

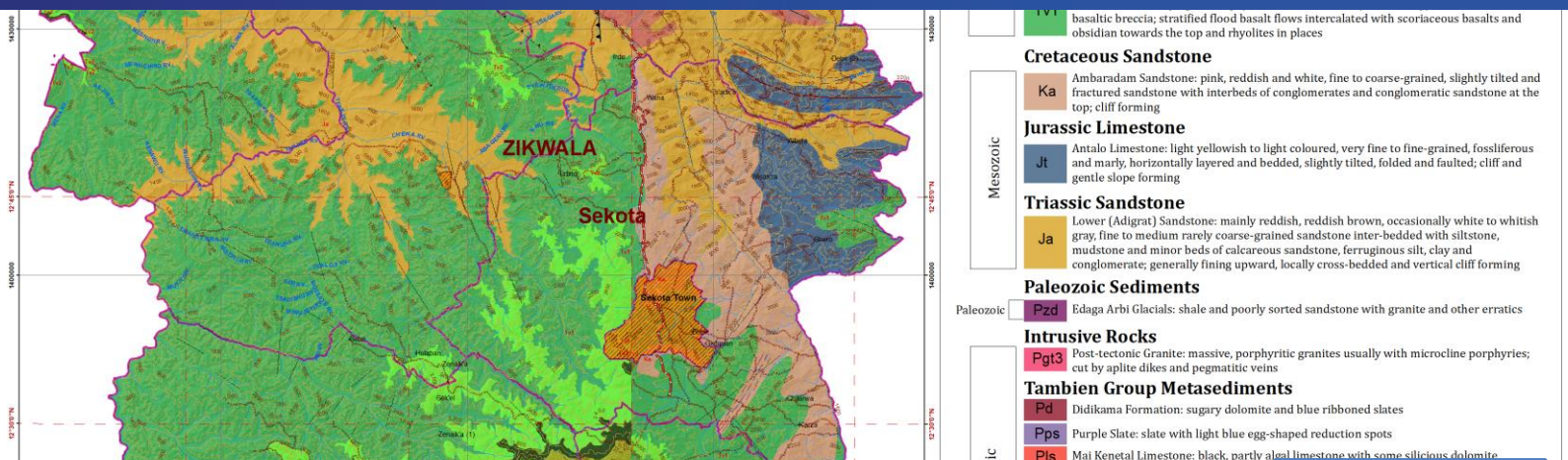
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Groundwater mapping for climate resilient WASH in arid and semi-arid areas of Ethiopia - Phase 1

Identifying the groundwater potential of 8 clusters

Final report



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Executive summary

UNICEF/EU RESET II program contracted Acacia water and a local team of experts to conduct a groundwater study to make groundwater suitability maps and to identify drilling target sites for 16 BH in the eight clusters of the RESET II program. The project areas encompass 41 water scarce woredas known to have complex hydrogeology. The complexity of the hydrogeology is manifested by low and indirect recharge, rugged topography, too low yielding shallow groundwaters, high salinity groundwaters and very low past drilling success rates. In addition, the widely dispersed communities and pastoral or semi pastoral livelihoods further complicated high WASH coverage and access in these areas.

Taking into consideration the complex hydrogeology, Acacia Water and its local partners have employed and improved the UNICEF developed groundwater exploration approach so as to achieve the objectives of the project. The method involves a GIS based overlay analysis and conventional and integrated hydrogeological mapping. The employment of the two methods comes in two phases. Phase 1 aims to conduct the groundwater suitability mapping using the UNICEF approach of overlay analysis. This report is the summary of results obtained during the Phase 1 activity.

The overlay analysis involves GIS computation of groundwater suitability by factoring various indicators for groundwater suitability and their weighting factors. The five indicator parameters that were chosen are: Permeability, Lithology, Slope, Recharge and Land use/Landcover. As lithology is the basis for the groundwater mapping, the existing geological maps have been harmonized and a new 1:250,000 scale geological map has been prepared for all clusters. The other indicators were derived from processed and supervised remote sensing images. Proper procedures have been followed during the conduction of the analysis including a) decision of the parameters following a detailed literature review and stakeholder/expert consultations, b) rating of criteria using SAATY methodology, c) ground verification of the output suitability maps and d) validation of the suitability maps with existing groundbased hydrogeology information. To complement the harmonized geological and groundwater suitability maps of the clusters, detailed conceptual groundwater occurrence models have been constructed along 21 geological sections.

The overlay analysis and the resulting suitability maps were then validated by a Peer Review Committee comprising experienced hydrogeologists and geologists.

All in all, the overlay analysis results match the ground conditions observed from previous studies. Nevertheless, unlike the initial assumption of feasibility of groundwater development for multi community schemes, only five of the eight clusters show the possibility of exploiting groundwater (cluster 2, 3, 4, 5, 7). The other three cluster are found to not be amenable for groundwater development (cluster 1, 6, 8).

During phase 1, water demand and socioeconomic maps have been produced as well, based on extrapolated 2007 census data. The groundwater suitability maps, and all other maps serve future drilling projects in the RESET II cluster areas and are disseminated to all stakeholders.

The geological, groundwater suitability, water demand and socio-economic maps formed the basis for the zonal consultation meetings in the RESET II cluster areas. In these meetings, which are actually part of Phase 2, stakeholders like NGO's, zonal and regional water bureaus and woreda representatives participated. The objective of the meetings was to select sixteen target areas for detailed hydrogeological mapping at a 1:50,000 scale. Detailed hydrogeological mapping is the aim of the phase 2 study under this project.

Colophon

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Glossary of terms

Hydrogeological map: scale 1:250,000; size equal to the existing Ethiopian gridded map series of the same scale. It is composite map based on the geological map where geological units having similar hydrological properties have been clustered. It shows aquifer productivity and hydrological features like rivers, springs, wells, structural geological elements, water quality data, groundwater head contours. The legend is conforming to international UNESCO standard. The background has topographical elements in grey.

Groundwater Suitability map: this is the 1:250,000 scale map produced from the overlay analysis which account for all physical criteria and which classifies areas according to the potential of drilling positive wells. It is a colour-coded map where colour codes correspond to specific potential classes for the different aquifers and potentially a correlation with the expected water quality. Features which are normally represented in the hydrogeology maps and which have led to the classification of the suitability zones may not be directly shown on such maps. Major land marks such as roads and rivers do feature on these maps.

Hydrogeological Operational map: this is the 1:50,000 scale map produced from the overlay of the Groundwater Suitability map and the socio-economic aspects and more specifically from the Demographic layer. The map sheets follow same grid and naming convention as the existing 1:50,000 topographic map series published by the Ethiopian Mapping Authority. The aim of this map is to identify the areas where the water demand is urgent and some potential for groundwater exists. With these maps, the Target area are going to be identified and selected for further investigations.

Target area: the part of the area chosen from the Hydrogeological Operational map that shall be the target for additional detailed hydrogeology survey at the scale of 1:50,000. Target areas are the areas which are to be chosen for the phase 2 studies. In RFP these are also called priority sites and detailed study areas.

Target site: specific drilling site which bears an X and Y coordinate. The (16) selected sites for drilling the groundwater wells. The target site shall be selected after a series of analyses and discussion with UNICEF and stakeholders. The final choice shall be presented to the steering-committee for 'validation' at the end of Phase 2.

Target site drilling maps: a detailed map to help locating the proposed sites. The maps include the exact location of the proposed sites as well as relevant geophysical measurements, profiles and cross sections and landmarks. In total 16 drilling maps are going to be prepared for this project.

1

Introduction

1.1 Project background and objectives

Drought is the major natural disaster affecting the livelihood of Ethiopians, resulting in water insecurity which in turn causes disruption of livelihoods and loss of life. A significant proportion of the Ethiopian population still lacks access to clean water, despite the fact that Ethiopia successfully achieved the Millennium Development Goal (MDG) in Water supply component of WASH in 2015.

Yet whilst emergency support is critical, it is also vitally important that resilient WASH development programmes take place in water insecure areas to break the cycle of emergencies. UNICEF has prioritized the implementation of resilient WASH programme by constructing large multi-village water supply systems, by drilling boreholes in Afar, Somali and Oromia and through expansion of existing water sources to enable access to sustainable water supplies.

However - by using different technologies/methodologies for groundwater exploration and targeting the regional groundwater flow, a few high yielding water sources can be successfully identified and developed. UNICEF has been using a new approach combining remote sensing, weighted GIS overlay analysis, hydrogeological mapping and geophysical surveying to increase the success rate of drilling and provide resilient water sources to communities.

UNICEF is building on this success by expanding the scale of the works with an EU-funded project entitled “Improving Access to Safely Managed Water Supply in the Resilience Building Programme for Ethiopia RESET II Woredas”.

The current project focusses on the mapping of the groundwater resources for a number of priority areas covering 39 woredas spread over 5 regions of Ethiopia. The so-called ‘operational maps’ should be an information base for water managers to take decision on locations for sustainable groundwater development. This innovative project will fine tune existing approaches and deliver a ‘mapping methodology’ replicable to other areas.

Objectives

The main objective of this project is to map the groundwater resources of 8 clusters spread over 5 regions of Ethiopia and pinpoint location with high water demand in combination with high potential for groundwater. With the compiled information, associated overlay analyses and extra geochemical and geophysical field surveys, the project team will propose 16 most promising drilling sites for groundwater abstraction and additional and optional sites as appropriate. It is believed, through such process drilling success rates will be enhanced. The following specific objectives are also associated to the project:

- Develop knowledge of the hydrogeological systems in the 8 proposed clusters;
- Improve the existing geological maps of the selected clusters;
- Build capacity on methodology and tools among the local professionals;
- Refine and test the methodology for allocating successful drilling wells.

1.2 General approach, deliverables and planning

The project is designed in 3 phases:

- Inception Phase
- Phase 1
- Phase 2

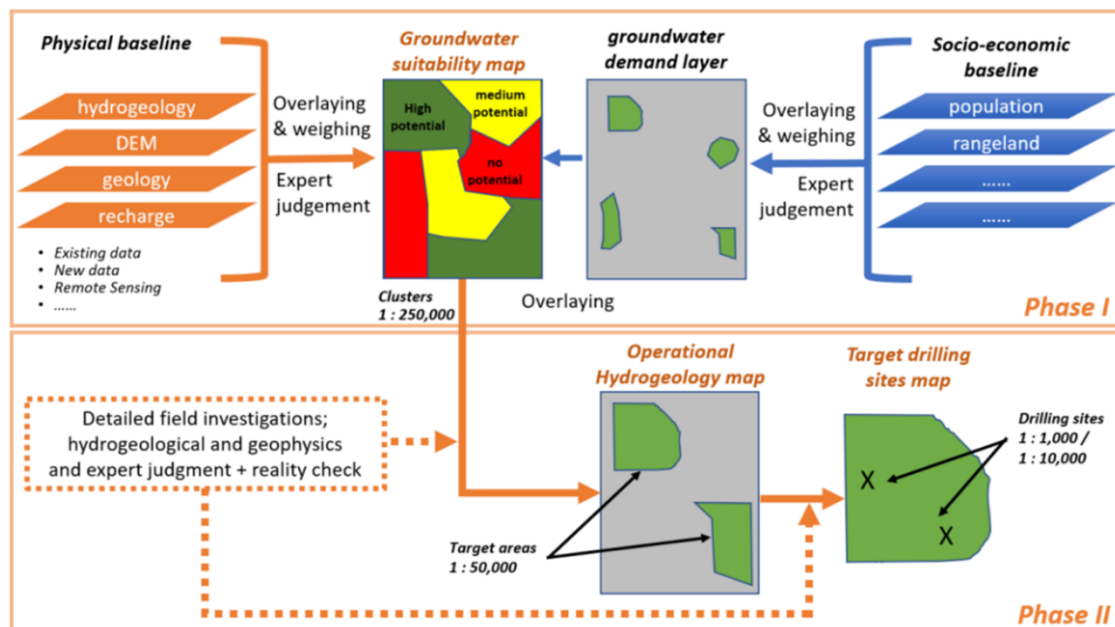


Figure 1. The project phases and the main deliverables.

During Inception Phase work has been done to further develop and detail the proposed methodology and work plan. The approach (figure 1) largely follows the flowchart in the RFSP which is based on the methodology of previous successful experiences in Afar, Somali and Tigray regions. The proposed method includes but is not limited to: geological and geomorphological exploration, geophysical exploration, Remote Sensing and GIS application, hydrological application for recharge estimation, geochemistry and isotope hydrology application, statistical approaches for validation of overlay analysis and data integration through conceptual model development.

The current report describes project activities and results of phase 1.

1.3 Phase 1 activities and deliverables

The following activities were carried out in phase 1:

- Remote sensing (RS) data acquisition and preparation with EU-JRC
- RS data processing and preparation input layers for overlay analysis
- Familiarization field visit to the cluster areas
- Water points inventory and Water quality survey
- Setting overlay analysis criteria & weighing criteria
- Peer review meeting
- Water balance studies and recharge estimations per clusters
- Overlay analysis, field work data integration and interpretation
- Preparation Groundwater Suitability maps (1:250,000)
- Ground truthing and validation of the Groundwater Suitability maps
- Dissemination workshop
- Phase I report writing and submission

The following main deliverables have been produced during Phase 1:

- Technical report: Overlay analysis criteria and weighting criteria;
- Technical report: Isotope application
- Peer review meeting minutes;
- Water balance study and recharge estimations per cluster;
- Groundwater Suitability map (1:250,000) at Woreda level (39 maps);
- Hydrogeological profiles (2-3) in each cluster
- Improved geological maps (1:250,000)
- Phase 1 Dissemination workshop
- Validated Phase 1 reports

In this Phase the main output are the groundwater suitability maps for each woreda. The maps combine general (hydro)geological features with zones with groundwater suitability, indicated by certain overlay textures. The groundwater suitability classes result from the overlay analysis and field verification.

1.4 Capacity building activities

A number of capacity building activities have been implemented under this project. During the water point inventory, junior and mid-career hydrogeologist from the zones and the regional government's bureaus have accompanied the senior field inventory team as part of an on the job training. The purpose of this on the job training was to transfer skills in taking water point data, and skills in the measurement of field water quality and other hydrological attributes. Each trainee spent a period of up to one month in the field.

Another capacity building activity has been undertaken during the suitability map field verification. A similar group of trainees attended the field training accompanying the field verification work. The various elements of the training include:

- Discussion of interest around any incidental matter regarding groundwater and hydrogeology.
- Use of QField Mobile Application for field tracking of georeferenced maps.
- Use of GPS Essentials Mobile Application for tracking of locations and recording of waypoints as well as for other uses such as: GPS coordinate recording, slope measurement, measurement of strike and dip directions.
- Use of Strike and Dip Mobile application for field measurement of dips strikes direction and amount of geologic structures.
- Field discussion about how to use field evidence to identify the various hydrostratigraphic units of the volcanic terrain according to the updated geology and hydro-stratigraphy of Ethiopia by Asfawossen Asrat (current work) and Seifu Kebede (2012).
- General discussion around BH monitoring, BH functionality diagnosis.
- Sharing of knowledge materials with the participants.

The third category of training involved lectures provided the junior staff members of the Ministry of Water, Irrigation and Energy and other junior staff members of the geological survey of Ethiopia. The topics covered so far include:

- Hydrogeology of Ethiopia (Seifu Kebede, a 1 hour 30 min hrs lecture).
- Geophysical methods (Koos , 2 hrs lecture).
- Isotope hydrology (Seifu Kebede, 2hrs 30 min).
- Geophysical methods practical assignments (Koos, 2 hrs lecture).

In addition to the activities above junior staff are invited to the weekly project meetings on Tuesday afternoons.

1.5 Content of this report

The report consists of a summary technical report with the main findings, based on field reconnaissance and desk study. The original large-scale maps are not included.

The text of this report and the accompanying maps and conceptual models can be found in a repository on the cloud server of Acacia Water. The url is <http://cloud.acaciadata.com/index.php/s/BDrDztpSve3I4wu>.

The structure of the repository is:

- **Suitability maps:** Suitability maps per cluster and per woreda
- **Geological maps:** Harmonized geological maps
- **Conceptual models:** Cross sections and conceptual models per cluster
- **Demographic maps:** Maps with water demand and demographics per cluster
- **Report:** This report

2 Basic data

2.1 Field inventory data

Existing data

Relevant information on existing water points, water quality, well logs and pumping tests was extracted from existing reports, maps and tables. The raw data is listed in a large Excel spreadsheet for easy reference. Secondary data sources are the ministry of water irrigation and electricity, and regional and zonal water offices of the respective cluster areas.

Next, the geographical coordinates in the Excel sheet were verified and translated to a uniform coordinate reference system (WGS84, UTM37N). Duplicate points and points without a geographical location or with wrong coordinates were discarded. After validation, 55243 datapoints were transported to a PostGIS database, linked to QGIS. Out of the 55243 datapoints, 1449 are within the 8 clusters of the project.

Inventory data

A field inventory was carried out as part of Phase 1 of the project. During the field visits, essential information about 653 existing water points lying within the cluster boundaries was collected. These water points are distributed over the clusters as follows in Table 1.

Table 1. Inventoried waterpoints

Cluster	Water points
Afar	164
Bale	95
Borena	103
Liben	31
Siti	54
South Omo	4
Wag Himra	156
Wolayita	46
Grand Total	653

The total number of waterpoints in the PostGIS database is 55.896, out of which 2.102 are located within the project area.

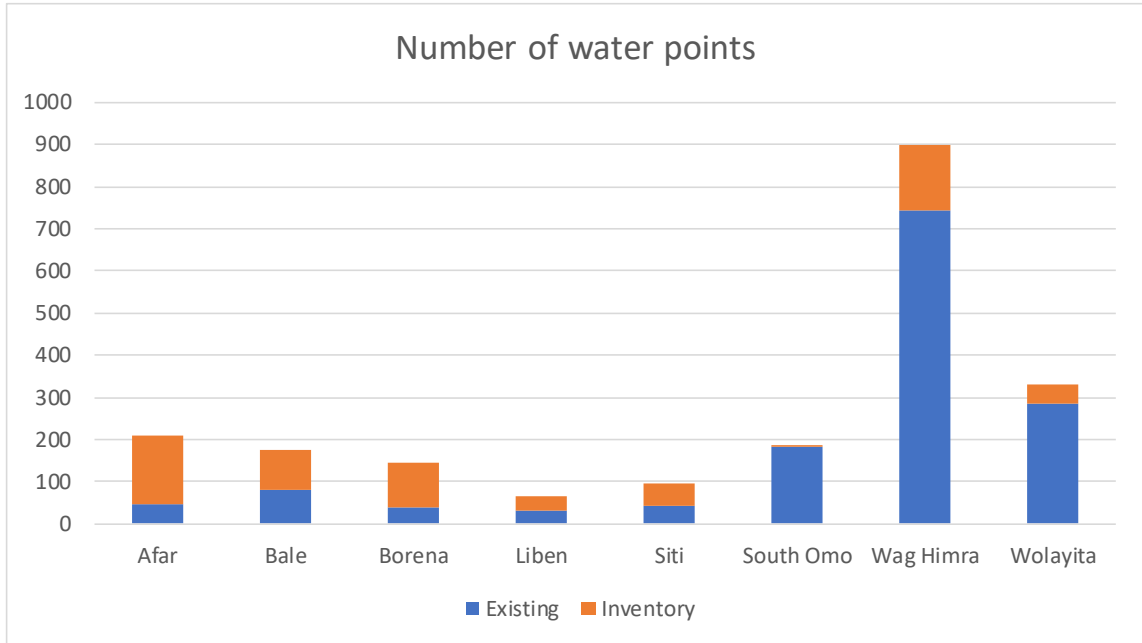


Figure 2. Number of water points per cluster in the database

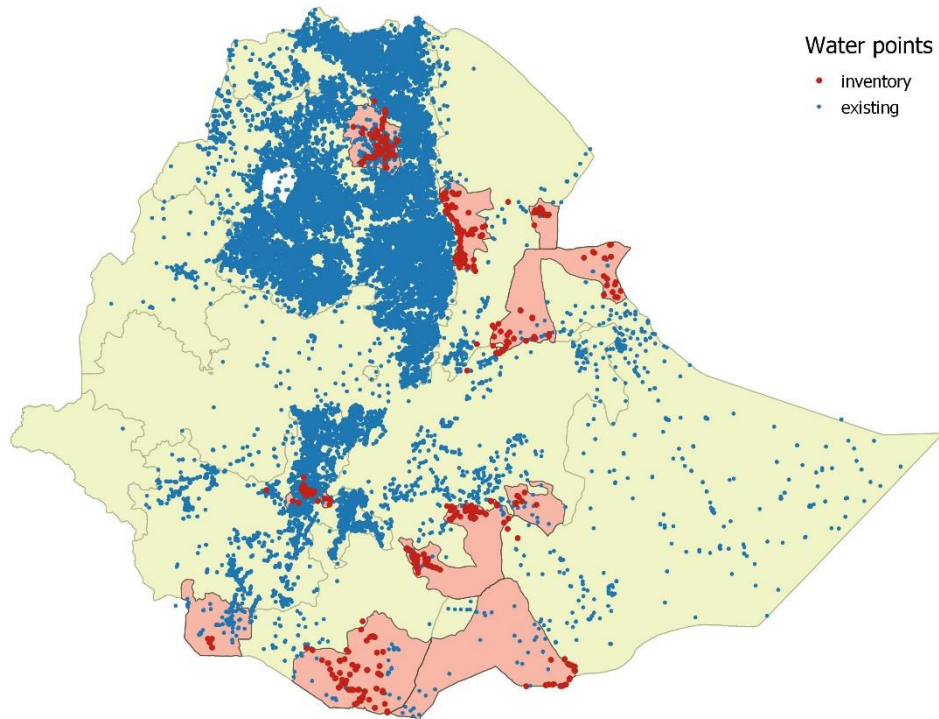


Figure 3. Water point locations

2.2 Remote sensing data

The following remote sensing imagery (Table 2) was obtained:

Table 2. Remote Sensing data sources

Theme	Source	Spatial resolution	Temporal resolution	Time	used	provided by
Elevation	SRTM	30 m	n/a	2013	yes	Acacia Water
Multiple	Landsat 8	30 m	n/a	Dec-17	yes	Acacia Water
Landuse	Sentinel-2	20 m	n/a	2016	yes	Acacia Water
Precipitation	CHIRPS	0.05 degree	daily	2000-2014	yes	JRC
evapotranspiration	MODIS	1 km	monthly	2000-2014	no	JRC
evapotranspiration	GLEAM	0.25 degree	daily	2000-2014	yes	Acacia Water
soil moisture	GLEAM	0.25 degree	daily	2000-2014	no	Acacia Water
soil moisture	SMAP	9 km	daily	2000-2014	no	Acacia Water
NDVI	MODIS	250 m	monthly	2000-2014	yes	JRC
Multiple	HydroSHEDS	1 km	n/a	2007	no	JRC

2.2.1 Digital elevation model

Elevation data was obtained from the NASA Shuttle Radar Topography Mission at 30 m resolution (SRTMGL1.003). The SRTM datasets result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA - previously known as the National Imagery and Mapping Agency, or NIMA), as well as the participation of the German and Italian space agencies. In the Version 3.0 products voids have been filled with ASTER Global Digital Elevation Model (GDEM) Version 2.0, the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), and the National Elevation Dataset (NED). For this project, 191 tiles of 1 by 1 degree were downloaded and merged into one single mosaic covering the entire country.

2.2.2 Landsat 8

For Phase 1 of the project, cloud free tiles were selected from the Landsat 8 Operational Land Imager (OLI). A total number of 71 cloud free tiles were downloaded (acquired between 16 Dec 2017 to 30 Dec 2017) covering the entire country. For the selected target areas, higher resolution multispectral imagery may be added from the Sentinel-2 mission.

2.2.3 Precipitation

CHIRPS v2.0 (Climate Hazards group InfraRed Precipitation with Station data version 2) developed by the U.S. Geological Survey (USGS) and the Climate Hazards Group of the University of California was used in this work as precipitation source. This dataset provides gridded global rainfall estimates at 0.05° (~5 km) spatial resolution and several temporal scales (monthly, decadal, pentadal or daily time steps) generated from a combination of in-situ station observations and satellite data (Funk et al., 2015). The decadal data was cumulated to annual precipitation sums. Then, the mean and standard deviation (SD) of annual precipitation sums were calculated for a 30-year period (1986-2015) and a short-term period (2000-2014).

2.2.4 Evapotranspiration

Two different evapotranspiration data sets were assessed to evaluate the evapotranspiration dynamics of the study area. The first ET product was the MOD16A3 from the Numerical Terradynamic Simulation Group at the University of Montana (<http://www.ntsug.umt.edu/project/mod16>) at 1 km spatial resolution.

The MOD16A3 ET is an annual product that covers the period 2000-2014 (Mu et al., 2011). Mean and SD for annual ET were calculated.

The second data set used was the Global Land Evaporation Amsterdam Model (GLEAM), which is a set of algorithms dedicated to the estimation of terrestrial evaporation and root-zone soil moisture from satellite data. GLEAM v3 is used to produce three new data sets of terrestrial evaporation and root-zone soil moisture, including a 36-year data set spanning from 1980-2015 and two satellite-based data sets. The global daily data was downloaded for the period 2000-2014 at a resolution of 0.25 degrees.

After inspection of the data, it was felt that the evapotranspiration was underestimated in areas with sparse vegetation (Afar and Somali clusters). Although at coarser spatial resolution, the evapotranspiration from GLEAM provides more reliable evapotranspiration estimates.

2.2.5 Land use Land cover

Two different available land cover datasets were evaluated as input for the overlay analysis. The first is Globeland30 at 30 m resolution dating from 2010 that was developed by NGCC (National Geomatics Centre of China) by a pixel-object-knowledge (POK) using multispectral images, including Landsat Thematic Mapper TM, Enhanced TM+ and multispectral images from the Chinese Environmental Disaster Alleviation Satellite (HJ-4). The final global product included ten land cover types and achieved an overall accuracy of 66.6% for Africa (<http://www.globallandcover.com/GLC30Download/index.aspx>).

On the other hand, the European Space Agency Land Cover of the Climate Change Initiative project (ESA LC CCI) developed a prototype high-resolution LC map at 20 m over Africa. LC-CCI used Random Forest and Machine Learning to classify cloud-free reflectance composites of Sentinel-2A observations from December 2015 to December 2016 (CCI LC, 2017). The CCI-LC legend product includes ten generic classes that appropriately describe land surface and the overall accuracy of the product was found to be 64% (Lesiv et al., 2017) (<http://2016africallandcover20.m.esrin.esa.int/download.php>).

Both datasets were visually assessed using high spatial resolution from Google Earth, after which it was found that LC-CCI outperformed Globeland30 because of misclassifications of cropland in cluster 2 (Afar). Consequently, in this study ESA LC-CCI was selected as land cover input.

2.2.6 Soil moisture

The Soil Moisture Active Passive (SMAP) mission provides soil moisture estimates with global coverage (Reichle et al., 2018). The SMAP sensor uses a microwave frequency that is sensitive to the soil moisture content in the top 5 cm of the soil column. In the Level 4 SMAP product, these shallow soil moisture data are combined with a model to obtain soil moisture estimates for the root zone. GLEAM also provides root-zone soil moisture estimates, but at a much coarser spatial resolution. Therefore, SMAP root-zone estimates were used in the overlay analysis. Daily SMAP root-zone soil moisture data with a spatial resolution of 9 km were downloaded for the 3-year period June 2015 to May 2018.

2.2.7 NDVI

The 10-daily eMODIS Normalized Difference Vegetation Index (NDVI) was used as proxy of vegetation productivity and to capture seasonal development of vegetation. eMODIS data was provided by FEWSNET (<http://earlywarning.usgs.gov/fews/>) and distributed by the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center. Their MODIS product is a composited and temporally smoothed product at 250 m spatial resolution from Moderate Resolution Imaging Spectroradiometer (MODIS) data.

Dekadal images from 2001-2015 were aggregated into monthly and annual images. Afterwards, the mean and standard deviation of the monthly and annual images were calculated.

2.2.8 HydroSHEDS

The HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) dataset (<https://hydrosheds.cr.usgs.gov/>) is used in this study as a source of hydrographic information (Lehner et al., 2008). HydroSHEDS provides a suite of data sets at regional- and global-scale (vector and raster) based on high-resolution elevation data of SRTM. The data used includes the river network (streamlines), drainage basin (watershed boundaries), flow accumulation and drainage direction (in a number of cells) at 15 arc-seconds (~ 500 m) spatial resolution.

2.2.9 Topographic Wetness Index

The Topographic Wetness Index (TWI) is a measure of the topographic control on hydrological processes and is defined as $TWI = \ln(a/\tan\beta)$, 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). The TWI is calculated by the r.watershed algorithm provided by the GRASS toolbox in QGIS using a depressionless DEM as input.

2.3 Harmonized geological map

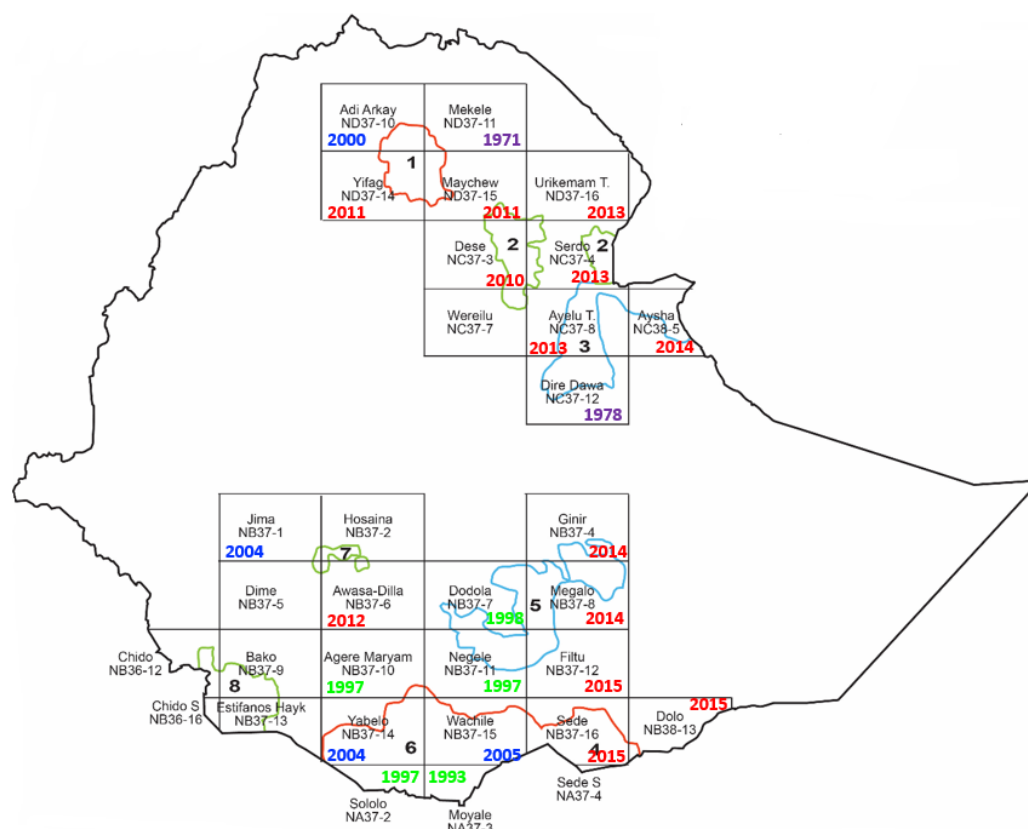


Figure 4. Visualization of the geological maps used during the harmonization, including the year they date from.

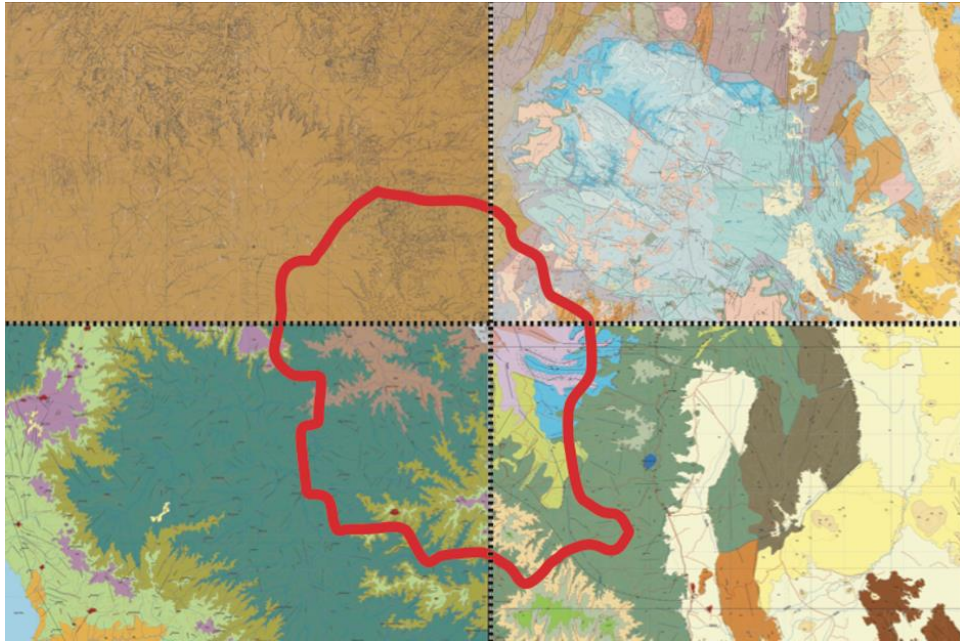


Figure 5. Example of the combined maps for Cluster 1 (Wag Himra).

Geology is arguably one of the most important aspects influencing the occurrence of groundwater. Therefore, the unavailability of a complete and unambiguous geological map covering all target areas would be a significant shortcoming for this project. Harmonization of the existing geological maps (Figure 4 & 5) was a complicated undertaking, of which the step-wise approach will be described hereafter.

1. Searching, sorting, and systematization of all existing point, discrete and spatial geological and structural data in the area of interest (clusters in this case):
 - Define the regional geological and structural setting, and geological evolution of the area.
2. Collecting, compiling, digitizing and harmonizing previous geological maps of the area (1:250,000 mostly GSE maps where available and dully cited in the prepared maps and reports; 1:50,000 or other scale maps from all other sources, including actual geological mapping conducted in other projects, and research works by our group):
 - Define the major gaps in information;
 - Prepare a 1:250,000 scale geological base map: harmonized geological map projected on a scanned mosaic of 1:50,000/1:250,000 scale topographic map of the area.
3. Tracing of major faults and lineaments from spatial imageries and previous maps:
 - Preparation of structural maps of the basin and catchments;
 - Fracture analysis and structural maps used to define the structural regimes of the basin and to determine their influence on hydrogeological and hydrological processes (e.g., flow regimes).
4. Preparation of geomorphological maps:
 - Surface geological mapping in the field;

- Preparation of TINs (Triangulated Irregular Network) from 30 m and 90 m resolution DTED maps;
 - Overlaying geological, structural, and drainage maps on the TIN maps: to characterize the geomorphic history with respect to the overall geological evolution; to characterize the geomorphologic processes and units with respect to their influence on groundwater movement and storage.
5. Finalize the geological, structural and geomorphological maps and the associated geological cross-sections:
 - Using all the geological, structural and geomorphological maps and secondary data (all existing data in our database including detailed geological maps and reports conducted by us or others, and data such as geophysical survey results, geological well logs, etc.).
 6. Preparation of detailed explanatory note of the geological map:
 - Clearly define the stratigraphic outline of the mapped units, as well as the lithological associations of the rock units;
 - Facilitate the interpretation of the geological, structural and geomorphological setting of the area in a usable form for further hydrogeological mapping and evaluation.
 7. Deducing the implication of the geological, geomorphological and structural setting of the basin on hydrogeological and hydrological flow regimes as well as on water quality:
 - Help to formulate conclusions and recommendations about the geological-structural parameters controlling the surface and groundwater regime of the basin and their impact on groundwater resource evaluation.

2.4 Data on socio-economy and water demand

Population, livestock, geographical and socio-economic data all originate from the Central Statistical Agency (CSA) of Ethiopia. They were provided directly by the CSA or were downloaded from the website <http://www.csa.gov.et>. We thank Gijs van 't Klooster of FAO and Zablou Adana of the World Resources Institute for supplying livestock and population data of the CSA in excel format.

PRIME (<https://www.prime-ethiopia.org/>) provided detailed information on population and livestock for the Borena zone (cluster 6).

In addition to data mentioned above the following websites and literature has been consulted for data, background information on water consumption by population and livestock and government policies related to water demand.

Data sources

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- Website United Nations, DESA/population division, world population prospects. consulted Januari 9, 2019. <https://population.un.org/wpp/>

3

Reclassification of basic data to groundwater information layers

The first step in the overlay analysis is the pre-processing of the input data and preparation of the input layers for the overlay analysis.

During the pre-processing, the GIS input layers are projected to WGS84, UTM 37N (EPSG:32637) and clipped to the extent of the cluster. (The cluster boundaries were provided by UNICEF as shapefiles). Because the actual overlay analysis is performed on raster files, all input layers are rasterized or resampled to a uniform resolution (250 m). The entire pre-processing process has been automated and is available as a graphical model in QGIS's processing toolbox.

We have used the input data from table 3 to prepare the 6 overlay layers. You are referred to Chapter 2 for a detailed description of the input data.

