.0 to +1.0. Negative NDVI values (approaching -1*)* correspond to surface water while barren areas of sand, rock, or snow are characterized by very low NDVI values (0.1 or less, also slightly negative). Sparse vegetation like shrubs and grasslands or senescing crops show moderate NDVI values (about 0.2 to 0.5) while dense vegetation for example in tropical and temperate forests or crops at their peak growth state show high NDVI values (about 0.6 to 0.9).

In this study, eMODIS NDVI data provided by FEWS NET (http://earlywarning.usgs.gov/fews/) was used to analyse the mean occurrence and seasonal development of vegetation. The 10-day composite images from 2001–2015 with a spatial resolution of 250m were aggregated to mean monthly and mean annual NDVI images. Then the mean and SD of the monthly and annual images were calculated.

In order to show the occurrence of vegetation and other landscape characteristics with a higher spatial resolution, **Landsat-8** (L8) images with a spatial resolution of 30 m were utilized. Aiming to show a kind of "maximum vegetation extent," indicating areas where soil moisture is available at least during certain times and could potentially contribute to recharge of deep groundwater or indicating areas where vegetation utilizes shallow groundwater, the eMODIS profiles for each *woreda* of the years 2013–2015 were visually analysed to find a period with high NDVI values. Then the availability of (nearly) cloud free L8 images for these periods was checked and if necessary the period of interest was refined. Afterwards, the following products were extracted for each Woreda and the selected time period:

- NDVI (as maximum-value composite of the available images)
- True colour composite (RGB = Band 6, Band 5, Band 4)
- False colour composite (RGB = Band 5, Band 4, Band 3)

Additionally, we extracted NDVI maximum-value composite images from the entire Landsat-8 archive available at this time (2013/02/01 to 2016/04/22).

3.1.5 Geology and lithology

Rock units (including unconsolidated material) and their physical characteristics (lithology) are important factors for groundwater recharge and storage as they are the medium where groundwater flows through and where it is stored. One groundwater relevant parameter of rocks is their permeability (κ) describing the ability to allow fluids to pass through it. The permeability depends on the porosity of the rocks, the shapes of the pores and their level of connectedness.

Regional geological maps with a scale of 1:250 000 produced by the Geological Survey of Ethiopia (GSE) were available to UNICEF in printed format and were digitized and re-projected. Map sheets used to cover the study *woredas* are listed in Table 2.

Table 2. List of geological maps and their source

Map sheet	**Covered *woreda***	**Source**
Geological Map of Hosaina	Alaba	GSE
Geological Map of Wabi Shebele Basin	Kumbi, Meyu Muluke	MoWIE
Geology & Geomorphlogy of Shinile Zone & adjoining areas	Shinile	MoARD[2]
Geological Map of Afar Regional State	Afdera, Bidu, Dalul, Kori	UNESCO-UNICEF
Geological Map of Eastern Ethiopia	Gashamo	UNESCO

Additionally to the geological/lithological units, geological structures were also digitized from geological maps and used in the validation process of RS-derived information.

[2] MoARD : Ministry of Agriculture and Rural Development

3.1.6 Other data

Additional information from non-RS sources are important to complement (like geology, see sub-chapter 3.1.5) and validate the RS-based analysis results. Ground information utilized in this project included water points (springs, hand dug, shallow and deep wells), settlements and roads. Some of these data were collected using GPS during the ground verification study and others were obtained from government offices and existing documents in soft and hard copy. The data was used to validate the analysis, to refine target areas for the detailed study and to identify accessibility conditions of the potential sites.

Information on **water points** were retrieved from different hydrogeological reports and maps, and utilized in the validation of the overlay analysis results. ***Kebele*** (smallest administrative unit, part of a *woreda*) **boundaries, the location of towns and roads** were extracted from the Central Statistics Census database. This data is important in ground verification of works and also to discuss borehole siting with the local administration.

3.1.7 Groundwater recharge

Groundwater recharge is a hydrologic process by which water moves downward from the surface through the vadose zone and then to the saturated zone to become groundwater. It is the primary method through which water enters an aquifer. Groundwater is recharged naturally by precipitation and to a smaller extent by surface water (rivers and lakes). In general, groundwater recharge is difficult to estimate. The most important methods include direct measurements, water balance, Darcyan and tracer methods (Kinzelbach et al. 2002). Due to data constraints in the study area a simplified water balance method (input – output = storage) is the only one that could be applied. Assuming a flat area without significant surface runoff, no permanent water bodies and small lateral inflow and outflow, the recharge can be estimated as the difference between precipitation and evapotranspiration (Brunner et al. 2002; Kinzelbach et al. 2002). However, these assumptions may not hold true in all the study areas. For example, the deep groundwater systems in the *woredas* may get additional inputs from lateral groundwater inflow of neighbouring areas (*woreda* borders do not reflect the extent of aquifers). Additionally, this method in general has a low accuracy due to the large inaccuracies of the input parameter (precipitation and evapotranspiration) at a regional scale. Therefore the results should be treated with caution.

For this study, the recharge map layer was derived from the product of precipitation (mean annual precipitation calculated from TARCAT for period 1986-2015) and hydraulic conductivity.

3.2 Overlay analysis

The overlay analysis aims to combine different groundwater relevant information (derived from RS products or existing maps and reports) in a meaningful way to create a map of groundwater potential and to identify priority areas for further analysis. Different assumptions were made to guide the selection and weighting of parameters:

- Regional permeability: groundwater yield potential increases with higher regional permeability
- Secondary permeability: groundwater yield potential increases with higher density of lineament, joints, and faults
- Topographic location: groundwater yield potential increases in areas with gentle slopes and in valley bottoms (as the contact/residence time of runoff water with the ground surface is higher than in steep terrain and therefore also the potential recharge could be higher)

- Groundwater recharge: groundwater yield potential increases with increasing recharge

The fundamental principle/assumption for the overlay analysis is that areas covered by permeable geological unit(s) of adequate thickness at suitable geomorphological positions that have sufficient recharge to store and transmit groundwater will be ranked with a high groundwater potential.

The overlay analysis utilizes a semi-quantitative approach in a GIS environment and consists of three main steps: a) the classification and weighting of primary parameters/factors (type 1 layers), b) the combination of the classified and weighted layers in an overlay analysis, and c) the refinement of the results with secondary factors (type 2 layers). Type 1 layers determine the occurrence, movement and storage of groundwater and include:

- Permeability (related to geology/lithology)
- Slope (related to geomorphology)
- Lineament density (related to geological structures)
- Groundwater recharge (related to infiltration and precipitation)

Type 2 layers are indicators for the occurrence of shallow groundwater and/or soil moisture, and comprise:

- NDVI
- TWI
- Flow accumulation
- Drainage network

A preliminary step in the overlay analysis is the correct preparation of the input layers. For each *woreda* all input layers need to have the same spatial extent, the same projection and the same spatial resolution. Therefore vector-based layers need to be rasterized and all layers need to be re-projected to the same coordinate system (here: UTM, xxx) and re-sampled to the selected common spatial resolution if necessary. In our analysis we applied the spatial resolution of the input layer with the lowest spatial resolution (groundwater recharge, i.e. 0.04°).

3.2.1 Classification and weighting

The selected type 1 layers do not have an equal contribution or importance for the occurrence, movement and storage of groundwater. Hence, a percentage of influence (layer weight) was assigned to each layer related to its degree of importance based on expert's judgment (Table 3). The assigned weights were peer-reviewed by a panel of senior experts in the field of groundwater research and utilization. The total influence for the four raster layers adds up to 100 per cent.

Table 3. Weights for type 1 layers

Layer parameter	Layer weight [per cent]
Permeability	30
Slope	30
Groundwater recharge	25
Lineament density	15

Then, type 1 layers were re-classified to obtain three to five classes per layer and a weighting factor (class weight) was assigned to each class corresponding to its groundwater potential (the higher the weight, the more favourable are the conditions for groundwater occurrence). The weights of all classes of a certain layer sum up to 100 per cent. Similar to the layer weight assignment, the assignment of class weight was based on expert's judgement. The (re-)classification of type 1 layers was necessary as the input of the utilized weighted sum module (from ArcGIS Spatial Analyst Toolbox) for the overlay analysis requires raster layers with integer values. Hence continuous (floating point) rasters like slope, lineament density and recharge were grouped into classes with certain value ranges and assigned a single new class weight during the reclassification process. The classification and weighting of each type 1 layer is presented below.

Permeability and hydraulic conductivity

The hydraulic conductivity is an indication of the permeability of porous media. Based on expert knowledge, the hydraulic conductivity of the different geological units occurring in the study *woredas* was estimated in categorical terms (i.e. very low, low, medium, high and very high) and infiltration coefficient values were assigned to each category (Table 4).

Table 4. Classification of the permeability and corresponding weights

Class of hydraulic conductivity	Hydraulic conductivity description	Infiltration coefficient	Class weight [per cent]
1	Very high	0.2	40
2	High	0.15	25
3	Medium	0.10	20
4	Low	0.05	10
5	Very low	0.03	5

Slope

The slope layer was reclassified into four slope classes which all have a certain weight (Table 5).

Table 5. Re-classification and weighting of the slope layer

Slope class	Slope range	Slope class description	Class weight
1	0° - 5°	Flat and valley bottom	55
2	5° - 15°	Gentle slope	30
3	15° - 25°	Moderate slope	10
4	> 25°	Steep slope	5

Lineament density

Lineament density is defined as the total length of the linear feature segments per unit area. A higher lineament density is assumed to increase the groundwater potential. A lineament density layer was generated from the lineament vector layer by rasterization using a line density function with a search radius of 1 km. It was assumed that the intensity of fracturing decreases after a 1 km radius and its contribution for groundwater occurrence and movement decreases significantly. The lineament density map was then re-classified into 3 classes using the equal interval classification method separately for each *woreda* (hence being a relative classification). Then, class weights were assigned to each lineament density class (Table 6).

Table 6. Lineament density classes with corresponding weights

Lineament density class	Lineament density	Class weight
1	High	65
2	Moderate	25
3	Poor	10

Groundwater recharge

The groundwater recharge map was reclassified in relative terms separately for each *woreda* using the equal interval method and three classes. The weight for each class is presented in Table 7.

Table 7. Weighting of the recharge classes

Recharge class	Recharge class description	Class weight
1	High groundwater recharge	55
2	Moderate groundwater recharge	35
3	Low groundwater recharge	10

3.2.2 Overlay analysis

Finally, all the weighted primary factor layers were combined into one layer displaying the groundwater potential utilizing the weighted sum overlay analysis module of the ArcGIS Spatial Analyst tool. Based on the type 1 layer weights, the following formula for the overlay analysis was applied:

GWP = 30 per cent * P + 30 per cent * S + 25 per cent *R +15 per cent *L,

where GWP is the resulting layer (groundwater potential), P is the weighted permeability layer, S the weighted slope layer, R the weighted recharge layer, and L the weighted lineament density layer. The resulting layer was then classified qualitatively into five classes using the natural breaks (Jenk) method. Again, this classification was done separately for each *woreda* and therefore is a relative classification (e.g. the high groundwater potential class has a different range of GWP values for each *woreda*).

3.2.3 Refinement of overlay analysis results

The information from the secondary factors (type 2 layers; namely NDVI, TWI, flow accumulation, and drainage network) as well as true and false colour images of Landsat 8 were used to check the results of the overlay analysis and to further refine priority areas for further (field) analysis in regions of high groundwater potential. This step was based on expert knowledge integrating the following assumptions:

- Areas with a higher mean NDVI indicate higher mean soil moisture and are hence more likely to have higher shallow groundwater potential, which could have a link to a deep groundwater system
- Areas with a reasonable mean NDVI (representing vegetation) and a low standard deviation in semi-arid regions indicate the present of shallow groundwater (or irrigation).
- Areas with higher TWI are more likely to have higher groundwater potential.
- A high density of the drainage network indicates a low permeability of the ground and hence low groundwater potential.

As type 2 layers do not enter in the overlay analysis itself, they were not classified so that the full range of information could be used.

3.3 Validation of the results

In order to verify the suitability of the utilised approach to map groundwater potential in the study *woredas*, the results (groundwater potential map) should be validated, preferably with field data on groundwater. However, due to data constraints an in-depth validation was not possible in the region. The attempt for a "light" validation in this study included field visits for ground-truthing and the utilization of existing well data.

UNICEF Ethiopia and the University College London (UCL) undertook a validation study to analyze the strength of the models outlined in this report. Three statistical tools were used; namely, Logistic Regression, Analytical Hierarchy Process (AHP) and Artificial Neural Networks (ANNs). The results indicate a high level of correlation between the AHP and the ANN and a lower correlation with the regression analysis. Full details will be available in https://www.ucl.ac.uk/library/theses

3.3.1 Ground-truthing

After the determination of target areas for further field hydrogeological and geophysical studies, field visits were undertaken to these target areas and their surroundings in order to check the information obtained from the input layers and the results from the overlay analysis.

The ground-truthing work involved the following steps:

- Observations on the geomorphological settings
- GPS readings and map verifications
- Water point survey and mapping
- Checking suitability zones presented on the RS output with general ground conditions
- Geological and hydrogeological observations
- Identification of target priority areas for immediate interventions (drilling of wells)
- Identification of limitations in the groundwater potential map outputs

3.3.2 Validation with water points and well data

Information from mapped shallow water points (dug wells, springs, and shallow wells) can be used to check the plausibility of the obtained groundwater potential map for shallow groundwater in the study *woredas*. The existing water point data was collected from different sources at all stages during the project and included in the GIS database. The point data was then plotted on the groundwater potential map to see the relationship between the different groundwater potential classes and the water points.

In the present study we are also interested in deep groundwater occurrence. Therefore, it was necessary to validate the methodology for deep groundwater mapping. The inventoried deep wells (depth > 150 m) in the study *woredas* were used for this purpose. However, sufficient data on wells with depth information was only available for Dalul (amount of deep wells n = 13; depth range = 150–250 m) and Alaba (n = 23; depth = 174–362 m). The location of the deep wells was overlain on the groundwater probability map and checked for plausibility (i.e. do the productive wells occur in areas with high groundwater potential).

4. Results and discussions

In this chapter, the results of the overlay analysis, the delineation of target areas and the validation of the results are presented for each *woreda*. Besides the groundwater potential maps, true-colour composite images from Landsat 8 are shown to get an idea about the appearance of the landscape.

4.1 Afar region – Afdera

The groundwater potential map (Figure 3) indicates that the north-western area and the eastern foot slope and adjacent north-eastern areas are classified as highly suitable zones, whereas the central and southern areas of Afdera are classified to have a moderate groundwater potential. However, the groundwater potential itself does not give an indication about the water quality. For example, it is well known that in the peripheries of Lake Afdera and adjacent areas, the issue of groundwater salinity persists as a constraint. The best locations for obtaining good quality groundwater are likely to be over high or moderate to high potential areas mapped adjacent to the western and eastern mountain areas which are fresh groundwater recharging zones.

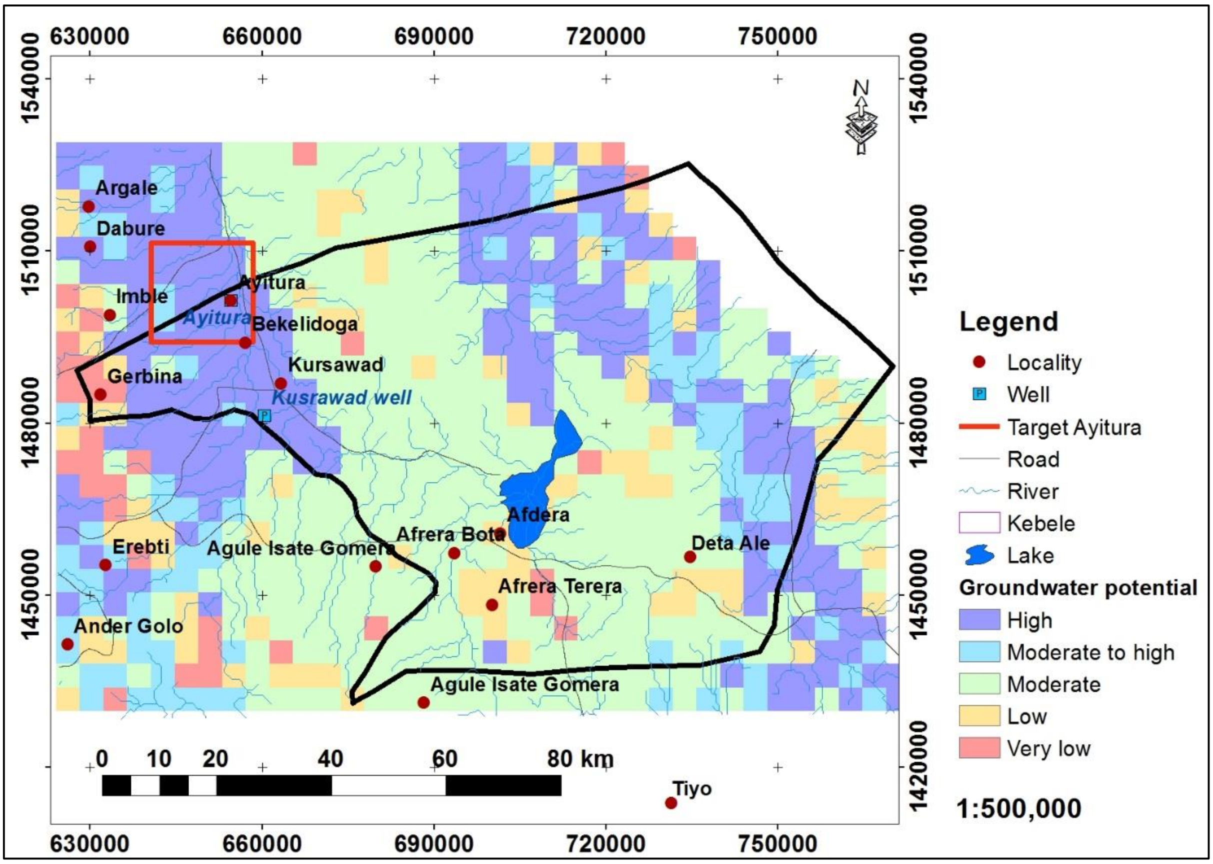


Figure 3. Groundwater potential map of Afdera

During the ground-truthing work, along the sections of Afdera-Erebti and then towards the east to Deta-Ale locality, it was found that the overlay output matches with the observed ground conditions. Similarly, a recently drilled (2016) productive well (reported depth of 60 m) by the Afar Water Bureau at Ali-Genda locality (Kusrawad well; SW of Kursawad) and with good water quality falls in the zone classified as highly suitable. In the eastern part of the *woreda* there are no drilled wells. Hence it was not possible to support the groundwater potential map with actual drilling records. The hot water springs on the bank of Lake Afdera and close to Afdera town are an indication of geothermal effects in the central sections of the area.

The areas with highest NDVI values indicating relatively dense vegetation cover are also found to be supporting evidence for the availability of moisture – especially for shallow groundwater occurrence – in the zone marked as of high potential in the northwest. The presence of vegetation in the NW of the *woreda* is also highlighted in the true-colour composite images (Figure 4, Figure 5).

Regional groundwater flow to recharge deep groundwater aquifers to the areas identified as suitable for drilling is inferred to come from the western highlands and adjacent valleys following the trends of the surface water flows directions, i.e. towards the east as illustrated by the conceptual models (hydrogeological cross-section; will be presented in another UNICEF report).

Within the Afdera *woreda*, it is inferred that both shallow and deep groundwater systems exist. The recently drilled productive well in the area (Kusrawad) to a depth of 60 m is evidence for the shallow groundwater system. The conclusion for deep groundwater was derived from the conceptual models.

The Ayitura *kebele* locality which partly falls in the high GWS zone in the NW of the study area was selected as a first priority area for immediate well drilling. The surface geology of the plain area is dominantly covered with silt, sand and gravel with some sand dune features. However, during the ground-truthing work, it was observed that the shallow groundwater intercepted by hand dug wells over the general location is saline. Therefore, in this area it is inferred that the salinity could be at shallow depth as a result of high evaporation effects. The regional deep fresh groundwater system could be intercepted at deeper horizons which should be confirmed by further studies.

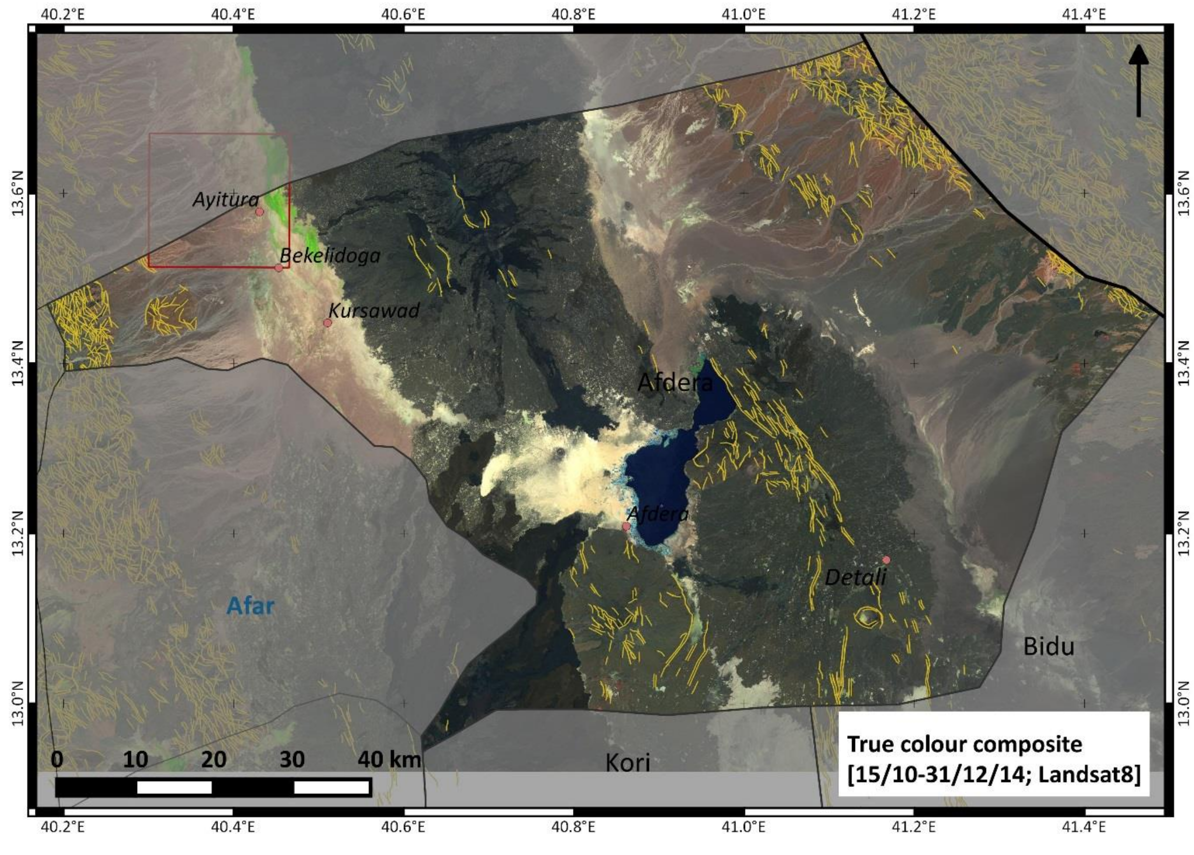


Figure 4. True colour composite (Bands 6-5-4) of Afdera for the period 15/10/2014–31/12/2014 (Landsat 8), lineaments (yellow; derived from SRTM data), and target area (red rectangle)

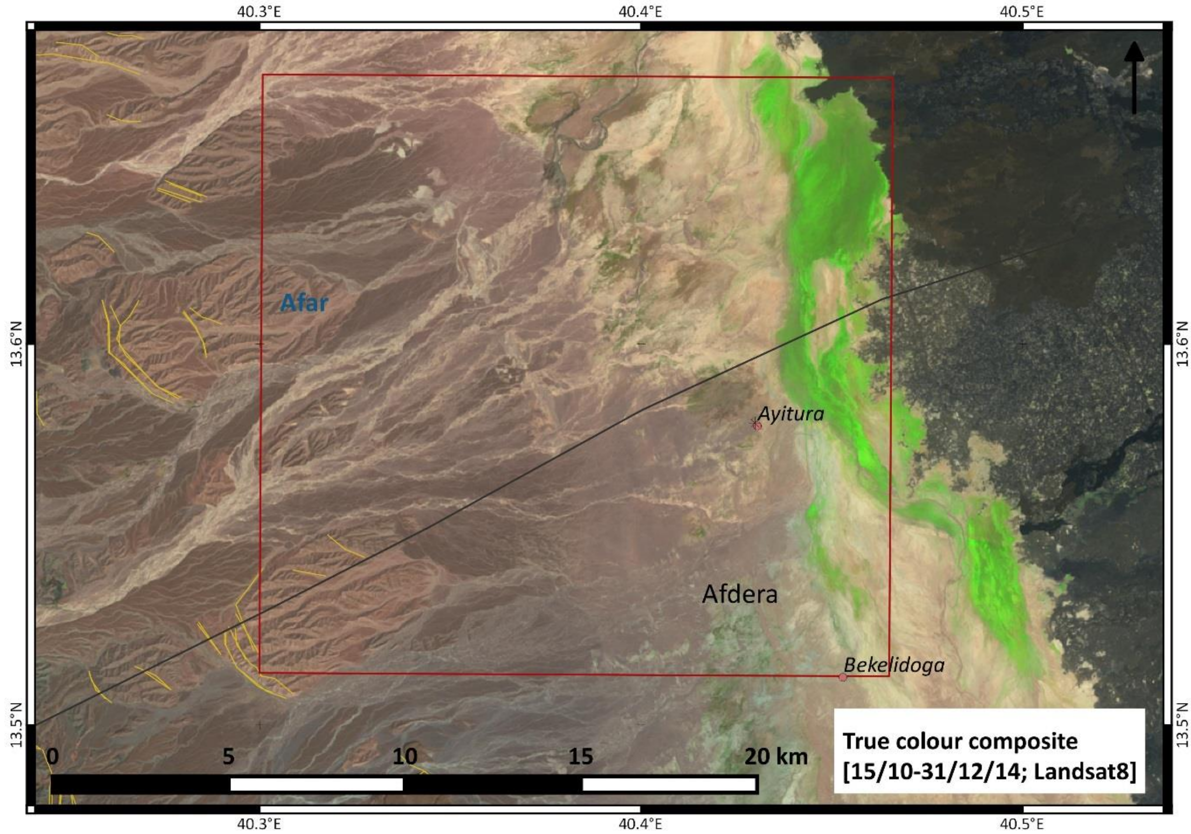


Figure 5. Zoom-in of Figure 4 showing the target area (red rectangle) around Ayitura.

4.2 Afar region – Bidu

The result of the overlay analysis shows that large parts of the *woreda* fall within the low and very low groundwater potential zones (Figure 6). This is mainly due to the rugged topographic setting of the *woreda* and other factors influencing groundwater occurrence. Parts of the central and western areas of the *woreda* are mapped as having moderate to high potential.

The selected priority area for detailed hydrogeological and geophysical studies to drill a productive well for community water supply is around Tiyo village (Figure 8). This place is located close to the high groundwater potential zone in the southwest. As the Tiyo village is in need of water, the target area was not set directly in the high potential zone, but around the village. The geology of this target area dominantly consists of alluvial and colluvial deposits in the depressions and of tuffs and basalt rocks in the adjacent highlands. The area has a large catchment area connected from the south where regional lineaments are inferred to guide water flow directions towards the target area. Additionally, a part of the Kori *woreda* is draining in the river network of the Bidu lowlands, which could also favour the possibility of groundwater recharge to the Bidu *woreda* area.

During the ground-truthing period, the only water points found around the area are two wells drilled for Bidu town water supply, though their characteristics could not be retrieved. It has been reported that wells located west of the *woreda* boundary have bad water quality of unknown chemistry due to the underlying geological units. According to local information, drinking the water from these sources creates problem to urinate, a serious health problem locally known as ‘Shint-mat” that needs further investigations. The possible variations in the groundwater conditions and supply of Tiyo and Bidu town should receive special attention for multi village approach during the detailed studies.

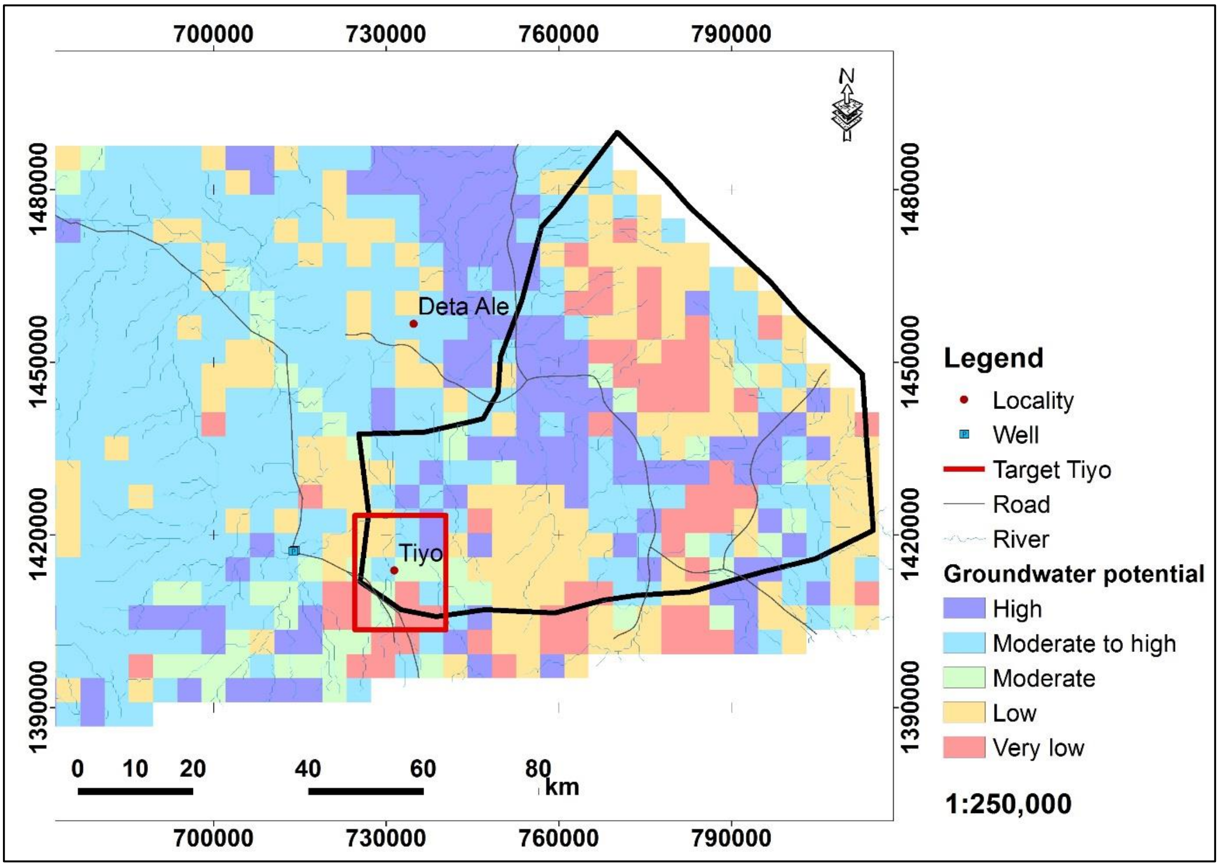


Figure 6. Groundwater potential map of Bidu

The dense geological structures (lineaments) having an orientation of nearly north–south mapped over the western part of the *woreda* (Figure 7) in the direction of Tiyo-Deta Ale land mass alignment, were vividly observed during the ground-truthing work.

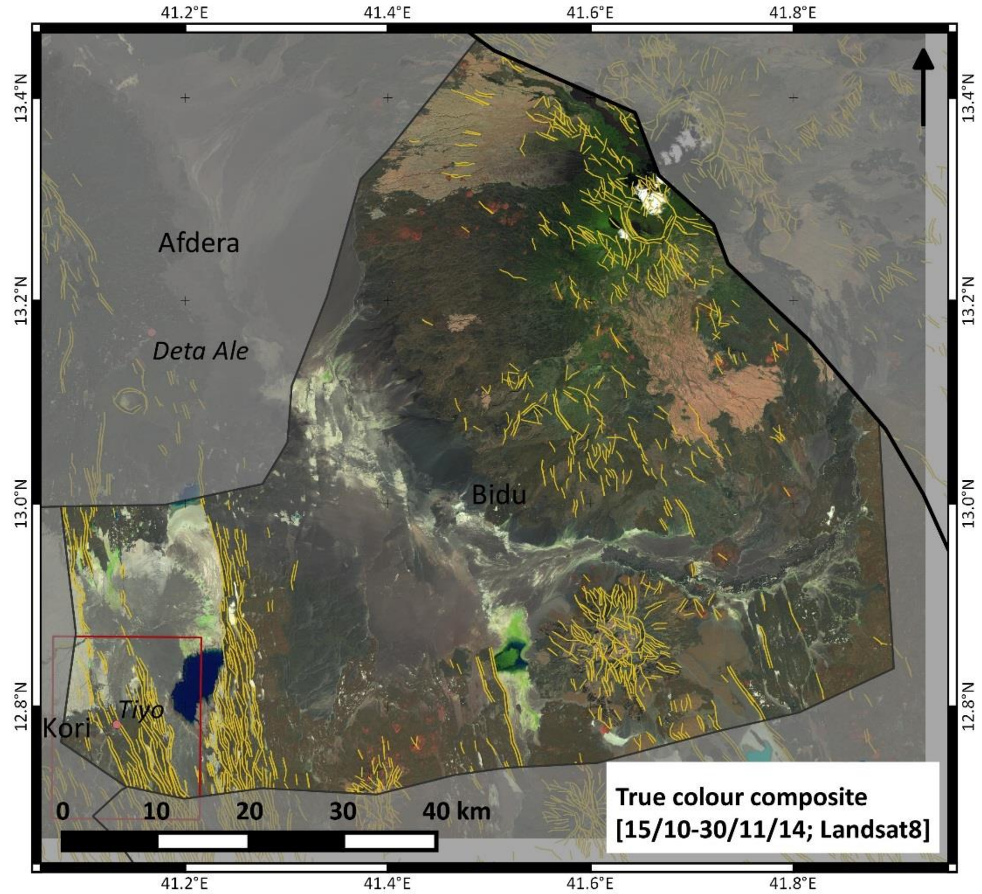


Figure 7. True colour composite (Bands 6-5-4) of Bidu for the period 15/10/2014–30/11/2014 (Landsat 8), lineaments (yellow; derived from SRTM data) and target area (red rectangle)

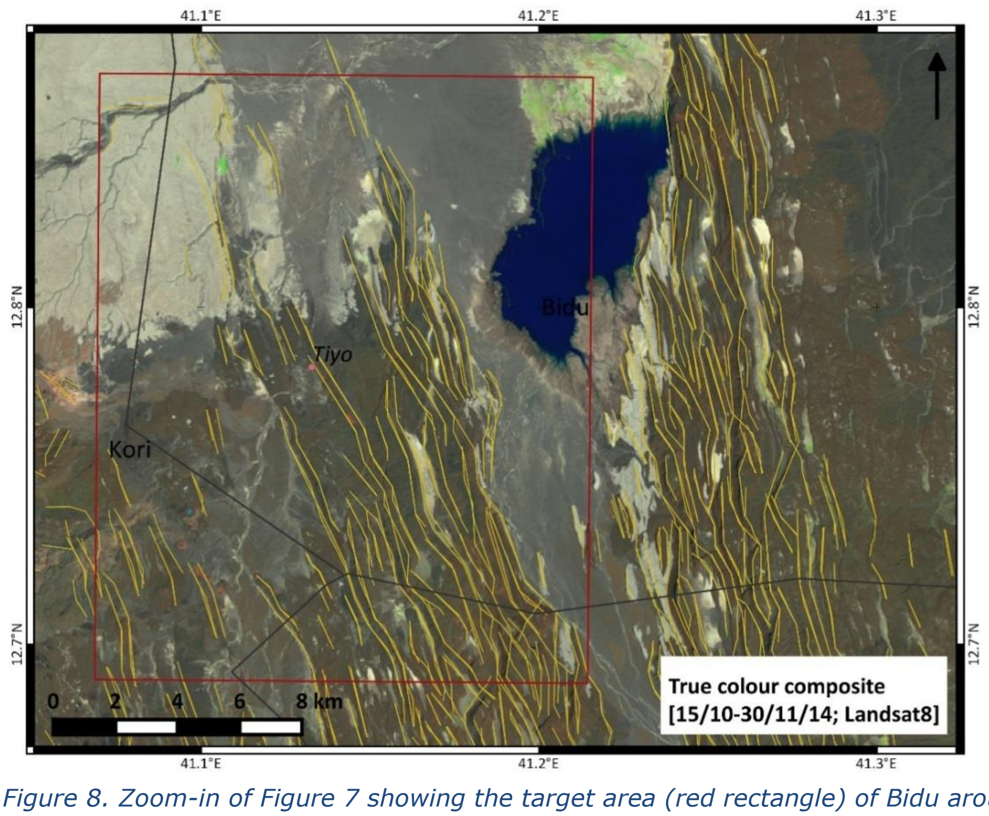


Figure 8. Zoom-in of Figure 7 showing the target area (red rectangle) of Bidu around Tiyo

4.3 Afar region – Dalul

The groundwater potential map of Dalul (Figure 9) indicates a high potential zone in the central area of the *woreda* along the Ayshit graben as well as some smaller regions east of the Awrimo Mountains. The mountainous regions in the west and east of the Ayshit graben are mainly characterised by moderate to very low potential.