Table 3. Overlay layers

Overlay layer	Main source
Landuse	ESA/Sentinel-2
Lithology	Harmonized geological map
Slope	SRTMGL1
Recharge	CHIRPS precipitation
Density	SRTMGL1
Proximity	Harmonized geological map

The preparation of the overlay layers is described in detail in the next sections. Samples of source data and overlay layers are included for illustrative purposes. The sample area is located in Borena (cluster 6).

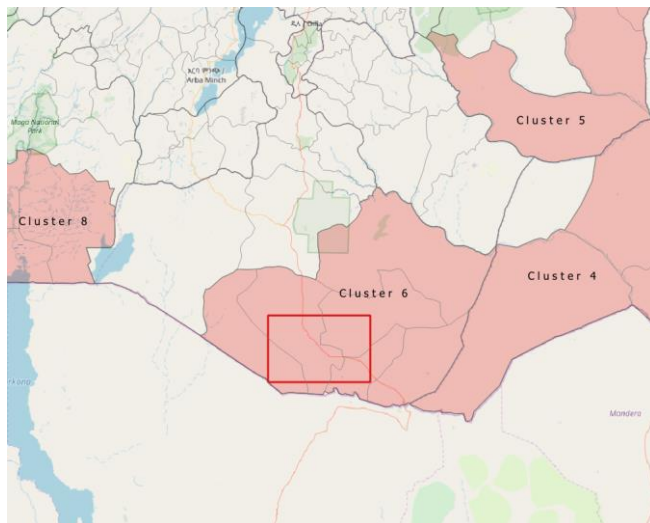


Figure 6. Location sample area (Borena cluster 6)

3.1 Slope

The SRTMGL1 digital terrain model is used to compute the slope of the terrain. First, the DEM is resampled to 250 m resolution. Next, the standard GDAL slope algorithm from QGIS is used to determine the slope in degrees.

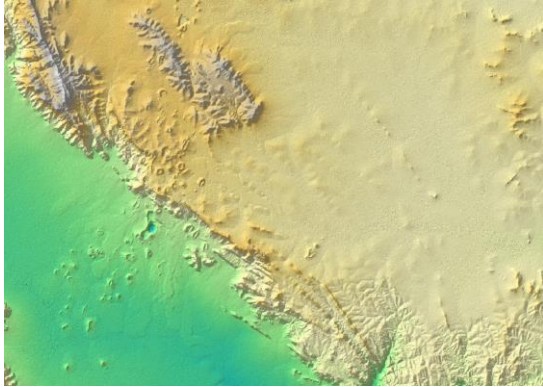


Figure 7. SRTMGL1 elevation

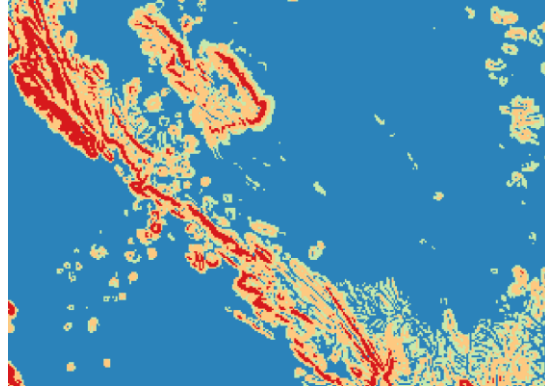


Figure 8. Slope overlay layer

3.2 Lineaments

Lineament density

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 PCI Geomatica. SRTM elevation data was used to calculate the different hillshades in QGIS. The solar elevation (vertical angle) was kept constant for all hillshade images and set to 30°. Using the LINE module of PCI Geomatica lineaments were automatically extracted using a solar elevation of 30 degrees and azimuths of 0, 45, 90, 135, 180, 225, 270, and 315 degrees. The results were converted to vector files.

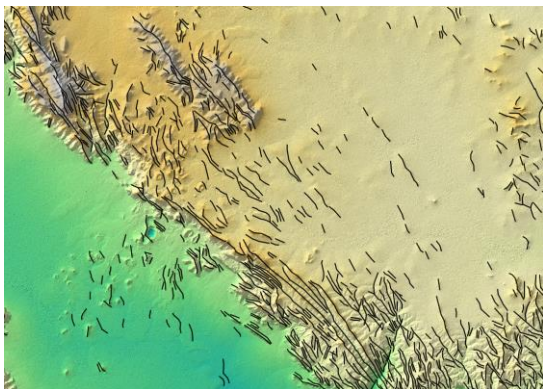


Figure 9. Lineaments from SRTM

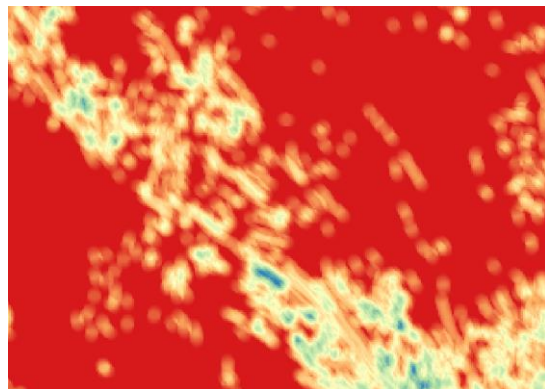


Figure 10. Lineament density overlay layer

The automatic lineament detection methodology applied here is unable to distinguish between geologically structured lineaments and other, unrelated linear features. Also, it appeared to result in an unwanted bias in suitability for steep terrain with outcropping hard rock. On the other hand, the suitability of areas with alluvial or regolith cover was underestimated. Therefore, the automatic lineament map does not provide a reliable image on its own.

Lineament proximity

To compensate for the unreliability of the lineament density map, a lineament proximity layer is introduced as well, which uses the proximity, or distance, to lineaments as a measure (as opposed to the density).

This layer uses the lineaments provided by the harmonized geological map instead of the lineaments resulting from the automatic detection algorithm. These structures mapped by geologists from map interpretation and field observations are relatively scarce, but more realistic and relevant. Therefore, proximity to these geological lineaments was introduced as a second criterium.

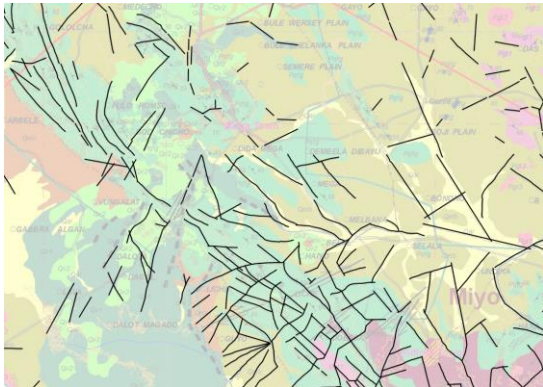


Figure 11. Lineaments from geological map

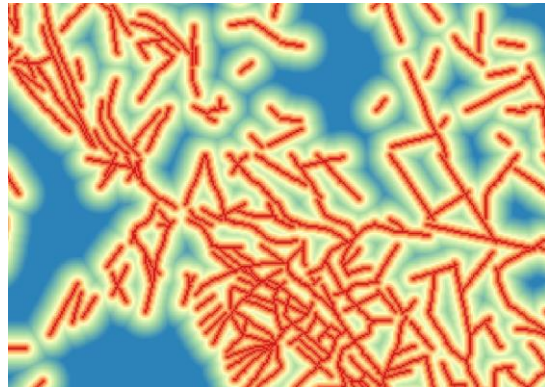


Figure 12. Lineament proximity layer

3.3 Recharge

The recharge overlay layer is computed as the total precipitation depth in mm/y multiplied by an infiltration coefficient. The source for the precipitation is the average precipitation in mm/y computed from daily CHIRPS data over the period 2000 – 2014. The yearly average is resampled (downscaled) to 250 m resolution using cubic interpolation.

For the recharge calculations, use is made of the study by MoWIE, BCEOM, ISL and BRGM in 1999 for the Abbay River Basin Integrated Development Master Plan Project. In the study, an infiltration coefficient was assigned to all lithological units appearing on the geological map of Ethiopia. These infiltration coefficients were assigned to the units of the harmonized geological maps. Combined with the precipitation data (Figure 13), the infiltration coefficients yield the recharge layer (Figure 14).

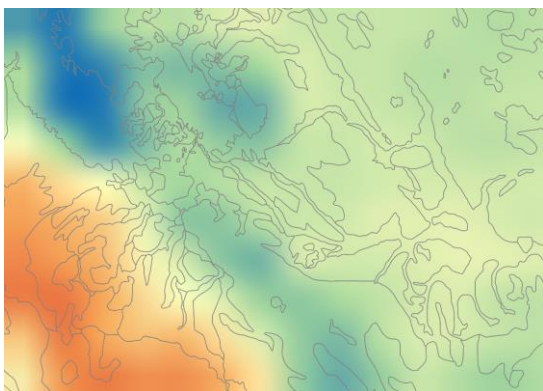


Figure 13. Precipitation

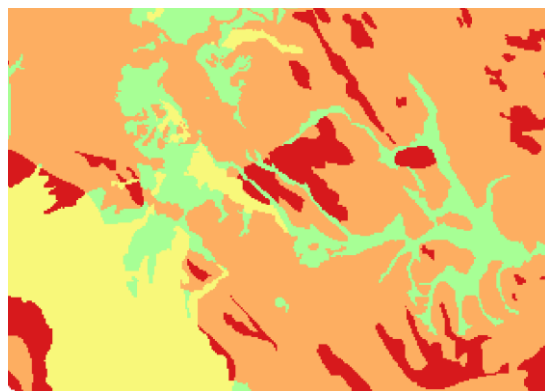


Figure 14. Recharge overlay layer

3.4 Land use and land cover

For the land use overlay layer, the Sentinel-2 land use classification by ESA's CCI was used. This dataset contains 10 land use classes on a 20 m resolution.

The data was resampled to 250 meter and reclassified to the 5 land use classes used in the overlay analysis (table 4).

Table 4. Land use re-classification

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

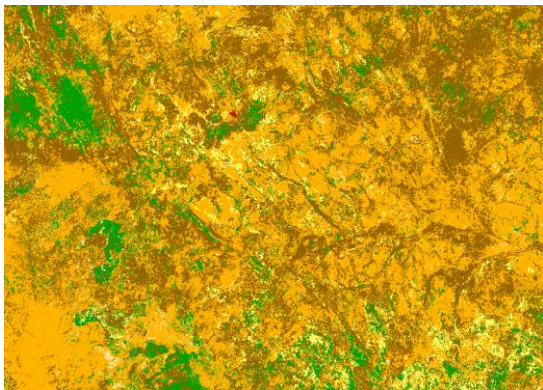


Figure 15. ESA Land use

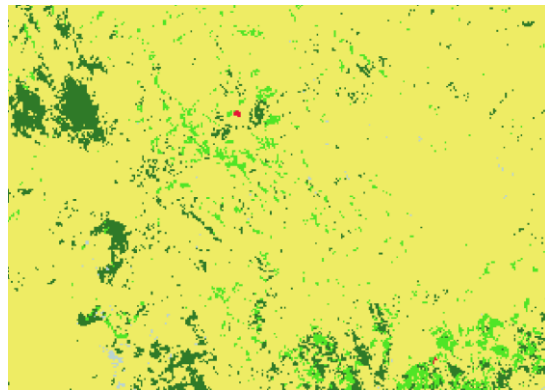


Figure 16. Land use overlay layer

3.5 Lithology and permeability

Lithology is used as a proxy for the permeability and the harmonized geological map is used as a source for the permeability classes. The 103 geological units that appear on the harmonized maps are grouped into 7 permeability classes (table 5). The source files (vector format) are reclassified according to Table 5 and rasterized to 250 m resolution.

Table 5. Permeability classes

Class	Description
1	Loose quaternary sediments including elluvials and Miocene sediments
2	Rift pyroclastics and rift silicics
3	Upper basalts, Quaternary highland basalts and rift basalts
4	Lower basalt
5	Limestone, Upper sandstone, shale, marl and all other Mesozoics
6	Lowgrade basement and Adigrate sandstone
7	Highgrade basement

Figure 17 and 18 show the original harmonized geological map (left) and reclassified permeability layer (right).

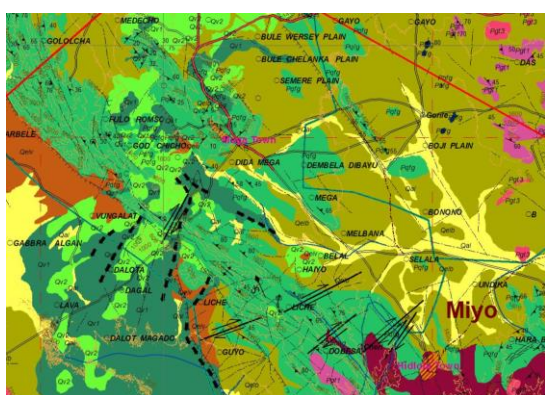


Figure 17. Harmonized geological map

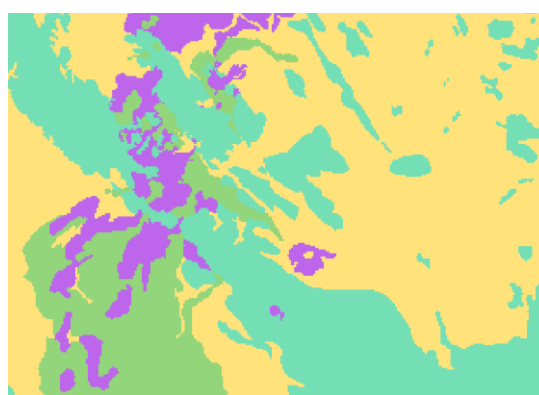


Figure 18. Permeability overlay layer

4 Overlay Analysis and groundwater suitability

4.1 Weighting factors

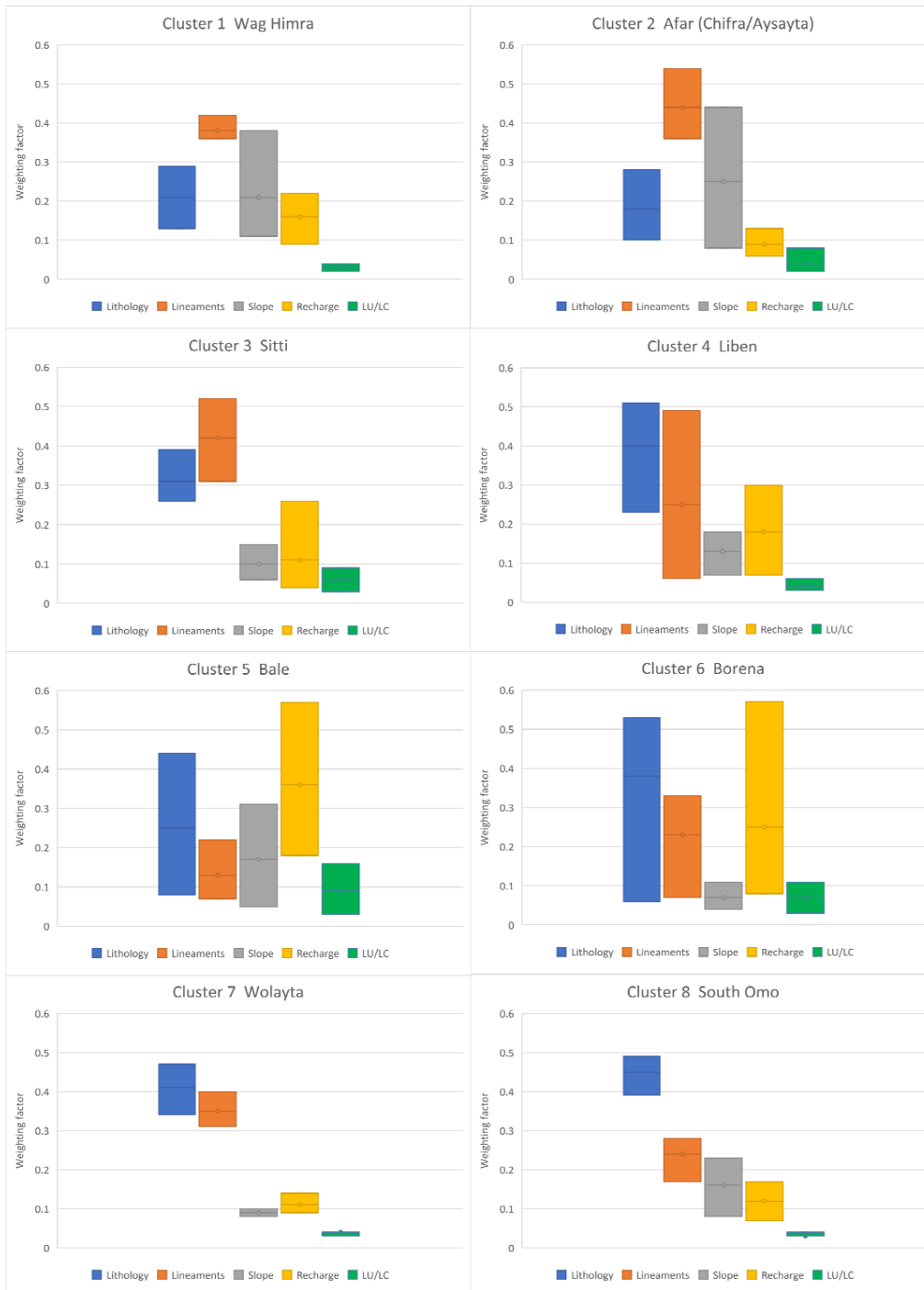
The five information layers described in Chapter 3 form the criteria which together determine the groundwater suitability. A workshop was organized to determine the weights for each criterium, during which 17 experts filled in Saaty questionnaires to define the respective weights. As the hydrogeological conditions vary greatly across the project's clusters, weights were determined for each cluster separately.

The results are shown in Table 6 and Figure 19 below. The minimum and maximum values are included as well, which will be taken as the basis for a sensitivity analysis on the mapped groundwater suitability zones (Paragraph 4.4).

Table 6. Weights factors for the overlay analysis based on Saaty questionnaires

	Weights Cluster 1, Wag Himra (3 resp.)			Weights Cluster 2, Afar (Chifra/Aysayta) (5 resp.)		
	Average	Minimum	Maxim.	Average	Minimum	Maxim.
Permeability.	0.21	0.13	0.29	0.18	0.10	0.28
Lineaments	0.38	0.36	0.42	0.44	0.36	0.54
Slope	0.21	0.11	0.38	0.25	0.08	0.44
Recharge	0.16	0.09	0.22	0.09	0.06	0.13
Landuse/cover	0.03	0.02	0.04	0.04	0.02	0.08
	Weights Cluster 3 Sitti (4 resp.)			Weights Cluster 4 Liben (5 resp.)		
	Average	Minimum	Maxim.	Average	Minimum	Maxim.
Permeability.	0.31	0.26	0.39	0.40	0.23	0.51
Lineaments	0.42	0.31	0.52	0.25	0.06	0.49
Slope	0.10	0.06	0.15	0.13	0.07	0.18
Recharge	0.11	0.04	0.26	0.18	0.07	0.30
Landuse/cover	0.06	0.03	0.09	0.04	0.03	0.06
	Weights Cluster 5 Bale (4 res.)			Weights Cluster 6 Borena (8 resp.)		
	Average	Minimum	Maxim.	Average	Minimum	Maxim.
Permeability.	0.25	0.08	0.44	0.38	0.06	0.53
Lineaments	0.13	0.07	0.22	0.23	0.07	0.33
Slope	0.17	0.05	0.31	0.07	0.04	0.11
Recharge	0.36	0.18	0.57	0.25	0.08	0.57
Landuse/cover	0.09	0.03	0.16	0.07	0.03	0.11

	Weights Cluster 7 Wolayta (4 resp.)			Weights Cluster 8 South Omo (6 resp.)		
	Average	Minimum	Maxim.	Average	Minimum	Maxim.
Permeability.	0.41	0.34	0.47	0.45	0.39	0.49
Lineaments	0.35	0.31	0.40	0.24	0.17	0.28
Slope	0.09	0.08	0.10	0.16	0.08	0.23
Recharge	0.11	0.09	0.14	0.12	0.07	0.17
Landuse/cover	0.04	0.03	0.04	0.03	0.03	0.04



Error! Reference source not found. Figure 19. Factors for each cluster as determined during the workshop.

For cluster 1, 2 and 3 the largest weight is given to Lineaments, followed by Lithology. For clusters 4, 6, 7 and 8 Lithology is the dominant criterium: for cluster 4, 7 and 8 this is followed by Lineaments and for cluster 6 by Recharge. In cluster 5, Recharge followed by Lithology are the most important factors. The primary weights of each cluster are also visualized in Table 7.

Table 7. Primary weighting factors for each cluster.

Cluster	Primary weight	Secondary weight
1 Wag Himra	Lineaments	Lithology
2 Afar	Lineaments	Lithology
3 Sitti	Lineaments	Lithology
4 Liben	Lithology	Lineaments
5 Bale	Recharge	Lithology
6 Borena	Lithology	Recharge
7 Wolayta	Lithology	Lineaments
8 South Omo	Lithology	Lineaments

As can be seen in Figure 19, for the clusters 4, 5 and 6 the bandwidth between minima and maxima of the primary and secondary weights is particularly high. During the discussion it became clear that these clusters were least hydrogeologically known to most attendees, which explains the large variance.

Given that clusters 1 and 2 are underlain by low storage old volcanic rocks (Ashengie basalts), in addition to the rugged topography of both sites, assigning high weights to lineaments and permeability makes sense. Cluster 3 is dominantly underlain by alluvio lacustrine sediments interbedded with volcanics forming a gently sloping area. Indirect recharge is principal pathway for recharge. Most productive zones are when coarse grained sediments and fractured basalts are encountered. The region is also characterised by dense network of faults/fractures. Giving high rates for lineaments and permeability makes sense in this environment. Given thin regolith cover and groundwater occurrence in basement fractures in the hard rock areas of cluster eight, giving a high rate for lineament makes sense. The overall conclusion drawn from the discussion of the results of the Saaty questionnaires was that average weights of the five criteria are logical and applicable to the overlay analysis. Another conclusion was that the large variance of some weights (mainly in cluster 4, 5 and 6) is due to the fact that the hydrogeological environment of some clusters is not well known in general or that some attendees personally did not know the area well. The variance (difference between max and min weights) will be used as a basis for the sensitivity analysis.

4.2 Classes and scores

General

For the mathematical procedures applied in an overlay analysis, basic groundwater information layers need to be reclassified and converted into normalized scores. For this study, equal classes and scores have been defined for all clusters. Differentiating classes and scores for the clusters individually - in addition to the already differentiated weighting factors - would create patterns in suitability which are difficult to interpret or to compare between clusters. Also, variation in scores would easily interfere with the already varying weighting factors and lead to double counting. For an overview of relevant literature on overlay analyses and the classes and scores applied in several studies we refer to Annex 3.

Slope

Table 8 contains the classes and scores for the slope criterium. The class of slopes greater than 15 degrees is a special class in the sense that zones falling into this category are immediately classified as unsuitable, regardless of the other criteria. These areas are indicated as dark grey.

Table 8. Classes en scores for criterium Slope

Slope in degrees	Score
0 – 3	0.6
3 - 5	0.3
5 – 15	0.1

Lineaments

As described in section 3.2, a combination of two subcriteria was used for the lineament criterium:

- lineament density based on remote sensing data and an automatic lineament detection algorithm
- proximity to lineaments/structures based on geological maps

The project expert team believes lineaments and structures mapped by geologists are more realistic and should get more weight. The weights for the subcriteria “lineament density” and “lineament proximity” are 0.8 and 0.2.

The classes and scores for the two subcriteria are summarized below (Table 9).

Table 9 Classes en scores for criterium Lineaments

Lineament proximity (subcriterium weight = 0.2)		Lineament density (subcriterium weight = 0.8)	
Class in meters to lineament/structure	Score	Class km/km ²	Score
0 – 500	0.62	< 0.3	0.03
500 – 1000	0.16	0.3 – 0.6	0.07
1000 – 2000	0.11	0.6 – 0.9	0.15
2000 – 4000	0.07	0.9 – 1.2	0.30
> 4000	0.04	> 1.2	0.45

Recharge

Annual recharge has been defined as the annual rainfall multiplied by an infiltration coefficient. The infiltration coefficients for all lithology classes have been defined by the expert project team. In Table 10 the major lithology classes are summarized with the range of infiltration coefficients. Annual rainfall was derived from TRMM satellite.

Table 10. Major lithology classes with ranges of infiltration coefficients

Lithology class	Infiltration coeff.
Loose quaternary sediments including elluvials and Miocene sediments	0.1 - 0.2
Rift pyroclastics and rift silicics	0.1 - 0.2
Upper Tertiary basalts, Quaternary highland basalts, Rift basalts	0.1 - 0.2
Lower Tertiary basalts	0.1
Limestone, upper sandstone, shale, marls, all other Mesozoic sediments	0.05 - 0.1
Lowgrade basement rocks and Adigrate sandstone	0.03 - 0.05
Highgrade basement rocks	0.03 - 0.05

The recharge classes are given in table 11.

Table 11. Recharge classes and scores

Class in mm	Score
< 25	0.05
25 – 50	0.11
50 – 100	0.27
> 100	0.57

Land use

For the criterium land use we used the map created by ESA based on interpretation of SENTINEL 2A data. For the overlay analysis the 10 classes of the ESA map have been reclassified into 5 classes (see section 3.1). The scores for the classes have been defined by the expert project team on the basis of Saaty enquiries (Table 12).

Table 12. Land use land cover classes and scores

Class	Score
Cropland	0.44
Bush/ range land	0.29
Forest	0.17
Degraded land	0.07
Urban	0.03

Lithology/permeability

For the suitability related to permeability of the rocks the harmonized geological map has been reclassified into 5 lithology classes. The expert project team attributed scores to these classes using Saaty enquiries (Table 13).

Table 13. Lithology classes and scores

Lithology class	Score
Loose quaternary sediments including elluvials and Miocene sediments	0.25
Rift pyroclastics and rift silicics	0.10
Upper Tertiary basalts, Quaternary highland basalts, Rift basalts	0.35
Lower Tertiary basalts	0.15
Limestone, upper sandstone, shale, marls, all other Mesozoic sediments	0.05
Lowgrade basement rocks and Adigrate sandstone	0.08
Highgrade basement rocks	0.03

Suitability score

The overall groundwater suitability score is calculated as weighted summation of all the scores of the 5 criteria mentioned above. Some clusters with unfavorable characteristics like arid zones or zones underlain by crystalline basement rocks will have low scores all over the cluster. If a unique color scheme would be applied for the entire project, the maps of these unfavorable clusters would render almost single colored maps with little differentiation. To avoid this, rainbow color schemes have been used showing grading from red (lowest score) to blue (highest score) for all clusters. The rationale for this “stretching” is that future users may still want to drill wells in areas with low suitability, particularly if other option like distant sources (multi-village schemes) are not feasible.

4.3 Overlay analysis

In the actual overlay analysis, the groundwater suitability is calculated as a normalized, weighted sum of the overlay layers per cluster. The overlay layers are calculated by recoding the input layers using their respective score tables (section 4.2).

The resulting suitability is calculated as a summation of the overlay layers multiplied by their cluster specific average weight (section 4.1). The entire process is automated in QGIS through a python processing script.

Figure 20 below shows the six recoded input layers and resulting suitability map for the sample area in cluster 6. Please refer to figure 6 for the location of the sample area. The layers and suitability map in figure 20 are coloured with the same colour scheme: from red (low score) to blue (high score).

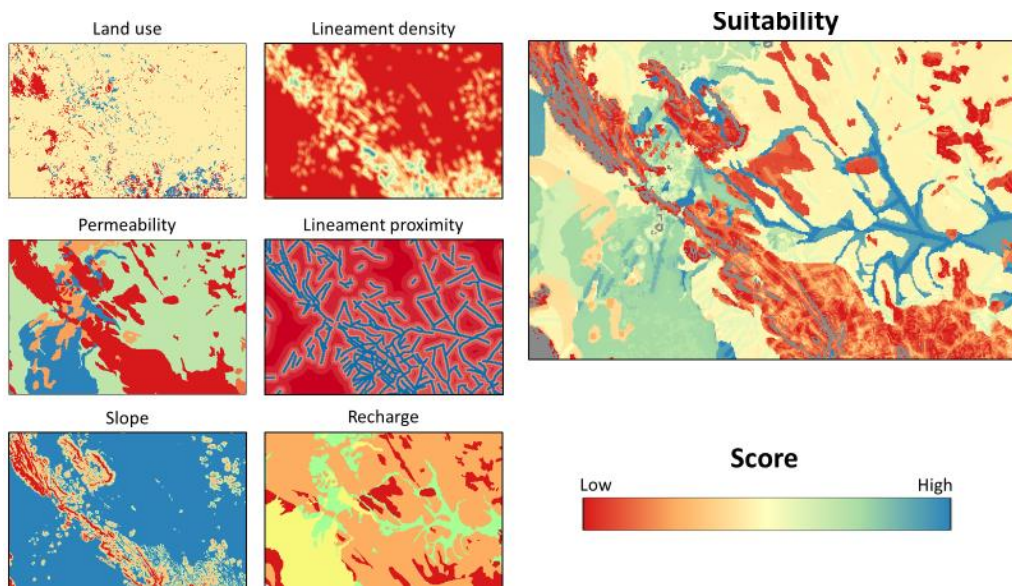


Figure 20. Recoded input layers and resulting suitability

4.4 Sensitivity analysis

During a workshop in September 2018 the members of the peer review committee assigned a set of weights for the overlay layers (see section 4.2). For the final suitability maps, the average weights were used. To determine how changes in weight affect the final suitability score, a sensitivity analysis was performed.

The analysis consisted of selecting the two most important input layers (the layers with the highest weights) and setting their weights to the minimum and maximum values assigned by members of the committee. The weights of the other layers were adjusted to keep the sum of weights equal to 1.

Thus, four additional sets of weights were prepared, and corresponding suitability maps were calculated, as well as the range and standard deviation in suitability per pixel. The standard deviation of the suitability is considered as a proxy for the sensitivity.

The same sample area from cluster 6 is chosen again to illustrate the sensitivity analysis (figure 22). In cluster 6 the weights for permeability and recharge show a relatively high range: the weight for permeability ranges between 0.06 and 0.53 and the weight for recharge between 0.08 and 0.57 (figure 21). The high variability of the weights of the input layers translates to a high sensitivity of the final suitability scores.

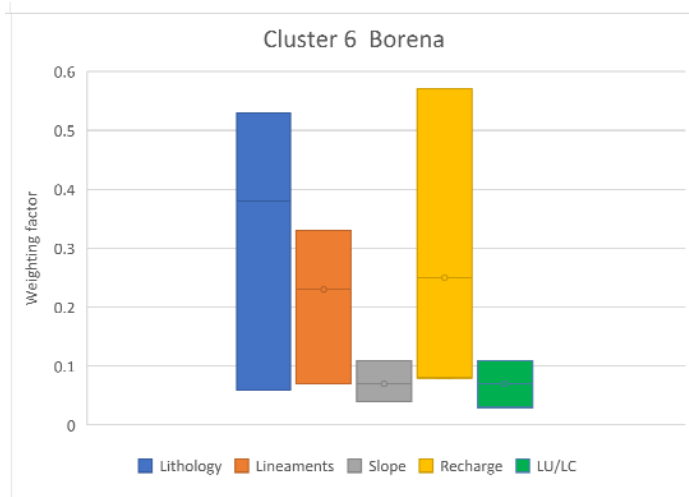


Figure 21. Weighting factors for overlay layers in cluster 6 (Borena).

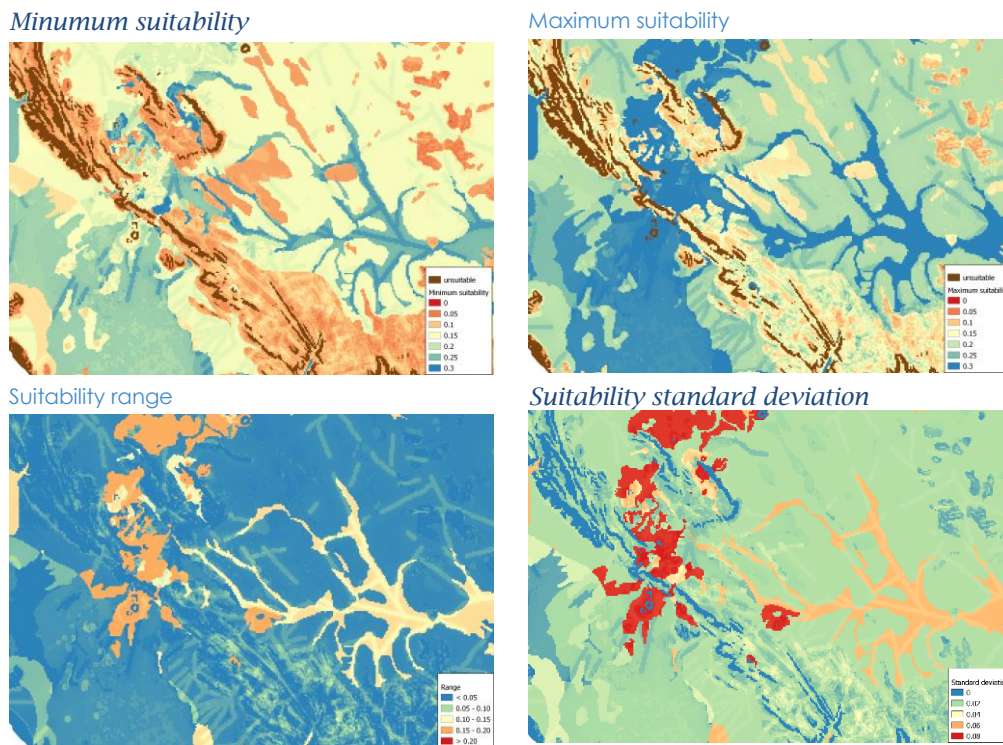


Figure 22. Sensitivity analysis for sample area in cluster 6

Figure 23 shows result of the sensitivity analysis for all clusters. To be able to compare between clusters, a uniform colour scale was used, ranging from low (blue) to high (red). Cluster 2 is predominantly orange to red in colour, which means that the sensitivity is relatively high when compared to clusters 1, 7 and 8 (blue colour). In clusters 3, 4, 5 and 6 yellow and green prevails, indicating an average sensitivity.

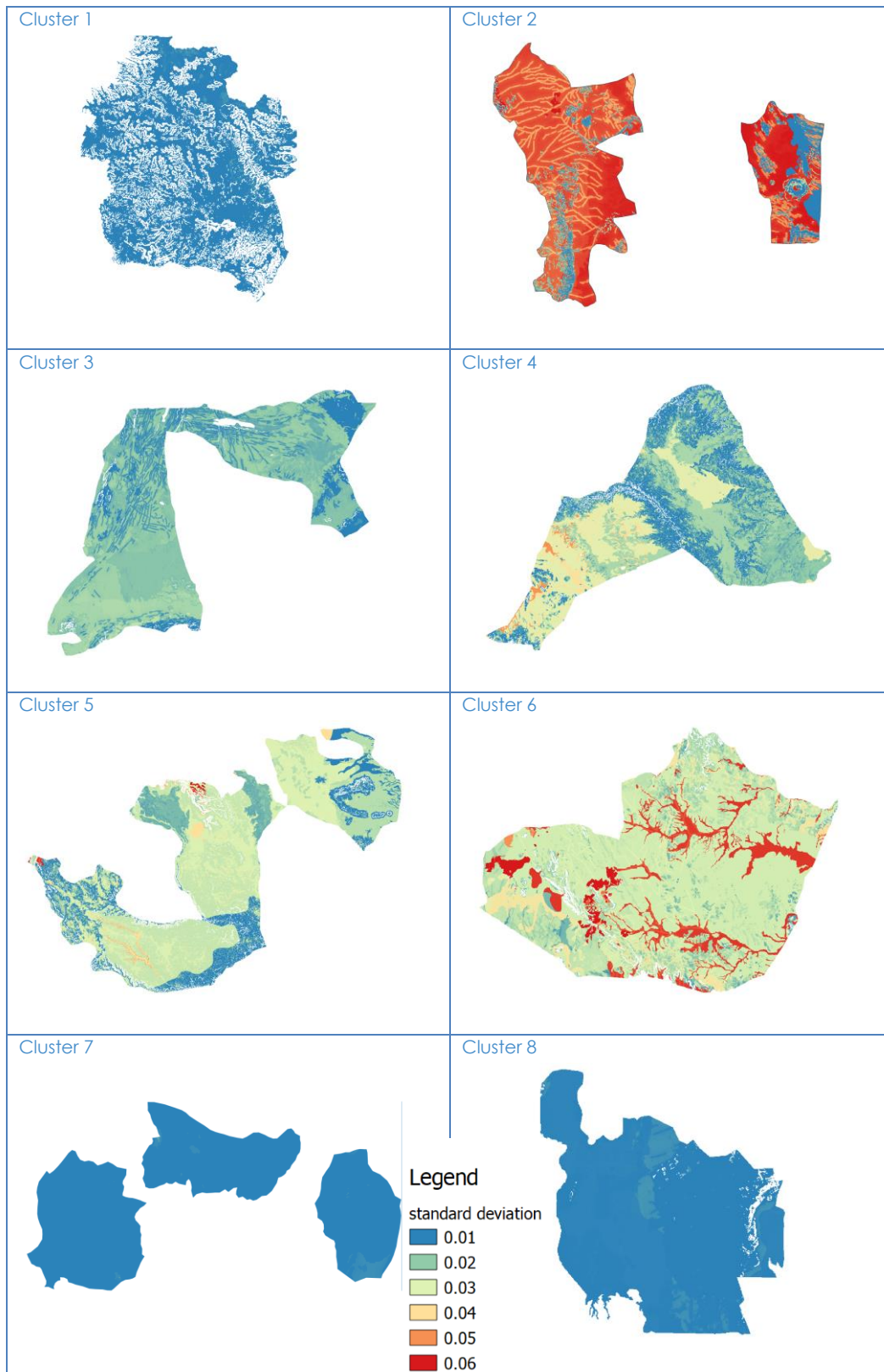


Figure 23. Standard deviation of suitability

4.5 Validation

Two types of validation were applied during Phase 1 of the project. The results of the overlay analysis could be compared to the data contained in the borehole database, as well as to the actual ground conditions during fieldworks.

Firstly, the results of the overlay analysis (suitability maps) were validated against the inventory data (653 waterpoints) and previously existing data (2102 waterpoints). For every waterpoint, the suitability score was extracted from the suitability maps. Figure 24 shows the histograms of the suitability scores of the waterpoints from the inventory and the previously existing waterpoint data in the clusters.

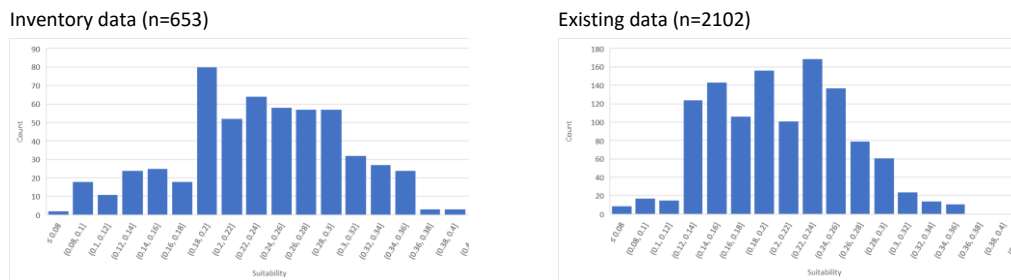


Figure 24. Suitability histograms

The majority of the waterpoints from the inventory are in areas with a suitability score between 0.17 and 0.30 (average = 0.23). For the existing data these figures are 0.15 and 0.26 (average = 0.20).

It is tempting to try to find a relation between the suitability score and the borehole yield. Because the dataset of existing waterpoints is not validated and incomplete, the exercise is carried out for inventory data only. At first glance, the yield and suitability score seem to be uncorrelated (Figure 15). It appears however, that high yields are found only in areas with a suitability score between 0.16 and 0.32 (shaded area).

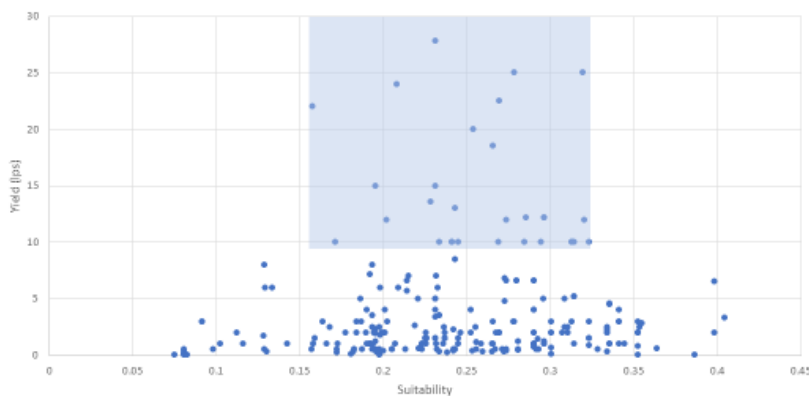


Figure 25. Correlation between suitability and borehole yield

Because the inventory dataset contains only a selection of waterpoints and is not randomly distributed, one cannot draw definite conclusions about the quality of the overlay analysis in relation to the existing boreholes.

Secondly, the results of the overlay analysis were validated against the ground conditions during ground truthing fieldworks in each cluster. While the fieldworks were carried out by different groups of people, generally the same methodology was used.

The suitability maps were printed as hard copies in appropriate scales to take into the field. The maps were also prepared in soft copy format in order to load them into the QField Mobile Application (which tracks the team's real-time location on the suitability map). Other tools were required as well, such as a GPS device.

In general, the following actions were performed during each fieldwork:

- Make observations on the regional and local geomorphological settings
- Verify the map with a series of ground control GPS readings
- Register water points and their characteristics as groundwater indicators
- Compare suitability zones on the output maps with general ground conditions
- Make geological and hydrogeological observations
- Consult with regional and zonal experts
- Identify the limitations in the groundwater suitability maps

The results of the ground truthing fieldworks will be described hereafter in summary. The complete fieldwork reports can be found in Annex 2.

Cluster 1

- Both in the northern and southern half of the cluster, blue (high suitability) areas are encountered. The field conditions however suggested otherwise. The topography in the south is very rugged and unsuitable for any form of drilling. The high suitability on the map is caused by the high density of lineaments that is suggested by the ruggedness of the terrain. Because of this, it was suggested to include an unsuitable rating for areas with a slope above a certain threshold (which was later implemented at 15%), and to use lineaments from the geological map (in addition to those generated using an algorithm).
- In the north, the high suitability rating is caused by the low slope, but only fracture zones were found to be suitable for drilling. Other suitability classes were not always distinguishable from the blue zones in the field and were generally found to be unsuitable for well extraction as well.

Cluster 2

- As was the case in cluster 1, areas with the highest suitability are classified as such because of the supposedly high number of lineaments caused by rugged topography. After the alterations to these overlay layers mentioned above, these areas should be classified as low suitability.
- The moderate suitability zone in the Western Afar sub cluster is in fact the most promising area of the cluster and should thus be classified as high suitability. On the other hand, the moderate suitability area in the Lower Awash sub cluster should be classified as low suitability, because of the limited aquifer extent and low recharge.
- Some (very) low suitability zones deserve this classification (steep and rugged terrain), but the low suitability area in the Lower Awash sub cluster should in fact be high potential. It should be noted that the salinity is high at this location, but this is not accounted for in the overlay analysis.

Cluster 3

- The suitability map for Ayesha woreda classifies the woreda as predominantly low to very low suitability. Some kebeles, however, seem to have a moderate to high suitability (like Biyo-Kabobe, Biyo-Gurgur and Degago).
- The remaining three woredas (Erer, Afdem and Meiso) are potential groundwater zones. The suitability map for these areas indicates a high suitability as well, so the map and ground conditions match very well here.

Cluster 4

- Only Dolo-Addo woreda was visited. It shows low to medium suitability across the area, with higher potential only found close to rivers. This is mostly coherent with the suitability map.

Cluster 5

- An extensive area of the Dawe Kachen woreda is indicated as high suitability. This is a result of the assumption that the present basalt unit continued deeper. The field observations indicate its thickness doesn't exceed 40 m, and the suitability should therefore probably be lower.
- The unwanted bias for steep and rugged terrain, which was encountered in clusters 1 and 2 as well, is found in cluster 5. The modifications to the input layers will improve this.

Cluster 6

- The main aquifer in this cluster is the Bulal aquifer system within the basalt formation (Dillo woreda). This area is correctly mapped as highly suitable. However, the map also depicts other high suitability areas in this woreda. Basement rocks occur there, which are less suitable than the basalt formation. The classification should therefore be adjusted to low or moderate. The steep areas should be indicated as unsuitable.
- The area surrounding Dubluk (Dire woreda) shows extensive moderate suitability on the map. The ground observations indicate that this should in fact be classified as low suitability, while some selective fracture zones could remain at moderate suitability.

Cluster 7

- The map mostly corresponds with ground conditions in the Diguna Fango and Boloso Sore woredas, apart from the earlier mentioned inconsistencies related to the slope and lineaments.
- The map of the Kindo Koysha woreda was hardly usable, because of the abundance of steep and rugged topography in this area, which yielded problems in the draft maps.
- In the Damot Pulasa woreda, the coherence between the map and the ground conditions was practically non-existent. Medium to high suitability zones were mapped as low suitability, while areas of low suitability were mapped as suitable.

Cluster 8

- The suitability map for cluster 8 was shown to be relatively reliable. The Omo Valley was classified as highly suitable, while the Hamer highland was assigned a low suitability. This is unsurprising, as the alluvial deposits of the Omo Valley are far more suitable than the crystalline basement rocks of the Hamer highland.
- While the map shows a decent insight in the potential for borehole drilling, care should be taken. Several instances of water quality issues were encountered (salinity, fluoride).

5

Geological and groundwater suitability maps and conceptual models

5.1 Cluster 1: Wag Himra

Geology

A small inlier of Late Proterozoic metavolcanics and metasediments is exposed in the northern part of the cluster. Its thickness is around 200 m.

Paleozoic shales and poorly sorted sandstone and tillites are exposed over most of the metamorphic basement with a thickness of roughly 100 m.

The northern and north-eastern area of the cluster expose up to 600 m thick Triassic sandstone inter-bedded with siltstone and mudstone. The sandstones are strongly jointed and fractured.

In the eastern part of the area there are limited exposures of Jurassic limestone (up to 400 m thick) and Cretaceous sandstone (up to 300 m thick).

Major areas in the west and south are covered by Oligocene plateau volcanics (Lower Basalt in particular) of up to 800 m thick.

On the high plateau in the south, isolated peaks of Upper Basalts are exposed.

Alluvial sediments rarely occur (except in small patches).

Hydrogeology

Cluster 1 is generally a water stressed dissected highland owing to the lack of suitable geology/physiography for storage of surface and groundwaters. A large part of the project area has slope greater than 15 degrees. The high relief means rain waters rapidly gets its way out of the catchment with little chance for downward percolation and little chance for regional groundwater flows.

Compared to regions elsewhere in the highland Ethiopia, the Wag Himra zone is characterized by a low groundwater potential. The low potential is the outcome of a) relatively small aerial extent of individual aquifers, b) the rugged topography which allows for rapid and almost immediate drainage, in addition to the low permeability and storage potential of the most dominant geological units.

Regardless of these difficulties there are some potential shallow groundwater exploitation/exploration sites for small scale rural water supply development. These include a) minor mountain/fault bounded alluvial valleys and river terraces, b) contact zones between the upper and the lower basalt formation where permeability contrast allows lateral flows of groundwaters to the slopes, c) local depressions formed in the basal basalt units (eg around Weleh valley) where groundwater converges to these low points and may result in shallow groundwater occurrence, d) narrow local plateaus developed on the upper basalt sequence (e.g. in Dahana woreda).

Conceptual model

Existing evidence (geology, hydrogeology) has been used to construct conceptual model for groundwater recharge, occurrence and flow. The conceptual model is presented in Annex 3. As can be seen from the figure, groundwater flow lines are short, and deeper aquifers are devoid of replenishment by downward percolation because of steep slopes. Natural water chemistry is generally good when productive wells are encountered.

5.2 Cluster 2: Afar

Geology

The majority of cluster 2 is covered with Miocene-Pliocene-Quaternary rift volcanics and sediments. The exception is a limited exposure of Oligocene Lower Basalt in the north-western corner of the area.

Miocene Mabla Rhyolite and Dahla Basalt are dominant in the western part of the cluster. Pliocene-Pleistocene Afar Stratoid Basalts and Basaltic Fissure Flows underlie the lowland plains at the axial parts of the Afar rift. The Afar Stratoid Basalts are interstratified with Quaternary lacustrine and alluvial sediments.

The Awash river valley exposes conglomerates and deposits of sheet flood terraces with a thickness of up to 100 m.

In the western and eastern margins of the area, successions of basalts are encountered. The eastern part of the Tendaho Graben (south/south-east of Aysaita) is covered in Quaternary lacustrine deposits of up to 50 m thick.

Hydrogeology

There two subclusters in this cluster. The western subcluster covers the western Afar escarpment. The eastern subcluster covers the lower Awash area adjacent to the Awash river. In the western sub cluster, groundwater occurs in the multi layered volcanic rocks of Miocene to Quaternary ages. Rainfall decreases from 800 mm/year near the mountains to less than 200 mm/year in the rift floor. There is isotopic evidence that the groundwater in the western subcluster is recharged from loosing wadi beds and from the perennial streams emerging from the western Ethiopian plateau.

Close to intermittent streams groundwater can be found at depths ranging from 80 to 120 meters. When there is sufficient thickness, the alluvial sediments mantling the area form an important source of groundwater for water supply uses. Fresh groundwater bodies can be found in association with alluvial materials and basalts. There are hundreds of deep productive boreholes of substantial yield (>10 l/s) encountered in this subcluster. Elsewhere in the Afar region, where the Afar stratoid basalt forms an extensive horst, the deeper water table limits prospects for groundwater development. In the southern part of the Afar depression and adjacent to the foothills of the escarpment in the west, productive zones within the Afar Stratoid Basalts are common.

The eastern subcluster falls within the geologically known area of the the Tendaho Graben. Recharge to the Tendaho Graben sediments takes place from a) the Awash River, b) from the escarpment adjoining from the western highlands (UNDP, 1973) and c) local recharge from rainfalls and floods emerging from wadi beds in the west.

Four types of aquifers have been recognized by previous studies. These include: a) shallow aquifers recharged mainly by the Awash river and secondarily by local rainfall and wadi bed percolation, b) hydraulically isolated multi layered shallow aquifers occupying the central plain (e.g. around Det Bahari), c) deep multi-layered and generally salty groundwaters underlying the Tendaho Graben, recharged from the western escarpment and d) volcanic aquifers of local extent and recharge. The salinity in the Tendaho Graben aquifer generally increases with depth and distance from Awash river.

At deeper levels the salt content may reach 200000 micro simens/cm. The extreme variation in salinity in the groundwater of Tendaho Graben makes it unattractive for major development. Nevertheless, for local supplies, fresh groundwater zones such as in the plain of Det Bahri and adjacent to Awash River could be utilized for conjunctive water supply and irrigation uses.

Conceptual model

The conceptual model depicted in Annex 3 shows the mode of groundwater occurrence, groundwater flow and recharge/discharge relationships. Groundwater in the western sub cluster generally gets its recharge from loosing wadi beds and from loosing perennial streams. Groundwater salinity increases towards the rift floor as one moves from the highlands to the lowlands. The areas adjacent to the rivers can be sites for shallow groundwater development (up to 150 m). Deeper horizons in the volcanics also yield a substantial amount of groundwater. The eastern subcluster is characterized by intercalations of thick sediments and basalts. Isotopic evidence shows the shallow aquifers here are recharged by the Awash river, while the deeper waters are recharged from the regional groundwater emerging from the plateau. High salinity and low yields of the fine-grained components of the sediments limit extensive groundwater development. However, zones with less saline groundwaters and high yields can be encountered given an in-depth study of the local hydrogeology.

5.3 Cluster 3: Sitti

Geology

Most parts of cluster 3 are underlain by the Afar Stratoid Basalts and Basaltic Fissure Flows, particularly by the Upper Afar Stratoid Series.

In the southern and south-eastern extremes of cluster 3, high-grade granitic gneisses and migmatites are overlain by strongly fractured and faulted Triassic sandstones (~200 m thick), Jurassic limestones (~300 m thick) and Cretaceous sandstones (~300 m thick).

Oligocene flood basalts (Lower and Upper Basalt) form isolated hills in the eastern area, in addition to a 150 m thick Upper Basalt ridge in the southern part.

Isolated, small hills of strongly fractured Quaternary basalts, and rhyolite domes are common in the western and south-western margins of the area;

Some graben floors in the west of the cluster expose up to 50 m thick Quaternary lacustrine sediments. Other grabens in the northern part of the area contain thin marshy deposits. The Upper Afar Stratoids in most places (particularly the flat plains) are covered by Quaternary deposits of around 50 m thick.

Hydrogeology

Cluster 3 is underlain by the most prolific aquifers known in the country, in the Shinile area. The geology of of this area comprises alluvial sediments, lava sheets, extensive basalt sheets and ridges, Mesozoic sequences and high-grade basement rocks. However, nearly 90% of the project area consists of the old Cenozoic/Oligocene basalts. The topographic position as well as the low permeability of the rocks means these units are of minor hydrogeological importance.

The alluvio lacustrine sediments come intercalated with the extensive sheets corresponding to the Afar stratoid basalts. This condition resulted in occurrence of several artesian wells in the region. The alluvio lacustrine sediments occur in three major zones. These are a) the proper Shinile alluvio lacustrine aquifers marked number 1 in Figure 26 below making up 9000 km², b) the Afdem-Erer alluvio lacustrine sediments which make the south-eastern part of the Alidegie plain, and c) the conglomeratic aquifers bounded between the Adigala plateau and the Dawale block.

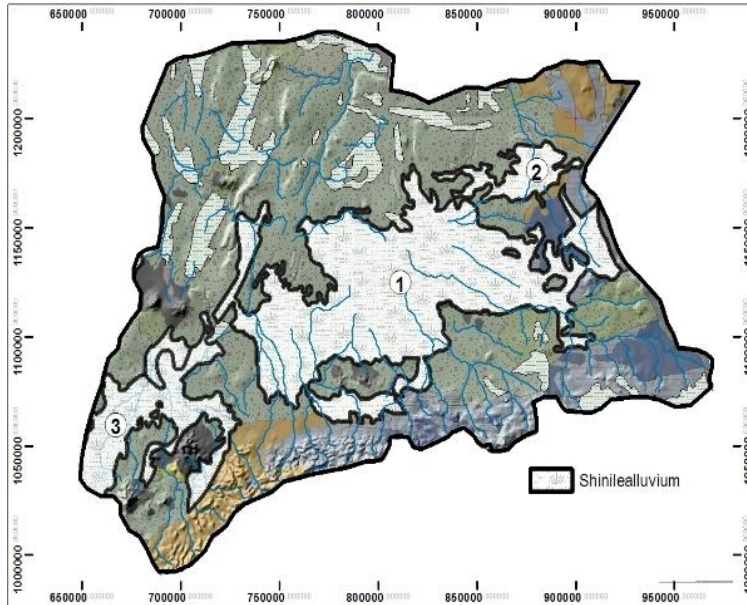


Figure 26. Hydrogeological map of the region

Total groundwater storage in a small part of the Shinile alluvial aquifers has previously been estimated to reach 12 billion m³. But, taking the complete cover of 9000 km², assuming a saturated thickness of 100 meters and porosity of 15 percent, the total groundwater storage is estimated at 150 billion m³. Transmissivity and specific yields obtained for the alluvial aquifer reach up to 700 m²/day and 3.2 l/s/m. In several places a higher transmissivity has been noted. For example, in the alluvial deposit a 150 m deep borehole at the foothill of the plateau in the south has a transmissivity of 3012 m²/day.

There are two principal recharge sources. The first is coming from loosing streams and accounts for the bulk of the recharge. The second is mountain block recharge coming trough aquifers, following the subsurface laterally from the mountains in the south. The basalt-loose sediment intercalation is an extensive and productive porous aquifer. Yields generally decrease as one moves northward. Salinity increases northward following the groundwater flow direction. Salinity is also higher in the allvio lacustrine sediments in the eastern part of the cluster (Aisha plain). Most of the groundwater shows a water table condition, while some wells exhibit artesian conditions.

Groundwater discharges into wetlands and thermal springs in the southern part of the cluster.

Important sites for large scale groundwater development are the intercalation of the allvio lacustrine sediments and basalts located in the southern sector of the cluster and along the banks of the wadi beds running down to the alluvial plains.

Conceptual model:

The conceptual model (Annex 3), which has been constructed based on multiple evidence (hydrogeologic, isotopic), shows groundwater flow, recharge/discharge relations and the origin of the groundwater. Groundwater flows from south to north, recharge comes from loosing wadi beds and from mountain blocks. Discharge takes place into wetlands and thermal springs in the Afar rift floor in the intervening closed grabens. Good sites for additional in-depth study are the plains adjacent to the foot hills of the mountains in the south. Decrease in yields and increase in salinity further north and east limits the groundwater potential in these zones.

5.4 Cluster 4: Liben

Geology

The south-western sector of the area (western part of Moyale woreda) is underlain by a succession of high-grade gneisses and schists. Some folded and sheared low-grade belts of metavolcanics and metavolcano-sediments are sandwiched between the high-grade gneisses and schists.

The gneisses and schists and the metavolcano-sediments are strongly foliated, folded and affected by frequent shearing and thrust faults. The metamorphic belts are intruded by mafic and granitic plutons of various sizes and ages.

The eastern part of the Moyale woreda and the entire Filtu and Dolo Odo woredas are underlain by a thick succession of Jurassic and Cretaceous sedimentary rocks.

Hydrogeology

Corresponding to the geologic units there are two major hydrogeologic regions in this cluster. The first one is located in the basement aquifer, cropping out in the western part of the project area. The second one is the multilayered Mesozoic sedimentary rock underlying the eastern part of the cluster.

In the basement sub region, groundwater occurs principally in the basement fractures and in the extensive wadi bed sediments. Yield of individual boreholes is generally less than 2 l/s. The Mesozoic sedimentary rocks are composed of two major formations (the Hammanelei and the Gabredare formations). The Hammanelei formation is generally a moderate to high permeability unit with deep water table and a thickness of up to 700 m. In highland areas (in the north), wells drilled into this unit turn dry. When exposed, the depth to water table exceeds 200 m. The water quality is generally good.

The overlying formation (Gabredare formation) is a bedded, massive formation with solitary karst features. It has a low permeability and productivity, and groundwater is generally of high TDS. The presence of the thick and low productivity Gabredare formation isolates the underlying, more productive Hammanelei formation beyond the reachable depth of economic drilling. In the region where the Gabredare formation is exposed, the good potential zones are the shallow sediments as well as sites adjacent to river beds.

Conceptual model

The conceptual model describing the groundwater occurrence, recharge, flow and discharge is given in Annex 3. The models generally depict the larger depth to the water table in the Hammanelei formation, and the thickness of individual layers. The conceptual model shows that it may be difficult to reach the productive formation without drilling deeper than 600 meters. Deeper drilling may be required to reach the productive horizons. Even if the Hammanelei formation is reachable by deeper boreholes, the low permeability of the overlying Gabredare formation does not allow sufficient vertical percolation to get a substantial discharge from the Hamannelei formation in this area.

5.5 Cluster 5: Bale

Geology

The western sector of the cluster (western part of Meda Welabu woreda) is underlain by a succession of high-grade gneisses. They are strongly foliated and folded and intruded by mafic and granitic plutons of various sizes and ages.

A limited, cliff-forming, ~600 m thick Triassic sandstone is exposed in the extreme north-western corner of the area.

The central part of the area, particularly most parts of the Meda Welabu and Gura Damole woredas, are underlain by a thick succession of Jurassic Limestones, while in the eastern part

of the cluster, particularly the Raytu woreda, Cretaceous sedimentary successions are exposed.

The Cretaceous sandstones, particularly the calcareous sandstones, are covered by patchy, but considerably thick calcrete.

Hydrogeology

The largest part of the cluster area, about 85%, consists of Mesozoic limestone formation, mainly in the central parts of the cluster covering the Mede Welabu and Gura Damole woredas. This formation is known to be thick and is classified as a low to moderate productivity aquifer. However, prospecting high yielding deep regional groundwater may require the drilling of very deep wells (>500 m?), which limits its feasibility.

A well drilled in this unit at the locality of Yedi, to a reported depth of 220 m, yields 5 l/s, indicating the possibility of intercepting moderately productive aquifers at a more reasonable depth. Sufficient penetrations into the Hammameli limestone formation would be necessary to intercept potential aquifer zones for high yielding wells.

The Hamaneli formation has intercalations of shale and sandstone. These limestones are well jointed and they have moderate to high permeability. According to the records from adjacent locations at Filtu and Negele, the depth to groundwater is high at about 200 m. At places where this limestone is highly fractured it could host productive wells. This is evidenced by the existence of a borehole around Bidre within a line running in an east-west direction (regional fracture zones).

In a region where groundwater flow is confined to the Gabredare karstified limestone, shallow groundwater is discharged in the form of springs at the contact zone of formations and fracture zones; recorded yield of springs is in the range of 0.3 l/s to 5 l/s.

Basalt formations are exposed in the north-central part of the area, particularly in the Berbere and Dawe Kechen woredas. The basalt unit does not form a potential aquifer due to its limited thickness. The aquifer in the area is inferred to be the underlying limestone formation. A large number of water points is recorded over the area, mainly in the form of springs and hand dug wells. Most of the springs are found within Berbere woreda. The springs have a high variability in their yields, ranging from 0.05 to 65 l/s. About 55 % of the recorded springs have yields >5 l/s. The springs are situated mainly at the contact zone of the formations.

Varieties of high-grade basement rocks and associated intrusive rocks cover the western sector of the area (western part of Meda Welabu woreda). These rocks are in general classified as regional aquiclude, with localized low yielding aquifers along their fractured and weathered zones. The thickness of weathering profiles is estimated to be mostly in the range of 10 to 30 m.

Alluvial deposits are exposed as patches in some wadi beds and extensive plains, particularly in the eastern part of the area. These sediments could bear shallow groundwater.

Conceptual models

Three hydrogeological sections have been constructed over the cluster area in the process of conceptual models development Annex 3.

The first section “A-B” runs north-west, from the north-east of Rayitu locality to wabe mena shet in the south-east. The section represents the two major parts of the model. The western section, which is about one third of the transect, is described as a region where groundwater flow is confined to the Gabredare karstified limestone.

The rest of the profile shows that, at lower elevations and suitable locations, groundwater could be stored within the Hammaneli formation regionally, resting over the underlying basement rocks.

The transect along line “C-D”, from the locality of Gura Mejo in the north-west to the intercept of Genale river in the south-east, has two prominent hydrogeological sections, as controlled by the geomorphological and geological conditions of the region. The western section of the model revealed that the sub-surface lithology is made of high-grade basement rock. Groundwater occurs in basement fractures, joints & in regolith deposits. Fracture lengths are generally short, groundwater flow lengths are short & local, well yields are generally <1 l/s. Water quality is good overall. The larger section in the east is characterized by the Hammanilei formation with an inferred deep groundwater system. Where the formation forms plateaus, the water table is much deeper. Towards its northern section, dry boreholes are encountered to a depth of 200 m. High regional permeability results in a deep water table, and locally the interbedded marl shale units result in high salinity waters. The third hydrogeological section “E-F” is constructed along a line from a locality at about 10 km to the north-west of Sof-umer up to the area of the Miyo locality in the south-east. This section illustrates the limited extent of the volcanic rock (basalt unit), which therefore cannot be considered a potential aquifer. The underlying limestone formation should be the target formation instead. The description of the model is divided into three zones based on their distinctive characteristics.

The first zone (western part of the section) is a plain area, with locally undulating relief of mild slopes and gully cuts. The basalt formation resting over the underlying limestone unit forms a low to moderate productivity aquifer within the permeable zone of the limestone units. Water table could be deep.

The middle part is a rugged and hilly area consisting of volcanic (basalt) rocks with poor permeability, with limited groundwater seepages leaking into the underlying limestone formation through fracture zones. This area is unsuitable for groundwater.

The eastern, relatively flat wide plain area is partly underlain by volcanic rocks resting over the limestone formation in the west, while the limestone unit is exposed to the surface in the east. Again, the possible aquifer zone in this area is the underlying limestone formation.

5.6 Cluster 6: Borena

Geology

Cluster 6 is underlain by a succession of high-grade gneisses and schists. Some folded and sheared low-grade belts of metavolcanics and metavolcano-sediments are sandwiched between the high-grade gneisses and schists, particularly in the north-eastern sector of the area. The gneisses, schists and metavolcano-sediments are strongly foliated and folded and affected by frequent shearing and thrust faults.

The metamorphic basement rocks are strongly weathered, forming a significant regolith deposit in most parts of the area.

In the western part of the cluster, Quaternary volcanics are represented by an extended ridge of ~50 m thick.

Alluvial deposits of considerable thickness and extent are exposed as patches in some wadi beds and extensive plains, and as prominent alluvial fans at the foot of fault escarpments.

Hydrogeology

Regoliths and fractures are the main groundwater holding and transmitting media in metamorphic terrain. The basement rocks of Southern Ethiopia show a variable degree of fracturing and regolith development. The crystalline hard rocks provide a yield ranging between 0.13 and 0.33 l/s.

A clear geographic groundwater potential zonation of the basement rocks exists in southern Ethiopia. In basement rocks in the highlands, straddling the rift from north, the regolith thickness is higher (may reach 30 meters in valleys). The recharge rate is higher as well,

owing to more rainfall. Shallow groundwater occurs in the regoliths and alluvial materials in the low-lying areas, as the recharge is relatively high (around 50 mm/yr). At 500 to 1500 mg/L, the total salt content of the groundwater is also suitable for domestic water supply. Fractures in granitic intrusions also provide low discharge springs during wet seasons. The midlands, between the lowlands of the cluster and the highlands in the north, show thin layers of weathering products. Groundwater occurrence is limited to low lying areas in alluvial sediments, the TDS is higher and may exceed 1500 mg/L. In the southern part of the basement areas, Quaternary alluvials and eluvials resting on the basement rocks provide shallow groundwater in valleys where recharge is relatively high. They have moderate salinities (1500 to 3000 mg/L).

The eluvial lateritic crust in the southern sector of the area consists of clay, silt and fine sand. The materials are promising hydrogeologic features for the construction of artificial water retention structures, such as subsurface dams for water collection and storage. The duricrust capping the eluvium materials has a low permeability and small thickness of less than 15 meters. Thicker weathering products are recorded in the plains of Yabelo, reaching 35 meters. It could contain shallow groundwater in low lying areas, where they are overlain by alluvial materials. Traditionally, groundwater from the shallow eluvial and alluvial materials in the lowlands of southern Ethiopia is exploited through large diameter wells called Ella.

The wadi bed aquifer complexes occur in two major zones: the first in the southern part of the Borena plain north of the Ethiopia-Kenya border, and the second in the central plain of the Borena lowlands in the north. Nearly 75 water points in the Borena plain are associated with these wadi bed sediments. Water quality in the wadi bed sediments is generally good for human and livestock consumption. However, groundwater salinity increases towards the outlets of the wadis.

The wadi bed aquifer gets its recharge from flood waters that originate in March, April and October through December. In the southern Borena wadi complex (Lagasure), the wadi beds are composed of alluvial sediments of medium to coarse grained sand. At their outlets from their river channels the wadis of the Borena lowland form extensive flat lying alluvial fans. The highest yielding borehole in this area as well as in the whole wadi system is the El-Gof borehole. This borehole, which taps the inter-granular aquifer of sand and gravel overlain by lacustrine sediments, has a yield of 5 l/s. Other boreholes in Elleh discharge about 4 l/s. The Bulal basalts underlay low lying areas between the Tertiary volcanic highlands in the west, and the Borena Precambrian basement rocks in the east. Separating the Bulal basalts and the Precambrian basement is the regional Mega fault belt running NW-SE.

Recharge to the Bulal aquifer mainly takes place at basin boundaries along the Mega fault belt and from floods confined to the Ririba fault system. Drainage is entirely intermittent. Flood water converges in the valley bottom and flows towards Kenya during flood periods. The mean annual rainfall of the area is estimated to be about 600 mm and occurs between September and November and between March and June. Mean annual potential evapotranspiration reaches 1700 mm/yr. Maar lakes dotting the plain are indicative of groundwater circulating at deeper levels during the explosion of the Maar Lakes. The overall weighted average recharge estimated for the area is about 54 mm per year. Yields from the Bulal basalts exceed 20 l/s.

Conceptual models

The conceptual model showing groundwater occurrence, recharge, discharge and flow is depicted in Annex 3. The model shows the two distinct zones of groundwater regime - one related to the basement aquifers and the other related to the Bulal basalts.

5.7 Cluster 7: Wolayta

Geology

Oligocene Lower Silicics are exposed in the western part of cluster 7 at major river gorges. They are up to 500 m thick. Lower Basalt is present in the form of a high, isolated ridge on top of the silicics. The basalt is massive, up to 150 m thick, and strongly weathered at the top, forming a thick regolith.

The Kindo Koyscha and Boloso Sore woredas are underlain by the Nazareth Group rhyolitic flows. It is capped by a layer of up to 250 m thick pyroclastic deposits. It is strongly weathered at the top, resulting in a typical soil layer called 'planosol'. This soil type consists of a mixture of devitrified grass, pumice, ash and clay minerals.

Strongly weathered and eroded 'badlands' of up to 50 m thick are encountered north of Boditi town. These badlands are a mixture of Quaternary ignimbrites, tuffs, water-lain pyroclastics, and lacustrine beds of the Dino Formation.

The Diguna caldera in the eastern part of the cluster shows a thick succession of pumice and tuffs in the center, surrounded by rhyolitic and trachytic lava flows. Quaternary Rift floor basalts are exposed to the south and north of the Diguna caldera. The volcanic complex is surrounded by unconsolidated sedimentary deposits of up to 50 m thick, forming extensive and flat plains.

Hydrogeology

Cluster 7 is characterized by the abundance of acid volcanic rocks such as tuffs, ignimbrites and ash fall, which are collectively known as the Dino and Nazareth series. This formation is characterized by low permeabilities and low aquifer productivity and yield. This is the main challenge with groundwater availability in this district. Drilled wells generally yield less than 2 l/s in many localities.

Groundwater in this area mainly occurs in fractured basalts and ignimbrites, where such rock is available. Groundwater flows are confined to the top layers which are less compact. Recharge comes from rainfall and discharge occurs into shallow wetlands.

Conceptual model

The conceptual groundwater model (recharge, flow, discharge) is depicted in Annex 3. Groundwater flow is generally confined to the top layer of the silicic units and discharge takes place to the wetlands. The large thickness of the Nazareth Series and Dino formation limit the access to the underlying Cenozoic basalts. Groundwater occurs in fractured zones of ignimbrites and the minor basalts associated with the silicics.

5.8 Cluster 8: South Omo

The eastern half of cluster 8 is underlain by a succession of high-grade gneisses (the Hammar range). Most of the gneisses are strongly weathered and form a thick regolith, with the exception of the highest elevations and vertical cliffs of the range.

Lower Basalts sparingly occur in the western margins of the cluster. In the southern part of the project area (near Fejej), basalts form up to 150 m high, faulted and weathered ridges. The western half of the cluster is represented by the wide and nearly flat Omo River Valley, underlain by a thick succession of unconsolidated sediments of fluvial and lacustrine origin. These sediments are interspersed with several layers of volcanic ash (tephra). The Shungura Formation, dominated by fluvial depositional conditions, is well exposed west of the Omo River and north of the Lake Turkana delta. It forms a 300 m thick layer of lacustrine silts and clays and is overlain by unconsolidated sand and silt deposits. These deposits in turn are

overlain by another layer of lacustrine silts and clays. The same phenomenon occurs north-east of the Lake Turkana delta, but with a smaller thickness (around 100 m).

The north-western part of the Omo valley consists of a succession of ~50 m thick lacustrine silt and clay, ~100 m thick lacustrine and deltaic deposits (Kibish Formation), and ~100 m thick undifferentiated alluvial, fluvial and lacustrine sediments.

The Kibish River and the Omo River flood plains are covered by ~30 m thick fluvial sand and silt. The Chew Bahir basin partly represented in the eastern part of the area is underlain by a thick succession of fluvial sand and silt intercalated with lacustrine silt and clay, as well as some alluvium.

Hydrogeology

Cluster 8 has two distinct hydrogeologic zones. The basement aquifers in the east (also called Hammer Koke block), as well as the 3 km thick loose interbedding of alluvio lacustrine sediment aquifer in the Omo valley.

The Hammer Koke domain is chiefly composed of various coarse grained and foliated rocks. In the basement rocks the groundwater flow is confined in wadi beds. Groundwater recharge to the wadi beds and the broad basement happens from occasional flash floods generated in the higher elevation area to the north, where more precipitation occurs. The principal discharge pathway is riparian evapotranspiration. Water quality is mostly of low TDS in the order of less than 1000 mg/L. The yield of existing wells in the Hammer Koke block is generally below 1 l/s, and often even less than 0.1 l/s (Sima 1987). It has little potential as a source of groundwater in the region.

The alluvio lacustrine sediments in the Omo delta are composed of clays, silts, sands and gravels. Groundwater flow is confined in the sandy and silty portions of the Omo basin sediments, which are predominantly silts and clays. Drilled wells may turn dry when drilled on clay and silty clay dominated sediments. Shallow groundwater occurs in abandoned distributary channels and beach sands bordering the sediments. The distribution of the water quality is extremely complex and appears to vary with the geomorphology. The TDS of groundwater can vary between 500 and 50000 mg/L. High TDS is associated with dissolution of evaporite lenses accumulated along with the lacustrine beds.

Conceptual model

The conceptual groundwater flow, recharge and discharge conditions are depicted in Annex 3. It shows groundwater flow is confined to the Wadi beds in the basement areas and occurs in the coarse-grained components of the Omo delta sediments. Groundwater eventually discharges into Lake Turkana.