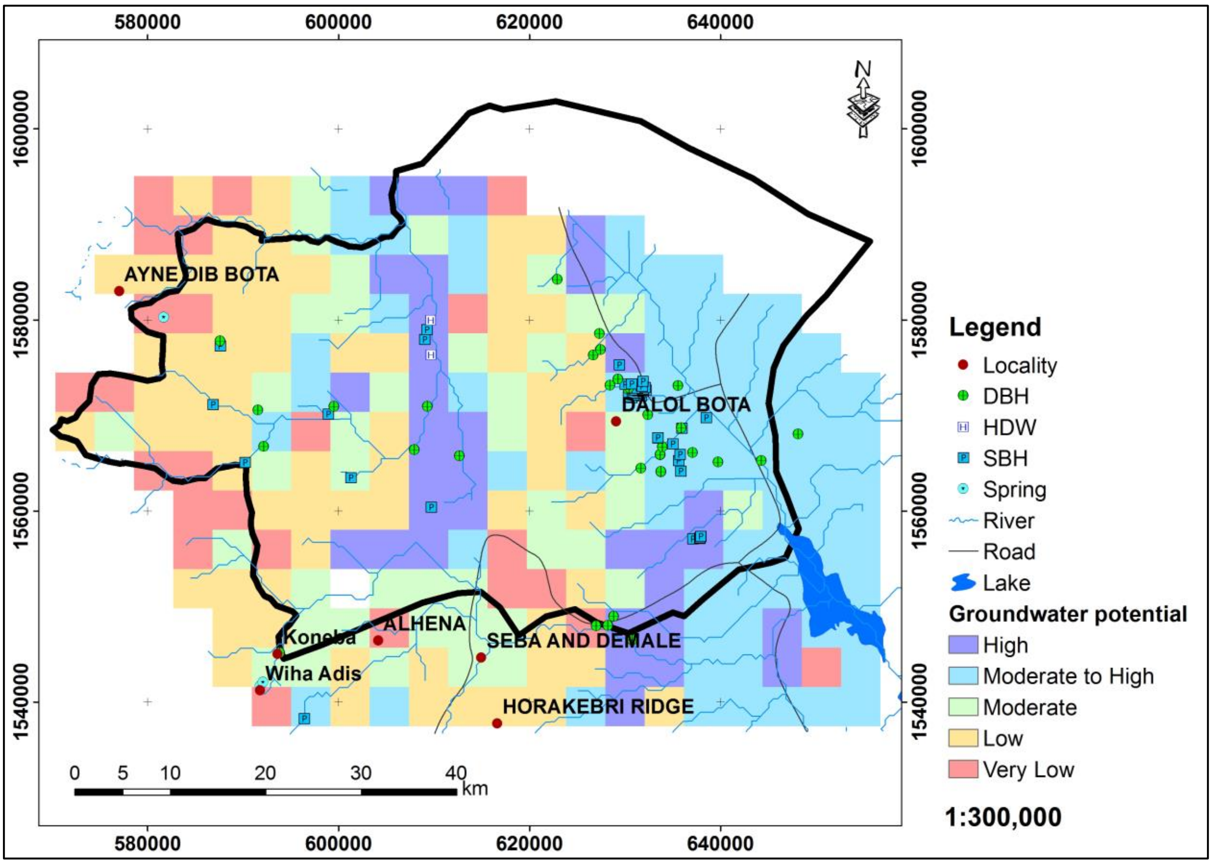


Figure 9. Groundwater potential map of Dalul

The Dalul *woreda* shows a huge variety of rock types. The oldest rocks occurring in Dalul are the basement rocks covering 33.8 per cent of the *woreda*. There are also Mesozoic sedimentary units composed of Adigrat sandstone and Antalo limestone overlays the Precambrian unit in the area. Overlaying the Mesozoic sedimentary unit is the Afar stratoid series (dominantly olivine basalts) and the marginal rhyolite centres of Pliocene-Pleistocene age. The youngest lithologic unit mapped in Dalul is the Quaternary sedimentary unit which covers about 40 per cent of the *woreda* area.

For this *woreda* a clear correlation of geomorphological control for occurrence of groundwater was observed during the ground-truthing activity as one traverses in the east-west direction where representative sections of the *woreda* area can be observed. The zones classified as low to very low potential as well as the high to moderate zones depicted on the groundwater potential map are in good agreement with the general ground observations described below. The high potential area of the Ayshit graben area east of Adequa town and extending longitudinally in a north-south direction is supported by the existence of high-yielding irrigation wells drilled in this zone and visited during the field work in the Simbilal *kebele*. The irrigated fields are clearly visible in the Landsat 8 composite image (Figure 10, 11). The Musley fan located in the eastern part of the *woreda* falls within the moderate potential zone. The highlands west of Adequa fall within low to very low potential areas.

The area is relatively well studied and a large number of well data exists. The inspected wells drilled within the Ayshit graben in the high groundwater potential zone reach a depth of 204 m and are reported to have yields in the range of 28 l/s with reasonable drawdown. During the ground-truthing period, two wells which were under pumping test and reported to last for a month (aquifer stress test) were observed to be in progress at Ayshit locality.

Superimposing the already existing water point data over the potential map reveals that all the productive wells drilled in the *woreda*, both deep and shallow ones, fall within the zone classified to have medium to high groundwater potential which indicates a good match of the overlay results with the actual ground. Springs are also found to fall in the zone mapped as low to very low groundwater potential.

Both shallow and deep groundwater exists in the *woreda* as it has been revealed by the well records obtained from the area. Influx of regional groundwater is inferred from the western adjacent highland area towards the areas identified as suitable for groundwater development.

Due to the relatively better groundwater sector knowledge and ongoing additional studies and drilling activities in Dalul, no target area was selected for this *woreda* and priority was given to other *woredas*.

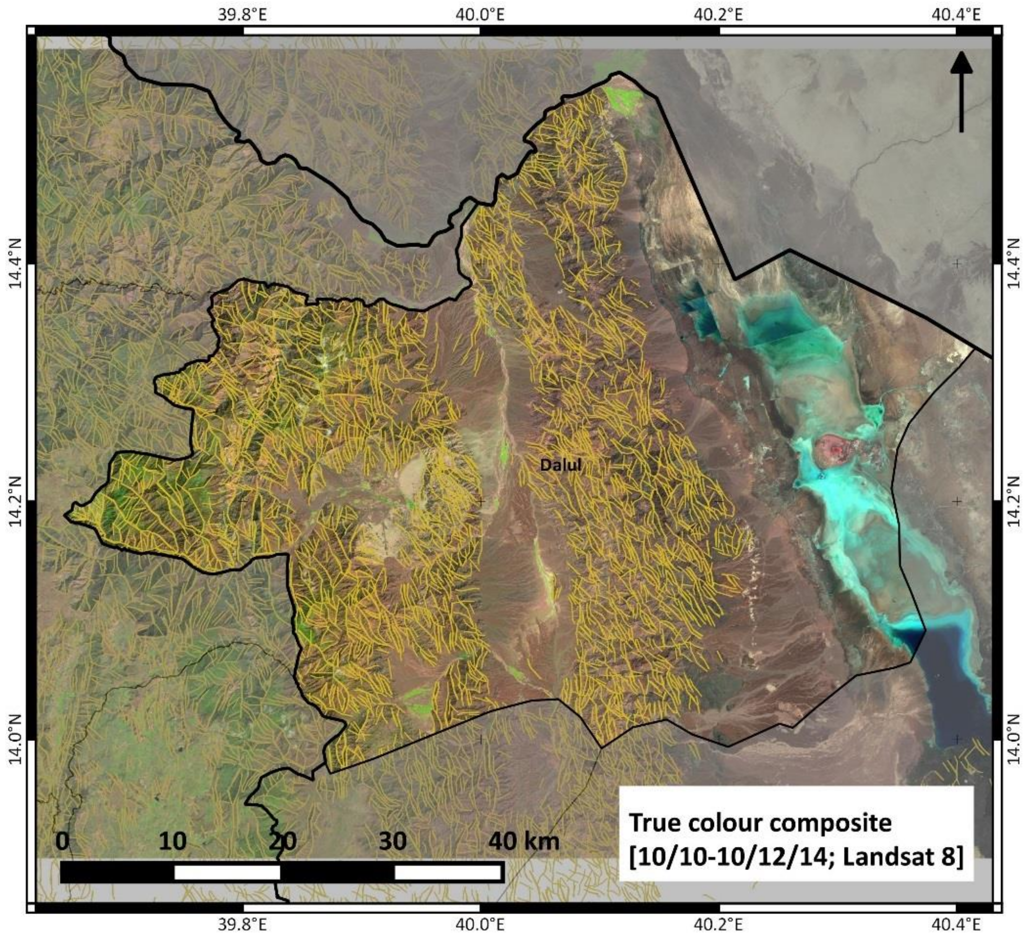


Figure 10. True colour composite (Bands 6-5-4) of Dalul for the period 10/10/2014–10/12/2014 (Landsat 8) and lineaments (yellow; derived from SRTM data)

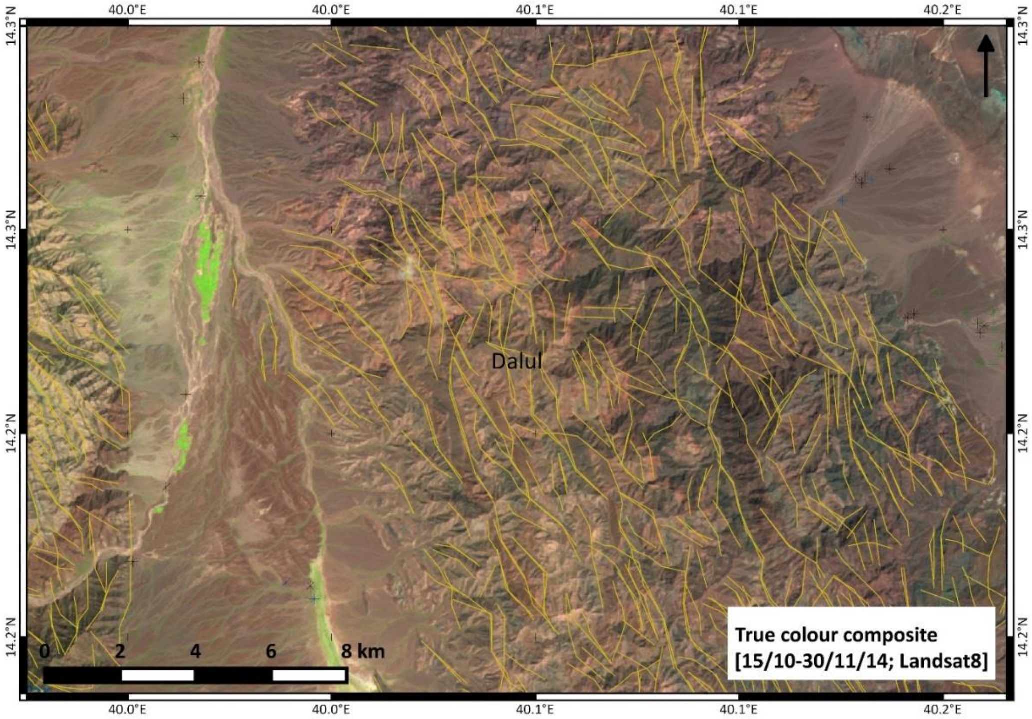


Figure 11. Zoom-in of Figure 10 showing irrigated fields in the Ayshit graben (intense green in left part of the image). Source: Landsat 8 for true colour composite; SRTM for lineaments (yellow)

4.4 Afar region – Kori

In a regional context, this *woreda* is situated over a water divide where drainage moves away from the local area to the adjacent valleys. Most parts of the *woreda* are characterized by moderate groundwater potential (Figure 12). A bigger connected patch of higher groundwater potential is indicated southeast of Agule Isate Gomera locality. The very low and low groundwater potential zones correspond to the mountainous and highland areas. It is also inferred that the locations identified as suitable could have interconnections with regional groundwater systems outside the *woreda* and could also receive local recharge. The target area in the Musley *kebele* was defined prior to the analysis of our study and hydrogeological and geophysical investigations have already been done.

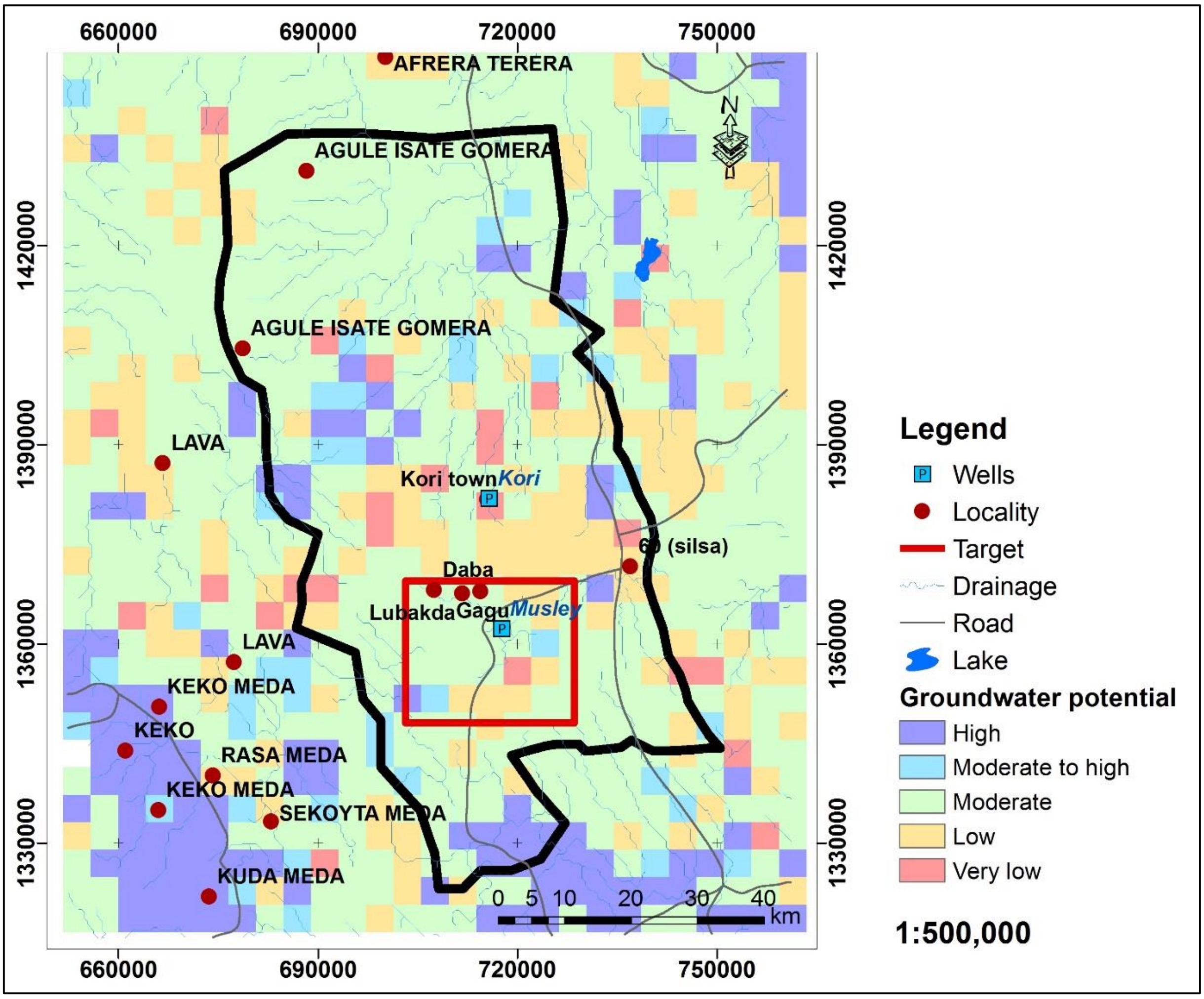


Figure 12. Groundwater potential map of Kori

The geology of the *woreda* is made of dominantly volcanic rocks (basalts, tuff, and rhyolites) and quaternary alluvial deposits as observed on the clear outcrops exposed over the area. Generally, except in the northern and southern parts, the area is rugged and less favourable for groundwater prospecting.

Though detailed records have not been retrieved, old non-functional boreholes have been observed to have been drilled at the centre of the *woreda* (Kori town) within the local aquifers reported with corrosive hot groundwater. As a result, it has been reported that electro-mechanical installations (pipes and pumps) face frequent damage and fall in the wells, resulting in re-drilling of wells every year. About 6 wells have already been drilled one after the other at the same location as replacements.

Recently UNICEF has also drilled a well to a depth of 394 m at Musley. This location falls within the moderate groundwater potential zone of the overlay analysis result. The result so far indicates the existence of hot and saline groundwater. The well is under construction at the time of the reporting period.

The rugged and rocky grounds in the south-eastern and north to north-eastern part of the *woreda* are characterized by dense geological structures trending northwest–southeast (Figure 13) within the domain of the regional structural framework. Some of these major geological structures have been observed on the ground.

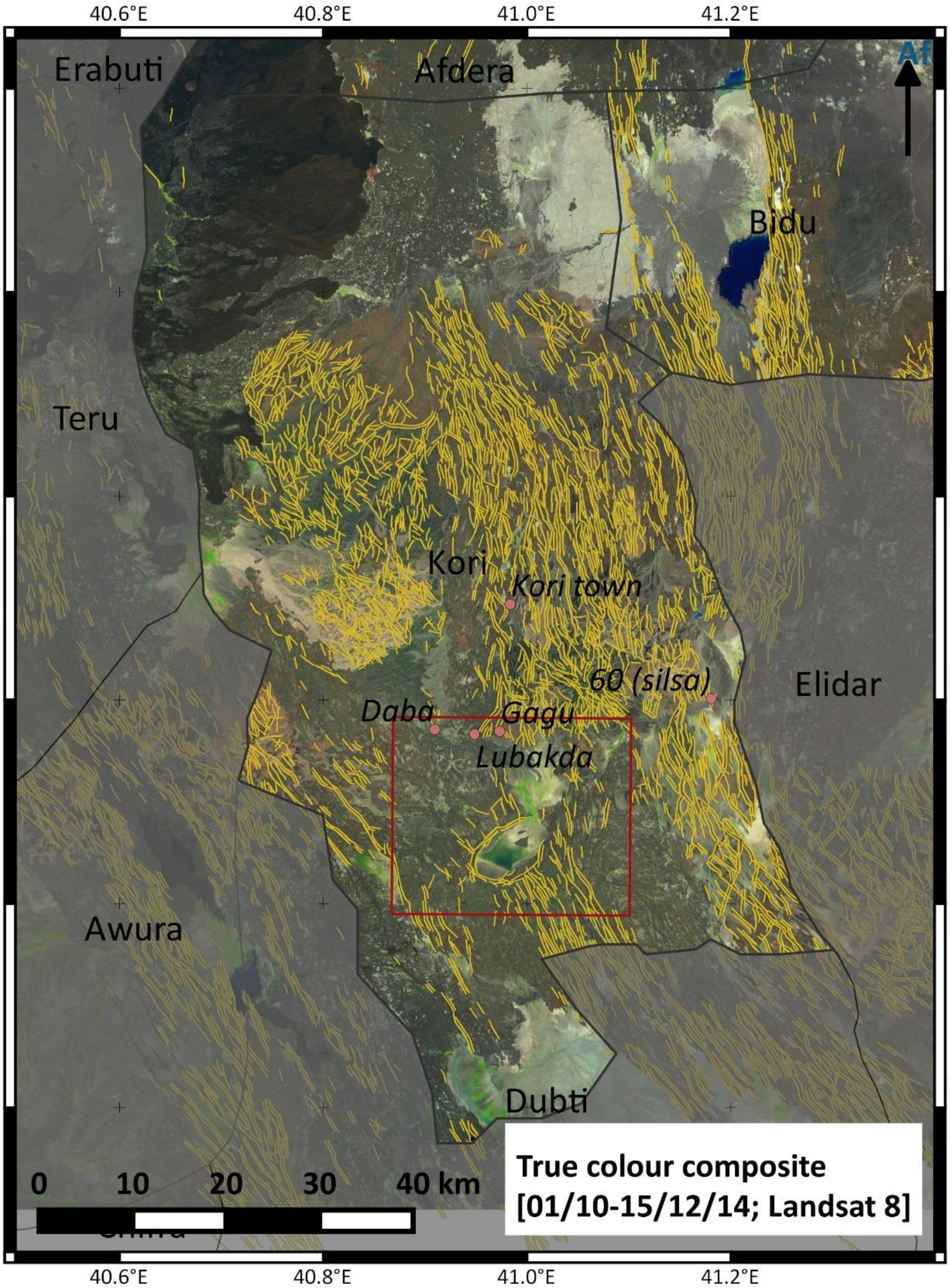


Figure 13. True colour composite (Bands 6-5-4) of Kori for the period 01/10/2015–15/12/2015 (Landsat 8) and lineaments (yellow; derived from SRTM data)