6

Socio-economy and water demand maps

Socio-economy maps

Information on socio-economic aspects relevant for decision making on water supply have been supplied by the Central Statistical Agency of Ethiopia. This information has been presented on the maps on a scale of 1:500,000 for the clusters 4, 5 and 6. The maps for the remaining clusters are on 1:250,000 scale. The information comprises:

- Boundaries of kebeles and woredas with their names (for clusters 3 and 4 only woredas)
- Population densities of kebeles (for clusters 3 and 4 only woredas)
- Villages and towns (localities) (not for clusters 3 and 4)
- Schools (not for clusters 3 and 4)
- Health facilities (not for clusters 3 and 4)
- Water facilities: springs, wells, tankers, wells, ponds, stand pipes (not for clusters 3 and 4)
- Electricity network (not for clusters 3 and 4)
- Roads (not for clusters 3 and 4)
- Rivers (not for clusters 3 and 4)

Population density of the kebeles is expressed as the number of total inhabitants in 2019 per km². The population is based on the census 2007 data (CSA, 2017, 2019) and is corrected for the average population growth of 2.46 % (CSA, 2013, 2017). For the 2030 horizon of the sustainable development goals of Ethiopia (National Planning Commission, 2017) population and population density in 2030 is equal to the presented figures multiplied by 1.31.

Total population is not indicated on the maps but can be deduced from the water demand maps (6.2). In these maps two numbers are presented in each kebele, number of localities and mean population in each locality, respectively (not cluster 3 and 4). Multiplying these two numbers give the total population.

Domestic water demand maps

Domestic water demand in m³ per day per kebele is based on number of inhabitants and daily per capita demand as defined in the GTP II (National Planning Commission, 2016). According to the GTP II water demand in rural areas is 25 l/cap/day. In urban areas water demand varies from 40 to 100 l/cap/day but has been defined here as 50 l/cap/day for urban kebeles. Where urban or rural conditions are not clear 30 /cap/day has been used. For the 2030 horizon of the sustainable development goals of Ethiopia 4 domestic water demand 2030 is equal to the presented figures multiplied by 1.31.

It is noted that these water demand figures are the quantities of water that population should access to according to national policy criteria. They do not present the actual water scarcity.

These depend more on the degree to which the present facilities meet these required quantities. This would require an inventory of these facilities and their state of operation and capacity. During the zonal consultation meetings insight can be provided by representatives of zonal water bureaus, woreda offices and local NGO's.

Livestock water demand

The project has attempted to map the livestock water demand based on livestock data of the Central Statistical Agency of Ethiopia on woreda level and typical daily voluntary water intake figures of different types of livestock (Pallas 1986). However, because CSA data (CSA, 2018, 2019) were not complete, consequent mapping was not carried out.

Nevertheless, the project wanted to have more insight in the livestock water demand.

Therefore, livestock water demand data were compared to domestic water demand data for a number of woredas based on the 2007 census data. For cluster 6, Borena, detailed information was available at kebele level (CARE, 2017). The results are shown in Figure 27 and 28.

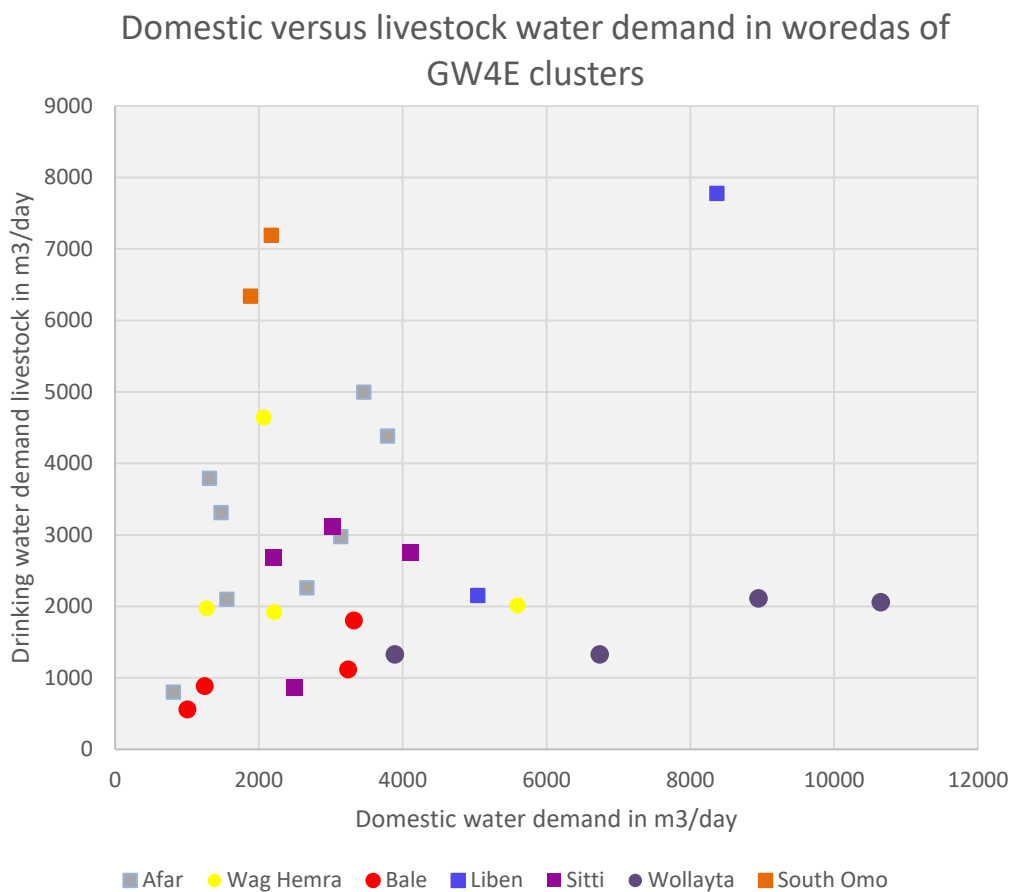


Figure 27. Domestic versus livestock water demand in woredas of the clusters of the GW4E project

In clusters where pastoralist rural communities dominate like Afar, Liben, Sitti and South Omo, the water demand for livestock is equal to 100 to 300 % of the domestic water demand. In the other woredas with mainly agro-pastoralist communities livestock water demand is 25 to 100 % of the livestock water demand. Note the high domestic water demand in some densely populated woredas in Wolayta.

For the Borena zone the available data allow a distinction between kebeles dominated by pastoralists and agro-pastoralists. Based on the population and the livestock data on kebele level we see the same pattern. In pastoralist dominated kebeles water demand for livestock is 100 to 800 % of domestic water demand, while in agro-pastoralist kebeles livestock water demand is 50 to 150 %.

Regarding livestock water demand the same caution should be taken as for domestic water demand. The shown water demand figures are based on the daily voluntary water intake according to literature times the number of the various livestock species. It is not representative for the actual water scarcity for livestock. Livestock depends often on natural or man-made sources like hafirs, which are not fit for human consumption and do not compete with domestic water supply. However, in some drought prone areas communities may prefer multi use water supply systems or even systems dedicated to livestock.

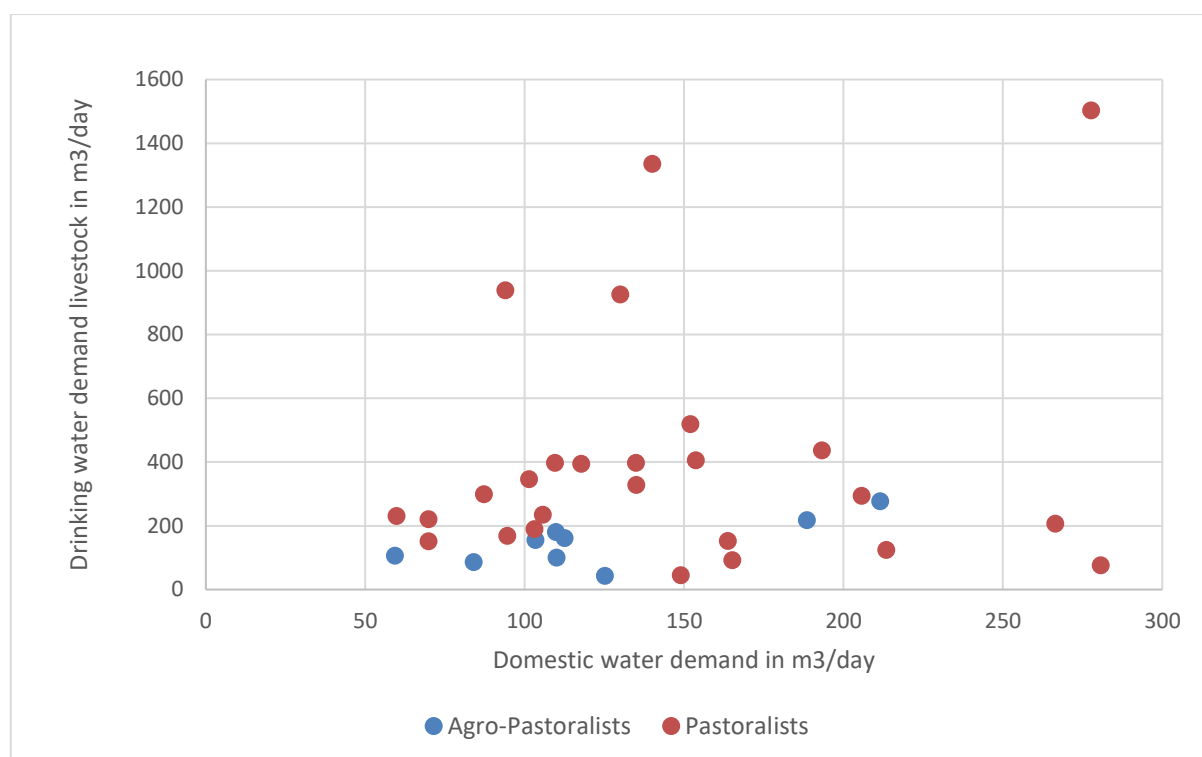


Figure 28. Domestic versus livestock water demand in kebeles of the Borena zone

7 Suitability maps

Followingly, descriptions of the suitability maps in relation to the geologic and hydrogeologic conditions described in chapter 5 will be given. The suitability maps (see methodology for the methods of producing the suitability map) can be found in small format after the following descriptions (Figure 29). The legend is similar to the legend shown in figure 20. Low suitability is displayed in red colour, high suitability in blue. Intermediate values range from orange, to yellow and green:



Suitability legend

Cluster 1

The groundwater suitability map matches the hydrogeologic description given in paragraph 5.1 very well. The region is generally characterized by the lowest suitability compared to the other mapped areas. All areas with a slope in excess of 15% are attributed as unsuitable. As can be seen in the suitability map, nearly a quarter of the cluster falls under the 'unsuitable' category because of the high slope (see methodology section). Parts of the cluster which fall in high and medium suitability classes correspond to the small patches of plateaus on the upper basalt unit and in the flat slope forming areas where basement rocks crop out in the north. The high and medium suitability zones in the figure can be the target of an in-depth hydrogeology investigation for development of shallow groundwaters for community water supply.

Cluster 2

The suitability map shows that most of the area in the western sub-cluster fall under moderate to high suitability class. The highest suitability is noted for the elongated areas along the wadi and river beds draining the western highlands. The eastern sub-cluster covering the lower Awash plain is characterized by moderate to low suitability classes. The low suitability mirrors the low recharge and low permeability of the formations. The suitability class for the western sub-cluster matches the field conditions in general. The high suitability corresponding to the areas adjoin the wadi beds and the rivers draining the escarpment matches previous drilling experiences. A few successful wells are located in these areas.

Cluster 3

The suitability map shows that most of cluster 3 falls under moderate to high suitability classes. The highest suitability is noted for the plains at the foothills of the escarpment in the south. This is the result of high recharge, small slope and suitable geology. The high relief, low recharge areas underlain by the crystalline rocks turn out to be the most unsuitable zones for groundwater development.

Cluster 4

Cluster 4 predominantly consists of Mesozoic formations. The Mesozoic units cover about 80% of the study area. The rest of the area is covered by basement rocks of various types and alluvial deposits, mainly along wadi beds and locally flat areas. The areas of the map that show a relatively high suitability are located over the alluvial deposit units. However, these units are not extensive in thickness. Besides the relatively flat areas, mainly within Filtu and Moyale woredas, which are mapped as moderately suitable, the larger areas covered by the Mesozoic formations are classified as very low to unsuitable for groundwater occurrence. This is mainly due to their rugged topographic configuration.

The suitability map depicts that large portion of the basement rock areas within Moyale woreda have a low to moderate suitability. However, except for zones along fractures and deeply weathered zones (which could be mapped as moderate), the entire area could have a low or very low suitability. Therefore, the map must be used with care and further assessment to identify these prospective localized zones.

Areas mapped as highly suitable make up about 5 % of the study area and are situated mainly within the Moyale woreda. Areas mapped as medium and low to medium form about 25 % of the total cluster area, while the rest (about 70 %) of the cluster is categorized as very low or unsuitable, mainly due to topographic controls and poor permeability of the most abundant lithological units.

Cluster 5

The areas of cluster 5 mapped as medium to high suitability correspond to the volcanic rock (basaltic) terrain and alluvial deposits, while the basement rock areas and rugged terrain of the Mesozoic (limestone) areas are mapped as low to unsuitable zones. The limestone terrain over flat areas is assigned a medium suitability. However, it should be noted that in areas like the Dawe Kechen woreda, the thickness of the basalt unit overlaying the limestone formation is limited, and thus it cannot form a potential aquifer. Therefore, in reality the suitability of zones like this must be considered as medium instead of high, corresponding to the nature of the underlying aquifer formation. This indicates the necessity of supplementing or verifying the suitability maps with sub-surface information for its use in practical applications.

The map indicates that areas marked with high suitability cover only about 10 % of the cluster area. Highly suitable areas are located in the north-east of Rayitu woreda, north of Gura Damole woreda, and along the valley bottom stretches of Mede Wolabu woreda. Areas mapped as medium and low to medium form about 30% of the total cluster area. The remaining area is categorized as either very low or unsuitable, mainly as a result of topographic controls and lithological units with poor permeability.

Cluster 6

The basalt formation is the major potential aquifer unit of cluster 6, covering the south-west of the cluster area (parts of the Dilo woreda). The suitability map (annex 8) also depicts the areas of this formation as medium to high suitability, as derived in combination with the other factors involved in the overlay analysis.

The basement rocks are generally known as poor in terms of their prospect for groundwater, in some cases they are also classified as regional aquiclude. In the Borena area, these units bear groundwater within their weathered sections when underlying the volcanics or along the weathered and fractured sections of the regional fracture zones.

Over the basement terrain the suitability map shows a low to very low suitability for flatter areas, while steeper areas are mapped as unsuitable. The zone mapped as highly suitable covers about 20% of the cluster area. This zone is mainly located within the Bulal basalt formation and the wadi bed sediments.

Large parts of the cluster, occupying about 70%, are mapped as low to very low suitability, while 20% is mapped as medium to high. The basement rocks forming hilly and undulating topography, which make up about 10 % of the area, are dry and generally should be considered unsuitable. Other areas classified as very low to unsuitable are areas within the basement terrain, devoid of significant permeable horizons or suitable topography for groundwater occurrence.

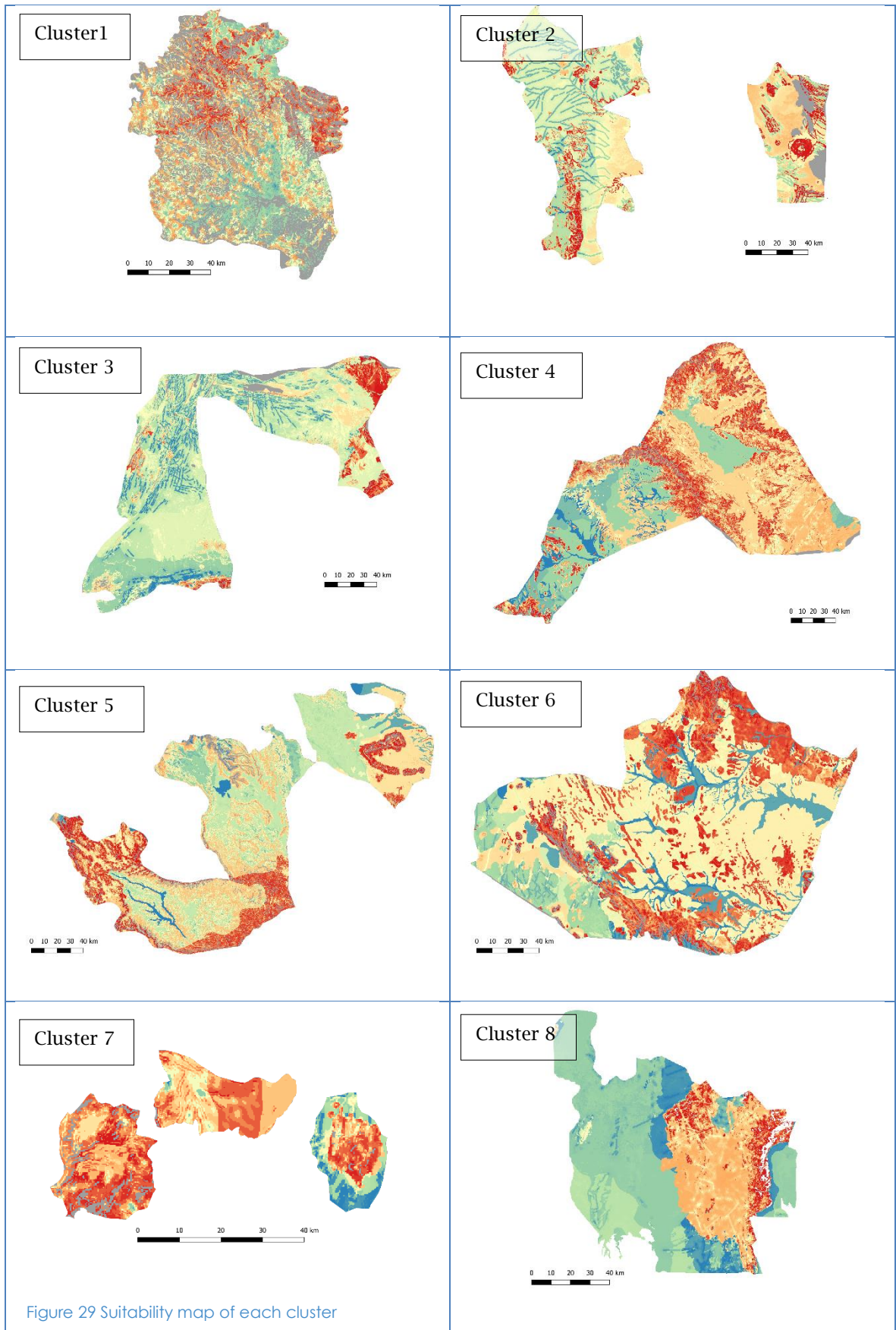
These categories of groundwater suitability are spatially distributed along ridges where the slope class is very high, the lithology is compact/massive basement, and the distance to lineaments is high.

Cluster 7

The suitability map shows most of the woredas in this cluster fall under low and very low suitability classes. This description matches the hydrogeologic conditions described in paragraph 5.7. Some plains in the Diguna Fango woreda show suitable sites for groundwater. However, the higher suitability in these areas is mainly caused by the gentle slope existing here (rather than by other aspects influencing the groundwater potential, e.g. permeability). Thus, care should be taken when considering the high suitability areas of cluster 7 as sites for groundwater development.

Cluster 8

The suitability map of cluster 8 mirrors the geologic and hydrogeologic characteristics depicted in paragraph 5.8 very well. Generally, the eastern basement aquifer areas are characterized by a low suitability, while the Omo delta areas fall under medium or high suitability zones. Care should be taken however, as the suitability map doesn't take groundwater salinity into account. One of the challenges in the Omo delta area may be the high salinity of the groundwater. The interface between the Omo delta and the basement rocks, which is characterized by solitary and coalescing alluvial fans, could be a good site for locating wells. This area also shows medium to high suitability.





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Annexes

Annex 1

Geologic description per cluster

Cluster I:

A small, ~200 m thick inlier of Late Proterozoic low-grade metavolcanics (chlorite schists and phyllites, metabasalts and metarhyolites with interbeds of sediments and lenticular limestones) and metasediments (siliceous and detritic dolomites, calcareous slates, black limestone, graphitic phyllites, greywackes, sericite schists, intruded by aplite dikes) are exposed in the northern part; these rocks are generally strongly foliated along N-S to NE-SW direction with vertical to sub-vertical dipping in most cases;

A thin (~100 m thick) Paleozoic shales and poorly sorted sandstone and tillites are exposed over the metamorphic basement in most cases;

The deeply incised gorges in the N and NE half of the area expose up to ~600 m thick Triassic, reddish to reddish brown, fine to medium, rarely coarse-grained generally fining upward, locally cross-bedded sandstone inter-bedded with siltstone, mudstone and minor beds of calcareous sandstone, ferruginous silt, clay and conglomerate; individual sandstone beds range from <1m to ~2m and are generally horizontally bedded; and where exposed, it forms very rugged, vertical cliffs; the sandstones are strongly jointed and fractured by several sets of inclined to sub-vertical joints, and are strongly weathered at their tops;

A limited exposure of up to ~400 m thick, fine-grained, fossiliferous and marly, 1-2m thick, horizontally layered and bedded, slightly tilted, strongly fractured and faulted, cliff forming Jurassic limestone, and up to ~300 m thick, vertical cliff-forming, fine to coarse-grained, up to ~3m thick, slightly tilted and fractured Cretaceous sandstone with interbeds of conglomerates and conglomeratic sandstone, are exposed in the eastern part of the area;

Major part of the area particularly the western and southern half is covered by Oligocene plateau volcanics, particularly the Lower Basalt which is Pyx-Pl, Ol-phyric basalt occasionally grading to Pl-Ol phyric and Ol-Pl phyric basalt, forming ~800 m thick, usually massive, horizontally to sub-horizontally bedded, 1-5m thick individual layers, heterogeneous flood basalt with erratically stratified, often tilted cyclic layers of massive basalts, columnar jointed basalts, basaltic agglomerates, vesiculated basalts, scoriaceous basalts, and highly fractured basalts with zeolite, calcite, and rarely quartz filled fractures, reworked sediments and occasional pyroclastics; and palaeosol layers forming rarely horizontal and mostly undulating profiles; the basalts are frequently cut by dikes; the basalts form prominently peneplained, erosional surfaces; gently to moderately steep topographic features, and prominent cliffs where the plateau is deeply incised, particularly in the deep gorges in the western part of the area; the Lower basalts, where not cliff forming, are moderately weathered and form a significant regolith;

On the rugged, high plateau in the southern part of the area, vertical cliff forming, isolated peaks of the Middle, Upper and Upper most Basalts are exposed;

An Oligocene, up to ~200 m thick, massive and moderately fractured, hardly weathered dolerite sill is exposed in the NE corner of the area;

Alluvial sediments are hardly exposed in the area, except in small patches

Cluster II:

Except a limited exposure of the Oligocene Lower Basalt exposed at a major Plateau-Rift escarpment at the NW corner of the area, Miocene-Pliocene-Quaternary rift volcanics and sediments cover the area; the Miocene Mabila Rhyolite and Dahla Basalt are dominant in the western part of the area close to the plateau-rift escarpment while the Pliocene-Pleistocene Afar Stratoid Basalts and Basaltic Fissure Flows underlie the lowland plains at the axial parts of the Afar rift; Quaternary volcanics form low circular and elongated ridges, while the Quaternary lacustrine and alluvial sediments are interstratified within the Afar Stratoid Basalts.

The Mabila Rhyolites are light-coloured, fine- to coarse-grained, flow banded, slightly to moderately weathered peralkaline rhyolites, intercalated with basaltic flows, ignimbrite and pumice deposits; forming strongly fractured and faulted elongated ridges; the Dahla Basalts are dark, fine- to coarse-grained, slightly weathered and highly fractured and faulted, vesicular, Ol-Pli phytic, fissural transitional basalt with some intercalated, detrital and lacustrine sediments, and rhyolitic flows and ignimbrites at the upper part;

The Lower Afar Stratoids form horizontally-bedded, laterally extensive sheets of black, vesicular (with a mm to 2cm big vesicles) transitional basaltic lavas and ignimbrite sheets locally covering massive rhyolites, submarine flows with pillow lavas, usually exposed along ridges, while the Upper Afar Stratoids are dark gray, aphanitic ferro-basalts and hawaiite flows with some intercalated rhyolitic flows, ignimbrites, and sediments, mainly in the upper part, exposed on top of faulted ridges; the Afar Stratoids are generally non-weathered;

The Basaltic Fissure Flows are dark, fine to medium grained transitional basalts, ferro-basalts and hawaiites and are moderately weathered, and mostly exposed along strongly fractured and faulted ridges;

The Awash River valley in the western part of the area exposes up to ~100 m thick, Plio-Pleistocene, coarse grained, rounded to sub-rounded continental conglomerates and deposits of sheet flood terraces (conglomerate, siltstone, sandstone), which are moderately weathered, and occasionally forming cone-shaped topography;

A succession of moderately fractured Quaternary Basalts ranging from porphyritic, Pli-phyric, mildly alkaline, cavernous, basaltic flows, to porphyritic, amygdaloidal, vesicular and aphyric basalts forming lava fields and related spatter and scoria cones in the Afar rift plains, to medium-grained, trachyte and basalt flows forming subdued topography along grabens and plains, are common in the western and eastern margins of the area; an isolated Quaternary rhyolite dome of fine- to coarse-grained, flow-banded, massive rhyolite forms a prominent topography east of Aysaita town;

The eastern part of the Tendaho Graben, S and SE of Aysaita is covered by Quaternary Lacustrine deposits which are up to ~50 m thick, very fine-grained, horizontally bedded, slightly weathered clay and silty clay, forming extended flat topography, intercalated with the Afar Stratoids in places; while the extended, flat plain west of the Awash River and the flat plain east of Aysaita are covered by Quaternary alluvial, alluvio-lacustrine, elluvial and colluvial deposits, which are up to ~30 m thick, sheet flood terraces, silty clays, fluvial silt, sand and gravel, a few diatomite outcrops, and sand dunes, covered in places by black cotton and reddish brown, clayey, silty and sandy soils

Cluster III:

Strongly faulted Late Proterozoic high-grade granitic gneisses and migmatites overlain by strongly fractured and faulted Triassic Sandstones, Jurassic Limestones and Cretaceous Sandstones are exposed at the Plateau-Rift escarpments in the S and SE extremes of the area, forming prominent cascading cliffs above the generally flat and extended plains of the rift to the north;

The Triassic sandstones are ~200 m thick, reddish to reddish brown, fine to medium, rarely coarse-grained generally fining upward, locally cross-bedded sandstone inter-bedded with siltstone, mudstone and minor beds of calcareous sandstone, ferruginous silt, clay and conglomerate; individual sandstone beds range from <1m to ~2m and are generally horizontally bedded, strongly jointed and fractured by several sets of inclined to sub-vertical joints, and are strongly weathered at their tops; the Jurassic limestones are up to ~300 m thick, massive limestone with very minor basal sandstone and conglomerate, horizontally layered and bedded, strongly tilted, strongly fractured and faulted, cliff forming; the Cretaceous sandstones are up to ~300 m thick, vertical cliff-forming, fine to coarse-grained, up to ~3m thick, strongly tilted and fractured sandstones with interbeds of conglomerates, conglomeratic sandstone and lenses of limestone;

Oligocene Flood basalts, particularly the Lower Basalt and the Upper Basalt, form small, isolated low hills in the eastern part of the area and a low, extended ridge at the foot of the escarpment in the southern part of the area, respectively; the Upper Basalt ridge is ~150 m thick, aphanitic to porphyritic, occasionally vesicular, Pyx-Pl, Ol-Pl, Ol, Pyx-phyric basalt, marked by prominent columnar jointing, and contains andesites and breccia, trachytes and pyroclastic tuff interlayered with basalt at the top and bottom of the unit, generally moderately weathered;

Miocene Mabila Rhyolite and Dahla Basalt are only exposed in the eastern and southern part of the area as low ridges of limited extent; the Mabila Rhyolites are light-coloured, fine- to coarse-grained, flow banded, slightly to moderately weathered peralkaline rhyolites, intercalated with basaltic flows, ignimbrite and pumice deposits; forming strongly fractured and faulted elongated ridges; the Dahla Basalts are dark, fine- to coarse-grained, slightly weathered and highly fractured and faulted, vesicular, Ol-Pl phyric, fissural transitional basalt with some intercalated, detrital and lacustrine sediments, and rhyolitic flows and ignimbrites at the upper part;

Most parts of the area forming the wide, flat plain is underlain by the Pliocene-Pleistocene Afar Stratoid Basalts and Basaltic Fissure Flows, particularly by the Upper Afar Stratoid Series, while the Afar Stratoid Silicics (peralkaline rhyolitic ignimbrites, unwelded tuffs, ash flows and lava flows), the Lower Afar Stratoid Series, the peralkaline rhyolitic and trachytic domes and peralkaline rhyolitic ignimbrites, and the basaltic fissure flows form isolated exposures scattered in the rift plain; the Upper Afar Stratoids are dark gray, aphanitic ferro-basalts and hawaiite flows with some intercalated rhyolitic flows, ignimbrites, and sediments, mainly in the upper part, exposed on top of faulted ridges; the Afar Stratoids are generally non-weathered but strongly fractured and faulted, forming low extended ridges on the Afar rift plains;

Several long and narrow grabens within the Upper Afar Stratoids exposed up to ~100 m thick, Plio-Pleistocene, coarse grained, rounded to sub-rounded continental conglomerates and deposits of sheet flood terraces (conglomerate, siltstone, sandstone), which are moderately weathered, and occasionally forming cone-shaped topography;

Isolated, small hills of strongly fractured Quaternary basalts, and rhyolite domes are common in the W and SW margins of the area;

Some graben floors in the western part of the area expose up to ~50 m thick Quaternary Lacustrine sediments which are horizontally bedded limestones and diatomite, while other grabens at the northern part of the area contain thin marshy deposits; the Upper Afar Stratoids in most places, particularly in the flat plains are covered by Quaternary alluvial, alluvio-lacustrine, elluvial and colluvial deposits, which are up to ~50 m thick, sheet flood terraces, silty clays, fluvial silt, sand and gravel, a few diatomite outcrops, and sand dunes, covered in places by black cotton and reddish brown, clayey, silty and sandy soils

Cluster IV:

The southwestern sector of the area (western part of Moyale woreda) is underlain by a succession of Late Proterozoic high-grade gneisses and schists which include banded and folded biotite-hornblende and biotite gneiss, hornblende-biotite, biotite-muscovite and quartzofeldspathic gneisses, biotite granite, amphibolite, and granodiorite; medium to coarse-grained plagioclase-quartz-microcline, oligoclase-quartz-microcline, biotite-quartz-oligoclase, quartz-feldspar, quartz-feldspar-biotite gneisses with interbeds of biotite and biotite bearing quartzofeldspathic gneisses, and sporadic undifferentiated schists, marble, metaconglomerate, and medium grained amphibolite; quartz-muscovite, kyanite-quartz-muscovite and sillimanite-quartz-muscovite schist; Intercalated clastic-calcareous metasedimentary schists (calc-silicate schists, marble, quartzite interlayered with graphite-quartz-mica, magnetite-serpentine-tremolite, quartz-graphite-muscovite, quartz-mica and minor quartzofeldspathic schists, and amphibolite);

Some folded and sheared low-grade belts of metavolcanics (greenschists with amphibolite, garnet-plagioclase-actinolite schist, serpentinite, and serpentinite-talc-tremolite schists with associated siliceous rocks) and metavolcano-sediments (fine to medium grained, greenschist facies amphibolite, plagioclase-chlorite-actinolite, epidote-amphibolite, chlorite-talc-serpentine, and chlorite schists, and serpentinites, intercalated with intimately interlayered graphitic quartzite, quartz-graphite, graphitic mica, muscovite, biotite, kyanite-muscovite, muscovite-kyanite-quartz, quartzofeldspathic, graphite schist; metagreywacke and metarhyodacite with minor metagabbro) are sandwiched between the high-grade gneisses and schists;

The high-grade gneisses and schists and the low-grade metavolcano-sediments are strongly foliated and folded with vertical to sub-vertical foliations and fold axes generally trending N-S and NNE-SSW and affected by frequent shearing and thrust faults;

The metamorphic belts are intruded by mafic and granitic plutons of various sizes and ages, particularly by pre-tectonic granitoid complex and metadiorites, which are variegated, medium to coarse grained, massive to distinctly foliated, deformed, and widely jointed biotite metagranite with blocky outcrop pattern and spectacular convex sheeting structures and containing xenoliths and roof pendants of banded gneiss; metamafic-ultramafic rocks (tremolite-actinolite, talc-chlorite-tremolite, talc-tremolite, chlorite-talc, and chlorite schists, serpentinite and silicified ultramafics or birbirite), and some isolated bodies of late to post-tectonic metagabbro, metagranodiorite and granites which are massive, hardly foliated masses at their margins;

The metamorphic basement rocks are strongly weathered forming a significant regolith deposit in most parts of the area;

The eastern part of the Moyale woreda and the entire Filtu and Dolo Odo woredas are underlain by a thick succession of Jurassic and Cretaceous sedimentary rocks;

The Jurassic Limestones are a thick succession of 4 limestone members forming a regionally E-dipping ramp where the older units are exposed in some limited windows in the western part of the project area and progressively covered by the younger units towards the east; the successive units exposed in the area are the (i) Lower Hamanneli Limestone (member 1 lower level), which is ~500 m thick, oolitic grainstone, lime mudstone and alternating beds of fossil reef limestones, dolomitic wackstones, packstones, pelletal-grainstones, black shales and sandstones; (ii) Upper Hamanneli Limestone (member 1 upper level), which is ~500 m thick, thickly bedded, to massive, micritic limestones with minor beds of dolomite, marly limestone, lime mudstone, sparry and microcrystalline allochemical limestones with lesser microcrystalline limestone; pelletal oolitic grainstones, mudstones, alternate beds of wackstones to packstones and packstones to grainstones; (iii) Limestone member 2, which is ~200 m thick, thinly bedded and laminated sandy limestone interbedded with shale and some gypsum lenses; (iv) Limestone member 3, which is ~300 m thick, intercalation of oolitic and fossiliferous limestone, and massive, horizontally and thickly bedded, microcrystalline and allochemical limestones, calcarenite with thin interbeds of marls, and at places calcilutite with marl layers; and (v) Limestone member 4, which is ~150 m thick, calcilutite limestone, with some intercalation of calcirudite and calcarenites, and some gypsum lenses;

The massive limestones of member 1 are generally karstified by dissolutions along prominent regional joints and widened along bedding plane discontinuities, while the younger members particularly members 2 and 3, where they are exposed in flat plains, are covered by patchy but considerably thick calcrete (well hardened calcareous duricrust, hardened and compact carbonate concretions associated with superficial alluvium and secondary limestone);

The Cretaceous sediments in the area are represented by a succession of sandstones, carbonates and gypsum-anhydrite deposits laying over the Jurassic limestone ramp and exposed as small or extended patches of isolated cliff forming low hills, which are strongly weathered on the surface to form sandy and silty regolith deposits; the major rock units exposed in the area are (i) fine to medium-grained, mostly horizontally stratified subarkose sandstone with lesser calcareous sandstone, interbedded with siltstone, shale and mud rock, and conglomerates towards the top; (ii) shally and silty limestone to a well hardened calcarenite, with intercalation of anhydrite, gypsum, clay, shale, basal siltstone and sandstone; and medium to coarse, thinly bedded micritic limestone with minor cherty limestone; and (iii) intercalations of medium to coarse-grained and massive limestone, and marl, sandstone, shale, claystone and ferricrete.

Cluster V:

The western sector of the area (western part of Meda Welabu woreda) is underlain by a succession of Late Proterozoic high-grade gneisses which include banded and folded biotite-hornblende and biotite gneiss, hornblende-biotite, biotite-muscovite and quartzofeldspathic gneisses, biotite granite, amphibolite, and granodiorite; biotite-plagioclase-K-feldspar-quartz mylonite with subordinate hornblende-biotite and hornblende gneiss, and quartzofeldspathic mylonite (plagioclase-quartz-microcline mylonite with lenses of biotite-plagioclase-microcline-quartz gneiss, muscovite-quartz-feldspar schists, quartzofeldspathic gneiss, and biotite granite); the high-grade gneisses are strongly foliated and folded with vertical to sub-vertical foliations and fold axes generally trending NE-SW and NW-SE;

The high-grade gneisses are intruded by mafic and granitic plutons of various sizes and ages, particularly by syn-tectonic foliated biotite granite, and late to post-tectonic granites, and some isolated bodies of metagabbro, which are massive, hardly foliated masses at their margins;

A limited, cliff-forming, ~600 m thick Triassic sandstone is exposed in the extreme northwestern corner of the area;

The central part of the area, particularly most parts of the Meda Welabu and Gura Damole woredas are underlain by a thick succession of Jurassic Limestones, while in the eastern part of the area, particularly the Raytu woreda, Cretaceous sedimentary successions are exposed;

The Jurassic Limestones are a thick succession of 4 limestone members forming a regionally E-dipping ramp where the older units are exposed in some limited windows in the western part of the project area and progressively covered by the younger units towards the east; the successive units exposed in the area are the (i) Lower Hamanneli Limestone (member 1 lower level), which is ~500 m thick, oolitic grainstone, lime mudstone and alternating beds of fossil reef limestones, dolomitic wackstones, packstones, pelletal-grainstones, black shales and sandstones; it is only exposed in deep river gorges in the area (ii) Upper Hamanneli Limestone (member 1 upper level), which is ~500 m thick, thickly bedded, to massive, micritic limestones with minor beds of dolomite, marly limestone, lime mudstone, sparry and microcrystalline allochemical limestones with lesser microcrystalline limestone; pelletal oolitic grainstones, mudstones, alternate beds of wackstones to packstones and packstones to grainstones; it is dominantly exposed in the area (iii) Limestone member 2, which is ~200 m thick, thinly bedded and laminated sandy limestone interbedded with shale and some gypsum lenses; and (iv) Limestone member 3, which is ~300 m thick, intercalation of oolitic and fossiliferous limestone, and massive, horizontally and thickly bedded, microcrystalline and allochemical limestones, calcarenite with thin interbeds of marls, and at places calcilutite with marl layers;

The massive limestones of member 1 are generally karstified by dissolutions along prominent regional joints and widened along bedding plane discontinuities;

The Cretaceous sediments in the area are represented by a succession of sandstones, carbonates and gypsum-anhydrite deposits laying over the Jurassic limestone ramp and exposed as extended cliff forming low hills; the major rock units exposed in the area are (i) fine to medium-grained, mostly horizontally stratified subarkose sandstone with lesser calcareous sandstone, interbedded with siltstone, shale and mud rock, and conglomerates towards the top; (ii) shaly and silty limestone to a well hardened calcarenite, with intercalation of anhydrite, gypsum, clay, shale, basal siltstone and sandstone; and medium to coarse, thinly bedded micritic limestone with minor cherty limestone; (iii) evaporite, which is alternating thick layers of massive gypsum with marls, anhydrites, gypsy clays, dolomites, and fine to medium, laminated shale; and (iv) intercalations of medium to coarse-grained and massive limestone, and marl, sandstone, shale, claystone and ferricrete;

The Cretaceous sandstones, particularly the calcareous sandstones are covered by patchy but considerably thick calcrete (well hardened calcareous duricrust, hardened and compact carbonate concretions associated with superficial alluvium and secondary limestone);

The Oligocene Lower Basalt and small and isolated patches of Oligocene-Miocene, Pliocene, and Quaternary volcanic rocks are exposed in the North-central part of the area, particularly

in the Berbere and Dawe Kechen woredas; up to ~150 m high, slightly to moderately weathered and eroded Lower Basalt ridges, but mostly ~50 m thick, extensively layered, aphyric and porphyritic basalt with lesser vesicular basalt, minor alkali trachyte flows and pyroclastic deposits (tuffs) at the top, and alkali syenite intrusions unconformably lie over the limestone ramp; it is in turn overlain by patches of non-weathered, Oligocene-Miocene ankaramite and lesser olivine-phyric basalt, and aphyric basalt;

Some limited exposures of Pliocene volcanics consisting of successions of trachytic tuffs with minor basalt and alkali trachyte flows and sediments, interlayered massive basalt flows, alkali trachyte and basalt flows, alkali trachyte flows and tuffs, and minor plugs overlie the Oligocene-Miocene volcanics;

Alluvial deposits of considerable thickness and extent are exposed as patches in some wadi beds and extensive plains, particularly in the eastern part of the area

Cluster VI:

Except for some considerable exposure of Quaternary volcanics in the lowlands of the Dilo Woreda and the high ridges of the Dire woreda, and some limited patches of Oligocene Lower Basalts and Jurassic limestones (Hamanneli Limestone) in the extreme north and east, respectively, most parts of the area are underlain by Late Proterozoic high-grade gneisses, limited low-grade metavolcanics both intruded by granitic and mafic intrusions;

The area is underlain by a succession of Late Proterozoic high-grade gneisses and schists which include pyroxene bearing quartzofeldspathic gneiss (banded diopside-quartz-feldspar, pyroxene-amphibole, amphibole-quartz feldspar, quartz-feldspar, and hornblende-epidote-feldspar gneisses); banded and folded biotite-hornblende and biotite gneiss, hornblende-biotite, biotite-muscovite and quartzofeldspathic gneisses, biotite granite, amphibolite, and granodiorite; biotite-plagioclase-K-feldspar-quartz mylonite with subordinate hornblende-biotite and hornblende gneiss; amphibolite gneiss; medium to coarse-grained augen granitic gneiss and biotite bearing quartzofeldspathic gneiss; plagioclase-quartz-microcline mylonite with lenses of biotite-plagioclase-microcline-quartz gneiss, muscovite-quartz-feldspar schists, quartzo-feldspathic gneiss, and biotite granite; medium to coarse-grained plagioclase-quartz-microcline, oligoclase-quartz-microcline, biotite-quartz-oligoclase, quartz-feldspar, quartz-feldspar-biotite gneisses with interbeds of biotite and biotite bearing quartzo-feldspathic gneisses, and sporadic undifferentiated schists, marble, metaconglomerate, and medium grained amphibolite; hornblende-plagioclase gneiss with granite sheets; biotite-microcline-quartz gneiss, medium-grained amphibolite and tremolite-actinolite schist, garnet staurolite bearing mica schist and gneiss, graphitic schist and graphite bearing marble; and intercalated clastic-calcareous metasedimentary schists (calc-silicate schists, marble, quartzite interlayered with graphite-quartz-mica, magnetite-serpentine-tremolite, quartz-graphite-muscovite, quartz-mica and minor quartzo-feldspathic schists, and amphibolite);

Some folded and sheared low-grade belts of metavolcanics (greenschists with amphibolite, garnet-plagioclase-actinolite schist, serpentinite, and serpentinite-talc-tremolite schists with associated siliceous rocks) and metavolcano-sediments (fine to medium grained, greenschist facies amphibolite, plagioclase-chlorite-actinolite, epidote-amphibolite, chlorite-talc-serpentine, and chlorite schists, and serpentinites, intercalated with intimately interlayered graphitic quartzite, quartz-graphite, graphitic mica, muscovite, biotite, kyanite-muscovite, muscovite-kyanite-quartz, quartzofeldspathic, graphite schist; metagreywacke and

metarhyodacite with minor metagabbro) are sandwiched between the high-grade gneisses and schists, particularly in the NE sector of the area;

The high-grade gneisses and schists and the low-grade metavolcano-sediments are strongly foliated and folded with vertical to sub-vertical foliations and fold axes generally trending N-S and NNE-SSW and affected by frequent shearing and thrust faults;

The metamorphic belts are intruded by mafic and granitic plutons of various sizes and ages, particularly by large and extensive pre-tectonic granitoid complex and metadiorites, which are variegated, medium to coarse grained, massive to distinctly foliated, deformed, and widely jointed biotite metagranite with blocky outcrop pattern and spectacular convex sheeting structures and containing xenoliths and roof pendants of banded gneiss; medium-grained, weakly to distinctly foliated syn-tectonic meta-tonalite, meta-granodiorite and granite; metamafic-ultramafic rocks (tremolite-actinolite, talc-chlorite-tremolite, talc-tremolite, chlorite-talc, and chlorite schists, serpentinite and silicified ultramafics or birbirite); and some isolated bodies of late to post-tectonic metagabbro, metagranodiorite and granites which are massive, hardly foliated masses at their margins; and isolated hills of post-tectonic granites, monzonites and syenites;

The metamorphic basement rocks are strongly weathered forming a significant regolith deposit in most parts of the area;

The Quaternary volcanics in the western part of the area are represented by extended, ridge forming, ~50 m thick, slightly to moderately weathered, aa type, vesicular-scoriaceous, rarely porphyritic, augite-olivine, augite-labradorite, and olivine-phyric basalt, with characteristic xenoliths of mantle nodules; and isolated hills, cones and ridges of pyroclastic fall and scoria deposits, which form thinly bedded, lapilli tuff fall deposit with poorly sorted and abundant rock fragments, and scoria cones;

Alluvial deposits of considerable thickness and extent are exposed as patches in some wadi beds and extensive plains, and as prominent alluvial fans at the foot of fault escarpments

Cluster VII:

The Oligocene Lower Silicics and Lower Basalt are exposed in the western part of the area; the Lower Silicics are up to ~500 m thick, generally horizontally bedded, slightly weathered and fractured, fine- to medium-grained and porphyritic, mainly massive trachyte and pyroclastic rocks (agglomerates, volcanic breccia, ignimbrite, vitric tuff and ash flow), exposed at major river gorges, while the Lower Basalt forms high isolated ridge on top of the Silicics, made up of up to ~150 m thick massive basalt, strongly weathered at the top to form a thick regolith;

The major part of the area particularly in the Kindo Koysha and Boloso Sore woredas, is underlain by the Late Miocene-Pliocene Nazareth Group alkaline and peralkaline rhyolitic flows intercalated with lapilli tuffs, moderately to highly welded ignimbrites flows, and phonolite flows capped by boulder pyroclastic falls; they form extensive flat terrains constituted by up to ~250 m thick pyroclastic deposits, strongly affected by N-S and NE-SW oriented faults forming stepped ridges and shallow grabens, particularly in the Boloso Sore woreda; they are strongly weathered and reworked at the top to form a typical soil layer called “planosol”, which is a mixture of devitrified glass, pumice and ash, mixed with clay minerals;

Quaternary ignimbrites, tuffs, water-lain pyroclastics, and occasional lacustrine beds of the Dino Formation are exposed north of Boditi town forming nearly flat, up to ~50 m thick, strongly weathered and eroded (forming “badland”) plains;

Quaternary Rift floor Basalts composed of vesicular basalts and rare basaltic hyaloclastites (phreatomagmatic deposits) are exposed S and N of the Diguna caldera; the vesicular basalts are slightly weathered but strongly fractured and faulted by NE-SW oriented normal faults;

Pleistocene-Holocene peralkaline silicics forming up to ~100 m thick, inclined flows and beds are exposed on top of the Nazareth Group deposits, while the Diguna caldera exposes a thick succession of pumice and unwelded tuffs at its central part and rhyolitic and trachytic lava flows at its rims; the rocks are hardly weathered but strongly fractured and faulted by NE-SW oriented normal faults;

The Diguna volcanic complex is surrounded by Pleistocene-Holocene, up to ~50 m thick, unconsolidated, horizontally bedded, volcano-lacustrine and volcanoclastic sedimentary deposits forming extensive and flat plains

Cluster VIII: The eastern half of the area is underlain by a succession of Late Proterozoic high-grade gneisses forming the Hammar range; the high grade gneisses are a succession of granulite facies layered mafic gneiss and amphibolite, two-pyroxene granulite, metasedimentary gneiss (layered biotite-quartz-feldspar gneiss, locally with muscovite, garnet, sillimanite; minor interlayered amphibolitic, quartzose, pyritic, graphitic and calc-silicate gneiss, and marble), undivided gneiss (predominantly biotite and hornblende gneiss, migmatitic in part, with minor metasedimentary gneiss, quartz-feldspathic gneiss, amphibolite and granitoid orthogneiss), leucocratic biotite-quartz-feldspar gneiss and magnetite-quartz-feldspar granulite, and muscovite-biotite granitoid gneiss and migmatite; the gneisses are strongly foliated, banded and folded/refolded with a generally NNW-SSE and N-S oriented fold axes, and vertical to sub-vertical dipping of the foliations; except at the highest elevations and vertical cliffs of the Hammar range, most of the gneisses are strongly weathered forming a thick regolith;

Eocene-Oligocene Lower Basalts and associated trachyte-rhyolite sequences are rarely exposed in the western margin of the area; Oligocene-Miocene basalts which form up to ~150 m high, faulted ridges of massive, moderately weathered basalts are exposed in the southern part of the project area in the vicinity of Fejej; in addition, isolated exposures of Pliocene and Holocene basalts are dotted on the southern part of the Hammar range and at the Kurath range in the western part of the Omo Valley;

The western half of the area is represented by the wide and nearly flat Omo River Valley underlain by a thick succession of Pliocene-Pleistocene-Holocene, unconsolidated sediments of fluvial and lacustrine origin interspersed with several layers of volcanic ash (tephra); the Pliocene-Pleistocene Shungura Formation dominated by fluvial depositional conditions is well exposed W of the Omo River and north of the Lake Turkana delta forming ~300 m thick (out of ~750 m total thickness), horizontally bedded, basal lacustrine silts and clays, overlain by, unconsolidated, fluvial, fining-upward cycles of sandy channel deposits overlain by finer siltstone deposits in the channel floodplain, in turn overlain by another lacustrine silts and clays; Similar but thinner (~100 m thick), Plio-Pleistocene fluvial sediments are exposed in NE of the Turkana Lake delta;

The NW part of the Omo valley is dominated by Pleistocene-Holocene sediments particularly by the Kibish Formation; a succession of ~50 m thick lacustrine silt and clay, ~100 m thick, lacustrine, marginal lacustrine, and deltaic deposits (Kibish Formation), and ~100 m thick, undifferentiated alluvial, fluvial and lacustrine sediments cover the Omo valley on either side of the modern Omo river flood plain;

The Kibish River and the Omo River flood plains are covered by Holocene, ~30 m thick, fluvial sand and silt; while the Chew Bahir basin partly represented in the eastern part of the area is underlain by a thick succession of fluvial sand and silt intercalated with lacustrine silt and clay as well as some alluvium

Annex 2

Observations during groundtruthing and validation

Ground truthing field report – Cluster 1

Groundwater mapping for climate resilience WASH in arid and semi – arid areas of Ethiopia

Start date: 09 Nov 2018

End date: 12 Nov 2018

Woredas visited: 5 of 6 Woredas [Gazgibla, Sahla, Zquala, Sekota Zuria and Abergele]

Ground truthing objectives:

- To check (quantitatively and qualitatively) the match between the groundwater suitability map produced by overlay analysis the actual field conditions
- To train local hydrogeologists on methodology that has been utilized for the production of the suitability maps and share field experience with local hydrogeologists

Methodology used

Three approaches have been used for the ground truthing work. The first method is the use of field evidences to check the match between the groundwater suitability map and the field conditions (eg possibility of groundwater occurrence from combination of information from slope/topography, degree of wetness, sufficiency of catchment sizes, presence of suitable lineaments, rock type and their estimate on permeability, degree of weathering in rocks, and manifestations of groundwater occurrences such as wetlands, springs, seepage zones etc). The second approach is to check the match between the various groundwater suitability zones and the actual conditions (i.e binary functionality-working not working-abandoned, yield of BHs, water quality, historical changes in yields, current yields etc) of pre-existing drilled shallow and deep BHs in the various suitability zones. The third method is to check the match between the groundwater suitability map and pre-existing localized and regional hydrogeology study reports (that were produced from field evidences and geophysical surveys).

The training has been provided on the following elements

- Use of QField Mobile Application for field tracking of georeferenced maps
- Use of GPS Essentials Mobile Application for tracking of locations and recording of waypoints as well as for other uses such as: GPS coordinate recording, slope measurement, measurement of strike and dip directions
- Use of Strike and Dip Mobile application for field measurement of dips, strikes direction and amount of geologic structures
- Field discussion about how to use field evidences to identify the various hydro stratigraphic units of the volcanic terrain according to the updated geology and hydro-stratigraphy of Ethiopia by Asfawossen Asrat (current work) and Seifu Kebede (2012)
- General discussion around BH monitoring, BH functionality diagnosis
- Sharing of knowledge materials (shared all documents, reports, maps, etc. that the trainer had in his collection and with key work Sekota and Tekeze). Some of the reference materials shared with the trainees is given in the annex.

The following hydrogeologists attended the training and capacity building activity

Ahmed Ali (?), Eastern Amhara Zone Water Works Head

Alamirew Salilew, Amhara region,

Wagaw Kibatie

Observations

Hydrostratigraphic Units visited: All the hydrostratigraphic units underlying the project areas has been crossed at least ones. The table below shows the sites where the various hydrostratigraphic units have been observed

Hydrostratigraphic unit	Observation sites, traverses
Basement rocks (mainly slates and low grade metasediments)	Abergele Woreda (between Tsirare river bridge and Abergele town and the surroundings of Abergele town)
Adigrat sandstone	In the Tekeze Valley in the Zquala and Sahla Woredas, on the road connecting Sekota with Sahla
Ashange basalts (Basal Basalt Unit I, according to Kebede 2012)	Road from Lalibela to Abergele, road from Sekota to Sahla, in many locations
Tekeze Sandstone	Sekota Zuria Woreda on the road from Sekota to Tirare bridge (at Abergele) + in the road between Sekoat and Siska
Aiba basalts (Upper Basalt Unit II, according to Kebede et al, 2012)	Road from Lalibela to Abergele, road from Sekota to Sahla, in many locations; occurs covering the Basal unit I

Assessment of match between the groundwater suitability map and the actual field conditions

1. Evidence from field observation:

It is to be noted that there are four color zones identified on the groundwater suitability map. The Blue colored area areas showing highest suitability, to be followed by green and brown color. The worst area is marked in red color. The following table shows where the spatial distribution of the suitable zones and the evaluation of their match with the actual field conditions.

Spatial distribution	Field condition	Evaluation	Recommendations
Blue areas in southern half of the project area (Blue colored areas in Gazgibla, Dahana, Sekota Zuria and Southern part of Zquala and Southern part of the Sahla woreda (western part of the project area)	Very rugged terrain with very unsuitable slope/topography. The geology is mostly the Basalt Unit II. In some places, basalt unit I underlay this area.	<u>The area is unsuitable for any form of deep drilling and even shallow BHs.</u> Shallow groundwater may be developed in some areas of Dahana woreda and in minor other topographic depressions. <u>The color and the actual field conditions doesn't match</u>	The rating given to slope should be modified. It is recommended to first remove (exclude) areas with slope in excess of certain threshold (eg slope >25 degree) before running the overlay analysis. Also using the lineament map drawn on the geology map is more realistic. The current lineament.
Blue areas in the northern half of the project area (Abergele Woreda)	Very flat plain underlain by basement outcrop and in locally by Adigrat Sandstone	<u>The area is unsuitable for any form of deep groundwater drilling except locally</u> along fracture zones. The deep blue color arises mainly because of very low slope (<2.5%) and slightly higher high degree of	Use only tensional lineaments in stead of all lineaments as indicators of high groundwater suitability.

		lineaments associated with the basement outcrops.	
Green areas	In the field the blue and the green areas are inseparable	The areas are unsuitable for any form deep drilling	Apply recommendations given above
Brown	This is very gentle slope forming terrain underlain by basal basalt unit I.	The areas is not suitable for any form of deep drilling targeting high yields.	Matches the actual field conditions. Some areas need to move to the red colored classes.
Red areas	The red areas are underlain by cliff forming Adigrate Sandstone, by the base of the Basalt unit I when it forms high slopes, and by basement outcrops when the slope is in excess of 2.5 degrees.	The areas are unsuitable for any meaningful deep wells drilling. Deep well drilling is unnecessary in this zone as permeability of the rocks are very low and yields could be very small. The basalt unit may be locally suitable for shallow groundwater development	Matches the field condition of very low groundwater suitability.

In all it is found out that the match between the actual field conditions and the groundwater suitability map is 50%.

2. Evidence from Boreholes

Attempt has been made to compare the suitability map and water wells drilling successes/failures in the project areas. This has been done by using the Qfield tracking tool to locate the exact location of the visited Boreholes on the suitability map and then marking the suitability class and documenting the BH conditions/history. A total of 25 BH sites and various springs sites (of which three are recorded) have been checked. The summary of the observation is given in the following table

Site Name	E	N	Suitability class of the exact site	Suitability condition of the surrounding	BH information	Evaluation
Lalkiwu			Blue	Brown/green	Dry well	No match
Sekota town shallow wells (5 sites)			Blue	Blue/Green	Very low yielding wells (0.5-3 lps) mostly not in use currently?	Partial match
Maylomite well 1	501742	1402806	Blue	Blue/Green	A productive shallow BH not in use because of damage by floods	Match
Maylomite deep well	502233	1407332	Blue	Blue/Green/Brown	A 450 m deep well in the Tekeze sandstone aquifer	No match
Maygunduo	501722	1411270	Green	Green/grown	70 m shallow well	No match?
Tsemere shallow well	502299	1414508	Blue	Brown/green	Shallow productive well, unknown depth	Match
Beltarb shallow well	495793,	1425820	Red/Blue	All colors	A 70 m shallow abandoned BH, abandoned after 1 month of construction because of poor yield	Match?
Bahrkidanemhre Monastery	495109	1427941	Blue		Spring	NA
Saka town BH	495462	1432338	Blue strip on river bank	Red	A 130 m deep BH, 8 lps but declining yield	Match
Tirare @diversion wier	494197	14342514	Blue strip	Red	A 200 m deep well in Adigrate SST and the Basement	No match
Zamrawonze, Abergele	498530	1439056	Extensive Blue are	Blue	Dry shallow well, not functional at time of visit	No match
Gemsare Abergele	498041	1442641	Extensive Blue area	Blue	A dry abandoned shallow well, unknown depth	No match
Woleh well	504683	1389607	Blue strip	Brown/Red	A 450 m deep well reported	Match

					to be productive but capped and not in use because of low yield?	
Weleh well	504683	1389607	Blue strip	Brown/Red	A 120 m deep well used to be productive but now abandoned because of decline in yield	Match
Woleh Antsaaraba	504068	1389049	Brown/green	Red	A 415 m deep productive BH in basalt unit I	No match
Maylomi deep well	501044	1406642	Patches of Blue	Patches of Blue and green	A 150 m deep well, yield 1.5 lps	Match
Sirel town well	500912	1406327	Blue strip	Brown	A functional shallow BH	Match
After Sirel	483872	1407416	Red	Red	A dry abandoned BH	Match
Coopi well before Siska town	482782	1408696	Red	Red	A productive well that stopped working after the vandalization of the solar panels	No match
COOPI Siska well	479538	1411727	Red	Red	A productive shallow well currently serving the town of Siska, working since 2004	No match
Tsiska Kidanmehret	478635	1411431	Red adjacent to Blue Strips	Red	A 120 m productive well	No match

The match between BH and the suitability map is estimated at 50%.

In addition to the Boreholes the following springs have been observed at the following sites

Kirna/Keny spring at UTM 507806 E, 1378895N, in Blue Zone

Debrebrhan twon spring at UTM 490661E, 1410090N, in Brown Zone, Yield 4 lps

Tekeze Bridges spring at UTM 461066E, 1416328N, yield less than 1 lps and falls in red zone.

Recommendation

1. Areas for phase 2 study to be selected once the suitability map is adjusted according to the proposal made above
2. As it stands now the Dahna and Sekota Zuria woredas show higher promising areas than the other Woredas.
3. Successful shallow wells can be drilled even in unsuitable classes given proper siting is made
4. Option for deep well is limited. Only two (?) out of six deep wells (>200 m) have been successful so far. Existing deep well in Adigrat Sandstone turns dry, in the basal basalt unit deep wells show very low yield at high drawdown, the promising upper basalt unit is located in very rugged terrain and is unsuitable for deep drilling.

Ground truthing field report – Cluster 2

Groundwater mapping for climate resilience WASH in arid and semi – arid areas of Ethiopia

Start date: 17 Nov 2018

End date: 20 Nov 2018

Woredas visited: Ewa, Hadar, Talalk, Chifra, Dewe, Asayita, Afambo,

Ground truther: Seifu Kebede

Ground truthing objectives:

- To check (quantitatively and qualitatively) the match between the groundwater suitability map produced by overlay analysis the actual field conditions
- To train local hydrogeologists on methodology that has been utilized for the production of the suitability maps and share field experience with local hydrogeologists

Methodology used

Three approaches have been used for the ground truthing work. The first method is the use of field evidences to check the match between the groundwater suitability map and the field conditions (eg possibility of groundwater occurrence from combination of information from slope/topography, degree of wetness, sufficiency of catchment sizes, presence of suitable lineaments, rock type and their estimate on permeability, degree of weathering in rocks, and manifestations of groundwater occurrences such as wetlands, springs, seepage zones etc). The second approach is to check the match between the various groundwater suitability zones and the actual conditions (i.e binary functionality-working not working-abandoned, yield of BHs, water quality, historical changes in yields, current yields etc) of pre-existing drilled shallow and deep BHs in the various suitability zones. The third method is to check the match between the groundwater suitability map and pre-existing localized and regional hydrogeology study reports (that were produced from field evidences and geophysical surveys).

Cluster II has two sub divisions, namely the Western Afar Woredas/zones and the Lower Awash plain. Two version of the suitability maps were available at the time of the ground truthing. The two versions (one downloaded from the cloud server @ Acacia and the other printed locally by the local project office). The difference in the suitability pattern didn't allow to ground-truth both maps. The web version was validated to keep consistency with the ground truthing exercise in the other clusters, where the web version was used.

The training has been provided on the following elements

- Use of QField Mobile Application for field tracking of georeferenced maps
- Use of GPS Essentials Mobile Application for tracking of locations and recording of waypoints as well as for other uses such as: GPS coordinate recording, slope measurement, measurement of strike and dip directions
- Use of Strike and Dip Mobile application for field measurement of dips, strikes direction and amount
- Field discussion about how to use field evidences to identify the various hydro stratigraphic units of the volcanic terrain according to the updated geology and hydro-stratigraphy of Ethiopia by Asfawossen Asrat (current work) and Seifu Kebede (2012)
- General discussion around BH monitoring, BH functionality diagnosis
- Sharing of knowledge materials (shared all documents, reports, maps, etc. that the trainer had in his collection and with key work Sekota and Tekeze). Some of the reference materials shared with the trainees is given in the annex.

The following hydrogeologists attended the training and capacity building activity

- Mahe Woleino, hydrogeologist, design enterprise
- Mohmud idris, hydrogeologist, water bureau

Evaluation of the suitability map/field observations

The suitability maps show the following classification

Map area (see attached)	Coverage	Evaluation
Western Afar sub-cluster: High suitability zone (Blue)	5	The very high suitability zone is located in the southern sector of the sub cluster. Actual field observation reveals that the reason for higher suitability class is because of the dense network of lineaments drawn from the JRC Map. In reality this areas is characterized rugged topography with low prospect for meaningful groundwater development. Some of these areas fall on mountains and hills. Once the correction is made for slope class and a field-based lineament map is used corrections this areas need to be classified as low or very low potential zone.
Western Afar sub-cluster (Medium suitability zone)	75	This zone is found to be the most promising area for extensive groundwater development except in its southern sector where the topography is slightly rugged and groundwater flows may be confined to narrow catchments. The extensive plain in the northern sector is already site for planned groundwater-based irrigation development with hundreds of drilled boreholes. This area deserves to be mapped as high potential (except in the north eastern portion of the area protruding into the rift where an extensive horst exist giving a false impression that these area is also promising- <i>this horst area need to be classified as low suitability</i>)
Western Afar sub-cluster (Very low zone)	20	This area is similar to the originally greenish (medium suitability zone) except that the low recharge conditions make the area of low suitability. In reality this area deserves to be medium suitability zone given the extensive nature of the afar stratoid basalts and the possibility of connection to recharge from rainfall and wadi flood
Western Afar sub-cluster (Low suitability zone)	5	With very rugged topography and cliffs this area needs to maintain the red or very low suitability status)
Lower Awash Sub cluster (very high suitability zone)	1	This area falls on highly dissected block mountain where density of fracture is very high and the lithology is also suitable. Nerveless the disconnection of the block mountain from any meaningful recharge and the apparent lack of lateral extent of the potential aquifer material means this area deserve to be mapped as red (very low suitability)
Lower Awash Sub cluster (moderate suitability zone)	5	This area is falls in highly dissected block mountain where the slope is also locally favorable. The narrow strips at the bottom of block mountains also fall in this category. The lack of lateral extent in the aquifer

		material and low recharge rate should put this area as low suitability area).
Lower Awash Sub cluster (low suitability zone)	85	This areas covers the extensive alluvial plain. At depth the alluvial plain is interbedded with basalts (younger basalts). The based of the alluvial-basalt intercalation is the afar Stratoid basalt (which is normally crossed at 700 m depth). Apart from its high salinity (not considered in overlay analysis) this area needs to be reclassified as high potential zone.
Lower Awash Sub cluster (very low suitability zone)	9	This area falls on hills in low recharge environment. This area deserves to be mapped as very low suitability.

Ground truthing field report – Cluster 3 & 4

Groundwater mapping for climate resilience WASH in arid and semi – arid areas of Ethiopia

1. Introduction

In order to support the evaluation of groundwater conditions of the woredas under investigation, overlay analysis techniques which is based on GIS methods has been applied during the present Phase 1 work of the project. The technique involves setting of overlay criteria for the five criteria applied to this study i.e., Litho logy, recharge, lineaments, slope and land use. Layer weights and class weights have been established during the peer-review workshop by expertise of the field as well as the consulting hydro geologists of the project. The final output of the work is production of groundwater suitability maps for each cluster classified as High, Medium, and Low, Very low to demarcate target areas for further detailed hydro geological and geophysical investigations during subsequent Phase 2 stage.

In this process, the output of the overlay analysis needs to be validated before application. As part of validation of the overlay analysis results (maps), ground-truthing work has been conducted over the clusters of the project areas. The eight clusters have been grouped into three teams as follows:

- Team 1 group: Cluster 1(Waghimra), Cluster 2 (Afar) and Cluster 3(Siti)
- Team 2 group: Cluster 4(Liben), Cluster 5(Bale) and Cluster 6(Borena)
- Team 3 group: Cluster 7(Wolayita) and Cluster 8(South Omo)

This report is prepared for Team1&2 group areas (Cluster 3&4)

2. Methodology

Following the production of the draft groundwater suitability maps and organizing both in soft copies to be used by GIS and other applications as well as printing them in appropriate scales they were taken to the field together with the required field tools such as GPS device.

During the ground-truthing work, the following steps are followed:

- Observations on the regional and local geomorphologic settings
- Verifications of the map with series of ground control GPS readings and plotting
- Registering water point and their characteristics as groundwater indicators and evaluation tools
- Checking suitability zones presented on the output maps with general ground conditions
- Geological and hydro geological observations
- Contact and consultations with the regional and zonal experts
- Identification of limitations in the groundwater suitability map outputs

3. Field observations and suitability indicators

3.1 Ayisha woreda

Most of this area has been classified as low to very low. The north east and North West boundary of the area mapped as moderate to High zone as it has been intersected along the road to Ayisha-Dewele, generally this woreda marks as very low to low ground water suitability.

All the boreholes that have been drilled in this woreda are either deep wells or hand dug wells; there are no shallow wells at all in this woreda. Most deep bore holes have problem of water quality that means the (TDS)of water are high except some area like Biyo kabobe which drilled deep borehole as well as hand dug well both wells shows fresh water but most area have hard water.

Fresh water for this woreda is found in the Biyo-gurgur kebele which is located in the south-eastern direction from Ayisha town. This kebele has both deep borehole and hand dug well and both water point shows fresh water and used for the people of this kebele, both for irrigation and drinking purpose.

The following may be mentioned as limitation of the output of the overlay analysis in this woreda:

- i) The aquifer in this area is either alluvial deposited overlying the Mesozoic formation mainly sand stone or limestone intercalation with gypsum or Mesozoic underlying basement. The basement is identified along the north east on the road between Ayisha and Dawele town, occasionally being overtopped by Mesozoic formation even though lack of primary porosity marks this formation as poor permeability and the area marks a very low ground water. However the map shows it as low suitability, otherwise all the rest part of Ayisha woreda, which is arid environment and the map also shows that this woreda is in the zone of low- very low ground water suitability (match).
- ii) For the geomorphology of this woreda, most area are flat plain and some area hill and swarm of dikes, cliffs and gentle slope forming Mesozoic formation and structural emplaced baseman complex. Most water points in this woreda are located in the area along the geological structures and stream channels. The map did not depict this adequately.
- iii) Water quality complains (hard water?) is reported for groundwater for most the functional wells in this woreda. Hand dug wells are the prominent type of scheme in this woreda it could be found at the depth 10-12m. The map has no information about the water quality; this is the general limitation of the overlay analysis maps.

The woreda is put as the most problematic by all parties i.e., regional water bureau, zonal and woreda water offices as well as the Unicef focal person for the region in terms of water supply, where by water trucking is practiced during dry periods and rural schools are reported to close due to critical water shortage. According to the Regional water office and as supported by united nations office for the coordination of humanitarian affair (OCHA), the following kebeles are identified as priorities for interventions: Adeley. Sinjeef, Dayah and surround area for both Ayisha and Dawele town, those kebele shows shortage of water, although, these kebele exists some hand dug wells and traditional hand dug well (Ela) but not in function and the located with zone of low to very low suitability area.

NB:-the Ayisha and Dewele town water supply from project (Adigala-Djibouti) water supply project. They connect pipe line from main line which passes through both towns.

The importance of drilling wells very closer to the river bank in order to avoid risk of salinity is recommended in this woreda.

3.2 Erer Woreda

During the ground-truthing work, a ground control observation has been made along the south-eastern, central and north sections over the volcanic terrain with thick alluvial deposit on the way from Erer- Aydora- Asbuli road. Most of the area is covered by fractured and weathering basalt unit out crops at places. The suitability map is found to match with the ground conditions. The woreda is typically characterized by the existence of high yielding ground water and springs emerging from the fractures zones of the basalt formations mainly along the slope breaks and vegetated northern higher grounds of the woreda the major recharge inducing to ground water of this woreda comes from precipitation regularly experienced on south boundary marking hararghe highland.

This woreda shows a lot of water point some are ground water, and surface water from either cold spring or thermal spring, and from rivers. This woreda shows high ground water suitability as a map shows match.

The main problem of this woreda is water quality which needs more analysis for laboratory to check content of anions and cat ions of this woreda and present buried layer of either gypsum or anhydrite which are easily dissolve in water.

3.3 Afdem Woreda

The suitability map over this woreda has high match with the local conditions. The water points dominantly found in this woreda are deep boreholes; also they are other water point like hand dug wells and traditional (Ela)

Fracturing and weathering of volcanic rock in this woreda are the ruling factors which play very important role in increasing the permeability of the fractured volcanic along the escarpment, which makes up the major area of recharge in the lowland areas of west of Afdem town. This tertiary volcanic could act as aquifers, if these rocks are traversed by faults. Likewise, among the existing boreholes available in this woreda, the one with depth of 500 m (Artesian borehole) which was drilled by private investor for irrigation purpose around 5km distance west of Afdem town, shows a good water bearing basalt formation and gives yield >10l/s.

The occurrence of ground water throughout the alluvial plain in the low land parts of this woreda depend on the function of primary porosity with in the thick alluvial deposits and secondary structures with in underlying volcanic rocks such as fracture, joints and contacts as well as effect of weathering. These structure have been observed in north direction of this woreda especially Sisilu kebele, salahdmer kebele and Alijir kabele where these are in the zone of high ground water suitability.

Pastoralist of this woreda mainly depend on shallow (Ela) for water supply and livestock. Deep boreholes are the dominant type of scheme in this woreda. This woreda has high potential of ground water and known as potential zone, as map shows high ground water suitability (Match) The water quality of this woreda is fresh water. In this woreda drilling of either shallow well or deep borehole is better than hand dug wells. Because most of the hand dug wells are not functional.

3.4 Meiso Woreda

The kabeles of Meiso woreda is characterized by undulated sloppy and mountainous. The escarpment area is covered with tertiary volcanic rocks of dominantly basalt with minor Trachyte domes. These volcanic rocks show variable degree of weathering and fracturing at different parts. Along the intermittent river cut exposed area within Mieso town, this basaltic rock shows columnar jointing.

In this woreda, the geological formation of the most area is the top alluvial deposited of clay, silt, sand and gravel interbred in the depth range 0-40 m. Some areas below the ground have low ground water potential, underlying this alluvial deposit is highly weathered and fractured volcanic rocks of basalt and this is the main aquifer system of this woreda.

The draft suitability map shows that this woreda is mapped as high ground water suitability. The most deep boreholes which are drilled in this woreda are characterized and located at site with both slope (under mountain) and wet land covered with spare shrubs and bushes which have promising setting for ground water occurrence and recharge potential from the catchments of the surrounding mountain chain. These deep water wells which have been drilled are characterized by moderate to high discharge rate from fractured and weathered basal aquifer.

This woreda shows that the high ground water suitability as shown on the map and we can say the map and ground match each other.

Top priority for water supply

- 1) Sanjeef kebele(Ayisha woreda)
- 2) Dayah kebele(Ayisha woreda)
- 3) Todobo shub (Afdem woreda)
- 4) Biyo- diidle (Ayisha woreda)
- 5) Jejeba (Meiso woreda)

4. Field observations and suitability indicators for Cluster(4)

4.1.Dolo- Addo woreda

The water point's source types in Dolo-Addo Woreda have been observed to be dominated by Mesozoic formation and alluvial deposit. in this woreda, ground water could be classified into three sub-basin: the Suftu-Fikow sub-basin, the Rama-Sedey sub-basin and the Wash-Akebar sub-basin.

The local geology of the overall study area comprises of: Alluvial deposited along the river flood plains, Kebridahar formation, which consists of limestone, marl and gypsum intercalation, Koraha formation, which consists of gypsum and limestone intercalation. These formations cover majority of the Suftu- Fikow sub-basin and Wash-akaber sub-basin. However, the koraha formation was not observed in the Rama-Sedey sub-basin. The formations that exist only in the Rama-Sedey sub-basin are Urandan, Beltuen formations. The urandab formation consists of Marly limestone with intercalation of Shale. The BeltUen formation consists of Shaly limestone with sandstone.