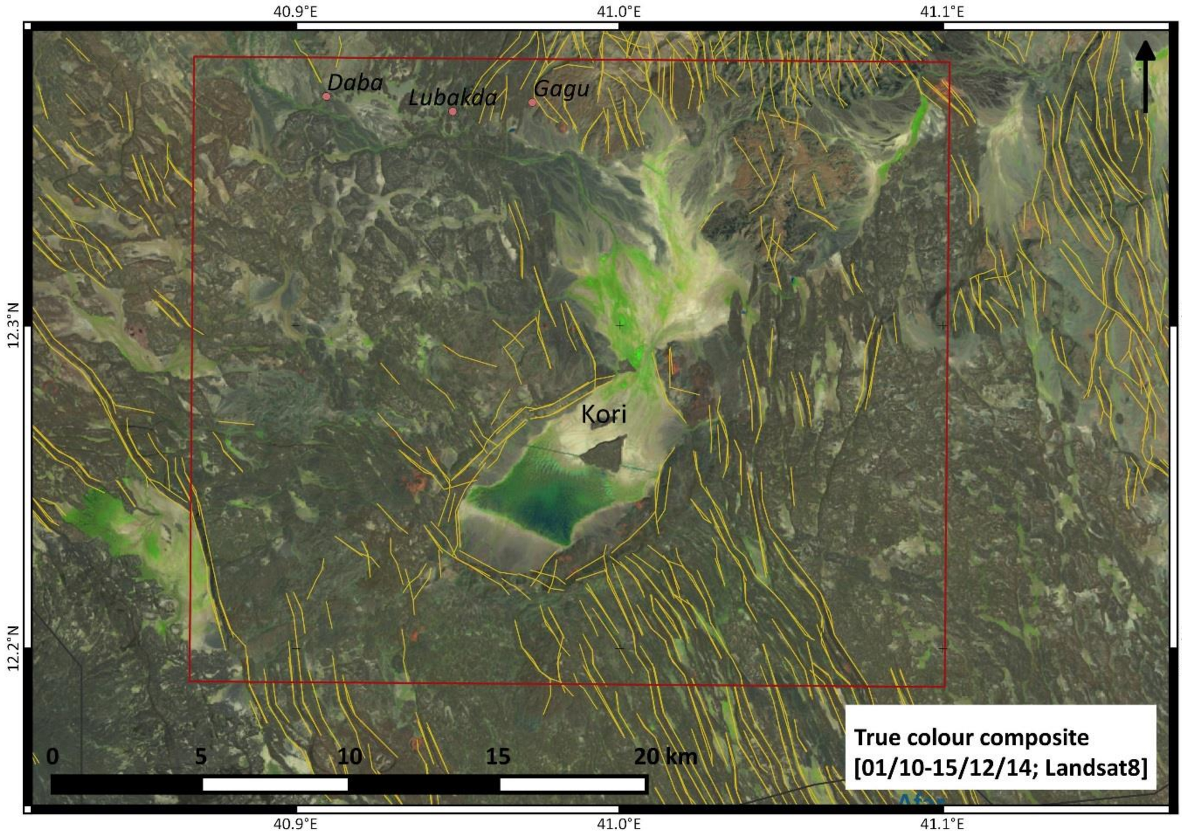


Figure 14. Zoom-in of Figure 13 showing the target area of Kori (red rectangle). Source: Landsat 8 for true colour composite; SRTM for lineaments (yellow)

4.5 Oromia region – Meyu Muluke and Kumbi

Meyu Muluke and Kumbi are located within similar geomorphological and geological settings, where the geology of the area is dominated by the Hamaneli limestone formation. Hence, the brief description of the groundwater potential maps (Figure 15, 16) and the results of ground-truthing are provided together.

The results of the overlay analysis show that large parts of both *woredas* fall within moderate to high groundwater potential zones. However, drilling depth issues (high depth to groundwater) are the main concerns for this region. According to detailed hydrogeological and geophysical studies completed over these areas following the RS work, the recommended depth for drilling is 350 to 400 m. From desk work and during the field observations, it has been inferred that in reference to the locations of the demand centres over the flat plateau areas, the regional groundwater could be intercepted by drilling a well exceeding the levels of the adjacent valley bottoms. The big perennial rivers and tributaries of the area drain in a southerly direction within deep-cut gorges adjacent to the plateau areas under focus.

Mean annual NDVI values in Meyu Muluke and Kumbi are generally higher than in the study *woredas* of Afar and Somali ranging mainly from 0.3 to 0.5. Also the Landsat 8 (Figure 17) composite image appears generally greener than the ones of the more northern study *woredas*. Mean monthly NDVI values show a strong seasonal cycle and hence vegetation development. However, from hydrogeological and drilling results it is inferred that the vegetation could only indicate soil moisture rather than the occurrence of shallow groundwater in this area.

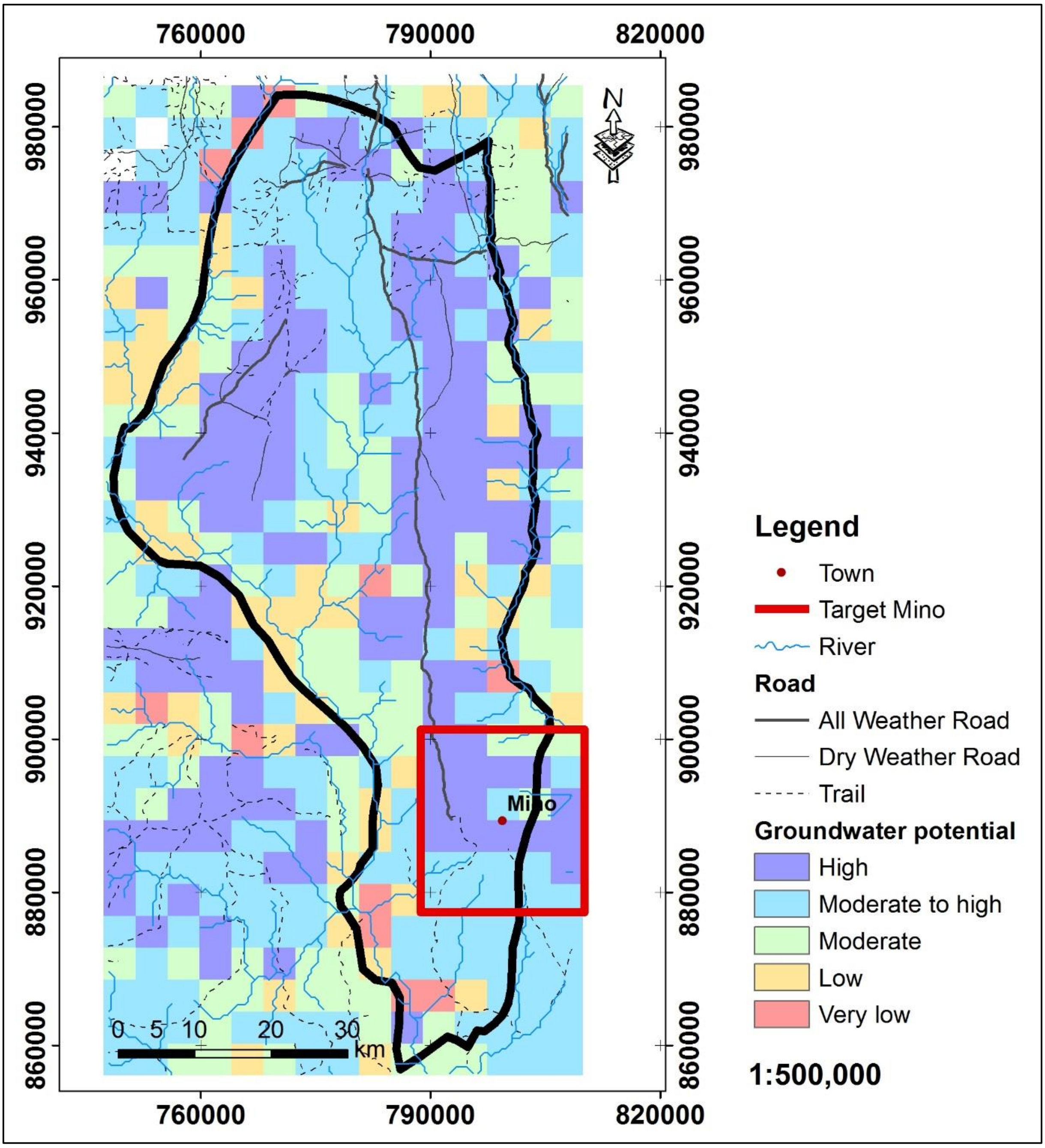


Figure 15. Groundwater potential map of Kumbi

There are not many boreholes drilled in the area especially in Kumbi. The only productive boreholes found in the area are those in the northern part of Meyu Muluke around Husse town and its surrounding locations in the Chulul valley. The depth of the wells ranges from 75–180 m and reported yields from 3.5–7 l/s. All these wells fall within the moderate to high groundwater potential zones on the overlay analysis map. The locations of these wells are about 250 m lower than the currently identified demand centres (target area) situated over the plateau area towards the south. In Kumbi, it has been reported that three wells have been drilled with two turning dry and one with a very low yield for which records could not be recovered.

The currently selected target areas are around Mino town in Kumbi (Figure 18) and around Chello village in Meyu Muluke (Figure 19). According to the result of the overlay analysis, these locations fall into the moderate to high potential class for prospecting groundwater by drilling deep wells.

The limitations of the overlay analysis when applied to these *woredas* could be the challenge of identifying flat areas over plateau land and mapped as suitable like other locations, whereas interceptions of the regional groundwater in this settings could go much deeper as a result of the deep cut adjacent steep valley bottoms, which needs further regional hydrogeological conceptualization synthesis.

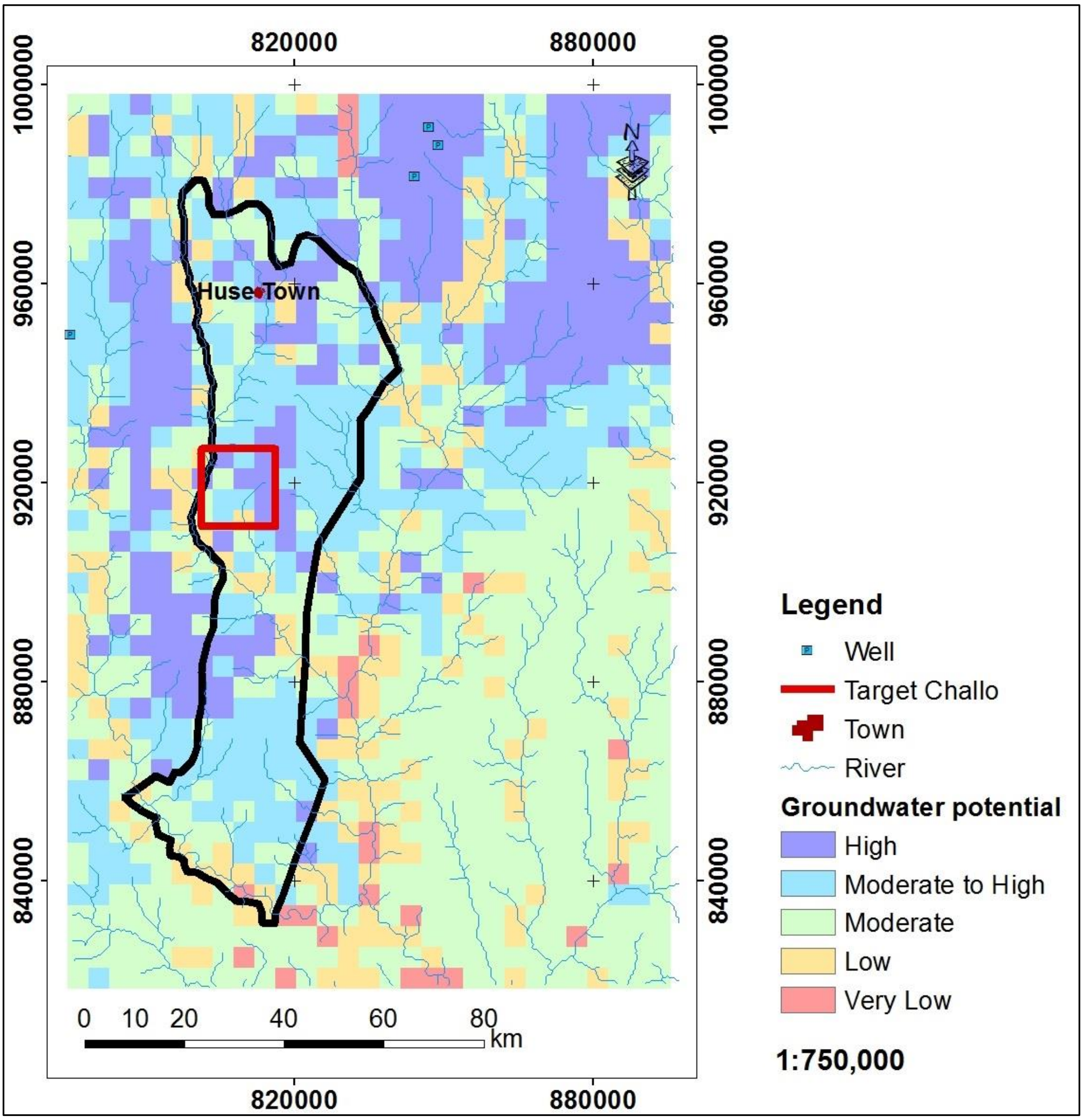


Figure 16. Groundwater potential map of Meyu Muluke

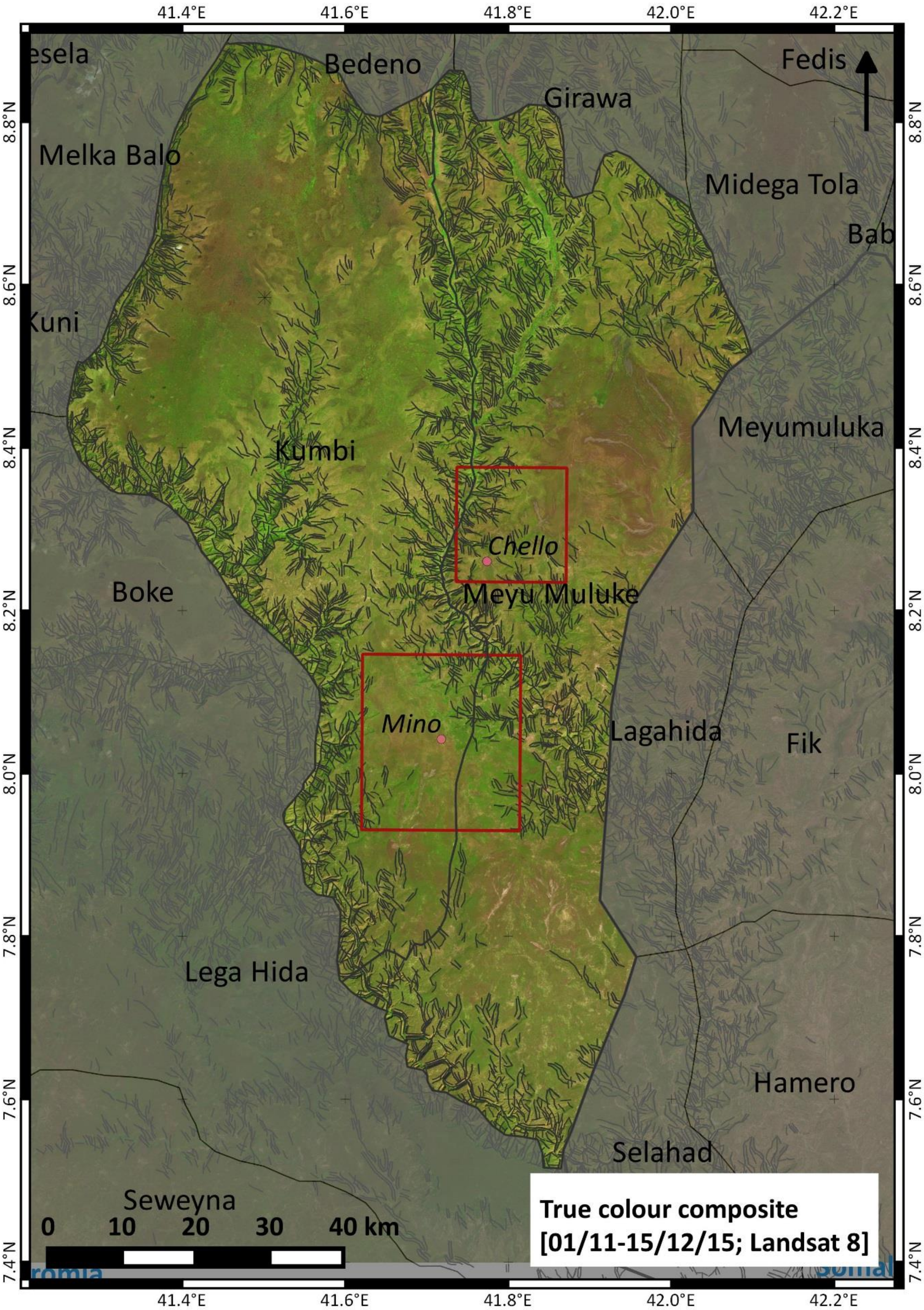


Figure 17. True colour composite (Bands 6-5-4) of Kumbi and Meyu Muluke for the period 01/11/2015–15/12/2015 (Landsat 8), lineaments (grey; derived from SRTM data), and target areas (red rectangles)

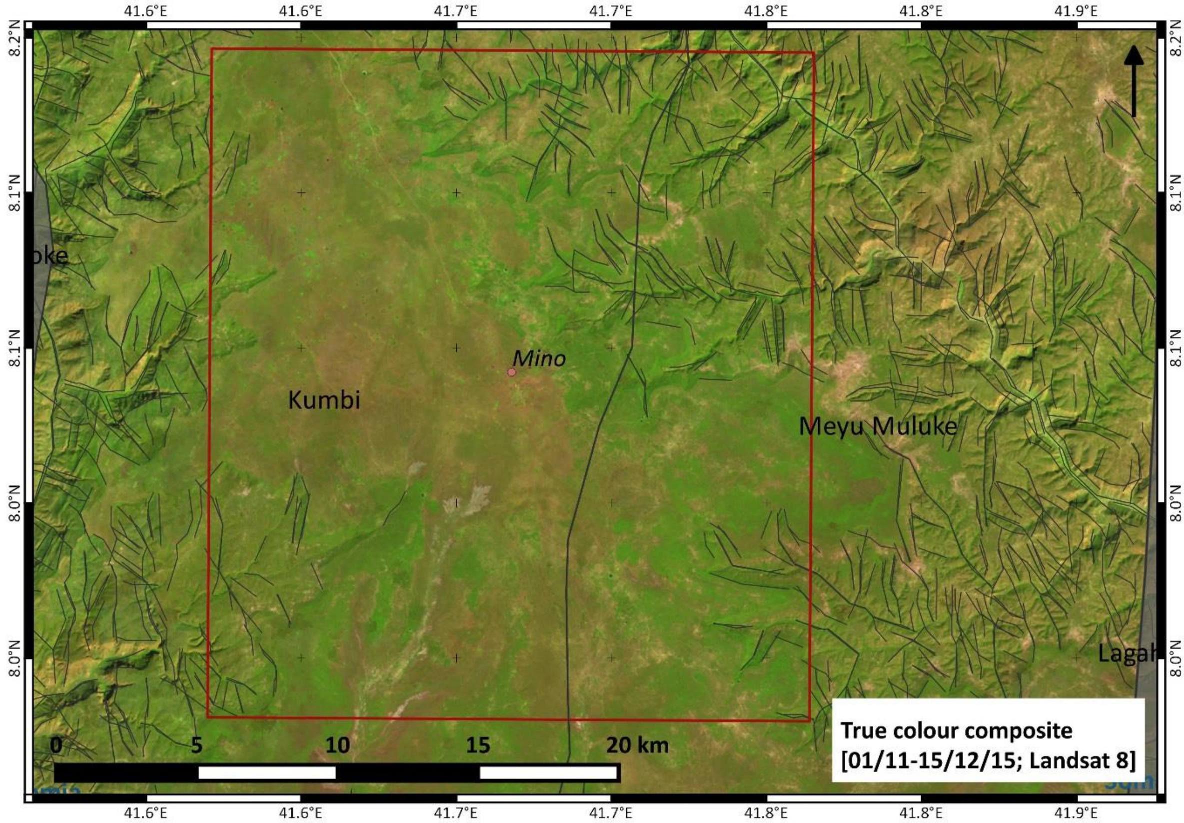


Figure 18. Zoom-in of Figure 17 showing the target area around Mino (red rectangle). Source: Landsat 8 for true colour composite, SRTM for lineaments (grey)

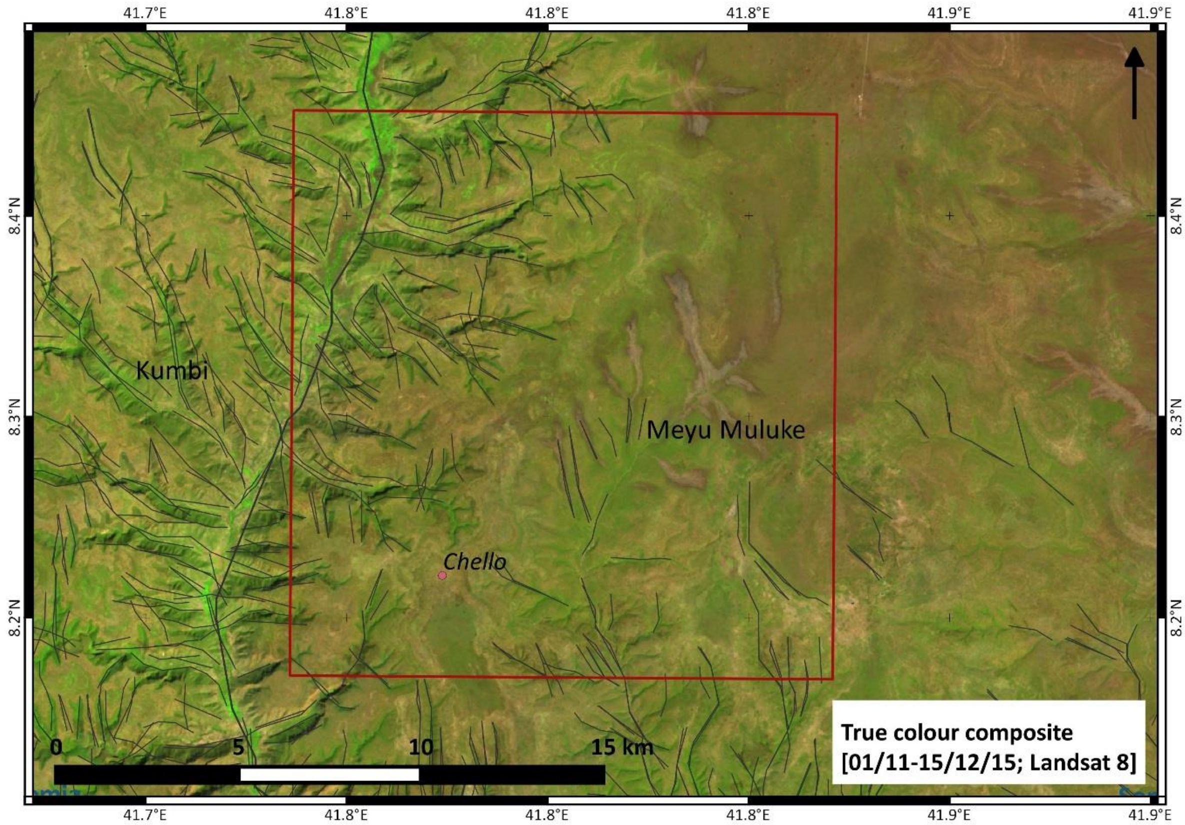


Figure 19. Zoom-in of Figure 17 showing the target area around Chello (red rectangle). Source: Landsat 8 for true colour composite, SRTM for lineaments (grey)

4.6 SNNPR region – Alaba

The groundwater potential map shows that nearly all regions of the *woreda* fall within the moderate to high or high class (Figure 20). The areas mapped as high potential zones are located in the central part of the *woreda* south of Besheno town and in the areas of Rokenana and Debeso localities.

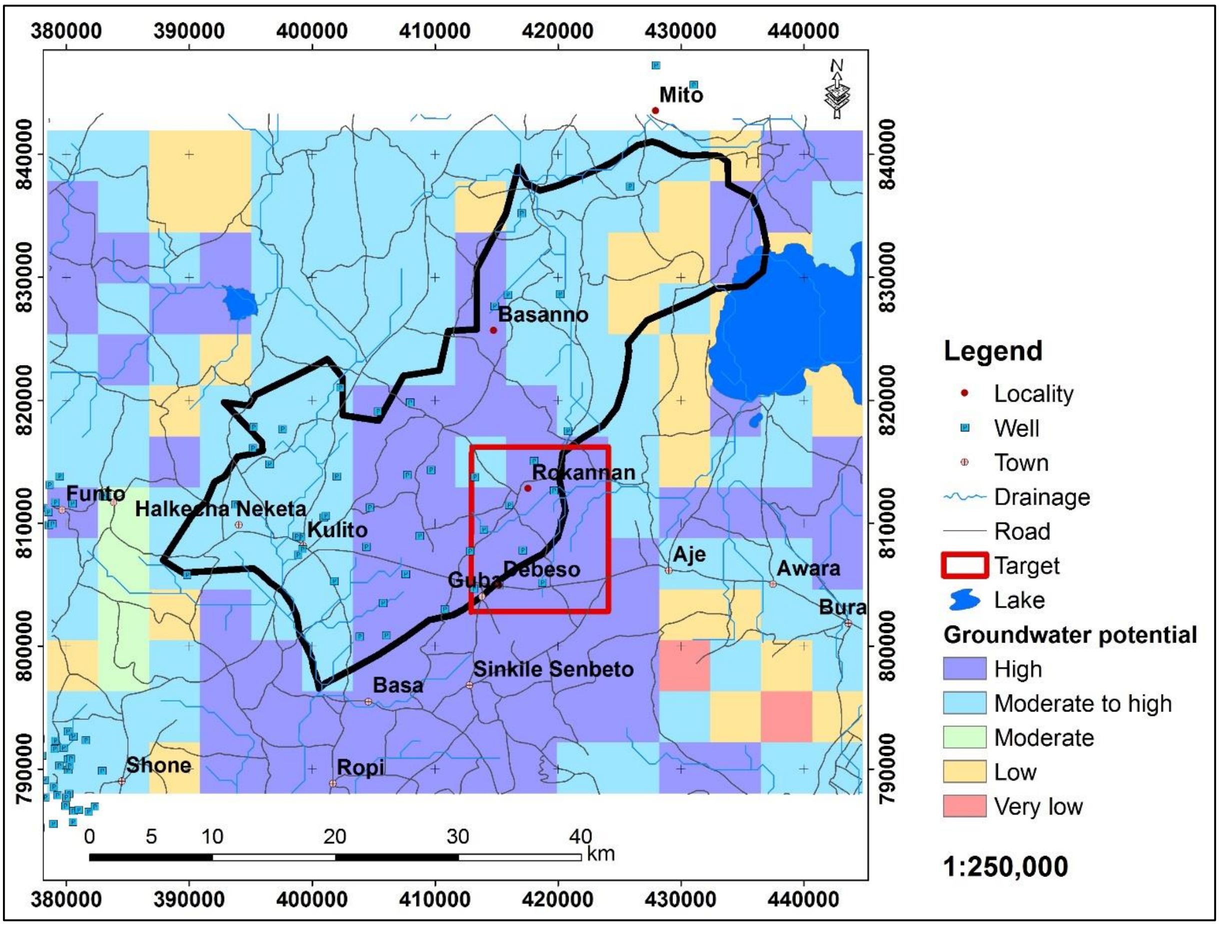


Figure 20. Groundwater potential map of Alaba

The Alaba *woreda* is dominantly covered by volcanic rocks – unwelded pumicious pyroclastic and ignimbrites, tuffs, water-lain pyroclastics and occasional lacustrine beds. This *woreda* is well known for its high population density and water supply problems. Apart from its availability at deeper depths, the groundwater resource in the Alaba *woreda* shows high levels of fluoride due to the nature of the geological formations (ash, pumice and volcanic rocks) bearing minerals from which fluoride is leached. During the ground-truthing period, it has been understood from regional experts that the inspected borehole at Bendo *kebele* has a fluoride level of 13 mg/l and is connected to the system for supply, due to the severity of water shortage. It is also reported that the levels of fluoride could not be reduced even when treatment was attempted. It has further been indicated that there are other *kebeles* also being supplied with water of high fluoride levels (5 to 10 mg/l), which is much more than the maximum permissible national standard (3 mg/l).

Currently, among the areas with water quality and water supply problems, the area around Debeso and Rokanene *kebeles* (Figure 21, 22) has been identified as a priority for detailed hydrogeological and geophysical studies to locate a drilling site at the most promising location. Besides critical water problems, this area has a potential of groundwater.

Except for the south-western parts and the northern border of the *woreda*, the area is poorly drained (low density of river network). As can be noted from the NDVI map and also observations during the field visits, the area is covered by relatively dense vegetation (see also Landsat 8 image; Figure 21). Very high resolution images show that large parts of the *woreda* are covered by agricultural fields. These are agricultural plantations which represent wet lands or moisture availability rather than shallow groundwater. According to the compiled borehole database, the groundwater system in the area is generally deep.

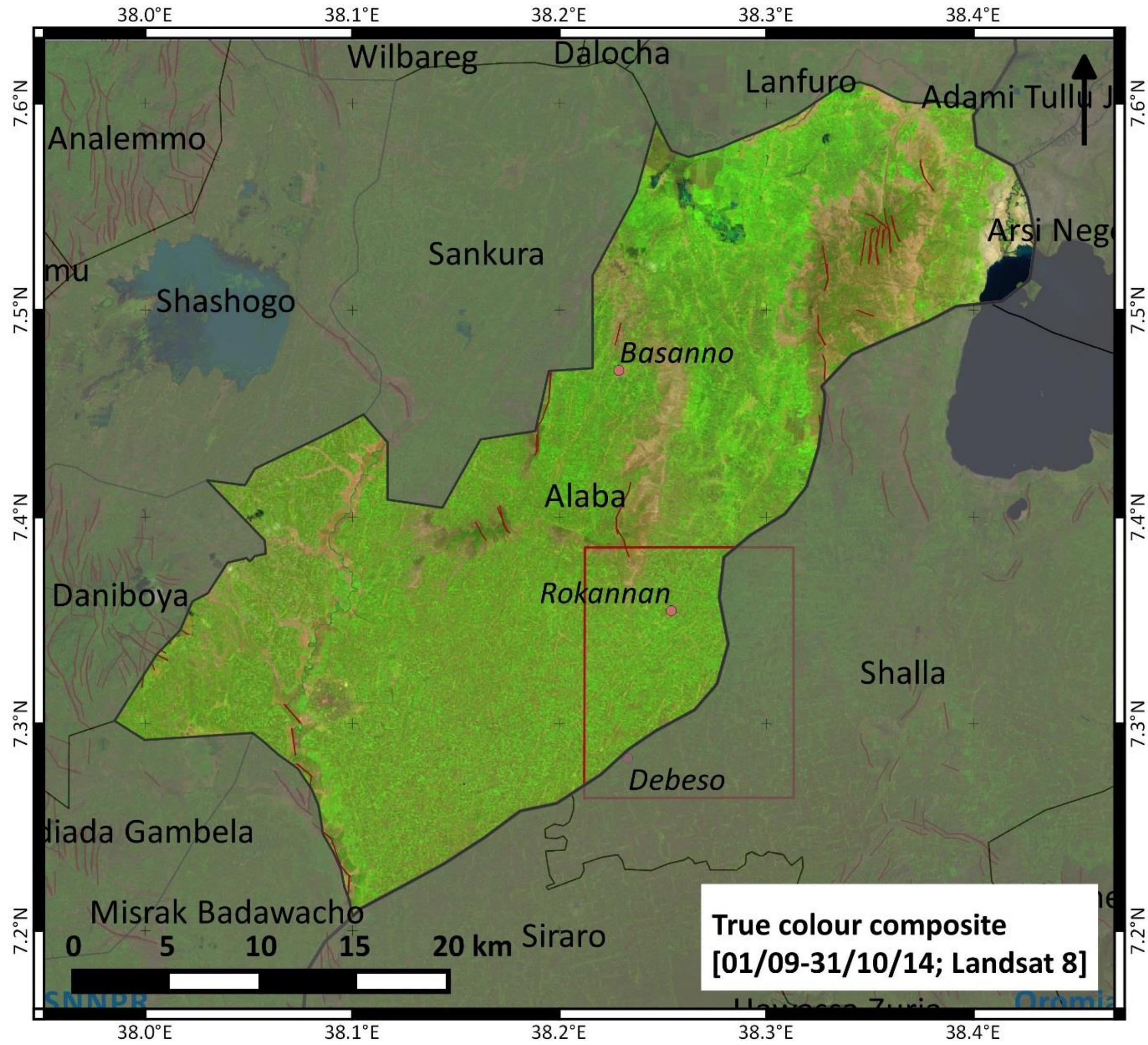


Figure 21. True colour composite (Bands 6-5-4) of Alaba for the period 01/09/2014–31/10/2014 (Landsat 8), lineaments (dark red; derived from SRTM data) and target area (red rectangle)

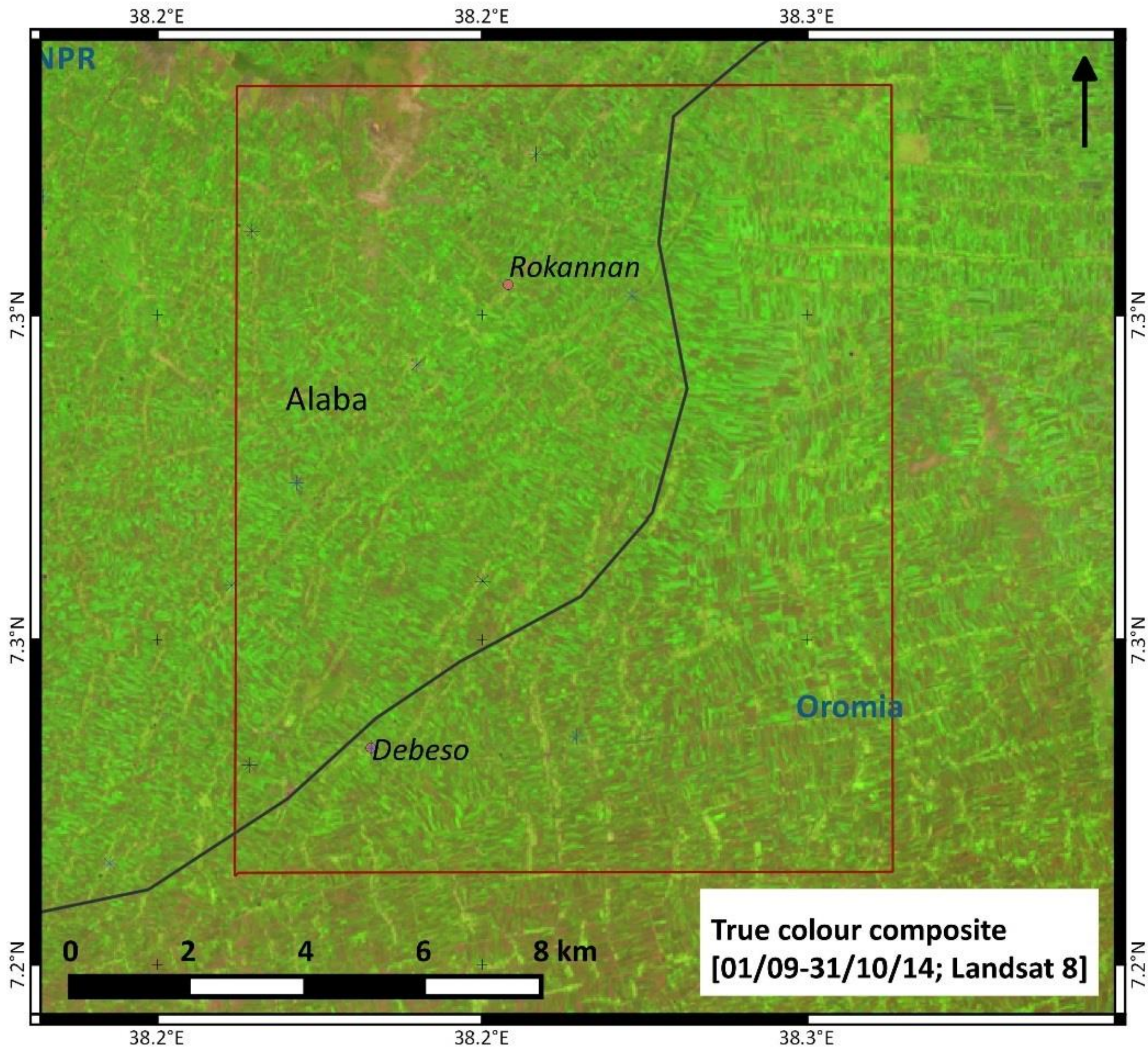


Figure 22. Zoom-in of Figure 21 showing the target area around Rokannan and Debeso (red rectangle). Source: Landsat 8 for true colour composite

4.7 Somali region – Gashamo

The Gashamo *woreda* has not been included in the present ground-truthing program as it showed just one groundwater potential class (Figure 23). Unlike other *woredas*, Gashamo is characterized by a generally flat topography which is fully underlain with uniform geology (Jessoma sandstone formation). No significant anomalies were obtained in the overlay analysis as a result of the uniformity in topography, geology, climatic conditions etc. The drainage pattern of the area is parallel to sub-parallel type with a major flow direction towards southeast following the gentle slope gradient of the sandstone terrain. The drainage pattern is very well reflected by the occurrence of vegetation as highlighted by the Landsat 8 image composite in Figure 24.

The hydrogeological challenges in this area are known to be the existence of deep groundwater systems with drilling difficulties due to circulation loss. The approach for prospecting groundwater in this *woreda* should be to conduct specialized studies supported by dense and deep penetration geophysical investigations to map the positions and depths of the sub-surface aquifer-aquiclude configurations in detail before launching drilling operations. The planning and preparations for the drilling work should also be done carefully.