In general, the main recharge in the study area could be direct from the perennial and intermittent Rivers (Dawa&Genale) or indirectly from precipitation. So, the aquifer productivity of the study area could be in the range of high to low.

The source of water in this woreda are shallow boreholes, hand dug wells and River-intake. In the field observed most of the wells either shallow wells or Hand dug wells which were drilled in this woreda are very close to the other Dawa River or Genale River.

Determinations of water quality parameters of shallow wells, which were drilled at the junction of two local stream is very fresh if and only at the shallow depth. On other hand, some wells which was drilled dawn stream of the main tributary is relatively with high salinity.

All the shallow wells which were drilled in this woreda have average maximum depth of 25m.

Most of water points in this woreda either boreholes or hand dug wells are generated by solar system and used the people for both domestic and cattle.

During the ground-truthing work, a ground control observation has been made along the south-eastern, central and north sections, and the most area cover alluvial deposited along the river flood plains, Kebridahar formation, which consists of limestone, marl and gypsum intercalation, Koraha formation, which consists of Gypsum and limestone intercalation. These formations cover majority of the Suftu- Fikow sub-basin and Wash-akaber sub-basin. However, the koraha formation was not observed in the Rama-Sedey sub-basin. The formations that exist only in the Rama-Sedey sub-basin are Urandan, BeltUen formations. The urandab formation consists of Marly limestone with intercalation of Shale. The Belt Uen formation consists of Shaly limestone with sandstone fractured and weathering basalt unit out crops at places. The suitability map is found to match with the ground conditions.

The woreda is typically characterized by the existence of medium to low yielding ground water and the area very close to both rivers(Dawa and Genele) marks as high suitability area. Main problem in this woreda are salinity of water which cause the gypsum lithology which is easily soluble when it becomes contact with water. This gypsum has been observed as outcrop on the way from Dolo-Addo to Yugta kebele. Most water point which drilled in this woreda and very close to river bank are fresh water and people of this woreda use it for water supply but some boreholes which are far from river bank are so saline and not giving any function either due to well capped or open well without submersible pump. Finally, it can be summarized that this woreda shows high ground water suitability mainly along the zones close to rivers, where as the remaining area medium to low ground water suitability.

5. Conclusion and Recommendation

- 1) The suitability map for Ayisha woreda indicating “low to very low” most area but some kebele shows as a high-to moderate like biyo-kabobe, biyo- gurgur and degago.
- 2) The remaining three woreda(Erer,Afdem and Meiso) are potential ground water zones, and the suitability map for those shows as high, this indicate the map and ground condition match 100%.
- 3) The cluster(4) Is done only one woreda which is Dolo- Addo which shows most area medium- to low ground water suitability where as the area were very so close to rivers show High ground water suitability.
- 4) A study of regional understanding of the areas identified as suitable by the help of development of conceptual models (hydro geological sections) is mandatory prior to delineation of target areas for phase 2 study.
- 5) Selection of priority of the woredas and kebeles should consider the recommendations from regional and zonal offices as presented in this report.

Annex 1- Ground truthing Representative Field Observations (Summary)

Woreda	Site Location ref.		Observation	Remarks
	X	Y		
Ayisha	243290	1136506	Flat low land with alluvial deposit, this site locates near to valley bottom.	Mapped as moderate to low ground water suitability and match with the ground condition.
	233951	1158904	This site located so close to main stream and flat plain with alluvial deposit	The suitability map match with the ground conditions
	193397	1197910	Flat low land with alluvial deposit, this site are drilled hand dug well which materialized by solar system but as I observed it is need to drill shallow borehole	Site conditions Match with the suitability map shows this area high ground water suitability.
	211558	1206305	This site so closely to local spring which the people of this area used for both domestic and irrigation purpose, it is flat plan with covered alluvial deposit. It is also cultivated area for garden purpose.	Mapped as medium to Low suitability. However this area are exist local spring which people used for domestic and irrigation, so I recommend to be drill in these are shallow well for water supply of this area, as map show medium to low ground water suitability.
Erer	763214	1057323	This site is located in side Erer- town and site for promising so closely to river bank, area slope to river, it is only way possible fresh water for Erer- town, deep borehole in this area contain high total dissolve solute (TDS) and not possible for water supply so, only possible either river- intake or shallow well very close to river.	This woreda shows high ground water potential because is is boundary in southern (E-W Hararghe High land) which are recharge area.Mapped as high suitability(Match)
	759582	1091436	This site shows flat alluvial plain which recognized as compartment with a big ground water areas regardless of the quality issue as field observed this area shows greater saline proportion	Mapped as high suitability (match)
	738945	1103498	Wide flat land area which cover alluvial deposit. This site drilled deep borehole which reached depth 500 m for irrigation purpose but still up to now the well capped not give any purpose. I recommend this borehole to make function and people o this kebele used for irrigation purpose	Mapped as high suitability(Match)
	789627	1062718	This site promising site but area near to military comb. It is flat plan which surround area covered a huge forest and vegetable, and suitability of ground water is high because it is boundary hararghe high land area.	Mapped as high suitability(match)
AfdemWoreda	714017	1040014	Fractured and weathering of volcanic rock in this site play very important and increase the permeability of the fractured volcanic rock along the escarpment, which makes up the major area of	This area have a lot of traditional (Ela) and promising area and high ground water area and it is map as high suitability (match)

			recharge. I observed this site a lot of traditional (Ela) which the pastoralist of this area used for cattle drink and washing their close. It is promising area for shallow and deep borehole.	
	715173	1047855	This is the area among the areas identified as priorities for intervention for water supply, shortage of water is observed and the people of this area use a stream water for drinking, the steam has water only during rainy season.	Mapped as a high suitability (match)
	715222	1049272	This site located over flat low land area with surrounded fracture and joint. There is a 500 m deep artesian well which was drilled by private investor for irrigation purpose and located around 5km distance west of Afdem town. Currently, this well not in use for any purpose.	Mapped as a high suitability(match)
	718700	106570	Plain land, following the existing intermittent river following direction the existing regional fault structural orientation (nearly E-W oriented) which is covered by thick alluvial unconsolidated sediment as a result along period of deposition overlying the Tertiary-Quaternary volcanic rocks of Basalt.	Mapped as a high suitability(match)
	699990	1079696	This site located the low land parts of this woreda following the foot of the margins of the rift valley which covered by thick alluvial unconsolidated sediment as a result of a long period of deposition this alluvial sediment mainly gravel; sand, silt and clay interbred having variable thickness.	Mapped as high suitability(match)
Meiso	702186	1027959	This site a vegetated plain land which covered black cotton soil it is located in south-eastern from Meiso –town, it is promising site and good for agriculture.	Mapped as high suitability(match)
	702241	1034068	This is site located 7km distance from Meiso town towards north-west direction. It is flat plain covered by alluvial deposited of clay, silt, sand and gravel inter bed with different range underlying this alluvial deposit is a highly weathered and fractured volcanic rocks mainly basalt and this is the main aquifer system in this site.	This site is sub-kebele known as (jejebe) so near to kebele kulmiya. During field observed this site is among one of the indicated priorities in which the shortage of domestic water supply is relatively high. At this site, it is recommended to drill either deep or shallow borehole. Mapped as high suitability area(match)
	696625	1072311	This site located in the low land part of the area near by the existing intermittent rivers that flows north direction. People use water by	This site is promising and are area high potential ground water zone Mapped as high suitability area(match)

			fetching from the sandy bed of those intermittent rivers even though; it is short lasted whenever the ground water table dropped during the very dry season of the area. It very important to drill deep bore hole in order to reach main aquifer of this site which are highly weathered basalt underlying a thick alluvial deposit.	
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Ground truthing field report – Cluster 5

Groundwater mapping for climate resilience WASH in arid and semi – arid areas of Ethiopia

Groundwater Suitability Draft Maps Ground-truthing field Report – Cluster 5 (Bale)

1. Introduction

In order to support the evaluation groundwater conditions of the woredas under investigation, overlay analysis techniques which is based on GIS methods has been applied during the present Phase 1 work of the project. The technique involves setting of overlay criteria for the five criteria applied to this study i.e., Lithology, recharge, lineaments, slope and land use. Layer weights and class weights have been established during the peer-review workshop by expertise of the field as well as the consulting hydrogeologists of the project. The final output of the work is production of groundwater suitability maps for each cluster classified as High, Medium, Low, Very low to demarcate target areas for further detailed hydrogeological and geophysical investigations during subsequent Phase 2 stage.

In this process, the output of the overlay analysis needs to be validated before application. As part of validation of the overlay analysis results (maps), ground-truthing work has been conducted over the clusters of the project areas. The eight clusters have been grouped into three teams as follows:

- Team 1 group: Cluster 1(Waghimra), Cluster 2 (Afar) and Cluster 3(Siti)
- Team 2 group: Cluster 4(Liben), Cluster 5(Bale) and Cluster 6(Borena)
- Team 3 group: Cluster 7(Wolayita) and Cluster 8(South Omo)

This report is prepared for Team2 group areas (Cluster 5)

2. Methodology

Following the production of the draft groundwater suitability maps and organizing both in soft copies to be used by GIS and other applications as well as printing them in appropriate scales they were taken to the field together with the required field tools such as GPS device.

During the ground-truthing work, the following steps are followed:

- Observations on the regional and local geomorphological settings
- Verifications of the map with series of ground control GPS readings and plotting
- Registering water point and their characteristics as groundwater indicators and evaluation tools
- Checking suitability zones presented on the output maps with general ground conditions
- Geological and hydrogeological observations
- Contact and consultations with the regional and zonal experts
- Identification of limitations in the groundwater suitability map outputs

3. Field observations and suitability indicators

3.1 Dawe Kachen Woreda

About half of the woreda size area has been classified as high suitability. The north western boundary of the area mapped as high suitability zone is intercepted along the road to Miyo town and suits the actual ground conditions.

It is reported that some boreholes have been drilled in the area to a depth of about 300 m and went dry while the inspected functional borehole close to Miyo town has yield of 2.3 l/s. This is

the maximum yield recorded so far in the area from a well drilled to a depth of 275m within the limestone aquifer. The rest of the recorded wells have low yields mostly <1 to 2 l/s.

The following may be mentioned as limitation of the output of the overlay analysis in this woreda:

- iv) The aquifer in the area is limestone formation underlying the volcanic rock (basalt). The thickness of the basalt unit as recorded in the boreholes drilled in the area as well as from the inspected well long of the well on progress during the field work which is located in the northern part of the woreda within the Sof Umer kebele (area mapped as high suitability) is about 40 m. The Suitability map has been prepared based on the assumption that the basalt formation could have greater depth and assumed as potential aquifer. The hydrogeological characteristics of the basalt formation and the Limestone also vary accordingly and the aquifer of the area is found to be the limestone formation. Therefore, the suitability map on this area lays on other factors mainly the geomorphologic factor which needs further discussion and evaluation.
- v) For the geomorphology (slope) also some zones indicated as suitable includes a wider areas including undulating and relatively elevated and rugged local morphology stretching North West – South east along the general west of the woreda area which do not favor as sites for groundwater. Therefore, the slope criteria may need revision to refine slopes and trace depressions and relatively lower elevation zones by discriminating local highs.
- vi) Water quality complains (hard water?) is reported for groundwater from the functional well near Miyo town within the limestone formation. The suitability map does not consider this. This is the general limitation of the method.

The woreda is put as the most problematic by all parties i.e., regional water bureau, zonal and woreda water offices as well as the Unicef focal person for the region; in terms of water supply where by water trucking is practiced during dry periods and rural schools are reported to close due to critical water shortage. According to the woreda water office and as supported by statistical data on target population (Annex 3A) the following kebeles are identified as priorities for interventions: O/Didibisa, D/Mole, Sof-Umar, K/Waldaya, H/Basaqa, B/Kora. From the preliminary evaluation of these areas with respect to the first draft suitability map, Sof-Umar and D/Mole fall within the zone of high suitability area while B/Kora and part of Didibsa Gale are over the suitability zone mapped as medium to very low mainly due to rugged topography over the Kebeles in the south western part of the woreda.

The up coming further evaluations of the suitability areas should be assisted by construction of regional hydrogeological x-sections (conceptual models), detailed hydrogeological mapping at 1:50, 000 scale, characterization of lateral variations of the limestone formation (fracturing, weathering, cavern formations etc) by the help of geophysical surveys, defining the regional water table, groundwater flow path/pattern and estimation of depth of drilling to tap the main aquifer.

3.2 Berbere Woreda

During the ground-truthing work, a ground control observation has been made along the northern, central and eastern sections over the volcanic terrain with thick soil development and fractured basalt unit out crops at places. The suitability map is found to match with the ground conditions. The woreda is typically characterized by the existence of high yielding springs emerging from the fractures zones of the limestone and basalt formations mainly along the slope breaks and vegetated northern higher grounds of the woreda. The yields of most springs are in the range of 1 to 25 l/s. During the inventory program a spring yielding 65 l/s has been reported over the north-western boundary of the woreda which has been developed for multi village water supply.

3.3 Gura Damole Woreda

The suitability map over this woreda has good match with the local conditions. The water points dominantly found in this area are springs. The woreda town “Jibri” is also getting its water supply

from springs. The hand dug wells excavated along the valley bottoms and narrow strips of highly weathered limestone zone and overlaying sediments have yields 0.3 l/s to 1.5 l/s and the water is reported to be hard water. Almost all water points except the springs emerging at the foot of the escarpments from the fracture zones of the cliff forming limestone rock unit in the area, are found within the zone delineated as high suitability zone in the map. However, due to the rugged geomorphologic nature of the woreda area which is clearly observed during the field regional and local observation, the suitability map also indicates large portion of the woreda area as very low suitability. Only the central part of the woreda area is observed to be moderately to highly suitable for further exploration. During the field observation, a borehole drilled to a depth of 220 m with a reported yield of 5l/s (Yedi-BH) has been inspected and this one also lies over the zone shaded as high suitability on the map. According to the woreda water office information, among the 17 kebeles in the woreda the following priority is given interns of their water supply problems: Habron, Okolta, Ocheche, Funale Kosse, Alshena, Jibo Samo and Yedi.

3.4 Rayitu Woreda

The draft suitability map shows that except in the central and northern border areas this woreda is mapped as medium to high suitability. However, from the field observations and previous water points records and information from the zonal water offices all the areas mapped as suitable do not seem realistic. During the ground truthing work, it is observed that areas such as east of Dedecha Bella town, calcrete units within the surrounding sandstone formation, poor permeability ground and relatively high place from the adjacent low laying areas are marginally suitable while it is mapped as high suitability.

The locality west of Dedecha Bella town (woreda town) where three inspected wells have been drilled, reported depth 94 to 162m, yield 0.6 to 8 l/s. over the flat area over sandstone formation with limestone intercalations? is found promising and matches with the map. However, except the small area in the south west mapped as moderate, the extensive area towards east is also marked as high suitability area. This needs revision to make sub divisions in suitability as within this zone it is reported that some wells drilled in the wider area are either with very low yield or found to be dry.

In this environment, relatively low elevation/depression horizons connected to recharge sources should be identified, local and high/resistant grounds to be classified as not suitable (splitting required).

Regarding priorities, the woreda water office reported that among the 19 kebeles in the woreda (Annex 3B) the following kebeles are put in priority for their severity in water supply problems: Beredimtu, Bokol, Borore, Kare Tule, Adala and Arda Negaya.

3.5 Meda Wolabu Woreda

Meda Wolabu woreda with its woreda town called Bidire is mountainous area and dominantly occupied by rugged terrain. The relatively flat to gentle slope areas that could be favorable for groundwater occurrence are those isolated patches of pocket areas within intermountain locations and along the sides of parallel to sub-parallel river channels draining the woreda mainly in the North West and south east of the woreda area.

The evaluation of the draft groundwater suitability map with the actual ground conditions has revealed that a good match has been noticed in most cases as the area is in general controlled by the geomorphologic factor where limited areas are mapped as suitable. However, still some locations may need to be re-evaluated.

Among the area of good agreement with the ground condition, the locality adjacent east of Bidire, North west-South east stretching flat land area, partly cultivated and where promising groundwater occurrence conditions exist within the overlying sediments and underlying limestone formation and the locality of the existing Bidre BH area drilled within regional fracture zone can be indicated (see Annex 1). This borehole is reported to have a depth of 69m and yield

of 4 l/s as well as existence of hand pumps shallow groundwater abstraction using hand pumps in the area, manifestations of groundwater discharge zone (seepages, swamps) observed within the limestone formation.

Areas that need attention for re-evaluation are such as the zone classified as high suitability area around Melka Amana locality, north eastern border of the woreda adjacent to Welmel river with basalt formation over a relatively flat to gentle slope pocket area which has been observed to be marginally suitable. Similarly, the area around the crossing of Shilani River on the way to Bidire, the basement rocks shows thick soil/regolith development may be suitable for shallow groundwater occurrence at suitable locations or along fracture zones. The North south stretch of low lying areas east of this locality is mapped as high to moderate potential. However, except along selected weathered and fractured zones, all the shaded area can not represent the ground conditions (massive basement rocks at the river beds), emphasis on further evaluation of lineaments/secondary structures is required. Similar conditions have been observed around the locality of Goble river on the road going to Bidre town where massive granite bed out crops exist and the general area could be considered as marginally suitable along selected fracture zones. The classification of high suitability needs further evaluations in terms of permeability and storage possibility in the area.

Regarding the priorities of the Kebeles, the information obtained from the woreda water office shows that among the 20 kebeles in the woreda (Annex 3C), the following priority is given interns of their water supply problems:

Top priority for water supply

- 1 Oda Boji
- 2 Bidire woreda town
- 3 Meda
- 4 Hora Kore
- 5 Waduma
- 6 Karjul (sub- kebele: Mazoria & Dire alabdo)

4. Training during ground-truthing program

One of the objectives of the present field work is to provide training and experience sharing during the ground truthing program. Accordingly, three experts as represented from ministry of water, Irrigation and electricity (MoWIE), Oromia regional water bureau(OWB) and bale zone (cluster 5) water, mineral and energy office has been attached to the field work and effectively participated in the work.

The training aspect includes the following:

- ✓ Map reading and use (geological, groundwater suitability) and ground controlling and field observations
- ✓ Proper use of GPS, recording and plotting to control locations
- ✓ Joint field observations discussions and gather field evidences (geological and hydrogeological)
- ✓ Inspecting water point sites and technical discussions
- ✓ Sharing reference materials relevant to the present work especially overlay analysis and hydrogeology

Table 1. List of participants as Trainee during ground truthing program

Sn	Name	Organization	Profession	Tele	Email
1	Zemichael Yosef	Ministry of Water, Irrigation and electricity	Water Resources Engineer	0912-873276	zemichaelyosef12@gmail.com
2	Desalegn Abera	Oromia Water , Mines and Energy Bureau	Geologist	0910-194006	10QGOD2017@gmail.com
3	Aduugna Tolla	Bale zone Water , Mines and Energy office	Hydrogeologist	0941-090510	Adugnatola2@gmail.com

5. Suggested priority of woredas

During the ground-truthing program, the Oromia regional water bureau, zonal water bureau, woreda water offices as well as the Unicef focal person to the Oromia region have been consulted to provide information for their evaluations and give priorities to the severity of water supply problems among the woredas included in the present study so that these can later be compared with suitability maps. Similarly, selected woredas have also been asked to prioritize the kebeles as per their views.

Table 2. Priority list of Cluster 5(Bale) Woredas

List of Woredas	OWB priority	Bale zone Water Office priority
Dawe Kachen*	1	1
Gura Damole	2	4
Rayitu *	3	3
Mede Wolabu	5	2
Berbere	4	5

**Priority in agreement*

6. Conclusion and Recommendation

- 1) The suitability map for Dawe Kachen woreda indicating “High” occupying extensive area of the woreda assumed the basalt unit mapped on the surface to continue deeper. However, records and field observations indicated that the thickness of the basalt does not exceed 40 m. The underlying aquifer is limestone formation having different characteristics from the basalt. This needs consideration for further evaluation and in the use of the suitability map.
- 2) The slope classifications need to be revised to discriminate local high grounds and delineate the relatively lower or depression areas where these are the target locations in terms of groundwater sites. This will allow sub-dividing the extensive area mapped as high as a result of lumped approach and generalization.
- 3) Special attention and evaluation may need to be given to secondary permeability liniments/structures criteria to delineate for the best groundwater zones especially in the basement and limestone areas.
- 4) The agreement of the map with the ground conditions is estimated to be about 70 %. The suitability zones identified as not fitting the ground conditions should be adjusted to improve the result.
- 5) A study of regional understanding of the areas identified as suitable by the help of development of conceptual models (hydrogeological sections) is mandatory prior to delineation of target areas for phase 2 study.
- 6) Selection of priority of the woredas and kebeles should consider the recommendations from regional and zonal offices as presented in this report.

Annex 1- Ground truthing Representative Field Observations (Summary)

Woreda	Site Location ref.		Observation	Remarks
	X	Y		
Dawe Kachen	691002	764914	Gentle slopes to partly undulating terrain/rugged covered by black cotton soil developed over volcanic rocks	Mapped as high suitability without discriminating unsuitable zones within the general geomorphological setting.
	696056	764801	Flat cultivated land around Oda Didibisa Kebele, the underlying unit is basalt formation, favor groundwater occurrence	The suitability map match with the ground conditions
	701377	761768	Site under drilling (Sofumer BH) by zonal water office, basalt unit surface geology, site adjacent to dry river channel within a valley stretch.	Site conditions Match with the suitability map (high). However, the thickness of the overlying basalt unit from the log is 40 m and the aquifer is the underlying Limestone formation, not the basalt.
	706302	756331	Site reported with dry BH drilled to a depth of 300 m? (Arda Oru village), flat to gentle slope over basaltic formation with local slope breaks, Surficially seems suitable area	Mapped as high suitability. However, due to the underlying sub-surface characteristics (variations in the nature of the limestone formation underlying the volcanics) the results could be different.
	708935	748085	Locally high and low relief (undulating) within the general wide and flat area, rocky ground (volcanics), not promising site.	Mapped as high suitability, reported that a dry borehole has been drilled at about 4 Kms east of this location to a depth of 300/350 m?
	710958	744653	Wide flat plain area around Dibe Kiloska locality, vesicular basalt out crops, pastoralist area using community ponds and water tracking,	The wider area in the west and North west extensions mapped as high suitability which needs to be revised for further delineations (consider revision of slope classes)
	719364	734781	Miyo BH locality, flat to gentle topography, limestone formation, functional borehole drilled to a depth of 275m is yielding 2.3 l/s	Site located within the moderate suitability zone and is in good agreement with the ground conditions.
Berbere	642806	759620	Locality at the northern border of the woreda on the road to woreda town (Haro Dumel), rugged terrain with steep slopes over limestone formation, not suitable for GW	The map shows very low suitability (match)
	642087	756759	Gentle slope stretch area between adjacent hills with potential recharge sources and highly weathered and fractured basalt unit, good aquifer	Mapped as high suitability (match)
	637459	748719	Wide flat land area with mild slopes, reddish and compact clay soil developed over volcanics, poor permeability, marginal suitability	Area within the extensive map delineations as high suitability area. GW is released mainly in the form of springs at the foot of slope breaks from the north and north east recharge sources. In this area currently there are temporary settlements of the Oromia displaced people.

	636458	746417	Locality of Hawas river bridge, on the way to Haro Dumel, irregular topography, valley sections, local high relief to flat lands over basaltic terrain. Selected horizons could be suitable, not the all the general wide area mapped as highly suitable.	The area falls within high suitability including unfavorable areas, needs further evaluations.
	643692	746742	Densely vegetated plain area over limestone terrain. Area with marginal suitability.	Falls over the moderate suitability zone on the map (match)
Gura Damole Woreda	651786	737470	Yedi locality, contact area of basaltic formation and limestone formations, undulating topography. Promising groundwater zone along the north south stretching valley.	Area mapped as moderate to high suitability. This is a match case where the inspected Yedi-BH situated close to the Yedi intermittent stream and drilled to a depth of 220 m has yield of 5l/s.
	659437	736104	Area adjacent north of Jibri town over limestone formation, gentle slope indications of seepage zones on the road cut, manifestation of shallow groundwater	Mapped as a high suitability zone within the very poor aquifers in the surrounding (within geomorphologic compartment) Due to the size of aquifer and geomorphologic setting this could be moderate to low instead of high.
	658768	738992	Contact zone of basalt and limestone unit. Rugged and steep slope area, not suitable for groundwater.	Mapped as strips of high and moderate suitability (no match)
	6549446	755910	Mountainous land scape around Rayitu kebele over basalt formation, watershed area recharge zone releasing groundwater in the form of springs, poor groundwater storage.	Low yielding aquifers in shallow groundwater system but mapped and moderate.
	653541	757631	Sado worku village area, depression area between hills over the plateau landscape, local groundwater storage within the sandstone formation, shallow groundwater system exploited using hand pumps.	The surrounding irregular and rugged area should be mapped as low in the suitability map, instead of moderate.
Rayitu	728951	763341	Area around the bridge crossing Chelchel river, thick alluvial deposit section at the river bank, sandstone formation over flat area with local undulations and mild slopes, The low lying zones parallel to the river could be promising.	The area towards south is mapped as moderate suitability while the extensive area in the east is mapped as high suitability without discriminating some unsuitable horizons, such as zones of poor permeability calcrete formations and local high grounds (partly matching)
	732823	761267	This is a locality west of Dedecha Bella town (woreda town) where three inspected wells have been drilled, reported depth 94 to 162m, yield 0.6 to 8 l/s., flat area over	Except the small area in the south west mapped as moderate, the extensive area towards east is marked as high suitability area. This needs revision to make sub divisions in suitability as within this zone some

			sandstone formation with limestone intercalations? , promising area.	wells are either with very low yield or found dry.
	739312	761807	Area east of Dedecha Bella town, calcrete units within the surrounding sandstone formation, poor permeability ground, relatively high place from the adjacent low laying areas, marginal suitability.	Area falling under high suitability zone, need for refinement (partial matching), a split may be need to medium and low.
	750569	753669	Area gently sloping in the south east, limestone, marl and mud stone as observed at a quarry site, poorly suitable.	Mapped as moderate to high, needs revision. Depression horizons connected to recharge sources should be identified, local and high/resistant grounds relative to adjacent areas to be classified as not suitable (splitting required).
Mede Wolabu	587262	689748	Melka Amana locality, north eastern border of the woreda adjacent to Welmel river, basalt formation over al relatively flat to gentle slope pocket area with marginal suitability.	The high suitability classification may need to be modified to moderate suitability.
	579938	668860	Area around the crossing of Shilani river on the way to Bidire, basement rocks with thick soil/regolith development, shallow groundwater at suitable locations or along fracture zones could be promising.	North south stretch of low lying areas in the north south direction east of this locality is mapped as high to moderate. Except along selected weathered and fractured zones all the shaded area can not represent the ground conditions (massive basement rocks at the river beds), emphasis on lineaments required.
	572255	654026	Locality adjacent east of Bidire, North west-South east stretching flat land area, partly cultivated, promising conditions for groundwater occurrence within the overlying sediments and underlying limestone formation.	Mapped as high suitability (match)
	574456	652579	Locality of the existing Bidre BH, area within regional fracture zone, the well drilled to a depth of 69m has a reported yield of 4 l/s. Shallow groundwater abstraction using hand pumps in the area, manifestations of groundwater discharge zone (seepages, swamps) observed, geology limestone.	The suitability map depicts as high and in agreement with the ground conditions.
	577983	662660	Locality on the crossing of Goble river on the road going to Bidre town. Massive granite bed rock, area with marginal suitability along selected fracture zones	The classification of high suitability needs further evaluations in terms of permeability and storage possibility in the area

**Annex 2: List of contact persons during the ground truthing work
Oromia, Cluster 5(Bale)**

Sn	Name	Organization	Position	Tele	Email
1	Gezahegn Lemecha	Oromia Water , Mines and Energy Bureau	Deputy Bureau Head	0911-103442	
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4	Masresha Mamo	Bale zone Water , Mines and Energy office	Hydrogeologist	0910-797428	
5	Seifedin Abdo	Dawe Kachen woreda water, mines and energy office	Deputy Head	0923-509817	
6	Abdurezak Aman	Gura Damole woreda water, mines and energy office	Head	0912-826905	
7	Mahamed Ahmed	Rayitu woreda water, mines and energy office	Head	0920-171020	Mamiahmed2008@gmail.com
8	Gelan Ahmed	Rayitu woreda water, mines and energy office	Hydraulic Engineer	0909-689222	Gelanahmed996@gmail.com
9	Siraj Sultan	Mede Wolabu woreda water, mines and energy office	Head	0920-234484	
10	Awal Ali	Mede Wolabu woreda water, mines and energy office	D/Bureua Head	0910-758398	Awalali951@gmail.com
11	Lema Abera	Mede Wolabu woreda water, mines and energy office	Water Supply and Sanitation Team Leader	0912-747890	

Ground truthing field report – Cluster 6

Groundwater mapping for climate resilience WASH in arid and semi – arid areas of Ethiopia

1. Introduction

Overlay analysis techniques which is based on GIS methods has been applied during the present Phase 1 work of the project, in order to support the evaluation of groundwater conditions of the woredas under investigation. The technique involves setting of overlay criteria for the five criteria applied to this study i.e., Lithology, recharge, lineaments, slope and land use. Layer weights and class weights have been established during the peer-review workshop by expertise of the field as well as the consulting hydrogeologists of the project. The final output of the work is production of groundwater suitability maps for each cluster classified as High, Medium, Low, and very low to demarcate target areas for further detailed hydrogeological and geophysical investigations during subsequent Phase 2 stage and to serve as planning tool for future development.

In this process, the output of the overlay analysis needs to be validated before application. As part of validation of the overlay analysis results (maps), ground-truthing work has been conducted over the clusters of the project areas. The eight clusters have been grouped into three teams as follows:

- Team 1 group: Cluster 1(Waghimra/Amhara), Cluster 2 (Afar) and Cluster 3(Siti/Somali)
- Team 2 group: Cluster 4 (Liben/Somali), Cluster 5(Bale/Oromiya) and Cluster 6 (Borena/Oromiya)
- Team 3 group: Cluster 7(Wolayita/SNNPR) and Cluster 8(South Omo/SNNPR)

This report is prepared for Team2 group areas (Cluster 6_Borena)

2. Methodology

Following the production of the draft groundwater suitability maps and organizing both in soft copies to be used by GIS and other applications as well as printing them in appropriate scales, they were taken to the field together with the required field tools such as GPS device.

During the ground-truthing work, the following steps are followed:

- Observations on the regional and local geomorphological settings
- Verifications of the map with series of ground control GPS readings and plotting
- Inspecting and registering of water point and their characteristics as groundwater indicators and evaluation tools
- Checking suitability zones presented on the output maps with general ground conditions
- Geological and hydrogeological observations
- Contact and consultations with the regional and zonal experts
- Identification of limitations in the groundwater suitability map outputs

3. General Information

According to the project document, the initial list of the woredas included for cluster 6 (Borena zone) are six in number i.e., Dillo, Moyale, Miyo, Dire, Dehas, Arero. This was based on the old classification of woredas. However, as per the recent information obtained from the local authorities during the inventory period as well as the present ground truthing work, it is learnt that the current number of woredas in the Borena zone are 13 in total as indicated in table below. A new map indicating the layout of the new woredas is not obtained.

Therefore, the descriptions for the field report is given based on the old woreda classification which actually includes the recent sub-divisions. It is also to be noted that Moyale woreda could not be visited during the present mission due to security issues.

Table 1. List of Woredas in Borena Zone

Sn	Woreda	Remarks
1	Yabelo	
2	Gomele	from Yabelo
3	Elweya	from Yabelo
4	Teltele	
5	Arero+	
6	Wachile	from Arero
7	Dubluk	from Dire
8	Dehas+	
9	Dillo+	
10	Dire+	
11	Miyo+	
12	Guchi	From Moyale
13	Moyale+	

+ included in the project list

4. Field observations and suitability indicators

4.1 Arero:

The woreda is dominantly made of basement rocks and the aquifers within this environment are in general localized along major fracture and weathered horizons and associated overlaying sediments at suitable topography. The suitability of the areas within this environment is very limited. However, the draft suitability map classified as High, medium, low and very low should be adjusted to “Medium, low and very low/un-suitable”. The hilly and mountainous areas within the basement terrain should be classified as “un-suitable”. Field observations and data from the inventory work indicates that the yield of most of the water points are <1 to 2.5 l/s. However, there are some exceptional localized horizons of high yielding wells where regional fracture zones are intercepted like in the areas inspected at the locality of Fugnan Diresa, south west of Meta Gefera where the two borehole with reported similar characteristics exist(depth 145m, Q:13 l/s, WQ:high salinity and corrosive).

4.2 Dehas

Small areas in the eastern boundary and western peripheral areas of the woreda are mapped as “high” suitability which may need to be modified to “moderate” and the rest large portion of area is with “low” suitability classification. The data from water point inventory indicates wells drilled in the woreda to a depth of 50 to 120 are yielding 2 to 3 l/s. One of the wells inspected during the field work is a borehole near Dehas town. This well is drilled within the regional fracture zone and reported to yield 2l/s. It is an area of alluvial sediment overlaying the basement formation. The fracture zone is marked with wet and partly marshy area, green vegetation and big trees along the lineament/fracture trend. It is also reported that downstream of this locality, there are other shallow wells sunk within this zone. However, the draft suitability map did not indicate these horizons and it is generalized under the unsuitable/very low suitability area. This indicates the need for detailed considerations of structural analysis at this stage as wells as during phase 2. The western part of this woreda is featured by a typical shallow groundwater area called Gumi Gayo plain area. This area is characterized by the presence of several traditional wells Tulas and Ellas excavated for extracting shallow groundwater, the depth of the traditional wells are in the range of 15 to 20 m. The suitability map has depicted these areas as “high” suitability which is a match case for the general suitability except the rating may have to be adjusted to “moderate”.

4.3 Dillo

Dillo woreda area is made of the two dominantly occurring geological formations that controls the occurrence and distribution of groundwater in the area i.e., volcanic rocks (basalt) and basement rocks with prominent features of eruption centers (craters) such as Dillo and Goray. In the region of this woreda, there is a relatively well studied regional aquifer system known as “Bulal basalt aquifer”. The main body of this aquifer lays in the west and northern adjacent of the woreda. The south east extension of this aquifer occupies the western, south central and south eastern part of the woreda area. This aquifer unit is mapped as “high” suitability which matches with the ground condition. The parts of the woreda which is covered by basement rocks and the volcanic crater localities are not suitable. The map has also depicted it as “low” to “very low” suitability. This needs further evaluation to demarcate as “low” suitability along lower elevations and fracture zones within the basement while the hilly and upland are “unsuitable”.

According to the woreda water office information, Dillo is given the top priority in terms of its water supply problem though there is a known huge potential of regional aquifer in the adjacent west and north of Dillo which may require option of designing and construction of multi village schemes to reach the remote parts of the woreda out of the potential aquifer zones in the area. Among the eleven kebeles in the woreda (Annex3) the following are identified as priorities for interventions: Goray, Quadim, Arbale, Chirete, Bilal, Magol.

4.4 Dire

The southern part of Medicho area where there is volcanic rocks within the regional mass of basement rocks is promising and can be mapped as “moderate suitability”. Correction is required for the designation as “high” suitability. Similarly, towards the northern Medicho area and further north-west around Dubluk locality, the area is not suitable. Limited shallow groundwater could only be prospected along localized fractured and weathered zones of the basement rocks such as like the well drilled within the periphery of Dubluk town for the community water supply as well as the traditional Elas (large diameter wells) situated at close proximity in the South of the town. Therefore, the zone mapped as “high’ and “moderate” for the corridor in the east and west adjacent to the asphalt road towards Yabelo and around Dubluk locality should be corrected to “low suitability”.

Similarly, the zones mapped as “very low suitability” shall be clearly mapped as “Not suitable” since these areas are not worth investigating for the case with Borena (basement rocks combined with un-favorable topography).

5. Training during ground-truthing program

One of the objectives of the present field work is to provide training and experience sharing during the ground truthing program. Accordingly, three experts as represented from ministry of water, Irrigation and electricity (MoWIE), Oromia regional water bureau(OWB) and bale zone (cluster 5) water, mineral and energy office has been attached to the field work and effectively participated in the work.

The training aspect includes the following:

- ✓ Map reading and use (geological, groundwater suitability) and ground controlling and field observations
- ✓ Proper use of GPS, recording and plotting to control locations
- ✓ Joint field observations discussions and gather field evidences (geological and hydrogeological)
- ✓ Inspecting water point sites and technical discussions
- ✓ Sharing reference materials relevant to the present work especially overlay analysis and hydrogeology

Table 1. List of participants as Trainee during ground truthing program

Sn	Name	Organization	Profession	Tele	Email
1	Zemichael Yosef	Ministry of Water, Irrigation and electricity	Water Resources Engineer	0912-873276	zemichaelyosef12@gmail.com
2	Desalegn Abera	Oromia Water , Mines and Energy Bureau	Geologist	0910-194006	10QGOD2017@gmail.com
3	Chala Mekonen	Borena e zone Water , Mines and Energy office	Geologist	0910-704582	chalatze@gmail.com
4	Godana Cherfo	“ “	Geologist	0926-478501	

6. Suggested priority of woredas

During the ground-truthing program, the Oromia regional water bureau, zonal water bureau, woreda water offices as well as the Unicef focal person to the Oromia region have been consulted to provide information for their evaluations and give priorities to the severity of water supply problems among the woredas included in the present study; so that these can later be compared with the suitability maps. Similarly, selected woredas have also been asked to prioritize the kebeles as per their views.