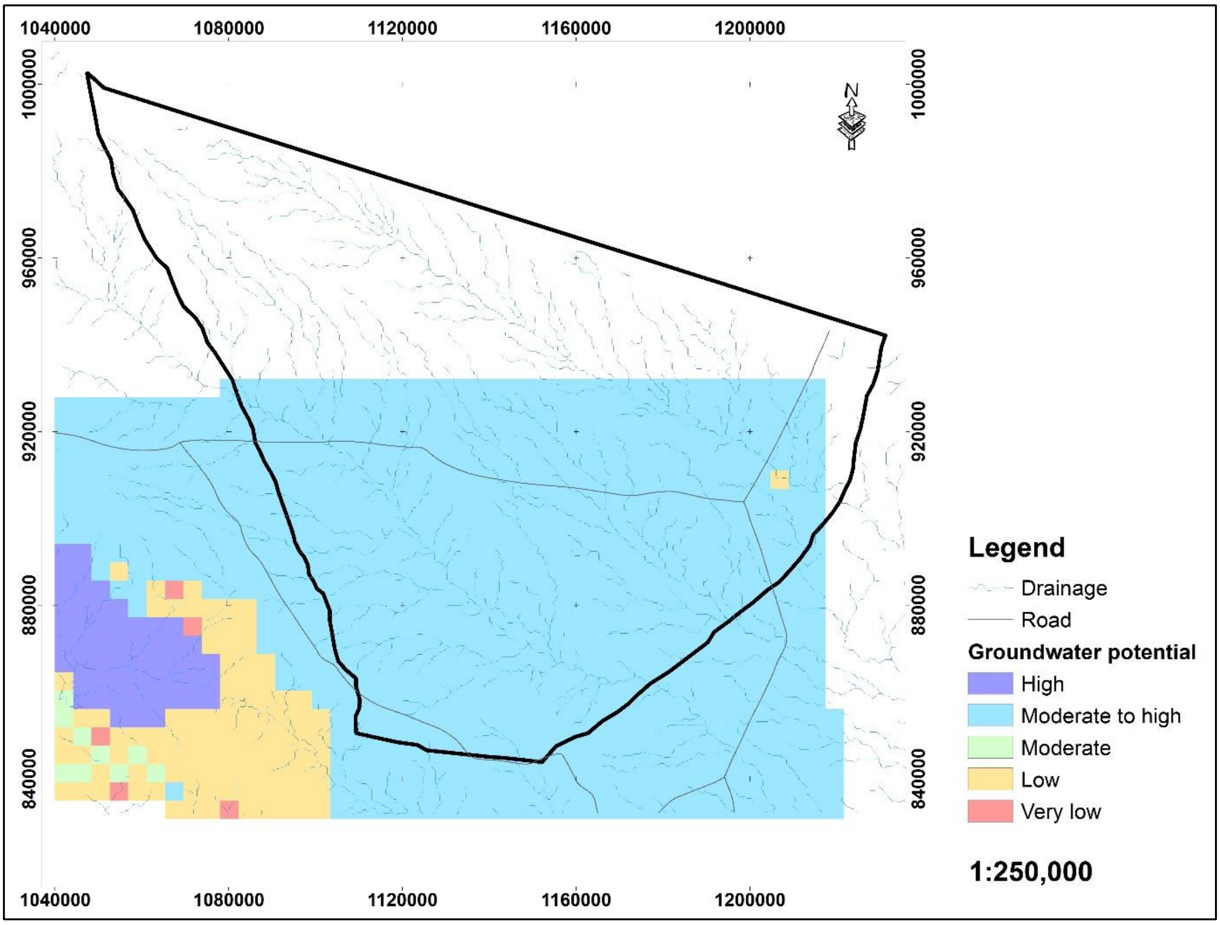


Figure 23. Groundwater potential map of Gashamo

There is a general gradient in mean annual NDVI values from northwest (lower) to southeast (higher). Additionally, higher NDVI values (around 0.3 to 0.4) are related to the river network. Areas of relatively high mean annual NDVI values in Gashamo could indicate the availability of soil moisture or the existence of local shallow groundwater.

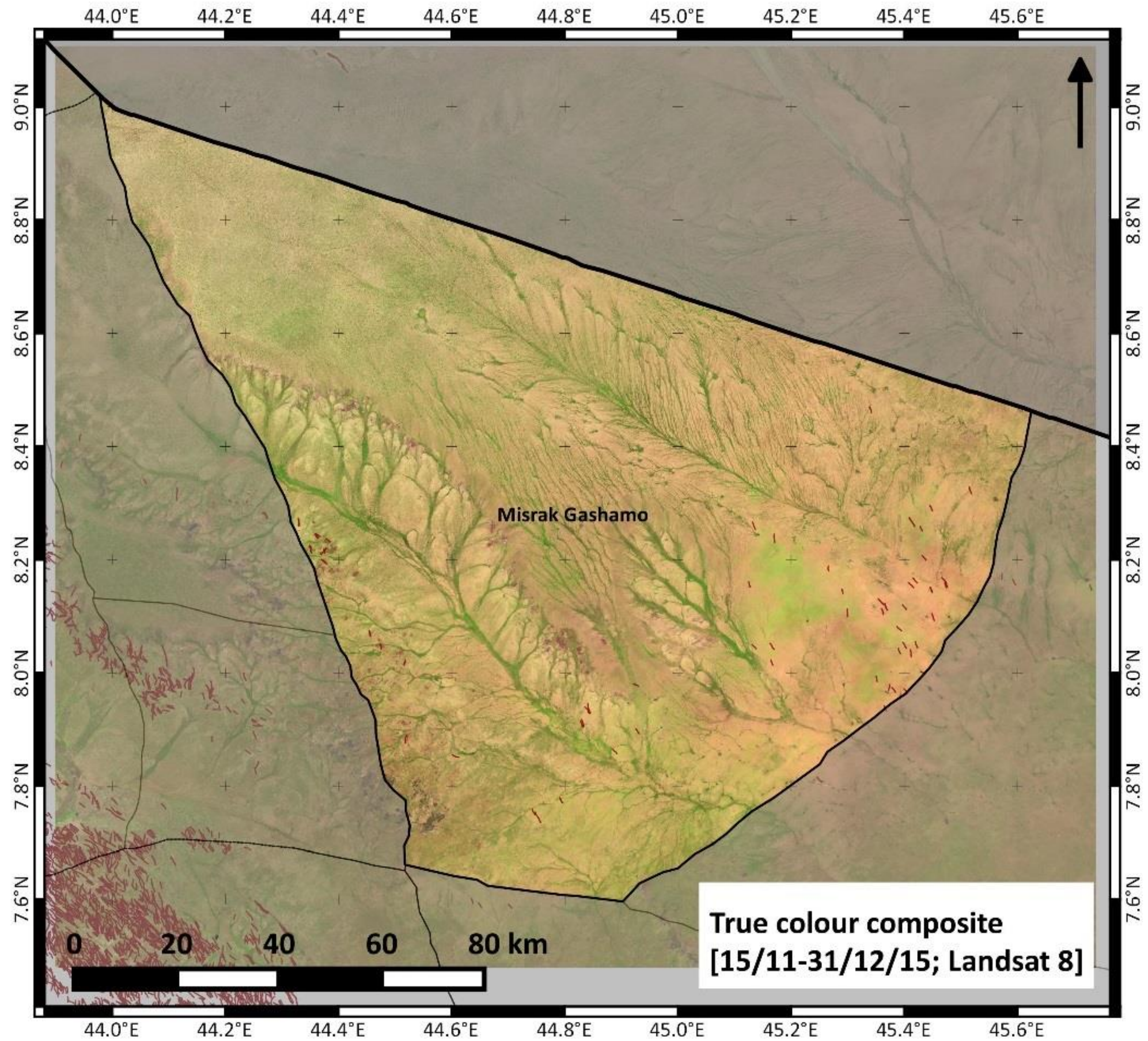


Figure 24. True colour composite (Bands 6-5-4) of Gashamo for the period 15/11/2015–31/12/2015 (Landsat 8) and lineaments (dark red; derived from SRTM data)

4.8 Somali region – Shinile

The groundwater potential map for Shinile (Figure 25) shows that more than 90 per cent of the *woreda* falls within the moderate to high or high potential class. The area is predominantly covered by alluvial deposits composed of sand, silt and clay with gravel. The characteristics of these units combined with the good recharge potential, as well as other factors considered in the overlay analysis make large portions of the area suitable. This has been supported by the boreholes drilled under previous works (depth: 74–350 m; yield: 5.6 to >50 l/s). There are several wells drilled at different locations within and adjacent to the *woreda*. The area receives significant regional recharge from the highlands of Dire Dawa and Harar as influx to the thick alluvial deposits of the *woreda*.

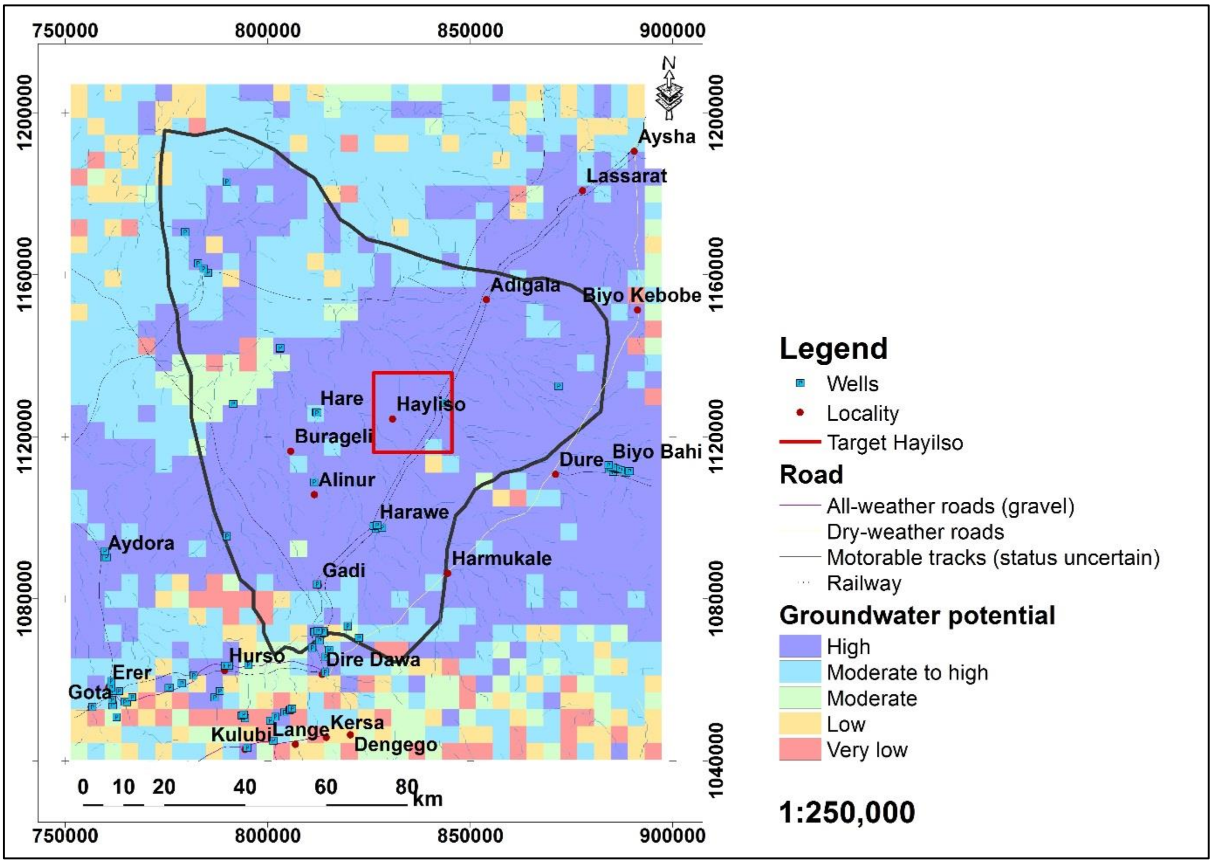


Figure 25. Groundwater potential map of Shinile

The Hayliso village area was selected as priority for drilling as it was identified by a survey to have critical water problem. This area is covered by alluvial deposits and falls within the high potential zone.

The existence of a spring (Barka spring) at the contact of zones mapped as having moderate and low potential in the southern part of the *woreda* towards Dire Dawa, can indicate the possibility of the existence of springs as a groundwater component within the zone mapped as low or very low in the overlay analysis.

The output of the overlay analysis has been verified with observations on the ground and from boreholes drilled in the area. During the traverse along the central access road towards Adigala, groundwater irrigation systems have been encountered in the locality of Harawe over the area mapped as highly suitable. However, some limitations have been inferred in the representation of the results at the north-eastern corner of the *woreda* towards Adigala area where geomorphologically unsuitable areas (areas situated over a water divide where groundwater storage is not expected) have been mapped as potential zones. This could be due to the influence of the existence of a highly permeable geological unit (scoria) in the locality. This could also be an indicator that there are some local areas within the domain of the groundwater potential zones that needs further verification and adjustment during detailed studies.

The disappearance of the main drainage radiating from the south and south-eastern highlands into the alluvial plains of the Shinile *woreda* area indicates the relatively high permeability of the thick deposits facilitating recharge. The occurrence of relatively high mean annual NDVI values in certain parts of Shinile (e.g. certain river channels) that is related to relatively dense vegetation could indicate the occurrence of shallow groundwater. Vegetated areas are highlighted in green in the Landsat 8 image (Figure 26).

Several boreholes have been drilled within and around the Shinile *woreda* where depths range from 129–250 m. All these boreholes are found to be productive with some cases of artesian conditions. Reported well yields ranges from 3 to >50 l/s.

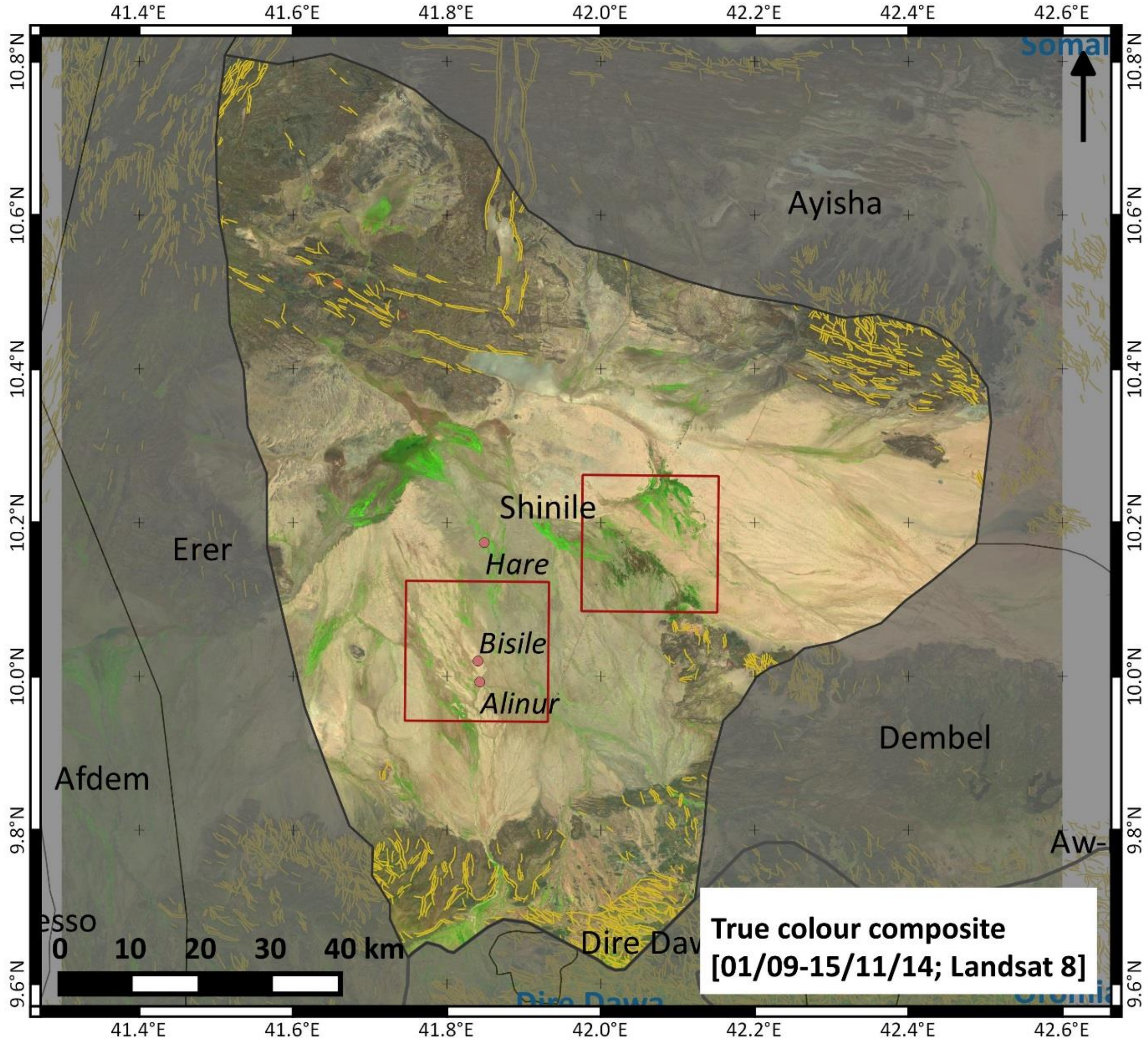


Figure 26. True colour composite (Bands 6-5-4) of Shinile for the period 01/09/2015–15/11/2015 (Landsat 8), lineaments (yellow; derived from SRTM data), and target area (red rectangle)

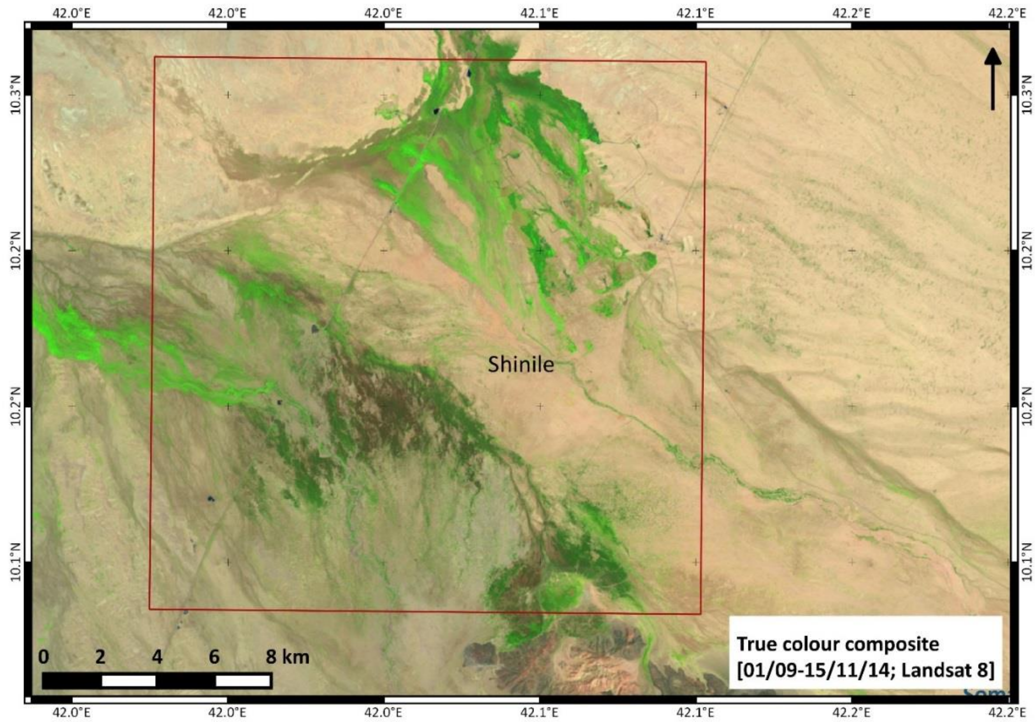


Figure 27. Zoom-in of Figure 26 showing the target area around Hayliso (red rectangle)