Table 2. Priority list of Cluster 6(Borena) Woredas

List of Woredas	OWB priority	Borena zone Water Office priority
Dehas or Arero	1	3
Dillo	2	1
Moyale	3	2
Miyo	4	5
Dire	5	4

7. Conclusion and Recommendation

- 1) The main aquifer system that should be mapped as “high suitability” in the mapped area is the “Bulal aquifer system” within the basalt formation. The basement rocks in the region are considered as aquiclude or aquifers of minor importance. However, the map has depicted other high suitability areas within the basement formation. Therefore, this has to be adjusted to “moderate” to “low” and all the hilly or mountainous areas of the basement to be classified as “not suitable”.
- 2) The areas around Dubluk surroundings and towards north on the way to Yabelo should be re-evaluated, as the map is indicating “moderate” suitability over wider area while the actual ground conditions and manifestations reveal that the large part of this area is with “low suitability” where by selective regional fracture zones could only be of “Moderate suitability”.
- 3) Special attention and evaluation may need to be given to secondary permeability liniments/structures criteria to delineate for the best groundwater zones especially in the basement areas. This may require re-evaluation and use of structures/lineaments from the geological maps.
- 4) A study of regional understanding of the areas identified as suitable by the help of development of conceptual models (hydrogeological sections) is mandatory prior to delineation of target areas for phase 2 study.
- 5) Selection of priority of the woredas and kebeles should consider the recommendations from regional and zonal offices as presented in this report.

Annex 1- Ground truthing Representative Field Observations (Summary)

Site Location ref.				
X	Y	Locality	Observation	Remarks
440319	529958	Yasuma Awetu	Flat to slightly undulating topography over basement terrain, very low suitability.	Low suitability classification on the map to be changed to very low
443178	530524	Bule	Black cotton soil covered volcanic (Basalt) area, thickness of basalt resting over basement reported to be only about 20 to 30 m, shallow well drilled but reported dry	The high suitability zoning to be modified to low
444320	532046	Alona	Extension of Bule area	Same as above
456177	528249	Fuldawa	An area crossed by Kililiwe dry stream channel where thick sediment deposit is exposed along the stream bank, area surrounded by poor suitability terrain. Locality could be marginally suitable	Mapped as low suitability (match)
469380	523898	Silala	Wide flat land surrounded by basement hills, top part reddish soil and alluvial deposits at depressions. Alluvial sections, weathered profiles and fracture zones make it moderately suitable.	The classification on the map as "High" should be changed to moderate (No match)
468963	519444	Koticha Michire	Alluvial deposits over basement rock formation ?, good topography, suitable for GW	The classification on the map as "High" match
467963	517852	Fugnan Diresa	Similar to Koticha Michire, in the area 2 BHs drilled in the same characteristics: depth 145m, reported Q=13l/s within highly weathered and fractured chlorite schist formation. WQ: high salinity and corrosive.	" "
504468	504804	Wachile	Flat area NW adjacent to Wachile town over basement formation, not promising.	The moderate rating of the map to be modified to low
503481	500360		Area NW of Wachile, wide plain area covered by alluvial sediments along dry stream channels, moderate suitability	The high rating of the map to be modified to moderate
448429	466714	Gayo	Flat plain area extending further north towards Gumi Gayo plain area, traditional wells (Tula/Elas), hand pumps and a borehole reported Q=1.5l/s exist tapping shallow GW, moderate suitability area	The high rating of the map to be modified to moderate
427529	463455	Soda	Area with mild slope over basement ground, not suitable	To be mapped as not suitable
423733	461394	Medecho	Moderate suitability area within the volcanic/basalt aquifer and at the contact zone with basement unit (Medicho South)	The high rating of the map to be modified to moderate
420210	460761	Medecho-BH	This functional well inspected during the visit is reported to have been drilled to a depth of 200 m with SWL at 120 m and Q=6l/s, Basalt aquifer.	Supporting the suitability map
419275	497041	Ranchi Dubluk	Northern border of Dire woreda, basement ground, not suitable	Area mapped as very low to moderate suitability, to be corrected to 'Not suitable'
419281	485575	Dublik	Gently sloping basement ground towards Dubluk town, manifestations of regional liniments, vegetation pattern, low suitability area along fracture zones	Map to be corrected from moderate to low.
420110	482693	Dublik-BH	Well located within the regional fracture zone, suitable zone	Partial match, the zone labeled high should be medium and the medium to low

394526	485954	Ola Kenchora	Flat to gentle slope, basement rocks, not suitable	Map to be revised to low suitability
388540	489824	Gobso village	Area over gentle slope, basement formation, not suitable	Very low suitability on the map, to be classified as unsuitable , except in the far NW of Gobso area (suitable)
376084	496215	Gobso	Contact zone of the volcanics/basalt in the west(Bulal basalt) and basement in the east	The suitability for the basement part should be corrected from moderate to low.
371543	501553	Gobso	This is a site around the productive borehole situated in the northern border of the woreda within the highly suitable Bulal basalt aquifer.	Match with the map
362989	477557	Dilo	Flat area over basement formation, not promising	Map to be revised to low suitability
356702	471368	Dilo crater	Center of volcanic eruption, pyroclastic deposits surrounding the crater area, not suitable	Map to be revised from very low to not suitable
353688	469893	Dilo	Gently sloping area west of Dilo town over volcanics. Except towards further west within the Bulal aquifer, the locality is not suitable for GW	Map to be revised from very low to not suitable
351780	469175	Dilo	" "	" "

Annex 2: List of contact persons during the ground truthing work Oromia, Cluster 6(Borena)

Sn	Name	Organization	Position	Tele	Email
1	Gezahegn Lemecha	Oromia Water , Mines and Energy Bureau	Deputy Bureau Head	0911-103442	
2	Dereje Abdeta	Unicef	Focal person for Oromiya		
3	Wako Liben	Borena Zone Water, Mines and Energy office	Head	0911-805690	wagayyodha@gmail.com
4	Chala Mekonen	" "	Geologist	0910-704582	chalatze@gmail.com
5	Godana Cherfo	" "	Geologist	0926-478501	
6	Kiya Dera	Dilo woreda Water Mines and Energy office	Head	0979-812061	Wariodera2007@gmail.com
7	Abdula	Dire woreda Water Mines and Energy office	Head	0946-590709	
8	Galma Tadi	Yabelo woreda Water Mines and Energy office	Head	0926-338790	
	Gamachu Balire	Elweya woreda Water Mines and Energy office	Head	0910-776843	
9	Jarso Molu	Dubluk woreda Water Mines and Energy office	D/Head	0912-857295	
10	Kiya Dera	Dillo woreda Water Mines and Energy office	Head	0979-812061	Wariodera20072gamil.com

Annex 3: List and priority of Dilo woreda kebeles

Sn	Woreda	Population (2010 EC)
1	Dilo magala	4650
2	Dilo badiya	2633
3	Bilal	
4	Kenchero	3733
5	Goray	4617
6	Arbale	4847
7	Liso	3626
8	Chirete	2633
9	Magole	2779
10	Quadim	3726
11	Hobok	3200

Priority woredas

Rank	Kebele	Rank	Kebele
1	Goray	4	Chirete
2	Qadim	5	Bilal
3	Arbale	6	Magol

Annex 4: List and priority of Dubluk woreda kebeles

Sn	Woreda	Sn	Woreda
1	Bokosa	8	Jigessa
2	Flobika	9	Dublik
3	Kersa Dembi	10	Arbala
4	Laffo	11	Gobso
5	Gale	12	Dhokole
6	Anole	13	Gorodada
7	Higo	14	

Priority woredas

Rank	Kebele	Rank	Kebele
1	Gobso	4	Gorodada
2	Bokosa	5	Laffo
3	Gale	6	Flobika

Ground truthing field report – Cluster 7

Groundwater mapping for climate resilience WASH in arid and semi – arid areas of Ethiopia

1. Introduction

In order to support the evaluation groundwater conditions of the woredas under investigation, overlay analysis techniques which is based on GIS methods has been applied during the present Phase 1 work of the project. The technique involves setting of overlay criteria for the five criteria applied to this study i.e., Lithology, recharge, lineaments, slope and land use. Layer weights and class weights have been established during the peer-review workshop by expertise of the field as well as the consulting hydrogeologists of the project. The final output of the work is production of groundwater suitability maps for each cluster classified as High, Medium, Low, Very low to demarcate target areas for further detailed hydrogeological and geophysical investigations during subsequent Phase 2 stage.

In this process, the output of the overlay analysis needs to be validated before application. As part of validation of the overlay analysis results (maps), ground-truthing work has been conducted over the clusters of the project areas. The eight clusters have been grouped into three teams as follows:

Team 1 group: Cluster 1(Waghimra), Cluster 2 (Afar) and Cluster 3(Siti)

Team 2 group: Cluster 4(Liben), Cluster 5(Bale) and Cluster 6(Borena)

Team 3 group: Cluster 7 (Wolayita) and Cluster 8(South Omo)

This report is prepared for Team 3 group areas (Cluster 7)

2. Methodology

Following the production of the draft groundwater suitability maps and organizing both in soft copies to be used by GIS and other applications as well as printing them in appropriate scales they were taken to the field together with the required field tools such as GPS device.

During the ground-truthing work, the following steps are followed:

Observations on the regional and local geomorphological settings

Verifications of the map with series of ground control GPS readings and plotting

- Registering water point and their characteristics as groundwater indicators and evaluation tools
- Checking suitability zones presented on the output maps with general ground conditions
- Geological and hydrogeological observations
- Contact and consultations with the regional and zonal experts
- Identification of limitations in the groundwater suitability map outputs

3. Field observations and suitability indicators

3.1 Duguna Fango Woreda

About two third of the woreda size area has been classified as medium to high suitability zone for deep groundwater. The peripheral parts of the Woreda falls in the high to medium suitability zone but the central mountainous part of the area mapped as low to very low suitability zone is intercepted along the road from Dima to Bedesa through the Woreda town Bitena which suits the actual ground conditions.

Evaluation of existing borehole data shows that groundwater in the Woreda is generally deep. Depth to the water is greater than 100 m. Depths of wells drilled around Boditi and Badesa towns ranges from 150 m to 200 m. Moreover; it was also observed during the ground truthing field campaign that well development activity was going on at a bore hole drilled to a depth of 483m (test well belong to Ministry of Water and Irrigation). This borehole is located at 384941UTME, 758129UTMN and ground elevation of 1470 masl on flat ground sloping down to the Main Ethiopian Rift (Bilate River Basin). It has a water level of 120 m bgs and estimated discharge of 14 l/s. The formation of this borehole is dominantly ash up to 263m. After 263m, the circulation of the drilling fluid totally lost. There is also another borehole at about 5km south of this borehole site which was drilled before 5 years to supply water to the community of Anka Mazoria kebele which is currently functional. Except dug wells located along river bank of Bilate River at Dimtu town, there is no any indication of shallow groundwater in the area.

The major aquifer in the dominant part of the area is thick rhyolitic, trachytic and pumaceous rock intercalations. In the extreme southern part of the Woreda, Quaternary basalts form productive aquifer. The hydrogeological characteristics of the formations mentioned above may vary due to the variations in their primary porosity. Generally topographically low grounds are suitable for deep groundwater development through deep well drilling. Therefore, the high and medium suitability zones on the suitability map needs further discussion and evaluation by considering geomorphology as major factor.

High and medium suitability zones on the first draft suitability map generally fit with prospective groundwater potential zones. However; in relation to geomorphology (slope), some zones indicated as suitable includes a wider areas including undulating and relatively elevated and rugged local morphology variations which do not favor as sites for groundwater. Therefore, the slope criteria may need revision to refine slopes and trace depressions and relatively lower elevation zones by discriminating local highs.

In relation to the water quality complains of fluoride that varies from 1.58 to 3.44 mg/l, is reported for groundwater from the functional wells near Boditi and Badesa towns. This might be related to the ash and rhyolitic formations. The suitability map does not consider this, which is considered as one of the limitations. This is something recommended for further study.

The woreda is put as the most problematic by all parties i.e., regional water bureau, zonal and woreda water offices as well as the UNICEF focal person for the region. People residing in the mountainous part including the Woreda town Bitena have limited access for clean drinking water, where tap water is supplied from a spring developed outside of the Woreda at Odo locality. Except a well at Anka Mazoria kebele that is supplying water through community water points, there is no other water source in the area.

From the preliminary evaluation of Duguna Fango Woreda, with respect to the first draft suitability map, areas that fall within the zones of high and medium suitability that form plain topography are proposed for further hydrogeological, geophysical and and water study. The upcoming further evaluations of the suitability areas should be assisted by construction of regional hydrogeological x-sections (conceptual models), detailed hydrogeological mapping at 1:50, 000 scale, characterization of lateral variations of the available formations (rhyolite, trachyte, ash and basalt) by giving due consideration to the deep regional water table, rift ward groundwater flow path/pattern and estimation of depth of drilling to tap the main aquifer with good quality water.

Table 1- Ground truthing Representative Field Observations in Duguna Fango Woreda

No	Woreda	Locality	Coordinate zone 37			Field observation	Suitability
			UTME	UTMN	Elevn		
1	Duguna Fango	Dimtu mountain	401725	769473	1627	<ul style="list-style-type: none"> The observation point is mountain side, there is no deep well, no shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	The specific site and its surrounding is recharge area or aquifer systems in the surrounding plains
2		Dimtu kebele town	403580	766025	1516	<ul style="list-style-type: none"> The observation point is along side of Bilate River, there is no deep well, no shallow well, but hand dug wells of 10-15m and water level of 6-0 m, thermal spring with high F is also available and the geology is alluvium underlain by trachytes as and ash observed on road cut exposure The area falls on High suitability zone on the draft suitability map. Shallow GW in river bank area 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development. Water quality in relation to F and TDS is in question
3		Bitena woreda town	393330	769716	2051	<ul style="list-style-type: none"> The observation point is mountain side, there is no deep well, no shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	The specific site and its surrounding is recharge area or aquifer systems in the surrounding plains
4		Qarchacha	387331	767092	1761	<ul style="list-style-type: none"> The observation point is mountain side, there is no deep well, no shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	The specific site and its surrounding is recharge area or aquifer systems in the surrounding plains
5		Anka Mazegaja	390604	760739	1421	<ul style="list-style-type: none"> The observation point is on flat plain sloping down to Bilate River, there are deep wells, no shallow well, no hand dug well, no spring and the geology is trachytes with some ridges of scoria as observed on quarry sites exposure The area falls on high suitability zone on the draft suitability map. Deep GW (wl>100 m) 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development. Water quality in relation to F and TDS is in question

6	Anka chiro river	399991	761070	1421	<ul style="list-style-type: none"> The observation point is on flat plain sloping down to Bilate River, there are deep wells, no shallow well, no hand dug well, no spring and the geology is trachytes with some ridges of scoria as observed on quarry sites exposure The area falls on high suitability zone on the draft suitability map. Deep GW (wl>100 m) 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development. Water quality in relation to F and TDS is in question
7	Anka Scoria cone quarry sites	386656	758371	1542	<ul style="list-style-type: none"> The observation point is on flat plain sloping down to Bilate River, there are deep wells, no shallow well, no hand dug well, no spring and the geology is trachytes with some ridges of scoria as observed on quarry sites exposure 2. The area falls on high suitability zone on the draft suitability map. Deep GW (wl>100 m) 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development. Water quality in relation to F and TDS is in question
8	Anka Drilling site	384941	758129	1490	<ul style="list-style-type: none"> The observation point is on flat plain sloping down to Bilate River, there are deep wells, no shallow well, no hand dug well, no spring and the geology is trachytes with some ridges of scoria as observed on quarry sites exposure The area falls on high suitability zone on the draft suitability map. Deep GW (wl>100 m) 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development. Water quality in relation to F and TDS is in question
9	Duguna Sore	386044	768007	1858	<ul style="list-style-type: none"> The observation point is mountain side, there is no deep well, no shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	Not Suitable for deep groundwater development
10	Duguna Sore	386255	768306	1796	<ul style="list-style-type: none"> The observation point is mountain side, there is no deep well, no shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	Not Suitable for deep groundwater development
11	Kachache	387432	768111	1824	<ul style="list-style-type: none"> The observation point is mountain side, there is no deep well, no shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	Not Suitable for deep groundwater development

3.2 Damot Pulasa Woreda

About one third of the woreda size area that lies in the western side has been classified as medium to high suitability zone for deep groundwater. Over two third of the Woreda area in the eastern side (running parallel to the asphalt road connecting Shone and Boditi towns) at the eastern side of the woreda falls in the low to very low suitability zone in the map.

Evaluation of existing deep and shallow borehole data shows that depth to the groundwater in the Woreda varies from 20 m to 70 m. Depths of wells drilled along Boditi Shone asphalt road in the Woreda ranges from shallow 50 m to deep 190 m. Deep boreholes fitted with submersible pumps located on flat ground sloping down to the Main Ethiopian Rift into the Bilate River Basin are available in the eastern side of the woreda. In the western side of the Woreda, shallow wells fitted with hand pumps are common. The major aquifer in the dominant part of the area is thick ignimbrites, trachytic and pumaceous rock with thin layers of basalt intercalations. Part of the Woreda, east of the NNE-SSW trending regional fault is highly promising for deep groundwater development. The hydrogeological characteristics of the formations mapped in the area vary due to the variations in their primary porosity and structural setting. Generally topographically low grounds are suitable for deep groundwater development through deep well drilling. Therefore, the suitability zones on the suitability map should be corrected by considering geomorphology, recharge-discharge zone, structural setting as major factors.

In this woreda, the suitability zones identified in the draft suitability map are not fitting the ground conditions. High and medium suitability zones on the suitability map does not fit with this prospective groundwater potential zone. The suitability map and ground truths are completely contradictory since medium to high suitability zones are mapped as low to very low suitability but areas of low suitability are mapped as suitable. Despite the fact that the western side of the Woreda is relatively rugged forming recharge area for the aquifer systems in the adjacent woredas in the western, is mapped as high suitability zone. Hence; in relation to geomorphology (slope), the western side of the Woreda indicated as suitable includes undulating and relatively elevated and rugged local morphology variations which do not favor as sites for regionally flowing groundwater. Therefore, the criteria may need revision to refine and re define suitability zones by considering slopes, fault structure and relative elevation sites by discriminating local highs, recharge areas and catchment size. Low and very low suitability zones on the suitability map fits with prospective groundwater of good productivity. High and medium suitability zones on the contrary fits with low and very low suitability where the aquifer productivity expected to be poor. However; in relation to geomorphology which is related to recharge and discharge zones, some zones indicated as suitable in the western side of the woreda including undulating and relatively elevated and rugged local morphology variations which do not favor as sites for regional groundwater development. Therefore, all the criteria set for suitability zone map preparation need revision to refine and re define the suitability zones again by tracing depressions and relatively lower elevation zones so as to discriminate local highs and recharge areas.

Even if the suitability map does not consider water quality issues, which need to be considered as one of the limiting factor, there is no any complain about the water quality in the area. However; it is something recommended for further study, since the formation in the area is dominantly acidic rocks that usually contributes high fluoride to the groundwater.

The woreda is put as the most problematic by all parties i.e., regional water bureau, zonal and woreda water offices as well as the UNICEF focal person for the region.

People residing in the mountaineous part including the Woreda town Shento have limited access for clean drinking water, where tap water is supplied from a spring developed at Zamine locality found about 5km north west of the town. Significant proportion the population of the Woreda have access to clean water from shallow wells fitted with hand pumps.

From the preliminary evaluation of the hydrogeological condition of the Damorte Pulasa Woreda, with respect to the first draft suitability map, areas that fall within the zones of Low and very low suitability that form plain topography are proposed for further hydrogeological, geophysical and water quality study. The upcoming further evaluations of the suitability areas should be assisted by construction of regional hydrogeological x-sections (conceptual models), detailed hydrogeological mapping at 1:50, 000 scale, characterization of lateral variations of the available formations (rhyolite, trachyte, ash and basalt) by giving due consideration to the deep regional water table, rift ward groundwater flow path/pattern and estimation of depth of drilling to tap the main aquifer with good quality water.

Table 2- Ground truthing Representative Field Observations in Damot Pulasa Woreda

No	Woreda	Locality	Coordinate zone 37			Field observation	Suitability
			UTME	UTMN	Elvn		
1	Dmot Pulasa	Buge	381154	783869	1906	<ul style="list-style-type: none"> The observation point is on flat plain land, there are deep well, shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	The specific site and its surrounding is for deep groundwater in the contrary to what is seen on draft suitability map
2		Abota Alto	378044	778044	1897	<ul style="list-style-type: none"> The observation point is along side of ridge, there is no deep well, no shallow well, but hand dug wells of 10-15m and water level of 6-8m, are available and the geology is trachytes as and ash observed on road cut exposure The area falls on low suitability zone on the draft suitability map. Which is in agreement with the observation 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development. Water quality in relation to F and TDS is in question
3		Worti Bolaka	376394	774426	1924	<ul style="list-style-type: none"> The observation point is on flat plain land, there are deep well, shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map in contrary to ground observation 	The specific site and its surrounding is good for deep groundwater in the contrary to what is seen on draft suitability map
4		Worti Bolaka SW	375607	774685	1926	<ul style="list-style-type: none"> The observation point is on flat plain land, there are deep well, shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map in contrary to ground observation 	The specific site and its surrounding is good for deep groundwater in the contrary to what is seen on draft suitability map
5		Shonto	374255	776093	1945	<ul style="list-style-type: none"> The observation point is on flat plain land, there are deep well, shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map in contrary to ground observation 	The specific site and its surrounding is good for deep groundwater in the contrary to what is seen on draft suitability map
6		Choroke junction	374527	778830	1938	<ul style="list-style-type: none"> The observation point is on flat plain land, there are deep well, shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map in contrary to ground observation 	The specific site and its surrounding is good for deep groundwater in the contrary to what is seen on draft suitability map

7		Gudicho	371714	780697	1900	<ul style="list-style-type: none"> The observation point is on flat plain land, there are deep well, shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map in contrary to ground observation 	The specific site and its surrounding is good for deep groundwater in the contrary to what is seen on draft suitability map
8		Gudicho school	370195	781116	1888	<ul style="list-style-type: none"> The observation point is on flat plain land, there are deep well, shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map in contrary to ground observation 	The specific site and its surrounding is good for deep groundwater in the contrary to what is seen on draft suitability map
9		Gudicho kebele	367823	782320	1844	<ul style="list-style-type: none"> The observation point is on flat plain land, there are deep well, shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure. The area falls on low suitability zone on the draft suitability map in contrary to ground observation 	The specific site and its surrounding is good for deep groundwater in the contrary to what is seen on draft suitability map

3.3 Boloso Sore Woreda

Except some hills and associated steep slopes, the dominant part of the area is classified as medium to high suitability zone for deep groundwater. The high to medium suitability zones in the Woreda covers the northern and north western foot of Mt. Damot. In the draft suitability map the flat slightly sloping ground surrounding Areka town (Woreda capital), extending northwest fall in the high to medium suitability zone. Small portion of the land forming local ridges and surrounding high grounds are considered as low to very low suitability zones.

Evaluation of existing deep and shallow borehole data shows that depth to the groundwater in the Woreda varies from 14m to 69m. Depths of wells drilled along Hosana-Sodo asphalt road in the Woreda ranges from shallow 29m to deep 182m. Deep boreholes fitted with submersible pumps located on flat ground sloping down to the Gibe River basin are available in the western part of the woreda. In the western mountainous part of the Woreda, shallow wells fitted with hand pumps are common. Part of the Woreda, sloping plain along Woibo River extending north east from Areka town is highly promising for deep groundwater development. The major aquifer in the dominant part of the area is thick ignimbrites, trachytic and rhyolites with thin layers of basalt intercalations.

High and medium suitability zones on the draft suitability map fit with this prospective groundwater potential zone. The medium to high suitability zones on the map and ground truths are in agreement with what has been observed during ground truthing campaign. Despite the fact that the eastern side of the Woreda is relatively rugged forming high grounds is more suitable for recharge than groundwater development. The major aquifer is found along the Woibo River catchment in the western side, it is mapped as high suitability zone. The draft suitability map needs only minor correction giving due consideration to geomorphology (slope) so as to modify the eastern part of the Woreda, Some parts indicated as suitable includes undulating and relatively elevated and rugged local morphology variations which do not favor as sites for regionally flowing groundwater development. Therefore, the criteria need slight revision to refine and re define suitability zones by considering slopes, fault structure and relative elevation of sites by discriminating local highs, recharge areas and catchment size.

Therefore, all the criteria set for suitability zone map preparation fine and the suitability zones needs only slight modification by avoiding locally elevated zones and mountainous part in the eastern side of the woreda.

The hydrogeological characteristics of the formations mapped in the area vary due to the variations in their primary porosity and structural setting. Generally topographically low grounds are suitable for deep groundwater development through deep well drilling. Therefore, the high to medium suitability zones on the suitability map are accepted for further detail groundwater study by employing different techniques.

Even if the suitability map does not consider water quality issues, which need to be considered as one of the limiting factor, there is no any complain about the water quality in the area. However; it is something recommended for further study, since the formation in the area is dominantly acidic rocks that usually contributes high fluoride to the groundwater.

The woreda is put as the most problematic by all parties i.e., regional water bureau, zonal and woreda water offices as well as the UNICEF focal person for the region.

People residing in the mountainous part except the Woreda town Areka and its surrounding kebeles sharing water through community water points from the same source, have limited access for clean drinking water. Areka town is supplied from deep drilled well located along Woibo River catmint. Significant proportion of the population of the Woreda have access to clean water from shallow wells fitted with hand pumps.

From the preliminary evaluation of the hydrogeological condition of the Boloso Sore Woreda, with respect to the first draft suitability map, areas that fall within the zones of high and medium suitability that form plain topography sloping down to Woibo River are proposed for further hydrogeological, geophysical and water quality study. The upcoming further evaluations of the suitability areas should be assisted by construction of regional hydrogeological x-sections (conceptual models), detailed hydrogeological mapping at 1:50, 000 scale, characterization of lateral variations of the available formations (rhyolite, trachyte, ignimbrites and basalt) by giving due consideration to the deep regional water table, rift ward groundwater flow characteristics and estimation of depth of drilling to tap the main aquifer with good quality water.

Table 3- Ground truthing Representative Field Observations in Boloso Sore Woreda

No	Woreda	Locality	Coordinate zone 37			Field observation	Suitability
			UTME	UTMN	Eln		
1	Boloso Sore	Pulsa town	367246	782573	1627	<ul style="list-style-type: none"> The observation point is on flat land, there is no deep well, there area shallow wells, no hand dug well, there are springs nearby Gamo River and the geology is trachytes The area falls on low suitability zone on the draft suitability map matches with high suitability zone 	The specific site and its surrounding is suitable for deep groundwater
2		Gara town	364899	782621	1516	<ul style="list-style-type: none"> The observation point is in the town here peple are getting water fro tap water source from Arekaarea, there is no deep well, no shallow well, no hand dug Trachyte is major rock unit The area falls on High suitability zone on the draft suitability map. Shallow GW in river bank area 	The specific site and its surrounding from groundwater occurrence point of view is is not suitable for deep groundwater development.
3		Basa Kebele	362473	783632	2051	<ul style="list-style-type: none"> The observation point is on flat land, there is no deep well, no shallow well, but hand dug wells fitted with afrideve pumps, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	The specific site and its surrounding is suitable for deep groundwater
4		Areka sermuma junction	357977	785486	1761	<ul style="list-style-type: none"> The observation point is mountain side, there is no deep well, no shallow well, no hand dug well, no spring and the geology is trachytes as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	The specific site and its surrounding is recharge arearor for aquifer systems in the surrounding plains
5		Chama Henbecho	356272	787665	1421	<ul style="list-style-type: none"> The observation point is on flat plain sloping down to Woibo River, there are shallow wells, no deep well, no hand dug well, no spring and the geology is trachytes The area falls on high suitability zone on the draft suitability map. 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development.

6	Bridge 1 Achura	356760	789717	1421	<ul style="list-style-type: none"> The observation point is on flat plain sloping down to Woibo River, there are deep wells, shallow well, no hand dug well, no spring and the geology is trachytes and ignimbrites The area falls on high suitability zone on the draft suitability map. 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development.
7	Achura bridge2	356435	791697	1542	<ul style="list-style-type: none"> The observation point is on flat plain sloping down The observation point is on flat plain sloping down to Woibo River, there are deep wells, shallow well, no hand dug well, no spring and the geology is trachytes and ignimbrites The area falls on high suitability zone on the draft suitability map. 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development.
8	Areka at Gununo junction	357638	779979	1490	<ul style="list-style-type: none"> The observation point is on flat plain sloping down The observation point is on flat plain sloping down to Woibo River, there are deep wells, shallow well, no hand dug well, no spring and the geology is trachytes and ignimbrites The area falls on high suitability zone on the draft suitability map. 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development.
9	Dola	359523	774827	1858	<ul style="list-style-type: none"> The observation point is on flat plain sloping down The observation point is on flat plain sloping down to Woibo River, there are deep wells, shallow well, no hand dug well, no spring and the geology is trachytes and ignimbrites The area falls on high suitability zone on the draft suitability map. 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development.

3.4 Kindo Koisha Woreda

Kind Koisha woreda with its woreda town called Bele is mountainous area and dominantly occupied by rugged terrain and chains of mountains. The plain where the town is located, is surrounded by these chains of mountains. The relatively flat to gentle slope areas that could be favorable for groundwater occurrence are those isolated intermountain plain surrounding Bele town along the sides of parallel to sub-parallel river channels draining the woreda mainly in the northwest direction ultimately drain to Gibe #3 dam reservoir. Only small patches of land within the hills are classified as medium to high suitability zone for deep groundwater. The dominant portion of the area in the woreda falls in the low to very low suitability zone.

Existing borehole supplying water to Bele town drilled at Koisha locality shows that the intermountain valley surrounding the town has good groundwater resource for further evaluation and development. This borehole is reported to have a depth of 140 m and yield of 2 l/s (source of information is community). According to the information from the local community, other deep boreholes are available along sides of the Gibe River and its tributary streams. Spring are also common at slopes breaks surrounding Bele town. Part of the Woreda, sloping plain along sides of the Gibe River extending to west from Bele town to Gib#3 dam site is highly promising for deep groundwater development. The major aquifer in the dominant part of the area is thick ignimbrites, trachytic and rhyolite flows. The hydrogeological characteristics of the formations mapped in the area vary due to the variations in their primary porosity and structural setting. Generally intermountain low grounds of extensive areal extent surrounding Bele town is suitable for deep groundwater development through deep well drilling. Further detail groundwater study by employing different techniques is recommended in the central part of the woreda surrounding Bele town.

Suitability zones (high, medium, low and very low) are not clear from the suitability zone map. Therefore, all the criteria set for suitability zone map preparation need revision. High and medium suitability zones that extends to the mountain part around Bele town on the suitability map does not fit with this prospective groundwater potential zone. The suitability zones on the map are not in agreement with ground truths what have been observed during the field campaign. Dominant part of the woreda forming mountains that surrounds Bele town form recharge area for the aquifer system in the central part of the woreda, Therefore, the map needs some correction giving due consideration to geomorphology (slope) so as to modify all the high grounds surrounding the town as low or very low suitability zone. The criteria set for suitability zone mapping need revision to refine and redefine suitability zones by considering slopes, fault structure and relative elevation of sites by discriminating all high grounds (recharge areas).

Even if the suitability map does not consider water quality issues, which need to be considered as one of the limiting factor, there is no any complain about the water quality in the area. However; it is something recommended for further study, since the formation in the area is dominantly acidic rocks that usually contributes high fluoride to the groundwater.

The woreda is put as the most problematic by all parties i.e., regional water bureau, zonal and woreda water offices as well as the UNICEF focal person for the region. People residing in the mountainous part surrounding Bele town, have limited access for clean drinking water. Significant proportion the population of the Woreda have access to unclean water from unsafe sources like unprotected springs. The evaluation of the draft groundwater suitability map with respect to the actual ground conditions has revealed that poor match has been noted in most cases of the woreda as the groundwater localization is in general controlled by the geomorphologic factor where sparsely distributed intermountain valleys of small areal extent including mountain tops are mapped as suitable. Therefore the suitability map need to be re-evaluated since different zones are not clearly defined before detail hydrogeological study.

The upcoming further evaluations of the suitability areas should be assisted by construction of regional hydrogeological x-sections (conceptual models), detailed hydrogeological mapping at 1:50,000 scale, characterization of lateral variations of the available formations (rhyolite, trachyte, ignimbrites and basalt) by giving due consideration to the deep regional water table, rift ward groundwater flow characteristics and estimation of depth of drilling to tap the main aquifer with good quality water.

Table 4- Ground truthing Representative Field Observations in Kindo oisha Woreda

No	Woreda	Locality	Coordinate zone 37			Field observation	Suitability
			UTME	UTMN	Elvn		
1	Kinde Koiha	Gununo quarry site	347507	761761	2000	<ul style="list-style-type: none"> The observation point is on mountain side, there is no deep well, no shallow wells, no hand dug well, there are springs at mountain foot and the geology is trachytes The area falls on low suitability zone on the draft suitability map matches with low suitability zone 	The specific site and its surrounding is not suitable for deep groundwater
2		Sorto	345500	763114	1694	<ul style="list-style-type: none"> The observation point is in the flat plain nearby Bele town where people are getting water from tap water source from Bele, there is no deep well, no shallow well, no hand dug Trachyte and trachy basalts are major rock unit The area falls on High suitability zone on the draft suitability map. 	The specific site and its surrounding from groundwater occurrence point of view is not suitable for deep groundwater development.
3		Bele town	337339	764780	1237	<ul style="list-style-type: none"> The observation point is on flat land, there is no deep well, no shallow well, but the town gets water from groundwater source from the well drilled at Koisah area in the same plain and the geology is trachytes and trachy basalts as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	The specific site and its surrounding is suitable for deep groundwater
4		Manara	332900	760032	1243	<ul style="list-style-type: none"> The observation point is mountain side, there is no deep well, no shallow well, no hand dug well, no spring and the geology is trachytes and trachy basalts as observed on road cut exposure The area falls on low suitability zone on the draft suitability map 	The specific site and its surrounding is recharge area for aquifer systems in the surrounding plains
5		Gibe #3 camp site	327744	754299	1361	<ul style="list-style-type: none"> The observation point is on mountain side, there no deep well, no shallow wells, no hand dug well, but small spring and the geology is trachytes The area falls on high suitability zone on the draft suitability map. 	The specific site and its surrounding from groundwater occurrence point of view is not suitable for deep groundwater development.
6		Gununo Junction new well	359279	761875	1906	<ul style="list-style-type: none"> The observation point is on flat plain at the foot Mt. Damot, deep well drilling is in progress, 40 m deep well became artesian with an estimated over flow of 5 l/s, shallow wells are also available, no hand dug well, no spring and the geology is trachytes and ignimbrites The area falls on high suitability zone on the draft suitability map. 	The specific site and its surrounding from groundwater occurrence point of view is suitable for deep groundwater development.

4. Conclusions

4.1 Duguna Fango woreda

In the draft suitability map for Duguna Fango woreda, high and medium suitability zones generally fit with prospective groundwater potential zones. However; in relation to geomorphology (slope), some zones indicated as suitable includes a wider areas including undulating and relatively elevated and rugged local morphology variations which do not favor as sites for groundwater. Therefore, the slope criteria need revision to refine slopes and trace wide plains and relatively lower elevation zones by discriminating local highs. Attention should also be given to the water quality problem in relation Fluoride content and greater epth to the groundwater. In order to get drilling sites for climate resilient wells, selection of priority sites is recommended to be done together with regional, zonal woreda and kebele offices without neglecting groundwater potential zones with best suitability.

4.2 Damot Pulasa woreda

In this woreda, the suitability zones identified in the draft suitability map are not fitting the ground conditions. High and medium suitability zones on the suitability map do not fit with this prospective groundwater potential zone. The suitability map and ground truths are completely contradictory since medium to high suitability zones are mapped as low to very low suitability but areas of low suitability are mapped as suitable. Special attention and reevaluation is needed to delineate the best groundwater zones especially in the eastern part of te wored . All the critera need to be revised to include the relatively lower or flat areas as high suitability where these type of areas are the target locations in terms of groundwater occurrence sites. In order to get drilling sites for climate resilient wells, selection of priority sites is recommended to be done together with regional, zonal woreda and kebele offices without neglecting groundwater potential zones with best suitability.

4.3 Boloso Sore woreda

In the draft suitability map for Boloso Sore woreda, suitanility area classified as high and very high suitability zones on the draft suitability map nearly fits with prospective groundwater potential zone for further study. Likewise, low and very low suitability zones fit with low and very low suitability to exclude from further study. The slope classifications need to be revised to discriminate local high grounds and delineate the relatively lower or flat areas as high suitability. These type of areas are the target locations in terms of groundwater occurrence sites. This will allow to consider extensive flat area as high. From the preliminary evaluation of the hydrogeological condition of the Boloso Sore Woreda, with respect to the first draft suitability map, areas that fall within the zones of high and medium suitability that form plain topography sloping down to Woibo River are proposed for further hydrogeological, geophysical and water quality study. However; in relation to geomorphology which is related to recharge and discharge zones, some zones indicated as suitable in the eastern side of the woreda including undulating and relatively elevated and rugged local morphology variations which do not favor as sites for regional groundwater development should be excluded. In order to get drilling sites for climate resilient wells, selection of priority sites is recommended to be done together with regional, zonal woreda and kebele offices without neglecting groundwater potential zones with best suitability.