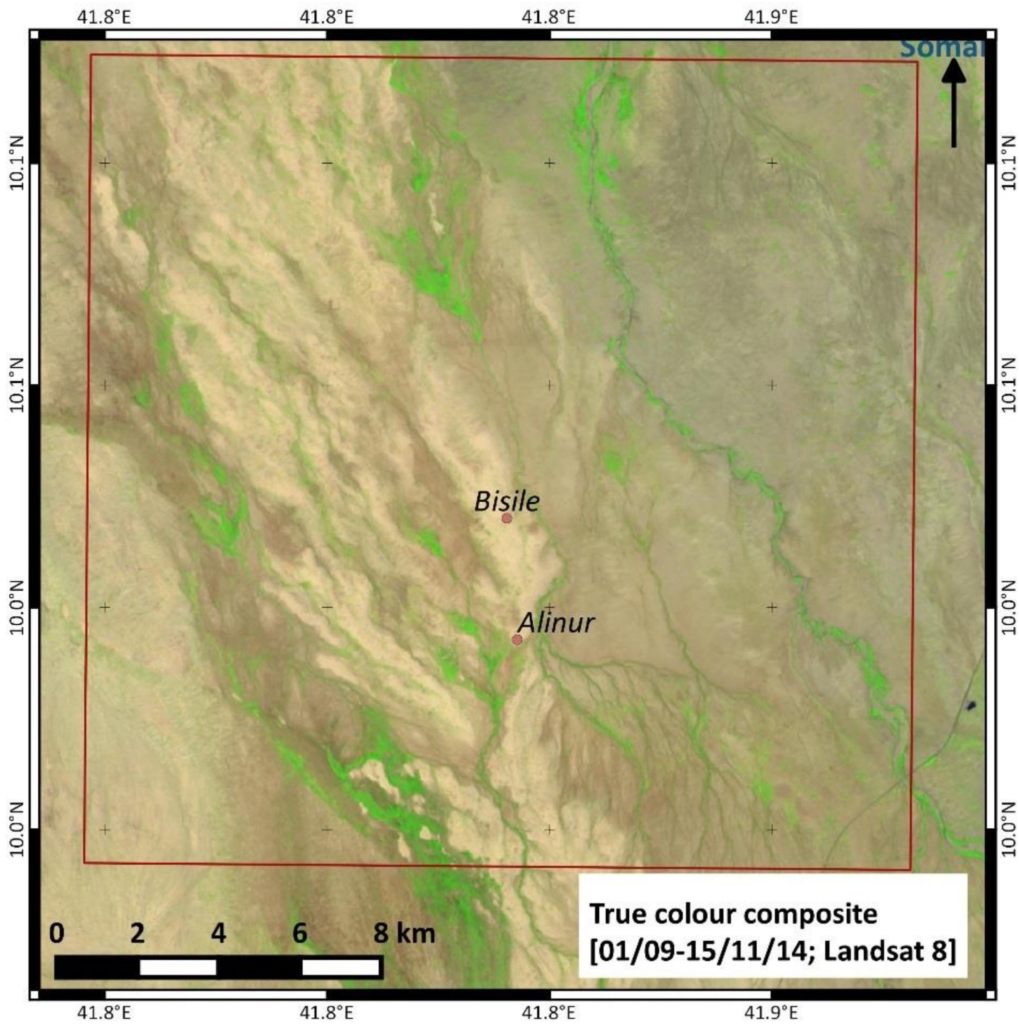


Figure 28. Zoom-in of Figure 26 showing the target area around Bisile and Alinur (red rectangle)

4.9 Suitability of overlay analysis results for deep groundwater

For Alaba *woreda* all 23 deep wells overlay on the high and moderate to high groundwater potential zones. For Dalul *woreda* four of the 13 deep wells overly a high potential zone, four on moderate to high, two on moderate, two on low and one on very low zones.

The classification of one Dalul productive well in an area categorized to have very low groundwater potential is assessed to be due to the influence of slope and recharge. The lithologic formation where this well is located is similar to another deep well nearby but the precipitation varies significantly between the two well points. As a result, the recharge weight at the two locations varies significantly i.e. 55 and 10. This well point is located within a distance of less than 300m from the area having a recharge weight of 55. In addition to the recharge, this site is located on the boundary of a slope with a weight of 55 and 30 (distance is less than 10m). Within such short distance a well cannot have been drilled on a steep slope. Therefore it can be concluded that there is error in the GPS reading of the well.

Another two productive wells are located in an area classified as having low groundwater potential. This area is evaluated against all the input factor maps. Accordingly, the lithology at one of the well sites with a depth of 223m is found to be schist and phylite. As a result the infiltration coefficient assigned to this lithologic unit is low (0.05). However from practice the wells drilled in basement terrain are not more than 100m deep. Therefore, the actual lithologic formation of the area is supposed to be different from that of the map. Hence the categorization of this site to a low groundwater potential area is attributed to incorrect lithologic mapping that needs to be verified.

In addition to the deep wells, in order to consider the deep groundwater system in its regional context, the study areas have been evaluated using conceptual models as supported by representative geological and hydrogeological sections. The results of this analysis will be presented in another report.

5. Conclusion

The present report is the first part of a hydrogeological study to improve groundwater knowledge and the access to safe water in nine *woredas* of Afar, Somali, SNNPR, and Oromia regions in Ethiopia. Specifically, the project aims to locate drilling sites with a substantial increase in drilling success. The purpose of this first phase of the project is the identification of areas with a high potential for groundwater occurrence for further field hydrogeological and geophysical studies.

The applied methodology comprised two main steps: 1) data acquisition, processing & RS analysis, and 2) overlay analysis. The RS analysis aims to generate thematic maps from RS-based products that are potentially relevant for the assessment of groundwater occurrence. Different RS datasets have been used to generate maps of the study *woredas* related to topography, geological structures (lineaments), climate (precipitation and evapotranspiration), vegetation, and hydrology. Information derived from these RS-based maps and other sources (i.e. geological maps) are then combined in a weighted overlay analysis to derive maps indicating the probability of groundwater occurrence (groundwater potential). Parameters assumed to be related to main factors for the occurrence of groundwater (type 1 layers namely permeability of the geological unit, lineament density, slope and recharge) were directly integrated in the overlay analysis that resulted in the generation of a groundwater potential map. Other parameters (type 2 layers like NDVI, TWI, and river network) were then utilised to specify areas with high groundwater potential and to determine target areas for further analysis.

Ground-truthing work was then undertaken in the target areas to check among others the results of the overlay analysis. Ground-truthing included the verification of the groundwater potential map against ground conditions, observation of the geomorphological settings, water point inventory, geological and hydrogeological observations, identification of target priority areas for immediate intervention, identification of limitations in the groundwater potential map. Following the ground-truthing works, currently the following areas have been selected for detailed studies and drilling: Tiyo *kebele* in the Bidu *woreda* (Afar region), Chello and Mino *kebeles* in Meyu Muluke and Kumbi *woredas* (Oromia region), Bisile *kebele* in the Shinile *woreda* (Somali region) and others will follow.

The input parameters of the analysis are indicators for the occurrence of shallow groundwater and the methodology was successfully applied in a previous study in three Ethiopian *woredas* in Afar and Tigray regions (Acacia water, 2015). In the present study we are also interested in deep groundwater occurrence. Therefore, it was necessary to validate the methodology for deep groundwater mapping. The inventoried deep wells (n = 36, depth > 150 m) in the study *woredas* were used for this purpose. Their location was overlaid on the groundwater probability map and checked for plausibility (i.e. do the productive wells occur in areas with high groundwater potential). The results showed a good correlation between the occurrence of deep wells and the groundwater potential map, providing a first hint for the suitability of the approach for deep groundwater. However, it needs to be acknowledged that the amount of available well data is low and additional attempts to verify the applicability of the approach for deep groundwater mapping should be undertaken. This was partly done by the evaluation of regional hydrogeological systems. This refers to expert's knowledge and judgment on the general understandings of the areas from their previous work experiences and literatures review of previous studies as well as evaluations of database records organized for the project.

Based on the modelling exercise, ground-truthing work and field evaluation, the following conclusions and recommendations are given;

- Type 1 layers (permeability, lineament density, slope and recharge) can be used in mapping of both shallow and deep groundwater systems. However type 2 layers (TWI, NDVI, and drainage density) cannot be used for validation of deep groundwater systems

- Drainage density does not have a direct relationship with the occurrence and movement of deep groundwater
- The groundwater quality cannot be inferred from the groundwater potential map.
- Availability of water points with associated information is a key model validation tool
- For better understanding of the deep groundwater system and the remote sensing and overlay analysis outputs, development of conceptual models (hydrogeological cross-sections) of the areas are very helpful.
- The applied groundwater occurrence controlling factors (weightings) may not be uniform for all geologic settings. Therefore, for future fine-tuning of these parameters, careful documentation and evaluation of borehole drilling results using the present approach and its applicability should be made.
- The results of previous similar works and actual drilling results obtained so far, as well as the present field verifications indicate that the method can certainly add value to conventional hydrogeological investigation methods to improve drilling success rates. Therefore, this approach should be encouraged and expanded to larger scale applications.
- Based on the results of the present phase I work, a detailed and site specific hydrogeological and geophysical investigation should be conducted (phase II) prior to launching the actual drilling operations.

Despite the promising results of the presented approach, there are several areas for improvement. The spatial resolution (thus spatial precision) of the groundwater potential zones map was constrained to the lowest spatial resolution in the input layers. The spatial precision can be improved by interpolating the low-resolution input layers to the highest spatial resolution in the other input layers. The information on existing wells and water points can be also included in the model by estimating an a priori probability of groundwater around those points. Landsat-8 imagery was used mainly for verification purposes. They can also provide information on the historical occurrence of vegetation and surface water in the last 30 years, information that can help refining the delineation of recharge zones in arid areas.

References

Acacia Water (2015) Improving drilling success rate in Afar and Tigray regions. http://www.acaciawater.com/dl-28008-7-58472/download/improving_drilling_succes_rate_in_afar_and_tigray_regions.html

Beven KJ, Kirkby MJ (1979) A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin 24(1): 43–69

Brunner P, Eugster M, Bauer P, Kinzelbach W (2002) Determination of recharge patterns by combining remote sensing and the chlorid method. In: Kovar K (Editor), Proceedings of Model Care, Prague, Czech Republic, 17-20 June 2002: Calibration and Reliability in Groundwater Modelling. IAHS Publications 277: 389-395

Chowdhury A, Jha MK, Chowdary VM, Mal BC (2009) Integrated remote sensing and GIS-based approach for assessing groundwater potential in West Medinipur district, West Bengal, India. International Journal of Remote Sensing 30(1): 231-250

Cumming O, Cairncross S (2016) Can water, sanitation and hygiene help eliminate stunting? Current evidence and policy implementations. Maternal & Child Nutrition 12 (Suppl. 1): 91–105

Demissie S, Worku A (2013) Magnitude and factors associated with malnutrition in children 6–59 months of age in pastoral community of Dollo Ado district, Somali region, Ethiopia. Science Journal of Public Health 1(4): 175–183

Dinesh Kumar PK, Gopinath G, Seralathan P (2007) Application of remote sensing and GIS for the demarcation of groundwater potential zones of a river basin in Kerala, southwest coast of India. International Journal of Remote Sensing 28(24): 5583–5601

Edet AE,Okereke CS,Teme SC, Esu EO (1998) Application of remote sensing data to groundwater exploration: a case study of the cross-river state, Southeastern Nigeria. Hydrogeology Journal, 6: 394–404

Eerens H, Haesen D, Rembold F, Urbano F, Tote C, Bydekerke L (2014) Image time series processing for agriculture monitoring. Environmental Modelling and Software *53:* 154–162

FAO (2014) Global Administrative Unit Layers (GAUL). FAO GeoNetwork. URL: http://www.fao.org/geonetwork/srv/en/metadata.show?id=12691

Fenn B, Bulti AT, Nduna T, Duffield A, Watson F (2012) Public Health and Nutrition 15(9): 1746–1754

Fenta AA, Kifle A, Gebreyohannes T, Hailu G (2015) Spatial analysis of groundwater potential using remote sensing and GIS-based multi-criteria evaluation in Raya Valley, northern Ethiopia. Hydrogeology Journal 23: 195–206

FMoH, UNICEF, EU (2016) Situation Analysis of the Nutrition Sector in Ethiopia: 2000-2015. Ethiopian Federal Ministry of Health, UNICEF and European Commission Delegation. Addis Ababa, Ethiopia. Available at http://www.unicef.org/ethiopia/ECO_Nutrition_Situation_Analysis_Main_Document.pdf

Funk C, Verdin A, Michaelsen J, Peterson P, Pedreros D, and Husa G (2015) A global satellite-assisted precipitation climatology. Earth Syst. Sci. Data, 7, 275–287, 2015

EWCM – GEOGLAM Early Warning Crop Monitor (2016) Crop conditions at a glance as of January 28th. Available at http://geoglam-crop-monitor.org/documents/ewcm/reports/EarlyWarning_CropMonitor_201602.pdf

Greenbaum D, Carruthers RM, Peart RJ, Shedlock SJ, Jackson PD, Mtetwa S, Amos BJ (1993) Project completion report: Groundwater exploration in southeast Zimbabwe using remote sensing and ground geophysical techniques. British Geological Survey Technical Report WC/93/26. Available at http://www.bgs.ac.uk/research/international/dfid-kar/WC93026_col.pdf

Jha MK, Chowdhury A, Chowdary VM, Peiffer S (2007) Groundwater management and development by integrated remote sensing and geographic information systems: prospects and constraints. Water Resources Management 21: 427–467

Kinzelbach W, Aeschbach W, Alberich C, Goni IB, Beyerle U, Brunner P, Chiang W-H, Rueedi J, Zoellmann K (2002) A survey of methods for groundwater recharge in arid and semi-arid regions. Early Warning and Assessment Report Series, UNEP/DEWA/RS.02-2. United Nations Environment Programme, Nairobi, Kenya. ISBN 92-80702131-3

Leblanc M, Leduc C, Razack M, Lemoalle J, Dagorne D, Mofor L (2003) Application of remote sensing and GIS for groundwater modelling of large semiarid areas: example of the Lake Chad Basin, Africa. Hydrology of the Mediterranean and Semiarid Regions (Proceedings of an international symposium held at Montpellier, April 2003), IAHS Publ. no. 278: 186–192

Leblanc M, Favreau G, Tweed S, Leduc C, Razack M, Mofor L (2007) Remote sensing for groundwater modelling in large semiarid areas: Lake Chad Basin, Africa. Hydrogeology Journal 15 (1): 97–100

Lehner B, Verdin K, Jarvis A (2006) HydroSHEDS Technical Documentation. World Wildlife Fund US, Washington, DC. Available at http://hydrosheds.cr.usgs.gov

Maidment R, Grimes D, Allan RP, Tarnavsky E, Stringer M, Hewison T, Roebeling R, Black E (2014) The 30 year TAMSAT African rainfall climatology and time series (TARCAT) data set. Journal of Geophysical Research: Atmospheres, 119(18): 10,619–10,644

Mu Q, Zhao M, Running SW (2011) Improvements to a MODIS global terrestrial evaportranspiration algorithm. Remote Sensing of Environment 115: 1781–1800

Muhammad MM, Awdal AH (2001) Automatic mapping of lineaments using shaded relief images derived from Digital Elevation Model (DEM) in Erbil-Kurdistan, northeast Iraq. Advances in Natural and Applied Sciences 6(2): 138-146

Rembold F, Meroni M, Urbano F, Royer A, Atzberger C, Lemoine G, Klisch A (2015) Remote sensing time series analysis for crop monitoring with the SPIRITS software: new functionalities and use examples. Frontiers in Environmental Science *3* (July): 129–134

Rinderer M, van Meerveld HJ, Seibert J (2014) Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid? Water Resources Research 50: 6067–6080

Salama RB, Tapley I, Ishii T, Hawkes G (1994) Identification of areas of recharge and discharge using Landsat-TM satellite imagery and aerial photography mapping techniques. Journal of Hydrology 162(1–2): 119–141

Sander P, Chesley MM, Minor TB (1996) Groundwater assessment using remote sensing and GIS in a rural groundwater project in Ghana: lessons learned. Hydrogeology Journal 4(3): 40–49

Shaban A, Khawlie M, Abdallah C (2006) Use of remote sensing and GIS to determine recharge potential zone: the case of Occidental Lebanon. Hydrogeol J 14:433–443

Shahid S, Nath SK (2002) GIS integration of remote sensing and electrical sounding data for hydrogeological exploration. Journal of Spatial Hydrology 2(1): 1–10

Sørensen R, Zinko U, Seibert J (2006) On the calculation of the topographic wetness index: evaluation of different methods based on field observations. Hydrology and Earth System Sciences 10: 101–112

Srinivasa Rao Y, Jugran DK (2003) Delineation of groundwater potential zones and zones of groundwater quality suitable for domestic purposes using remote sensing and GIS. Hydrological Sciences Journal 48(5): 821-833

Tarnavsky E, Grimes D, Maidment R, Black E, Allan R, Stringer M, Chadwick R, Kayitakire F (2014) Extension of the TAMSAT satellite-based rainfall monitoring over Africa and from 1983 to present. Journal of Applied Meteorology and Climatology, 53(12): 2805-2822

Teeuw RM (1995) Groundwater exploration using remote sensing and a low-cost geographical information system. Hydrogeology Journal 3(3): 21–30

Tweed SO, Leblanc M, Webb JA, Lubczynski MW (2007) Remote sensing and GIS for mapping groundwater recharge and discharge areas in salinity prone catchments, southeastern Australia. Hydrogeology Journal 15: 75–96

UNICEF, EU (2016) Memorandum of Understanding relating to the hydrogeological study in seven *woredas* of Afar, Somali, Oromia and SNNP regions in Ethiopia between United Nations Children's Fund and the European Union. February 2016

UNICEF, World Health Organization (2015) Joint Monitoring Programme - Progress on sanitation and drinking water – 2015 update and MDG assessment. ISBN 978-92-4-150329-7

Additional references not cited in the main text

Alemayehu T (2006) Groundwater occurrence in Ethiopia. URL: http://www.eah.org.et/docs/Ethiopian%20groundwater-Tamiru.pdf

Al-Ruzouq, Shanableh A, Merabtene T (2015) Geomatics for Mapping of Groundwater Potential Zones in Northern part of the United Arab Emiratis - Sharjah city. 36th International Symposium on Remote Sensing of Environment, 11–15 May 2015, Berlin, Germany. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-7/W3: 581-586

Elbeih SF (2015) An overview of integrated remote sensing and GIS for groundwater mapping in Egypt. Ain Shams Engineering Journal 6 (1): 1–15

Grabs T, Seibert J, Bishop K, Laudon H (2009) Modelling spatial patterns of saturated areas: a comparison of the topographic wetness index and a dynamic distributed model. Journal of Hydrology 373(1–2): 15–23

Liu T, Yan H, Zhai L (2015) Extract relevant features from DEM for groundwater potential mapping. International Workshop on Image and Data Fusion, 21 – 23 July 2015, Kona, Hawaii, USA. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-7/W4

Megesh NS, Chandrasekar N, Soundranayagam JP (2012) Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. Geoscience Frontiers 3(2): 189–196

Naveenkumar, Soraganvi VS, Hooli SS (2015). Groundwater potential mapping in a part of Malaprabha river basin using remote sensing data and geographic information system (GIS). Journal of Environment and Earth Science 5(5): 41–47

Sikakwe GU, Ntekim EEU, Obi DA, George AM (2015) Geohydrological study of weathered basement aquifers in Oban Massif and environs Southeastern Nigeria: using Remote Sensing and Geographic Information SystemTechniques. ISOR Journal of Applied Geology and Geophysics 3(2): 27–40

Solomon S, Quiel F (2003) Integration of remote sensing and GIS for groundwater assessment in Eretria. In: Benes T (ed.) Geoinformation for European-wide integration. Proceedings of the 22nd Symposium of the European Association of Remote Sensing Laboratories, Prague, Czech Republic, 4–6/06/2002. Millpress, Rotterdam, p. 633–640

http://earthobservatory.nasa.gov/Features/MeasuringVegetation/

List of abbreviations

AVHRR	Advanced Very High Resolution Radiometer
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
DEM	Digital Elevation Model
ET	Evapotranspiration
EU	European Union
GAUL	Global Administrative Unit Layers (014)
GIS	Geographic Information System
GPS	Global Positioning System
GSE	Geological Survey of Ethiopia
HydroSHEDS	Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales
IRS	Indian Remote-Sensing Satellite
JRC	Joint Research Centre of the European Commission
κ	permeability
Landsat ETM	Landsat Enhanced Thematic Mapper
Landsat TM	Landsat Thematic Mapper
LISS	Linear Imaging Self Scanning Sensor
MODIS	Moderate Resolution Imaging Spectroradiometer
MoARD	Ministry of Agriculture and Rural Development
MoWIE	Ministry of Water, Irrigation and Electricity
MoU	Memorandum of Understanding
NDVI	Normalized Difference Vegetation Index
PET	potential evapotranspiration
RFE	rainfall estimates
RS	remote sensing
SAGA	System for Automated Geoscientific Analysis
SD	standard deviation
SNNPRS	South Nations and Nationalities Peoples Regional State
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
TAMSAT	Tropical Applications of Meteorology using SATellite data and ground-based observations
TARCAT	TAMSAT African Rainfall Climatology and Time-series
TWI	Topographic Wetness Index
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children's Fund
WASH	water, sanitation and hygiene
WGS	World Geodetic System

List of figures

List of tables

Appendix 1 – Details of utilized data and methods for RS-based layers/products

1 Digital Elevation Model and derived products

Data. The Shuttle Radar Topography Mission (**SRTM**) 1 Arc-Second Global product (SRTM-1sec, available from the U.S. Geological Survey, e.g. via the USGS EarthExplorer: http://earthexplorer.usgs.gov/) was used as a source for elevation data. The product offers worldwide coverage of void filled elevation data with a spatial resolution of 1 arc second (~30 meters). The product can be downloaded as 1 degree tiles (Coordinate Reference System (CRS): Latitude/Longitude, Datum: WGS84, EPSG: 4326) in GeoTIFF format.

Processing. The tiles needed to cover the study *woredas* were downloaded via the USGS EarthExplorer and then mosaicked with ENVI[3] using the nearest neighbour method (background value = -999). The mosaics for Meyu and Alaba SP *woreda* contained some bad data pixels. These were removed using ENVI (Topographic/Replace bad values → applying a surface fitting technique using Delauney triangulation).

1.1 Terrain Analysis

Based on the elevation data from SRTM the parameters **slope, aspect, and hillshade** were calculated. To perform the terrain analysis it was necessary to reproject the data into a CRS which has metre as unit. Therefore the data was reprojected to UTM zone 38N, WGS84 datum (EPSG: 32638) using QGIS [4] (Raster/Reproject/Warp (Reprojection)). Subsequently, QGIS was used to calculate the three terrain layers (Raster/Terrain Analysis). For the hillshade, default values were used as horizontal (solar azimuth, sun angle) and vertical angle (sun elevation).

The overlay analysis of UNICEF does not require slope in degrees, but **slope classes**. Therefore the slope layer was reprojected to Latitude/Longitude, WGS84 datum (EPSG: 4326) with QGIS and then ArcMap[5] was used to reclassify the slope values (Spatial Analyst/Reclass/Reclassify) into slope classes (Table A1).

Table A1. Slope classes and corresponding slope values

Slope range	Assigned class
0° - 5°	1
5° - 15°	2
15° - 25°	3
> 25°	5

1.2 Lineament Analysis

The methodology for the automatic extraction of lineaments is based on the study of Muhammad & Awdal (2012). Shaded relief images with different azimuth angles were used as an input for the LINE module of Geomatica[6] (trial version).

SRTM elevation data (UTM zone 38N, WGS84 datum; EPSG: 32638) was used to calculate the different hillshades in QGIS (Raster/Terrain Analysis/Hillshade). The solar elevation (vertical angle) was kept constant for all hillshade images and set to 30°. The solar azimuth (horizontal angle) was set to the following different values: 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. After the creation of the eight hillshade images, we

[3] ENVI version 5.0.3 [classic], Exelis Visual Information Solutions, Inc., www.exelisvis.com
[4] QGIS version 2.14.1-Essen. http://qgis.org/en/site/
[5] ArcGIS 10.3.1 for Desktop, Esri Inc., http://www.esri.com
[6] Geomatica 2016 (Trial Version), PCI Geomatics, www.pcigeomatics.com

used ENVI (File/Save File As/ENVI Standard) to save them in one image with eight bands. Additionally, two combined hillshade images were calculated from single hillshade images using ENVI (Basic Tools/Band math: b1+b2+b3+b4), namely combination 1 (0°+45°+ 90°+135°) and combination 2 (180°+225°+270°+315°).

In the LINE module of PCI Geomatica lineaments were automatically extracted using the following setting:

- input parameters: default values (RADI = 10, GTHR = 100, LTHR = 30, FTHR = 3, ATHR = 30, DTHR = 20)
- input files: three different inputs were tested
    - A) all eight bands of the hillshade image (producing eight output files)
    - B) combined hillshade (combination 1: 0°+45°+90°+135°; producing one output file)
    - C) combined hillshade (combination 2: 180°+225°+270°+315°; producing one output file)

After the calculation of the lineaments, the outputted pix-files needed to be converted to a shape-files. To do so, the pix-files were added to the Focus module of PCI Geomatica (Layer/Add) and then saved as (right click on the layer/Save as) shp-files.

1.3 Topographic Wetness Index

The Topographic Wetness Index (TWI) is a measure of the topographic control on hydrological processes and is defined as

$$\mathrm{TWI} = \ln(a/\tan\beta),$$

where a is the local upslope area draining through a certain point per unit contour length and β is the local slope (Beven & Kirkby 1979; Sørensen et al. 2006). This index can be computed in many different ways, depending on how the upslope area and the local slope are calculated. We followed the approach described in a Geographic Information Systems Forum (http://gis.stackexchange.com/questions/90064/calculating-topographic-wetness-index-choosing-from-different-algorithms) using SAGA[7] GIS.

First the slope (Geoprocessing/Terrain Analysis/Morphometry/Slope, Aspect, Curvature → default algorithm: 9 parameters 2nd order polynom) and the upslope area (Geoprocessing/Terrain Analysis/Hydrology/Catchment Area/Catchment Area (Parallel) → Multiple Flow Direction algorithm, default parameters) need to be calculated from the SRTM elevation data (projection: UTM zone 38N; datum: WGS84; EPSG: 32638). Then the TWI is computed from the slope and upslope catchment area (Geoprocessing/Terrain Analysis/Hydrology/Topographic Indices/Topographic Wetness Index (TWI) → Standard Calculation; option convert area to 1/cell size). Finally, the TWI images are exported as GeoTIFF (Tool libraries/Import, Export – GDAL/OGR/GDAL: Export Raster to Geotiff). Then, QGIS is used to reproject the TWI images to Latitude/Longitude, WGS84 Datum (EPSG: 4326).

2 Hydrological information

The HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) product (Lehner et al. 2006) was used as a data source for the hydrographic information **drainage direction** (DIR), **flow accumulation** (in number of cells; ACC), **river network** (stream lines), and **drainage basins** (watershed boundaries). All these layers are provide in Latitude/Longitude projection with WGS84 datum. The raster layers (DIR, ACC) have a spatial resolution of 15-arc seconds (approx. 500 m at the equator). The HydroSHEDS layers were downloaded from http://hydrosheds.cr.usgs.gov.

[7] SAGA System for Automated Geoscientific Analysis, Version 2.1.2, http://www.saga-gis.org

HydroSHEDS are derived from hydrologically conditioned SRTM data. According to the quality assessment of the technical documentation (Lehner et al. 2006), known sources of errors are among other related to areas of low or not well-defined relief. For the full quality assessment see Figure A1.

4. Quality assessment

At the present stage of developing HydroSHEDS, the final data quality has not been evaluated systematically. Yet preliminary comparisons with other global hydrographic data sets indicate the following:

- Generally, HydroSHEDS shows significantly better accuracy than HYDRO1k, a global hydrographic data set at 1-km resolution (USGS 2000), due to HydroSHEDS being based on a superior digital elevation model.
- Generally, HydroSHEDS shows significantly better accuracy than the river layer of ArcWorld (even in difficult areas) as ArcWorld has been incorporated in the conditioning process of HydroSHEDS.
- Generally, HydroSHEDS shows better accuracy than DCW. However, the accuracy of both data sets varies by location. In some regions where HydroSHEDS is particularly susceptible to errors, such as vegetated floodplains, the quality of DCW can be superior to HydroSHEDS.
- Generally, HydroSHEDS does not reach the accuracy of high-resolution local river networks as depicted in existing maps or remote sensing imagery. The user is thus encouraged to further improve HydroSHEDS through incorporating local information.

Typically, river network products derived from digital elevation surfaces are susceptible to various errors, foremost in flat regions without well-defined relief. Additionally, the quality of HydroSHEDS depends on the characteristics of the SRTM-based elevation model. Being a radar product, SRTM elevation values are influenced by vegetation and other surface effects, such as roughness, wetness, low backscatter signal at open water surfaces and radar shadow (Freeman 1996). At this point, known sources of errors in HydroSHEDS include:

- Areas of low or not well-defined relief, including lake surfaces.
- Varying vegetation cover, particularly in areas of low relief, e.g. large river floodplains. The radar signal is, at least partly, reflected from atop and within the vegetation cover and the returned signal is thus a complex mix of land surface elevation and vegetation height.
- Low-relief coastal areas, in part due to the barrier effect of mangroves.
- Large-scale roads or clearings in vegetation of low-relief areas. The lack of vegetation causes artificial depressions in the elevation surface.
- Rivers less than 90 m wide enclosed by riparian vegetation. The vegetation effect can cause the river channel to appear slightly elevated.
- Braided rivers and deltas. The use of the single flow direction algorithm does not allow for depiction of river bifurcations.
- Narrow gorges. If the gorges are less than 90 m wide, they can appear closed on the elevation surface at 3 arc-second resolution.
- Inland sinks and depressions. These are often ambiguous or temporary in nature. Additionally, in karst areas flow paths are not necessarily terminated at sinks due to possible underground connectivity, and artificial depressions like large-scale mining may have flow bypasses.
- Elevated "barriers" in the elevation surface that in reality have no effect on flow continuity (e.g. bridges, high-density housing areas).
- Areas of no-data voids in the original SRTM data. The larger the void, the more uncertain is the filled surface (see 3.2).

Figure A1. Quality assessment of HydroSHEDS (extract from the Technical Documentation, Lehner et al. 2006)

3 Climate Data

3.1 Precipitation

Two different precipitation data sets were used to calculate the mean and the standard deviation (SD) of annual precipitation sums. The SPIRITS[8] software was used to process the data and to calculate the statistical parameters. Both data sets are available via the SPIRITS website (http://spirits.jrc.ec.europa.eu/download/downloaddata/downloadmeteodata/).

The first precipitation product are ten-daily (dekadal) **TAMSAT** Rain Fall Estimates (RFE) (1986–2015) from the TAMSAT Research Group at the University of Reading, UK (Maidment et al., 2014; Tarnavsky et al., 2014) with a spatial resolution of 0.04°. Routine products are derived from Meteosat thermal infra-red (TIR) channels based on the recognition of convective storm clouds and calibration against ground-based rain gauge data. The 17 missing dekads in the dataset were filled in with the dekadal mean precipitation computed for the entire study period (Processing/Temporal/Long-term statistics). Then, the dekadal data was cumulated to annual sums (Processing/Temporal/Cumulate → Sum (float)). Afterwards, mean and SD of the annual precipitation sums were calculated for the periods 1986–2015 (30 years) and 2000–2014 (15 years to match the evapotranspiration data) (Processing/Temporal/Long-term statistics).

Besides the TAMSAT dataset, the **CHIRPS** version 2.0 dataset (Climate Hazards Group InfraRed Precipitation with Station data; Funk et al., 2015; obtained from: http://chg.geog.ucsb.edu/data/chirps/) with a spatial resolution of 0.05° was used in order to provide an additional source for precipitation data. CHIRPS incorporates satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring. As for the TAMSAT data, annual precipitation sums were calculated from the dekadal data and then mean annual precipitation sums and SD were computed for the period 1986–2015 and 2000–2014.

3.2 Evapotranspiration

Annual evapotranspiration (ET) and potential ET (PET) data were obtained from the MODIS **MOD16A3** product (Mu et al. 2011). The product has a spatial resolution of 1 km, covers the period 2000–2014 and is provided in 0.1mm/yr units. For more information on the product and the download use the following website: http://ntsg.umt.edu/project/mod16. Mean and SD for annual ET and PET were calculated with ENVI (Basic Tools/Statistics/Sum Data Bands).

4 Vegetation and land cover

The mean occurrence and seasonal development of vegetation was analysed utilizing 10-daily **eMODIS Normalized Difference Vegetation Index** (NDVI) data provided by FEWS NET (http://earlywarning.usgs.gov/fews/) and distributed by U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center. The eMODIS product is a composited and temporally smoothed product with a spatial resolution of 250 m derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data.

SPIRITS was used to aggregate the dekadal images from 2001–2015 to monthly and annual images (Processing/Temporal/Cumulate → Mean). Then the mean and SD of the monthly and annual images was calculated (Processing/Temporal/Long-term statistics).

[8] SPIRITS Software for the Processing and Interpretation of Remotely sensed Image Time Series, Version 1.3.1, http://spirits.jrc.ec.europa.eu/

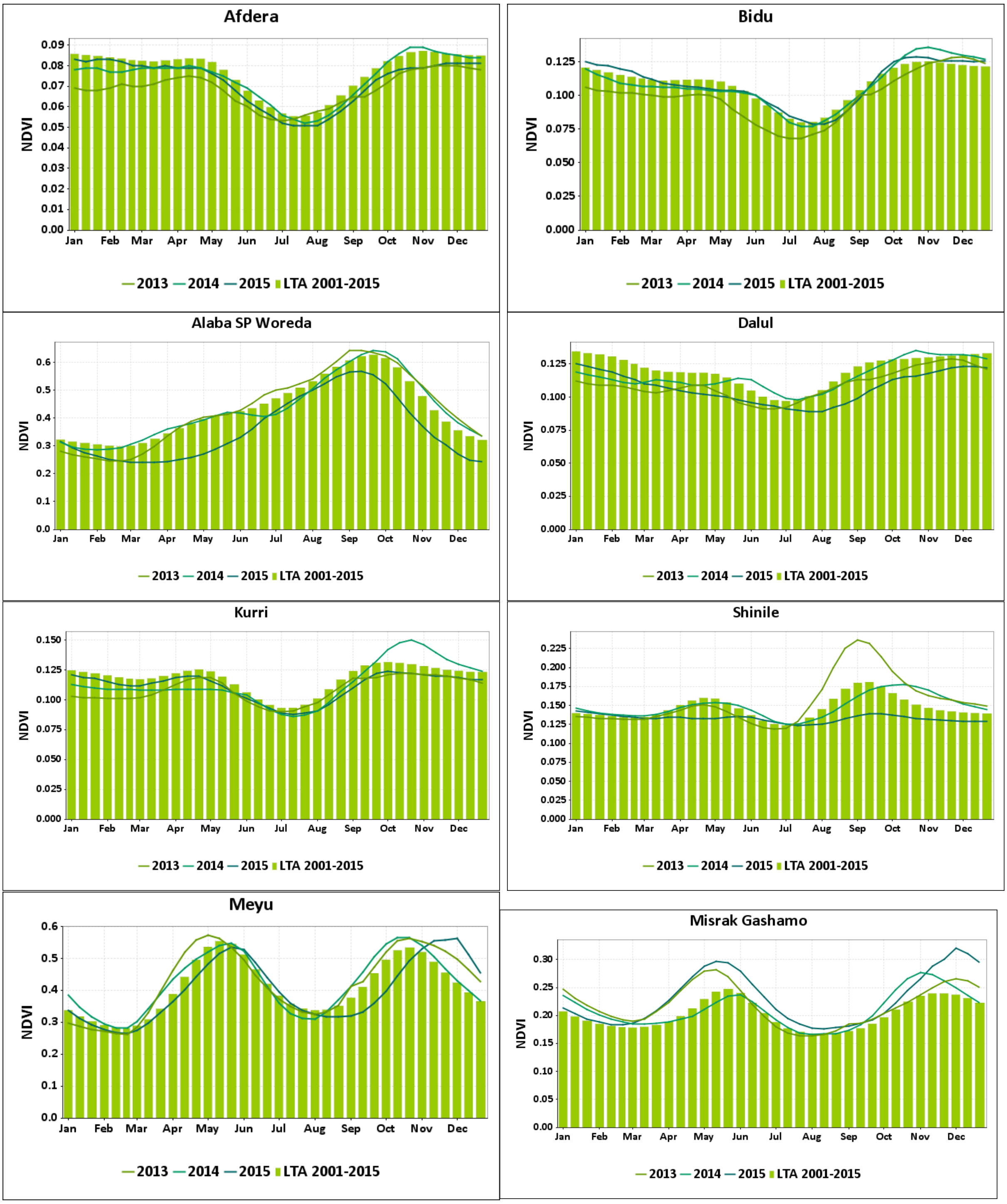


Figure A2. Temporal profiles of eMODIS NDVI (regional mean for each woreda) for the years 2013–2015 and the long-term average

In order to show the occurrence of vegetation and other landscape characteristics with a higher spatial resolution, **Landsat 8** (L8) images with a spatial resolution of 30 m were utilized. Aiming to show a kind of "maximum vegetation extent", the eMODIS profiles (computed with SPIRITS) for each *woreda* of the years 2013–2015 were visually analysed to find a period with high NDVI values (Figure A2). Then we checked in Google Earth Engine[9] (GEE) if there are (nearly) cloud free L8 images available for this period

[9] Google Earth Engine. https://earthengine.google.com/

and if necessary adapted the period (the image collection was restricted to images with cloud cover < 10 per cent, these were then checked manually). We then used GEE to extract the following products for each *woreda* and the selected time period (the composite period is indicated in the image name):

- NDVI (as maximum-value composite of the available images)
- True colour composite (RGB = Band 6, Band 5, Band 4)
- False colour composite (RGB = Band 5, Band 4, Band 3)

Additionally, we extracted NDVI maximum-value composite images from the entire L8 archive available at this time (2013/02/01 to 2016/04/22). Finally we exported the images from GEE in Latitude/Longitude projection, WGS84 datum (EPSG: 4326).

LB-NA-28179-EN-N

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office

doi:10.2788/050278

ISBN 978-92-79-63205-1