4.4 Kindo Koisha woreda

In the draft suitability map for Kindo Koisha woreda the evaluation of the draft groundwater suitability map with respect to the actual ground conditions has revealed that poor match has been noted in most cases of the woreda as the groundwater localization is in general controlled by the geomorphologic factor. Sparsely distributed intermountain valleys of small areal extent including mountain tops are mapped as suitable. Different zones are not clearly defined on the draft suitability map. Therefore the suitability map needs to be re-evaluated. Furthermore; the slope classifications need to be revised to discriminate local high grounds and delineate the relatively lower or flat areas as high suitability where these type of areas are the target locations in terms of groundwater occurrence sites. In order to get drilling sites for climate resilient wells, selection of priority sites is recommended to be done together with regional, zonal woreda and kebele offices without neglecting groundwater potential zones with best suitability.

Ground truthing field report – Cluster 8

Groundwater mapping for climate resilience WASH in arid and semi – arid areas of Ethiopia

Report of fieldtrip of November 12 and 13, 2018

Koos Groen, November 21, 2018

Itinerary:

- November 11, 2018, Arrival Jinka, night at Jinka Resort
- November 12, 2018, visit Hammer and Dassanech woredas, villages of Dimeka, Turmi, Omerate and Nakiya, night at Turmi lodge.
- November 13, 2018, visit Nyangatom woreda, villages of Kangaten and Lokorlum, night at Jinka resort.
- November 14, 2018, return to Addis Ababa

Participants:

- Tilahun Azegegn, hydrogeologist GW4E team
- Koos Groen, team leader and hydrogeologist GW4E team
- Jenberu Aberie, hydrogeologist zonal water bureau Jinka, email lifeheavenwater@gmail.com
- Abdela Yimer, hydrogeologist regional water bureau Awassa, email abdyim@yahoo.com, tel 0916158411
- Fasika Tesfaye, WASH officer Nyangatom woreda, tel 0973658931

Hydrogeology of the cluster 8

In terms of geology and landscape Cluster 8 can be divided in two areas: The highlands of the Hamer woreda underlain by crystalline basement rocks mainly consisting of gneiss and amphibolite rocks and the alluvial deposits in the Omo valley west of the Hamer highland. The Hamer highland is a basement block that has experienced uplift and denudation since Tertiary times. Overlying regolith and possibly Mesozoic rocks have been removed (Kebede, 2013). The block is somewhat tilted to the west. All water is drained by numerous wadis into the Omo valley. The crystalline rocks have a low hydraulic conductivity and wells in these rocks are not very productive. Only where sandy regolith is present or alluvial sands in and along the wadis (sand rivers) groundwater can be recovered by boreholes, dug wells and scoop holes. A wide depression in the middle part of the Hammer highland forms the valley of the Keskie river. In the northern part of this valley course alluvial sands have been deposited. Thickness can reach 30 to 40 m. These deposits form a good continuous aquifer provided groundwater level is not too deep. This area stands out as a zone with high groundwater suitability. Boreholes in Hamer are confined to this zone of high groundwater suitability and along wadis, where sand deposits have accumulated and where the basement rocks have been weathered more deeply or are more intensely fractured. The rest of the Hamer highland is characterized as a zone with low groundwater suitability, especially the zones with steep slopes. Spots with higher suitability are related to higher lineament densities. Where sand deposits in and along the sand rivers are thin (few meters) opportunities for construction of sand dams in conjunction with shallow wells. This is a form of managed aquifer recharge. Wells can best be sited by using by vertical electrical soundings (VES) or frequency domain electromagnetic (FDEM) profiling. With VES soundings the thickness of the sand deposits or regolith can be determined at certain locations. Generally the transition from bedrock to the overburden of regolith and alluvial sands, forms a good contrast in electrical resistivity. With FDEM profiling lateral variations in thickness of sand and regolith or fracture zones can be detected along sections. This a fast method and allows several kilometers per day of profiling

The Omo valley west of the Hamer valley (Dasanech and Nyangatom woredas) forms a wide downthrown block filled with alluvial unconsolidated sediments. The Omo river is the second largest river of Ethiopia and receives water from a large catchment extending as far as Ghion in the north. The wadis emerging from the Hamer highland flow into the valley, but lose most of their water before reaching the Omo river. Water infiltrates in the permeable alluvial sediments along the Hamer highland. Near the center of the valley along the Omo River sediments are reported to contain more silt and clay (zonal water bureau), though there are wells drawing water from sand strata. At depths below 80 m groundwater is often brackish according to the zonal water bureau. Occurrence of brackish groundwater is common in the Omo valley as reported in Kebede (2013). Because of the sandy deposits the Omo valley is a zone with high groundwater suitability particularly the zone bordering the Hamer highland. However, the presence of brackish groundwater is a complication, which is not considered in the suitability. VES soundings would be an appropriate technique to explore fresh sand deposits as these can be discriminated from the fine grained and brackish sediments which have a relatively low electrical resistivity.

It can be concluded that the suitability map in cluster 8 gives a reliable insight in the potential for borehole drilling except for the water quality issues (salinity, fluoride). The map displays a pattern of high suitability in the Omo Valley and low suitability in the Hamer highland. This was expected as the hydraulic conductivities of the crystalline basement rocks of the Hamer highland and the alluvial deposits in the Omo valley differ strongly. Moreover, lithology was by far given the highest weight for the overlay analysis (GW4E, Technical report 1, October 2018)

Observations

Shallow well/handpump Aria Kayisa, Hamer highland, woreda Hamer

Shallow well AMREF with handpump in a valley. Water level only a few meters below surface. There is a sand river nearby at 20 m with scoopholes. Depth well probably not more than 30 m. Also nearby an abandoned well with handpump
About 200 m uphill from the well outcrop of gneiss
Location is in high suitability zone

Wells Dimeka, Hamer highland, woreda Hamer. 05°10'47.29" 36°32'22.29"

Borehole Dimeka with submersible pump driven by diesel generator. Water is pumped to reservoir and from there gravity supply to village. Depth 42 m. Pumps only a few hours per day to save fuel.
Also unfinished well by World Vision. Depth 24 m
Also borehole by Catholic Mission. Subm, pump was burned. Used to pump to reservoir. Depth 38 m.
Location is in high suitability zone

Well/handpump Senbele, Hamer highland, woreda Hamer. 05°08'59.83" 36°31'49.33"

Depth unknown. Located in high suitability zone

Concrete rainwater harvesting catchment with reservoir and handpump Dambaite, Hamer highland, woreda Hamer

Along main road from Dimeka to Thurmi, about 2 km north of Dambaite.
Dimensions catchment 25 a 30 m; dimensions reservoir depth 3 m and radius 4 m. Volume reservoir 150 m³. Reservoir was almost empty.
This location is in low suitability zone. Alluvial sand or weathering layer is too thin for boreholes.

Well at Omorate town, Omo valley, woreda Dassanech, 04°47'37.72"N, 36°02'44.49"E

Well with handpump near the town has sand aquifer with thickness of 22 m Experience of water bureau is that sediments near Omo river are more clayey. Further away from river (about 10 km) sediments are sandy. Experience of water bureau is that below 80 m aquifers are brackish. Aquifer is fed by infiltration at foothills of Hamer hills in the east and not by Omo river according to water bureau.

Well with handpump at Nakiya village, woreda Dassanech, 04°43'05.3"N, 36°09'55.9"E

Well with India Mark II handpump. Depth 80 m. Water level at 25 m.

Well with handpump at Lokorlum village, woreda Nyangatom, 05°19'25.27"N, 36°52'25.39"E

Well with handpump. Depth 90 m. Static water level at 57 m. Discharge 20 l/minute. Pump needs repair. There are shallow dugwells in neighbourhood near wadis. Water level in dugwells is more shallow, but wells dry up in dry season. People use water from scoop holes in wadi.

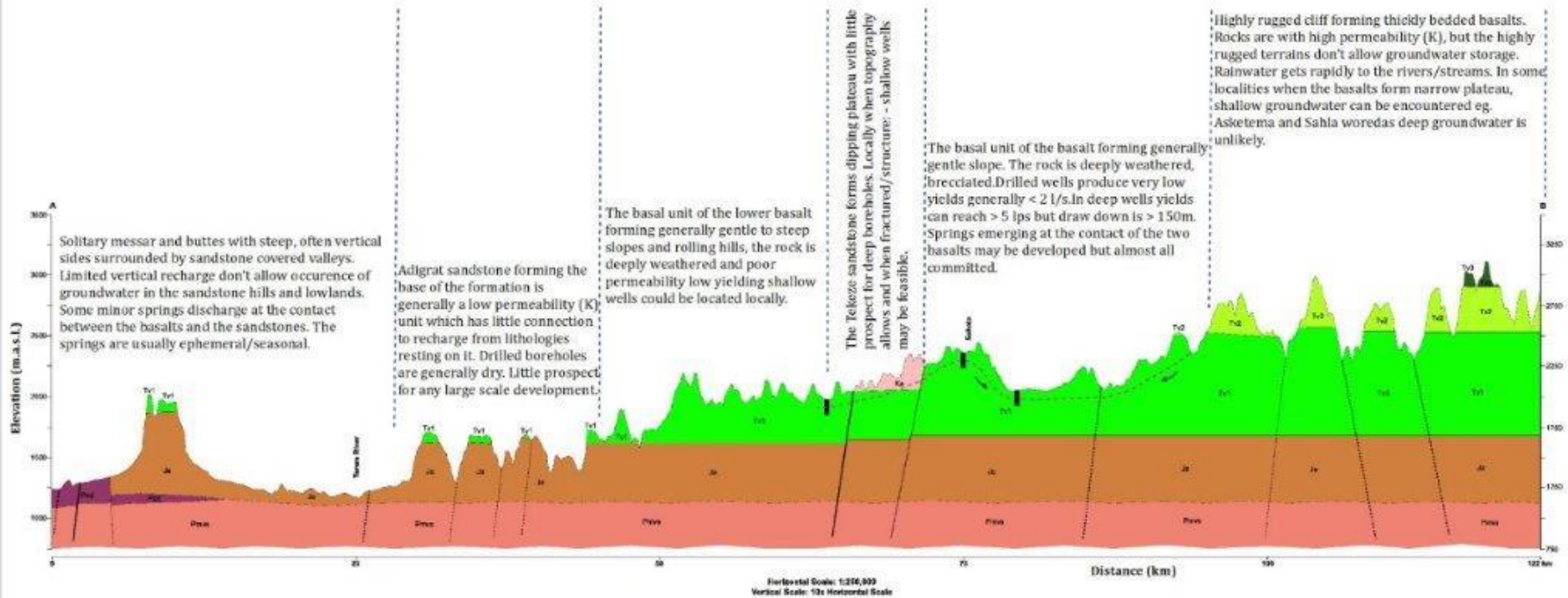
Bank infiltration well Kangaten town, woreda Nyangatom, 05°10'38.11"N, 36°05'27.93"E

Well with submersible pump at 30 m from Omo river. Made by contractor. Depth 24 m. Sand aquifer.

Annex 3

Conceptual models along hydrological sections

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-1 (WAG HIMRA) - SECTION "A - B"



Legend

LITHOSTRATIGRAPHIC UNITS

- Tv3 Upper Basalt
- Tv2 Middle Basalt
- Tv1 Lower Basalt
- Ha Ambaradam Sandstone
- Ja Lower (Adigrat) Sandstone
- Pzd Edaga Arbi Glaciols
- Pmvs Tsaliel Metavolcanics

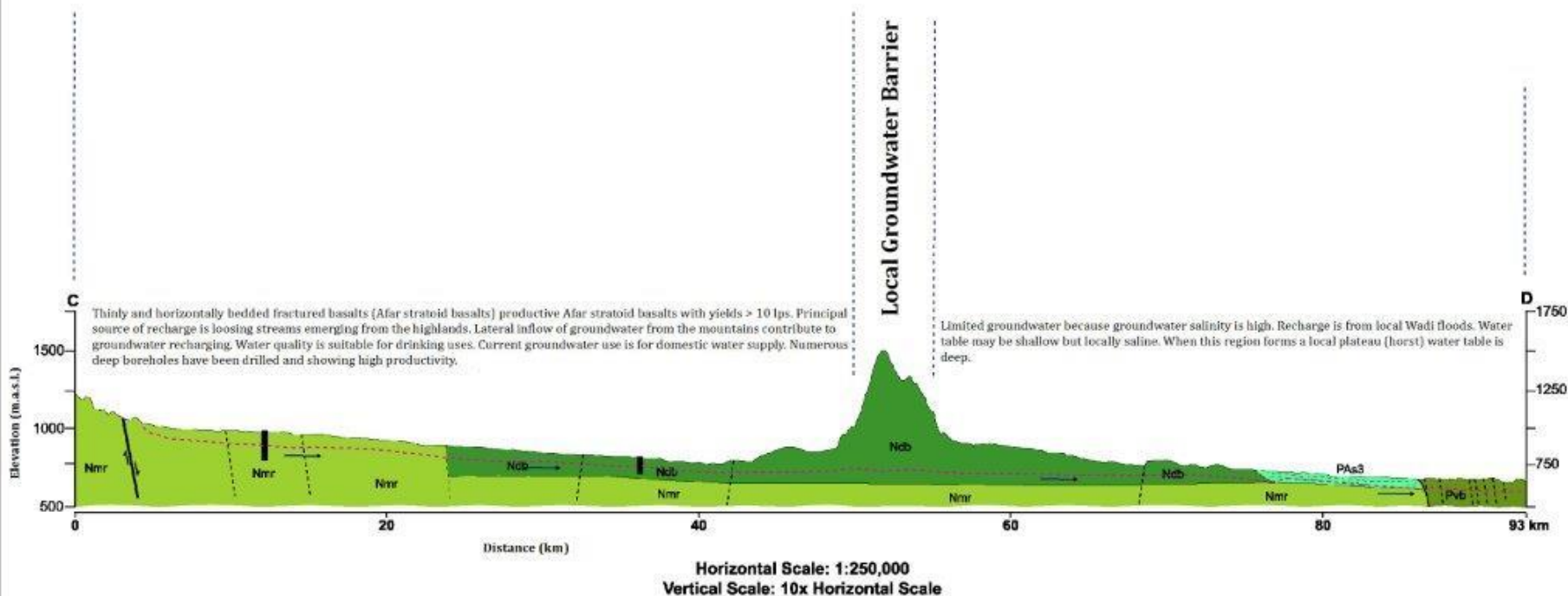
GEOLOGICAL STRUCTURES

- Normal Fault
- Lineament

OTHER SYMBOLS

- Borehole
- Inferred Water Level
- Groundwater Flow Direction

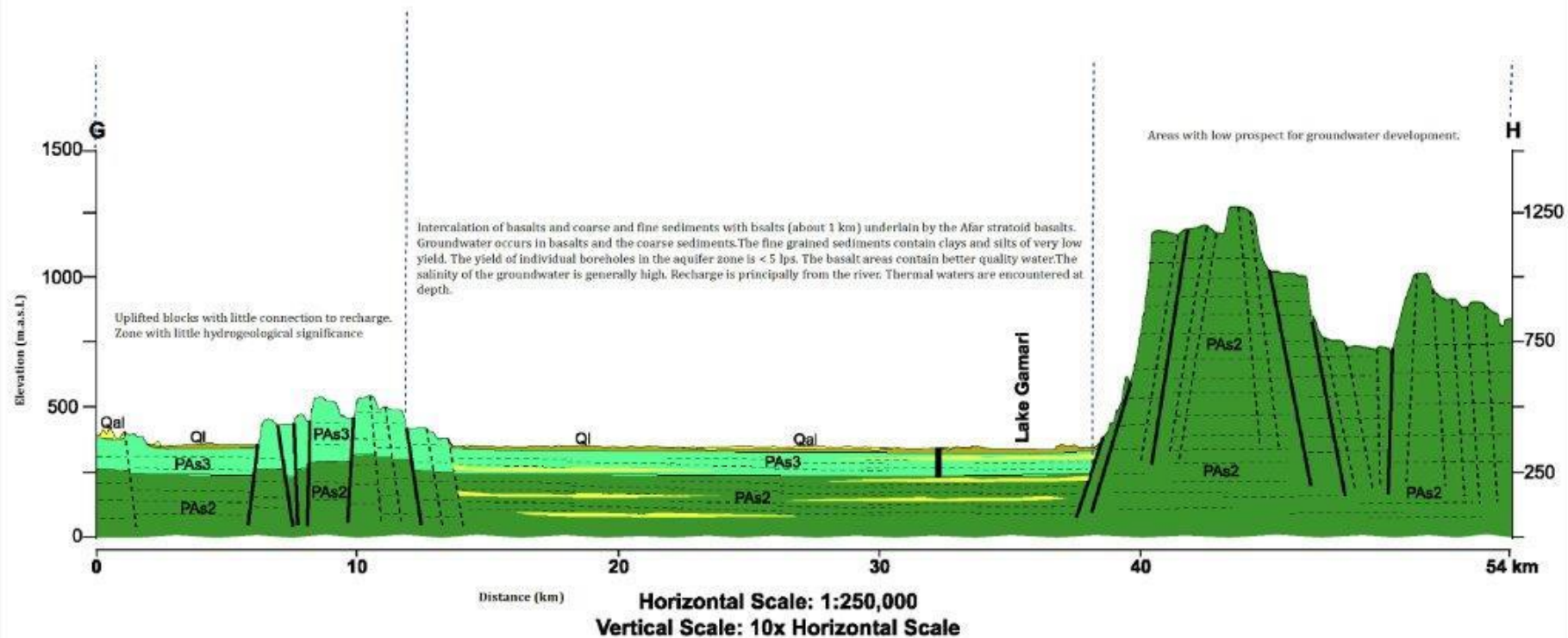
HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-2 (AFAR) - SECTION "C - D"



Legend

LITHOSTRATIGRAPHIC UNITS	GEOLOGICAL STRUCTURES
 Qal Alluvial Sediments	Thrust Fault
 Pvb Basaltic Fissure Flows	Lineament
 PAs3 Upper Afar Stratoid Series	OTHER SYMBOLS
 Nrb Dahla Basalt	Borehole
 Nmr Mabla Rhyolite	Inferred Water Level
	Groundwater Flow Direction

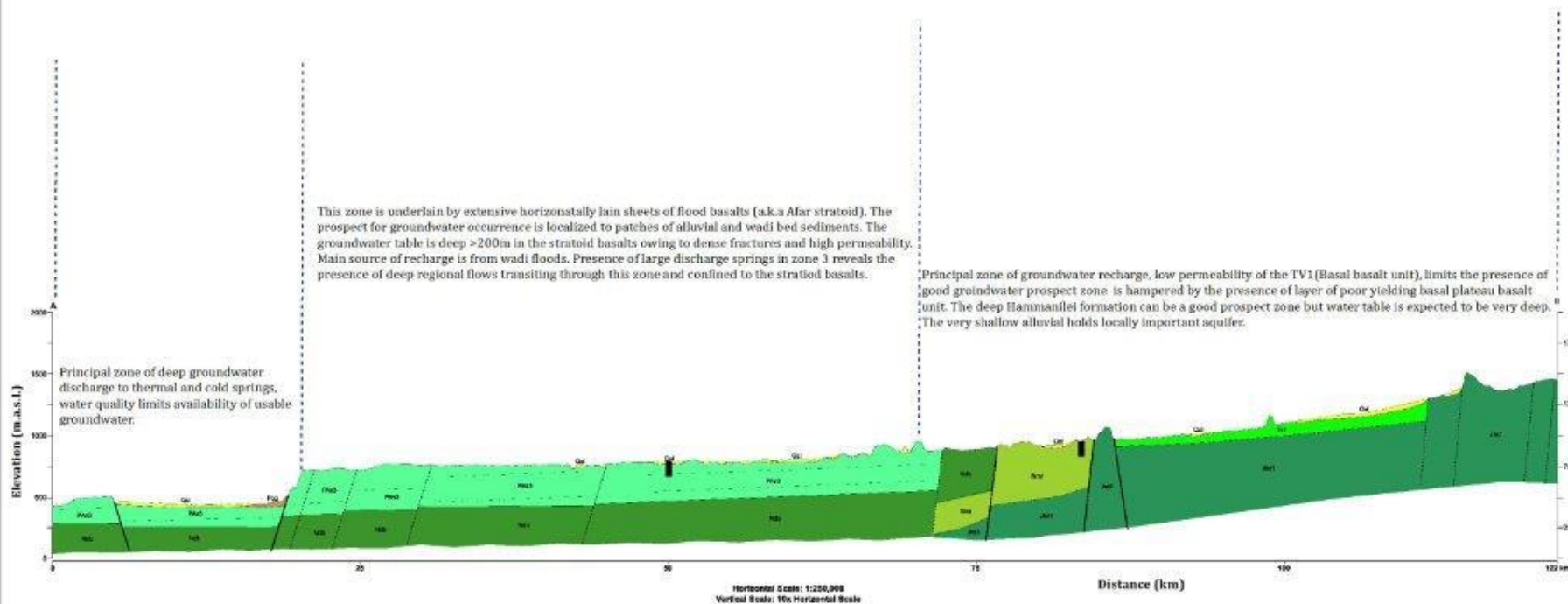
HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-2 (AFAR) - SECTION "G - H"



Legend

LITHOSTRATIGRAPHIC UNITS	GEOLOGICAL STRUCTURES														
<table border="0" style="width: 100%;"> <tr> <td style="width: 20px; background-color: yellow; border: 1px solid black;"></td> <td>Qal Alluvial Sediments</td> </tr> <tr> <td style="width: 20px; background-color: olive; border: 1px solid black;"></td> <td>Ql Lacustrine Deposit</td> </tr> <tr> <td style="width: 20px; background-color: lightblue; border: 1px solid black;"></td> <td>PAs3 Upper Afar Stratoid Series</td> </tr> <tr> <td style="width: 20px; background-color: green; border: 1px solid black;"></td> <td>PAs2 Lower Afar Stratoid Series</td> </tr> </table>		Qal Alluvial Sediments		Ql Lacustrine Deposit		PAs3 Upper Afar Stratoid Series		PAs2 Lower Afar Stratoid Series	<table border="0" style="width: 100%;"> <tr> <td style="width: 20px; border-bottom: 1px solid black;"></td> <td>Normal Fault</td> </tr> <tr> <td style="width: 20px; border-bottom: 1px dashed black;"></td> <td>Lineament</td> </tr> </table> <p>OTHER SYMBOLS</p> <table border="0" style="width: 100%;"> <tr> <td style="width: 20px; border: 1px solid black; height: 10px;"></td> <td>Borehole</td> </tr> </table>		Normal Fault		Lineament		Borehole
	Qal Alluvial Sediments														
	Ql Lacustrine Deposit														
	PAs3 Upper Afar Stratoid Series														
	PAs2 Lower Afar Stratoid Series														
	Normal Fault														
	Lineament														
	Borehole														

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-3 (SITI) - SECTION "A - B"



Horizontal Scale: 1:250,000
Vertical Scale: 10x Horizontal Scale

Legend

LITHOSTRATIGRAPHIC UNITS

- Qal Alluvial Sediments
- Pcg Continental conglomerates & deposits of sheet flood terraces
- PAs3 Upper Afar Stratoid Series
- Hdb Dahla Basalt
- Nmr Mabla Rhyolite
- Tv1 Lower Basalt
- Hm1 Hammanlei Limestone Formation

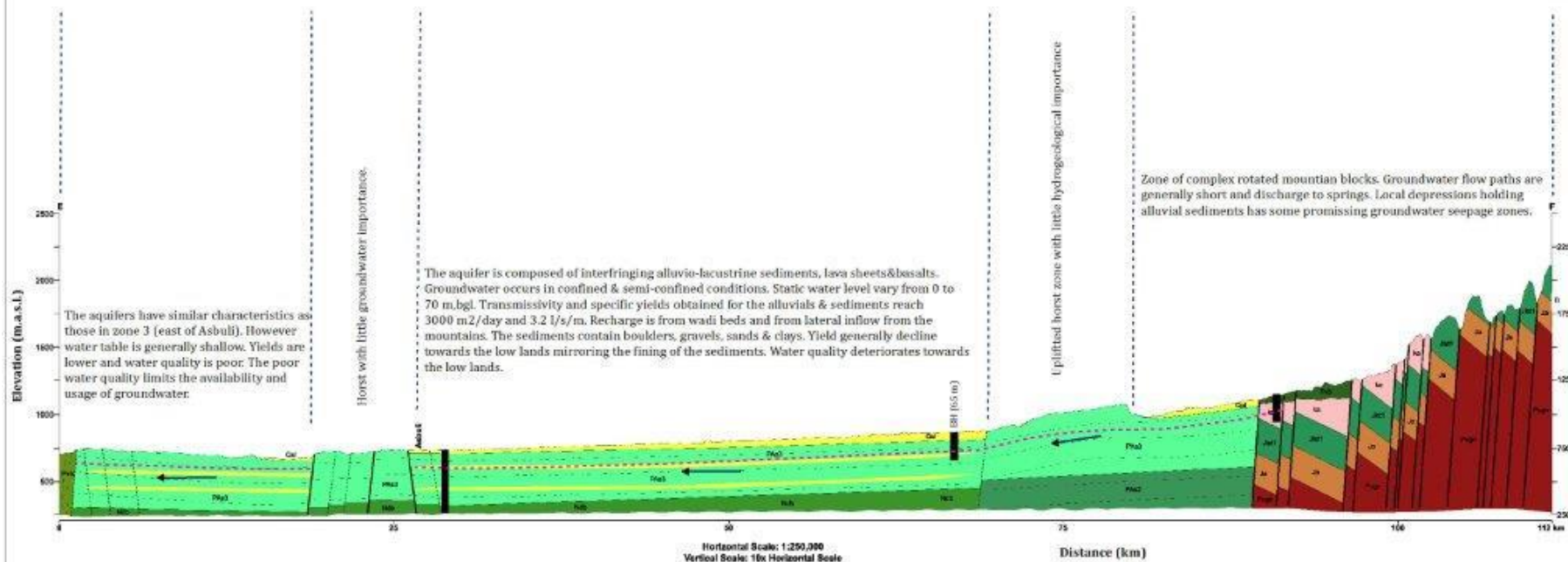
GEOLOGICAL STRUCTURES

- Normal Fault
- Lineament

OTHER SYMBOLS

- Borehole

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-3 (SITI) - SECTION "E - F"



Legend

LITHOSTRATIGRAPHIC UNITS

- Qal Alluvial Sediments
- Pvb Basaltic fissure flows
- FA3 Upper Afar Stratoid Series
- FA2 Lower Afar Stratoid Series
- Nb0 Dahla Basalt
- TV3 Upper Basalt
- Ka Upper (Amharadam) Sandstone
- Jm1 Hammanlei Limestone Formation
- Jm Lower (Adigrat) Sandstone
- Pugn High grade granitic gneisses & migmatites

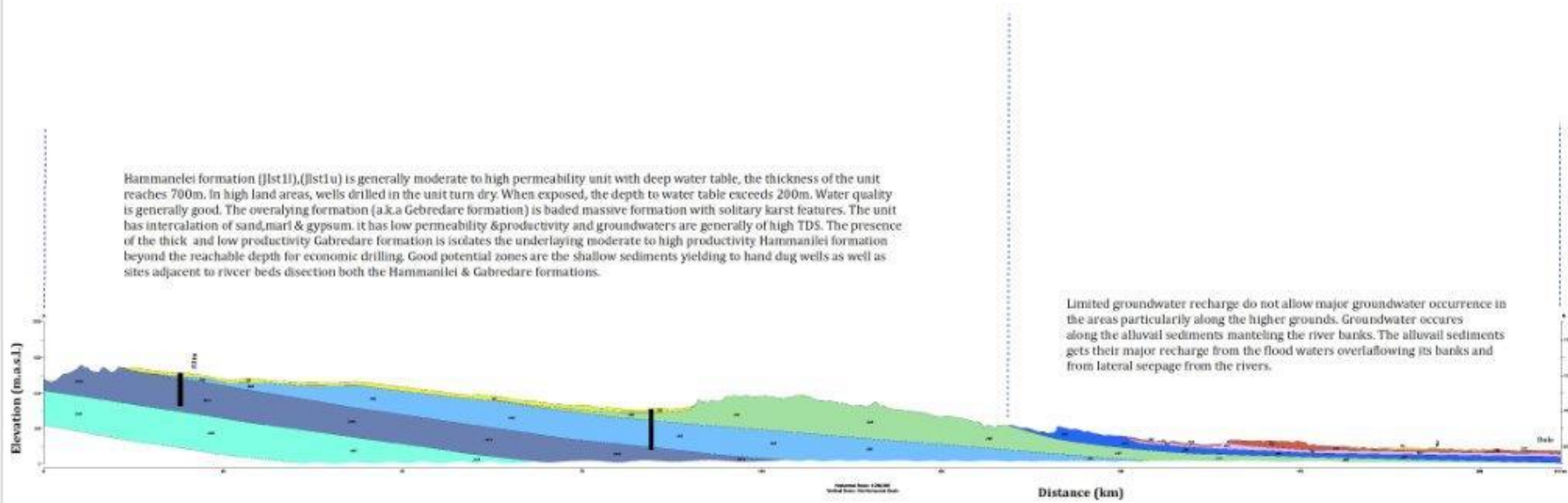
GEOLOGICAL STRUCTURES

- Normal Fault
- Lineament

OTHER SYMBOLS

- Borehole
- Inferred Water Table
- Groundwater Flow Direction

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-4 (LIBEN) - SECTION "A - B"



Legend

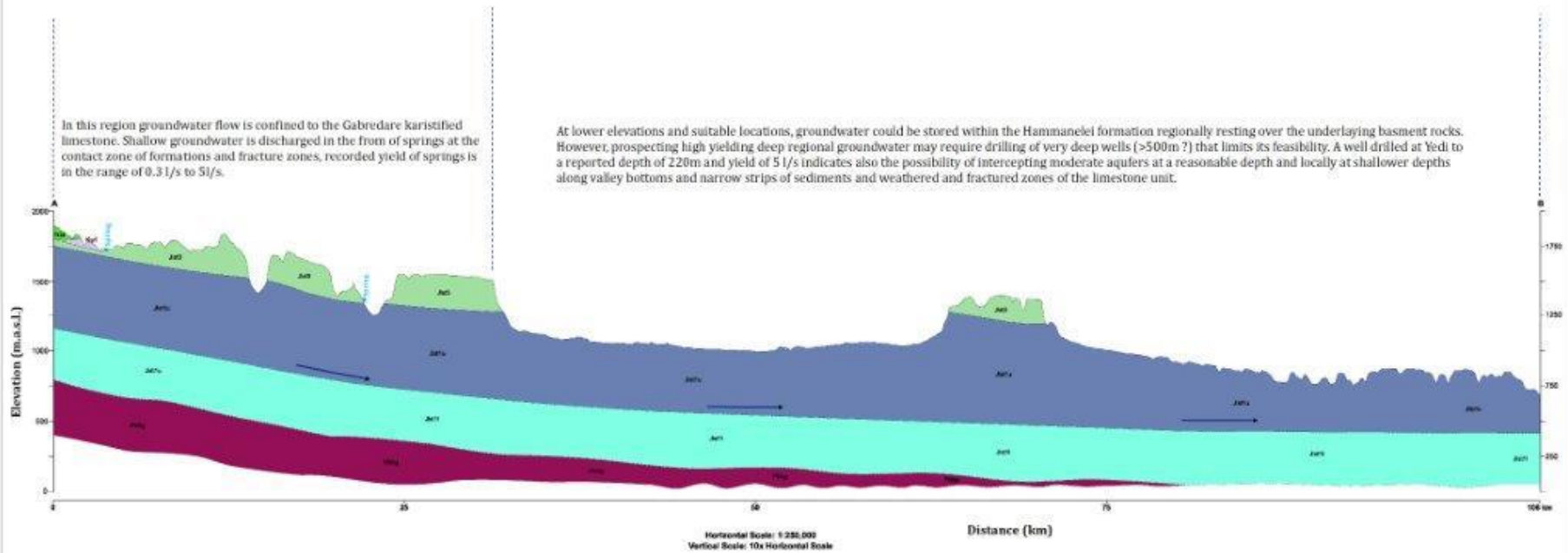
LITHOSTRATIGRAPHIC UNITS

- Qal Alluvial Sediments
- Qcf Calcrete with subordinate ferricrete
- QeIs Elluvial deposit over the sedimentary bedrock
- Ka2 Limestone-Shale intercalations
- Ka1 Sandstone fine to medium grained
- Jst4 Limestone member 4: Light grey, calcilitic limestone
- Jst3 Limestone member 3: intercalation of oolitic and fossiliferous limestone
- Jst2 Limestone member 2: bedded, light grey, sandy limestone
- Jst1u Upper Hamanneli Limestone
- Jst1l Lower Hamanneli Limestone

OTHER SYMBOLS

- Borehole

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-5 (BALE) - SECTION "A - B"



Legend

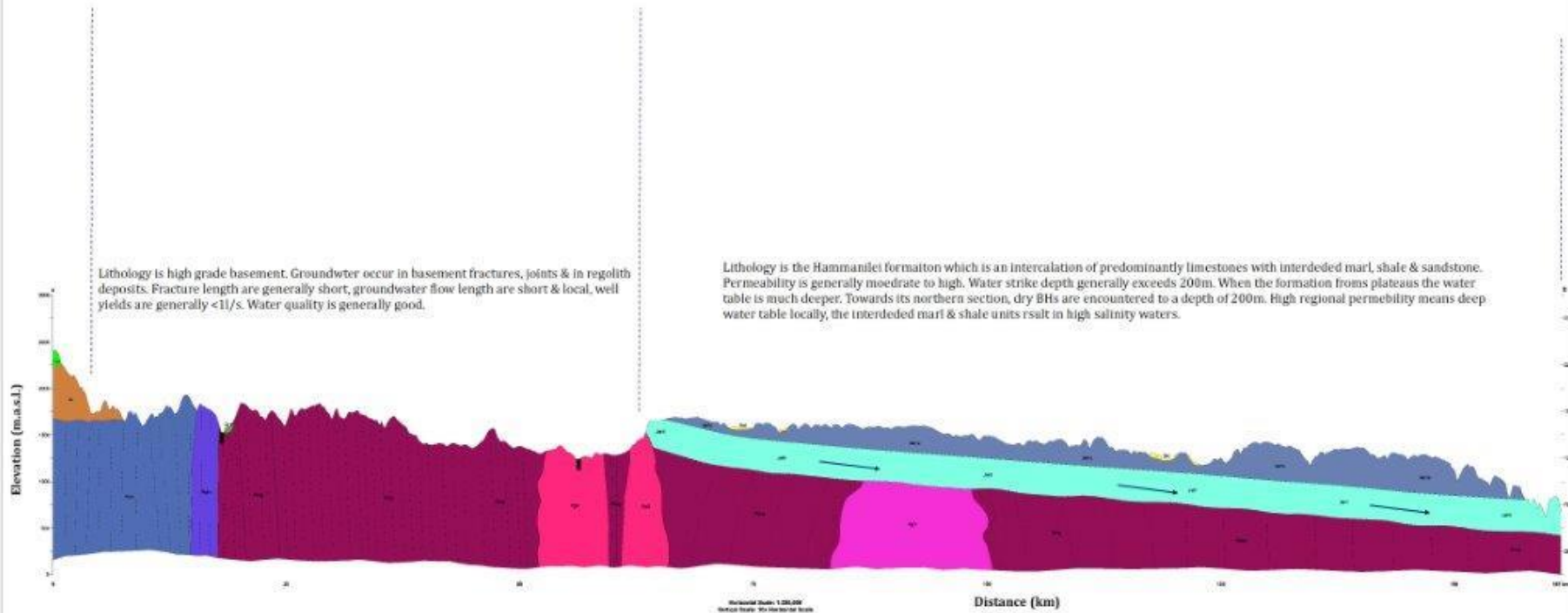
LITHOSTRATIGRAPHIC UNITS

- Jhb1 Inerlayered massive basalt flows, alkali trachyte and basalt flows
- Ka1 Sandstone fine to medium grained
- Jla12 Limestone member 3: intercalation of oolitic and fossiliferous limestone
- Jb11u Upper Hamannell Limestone
- Mb1 Banded and folded biotite-hornblend and biotite gneiss

OTHER SYMBOLS

- Spring
- Groundwater Flow Direction

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-5 (BALE) - SECTION "C - D"



Legend

LITHOSTRATIGRAPHIC UNITS

- Gal Alluvial Sediments
- Qv1 Dark grey to black, vesicular scoriaceous basalt
- Tv1 Lower Basalt
- Jattu Upper Hamanneli Limestone
- Jattu Lower Hamanneli Limestone
- Ja Lower sandstone with lesser basal conglomerate
- Pgt9 Post-tectonic granite
- Pgt1 Synt-tectonic foliated biotite granite
- Pqtm Quartzofeldspathic mylonite
- Pqtm Biotite-plagioclase-K-feldspar-quartz mylonite
- Pqtm Banded and folded biotite-hornblend and biotite gneiss

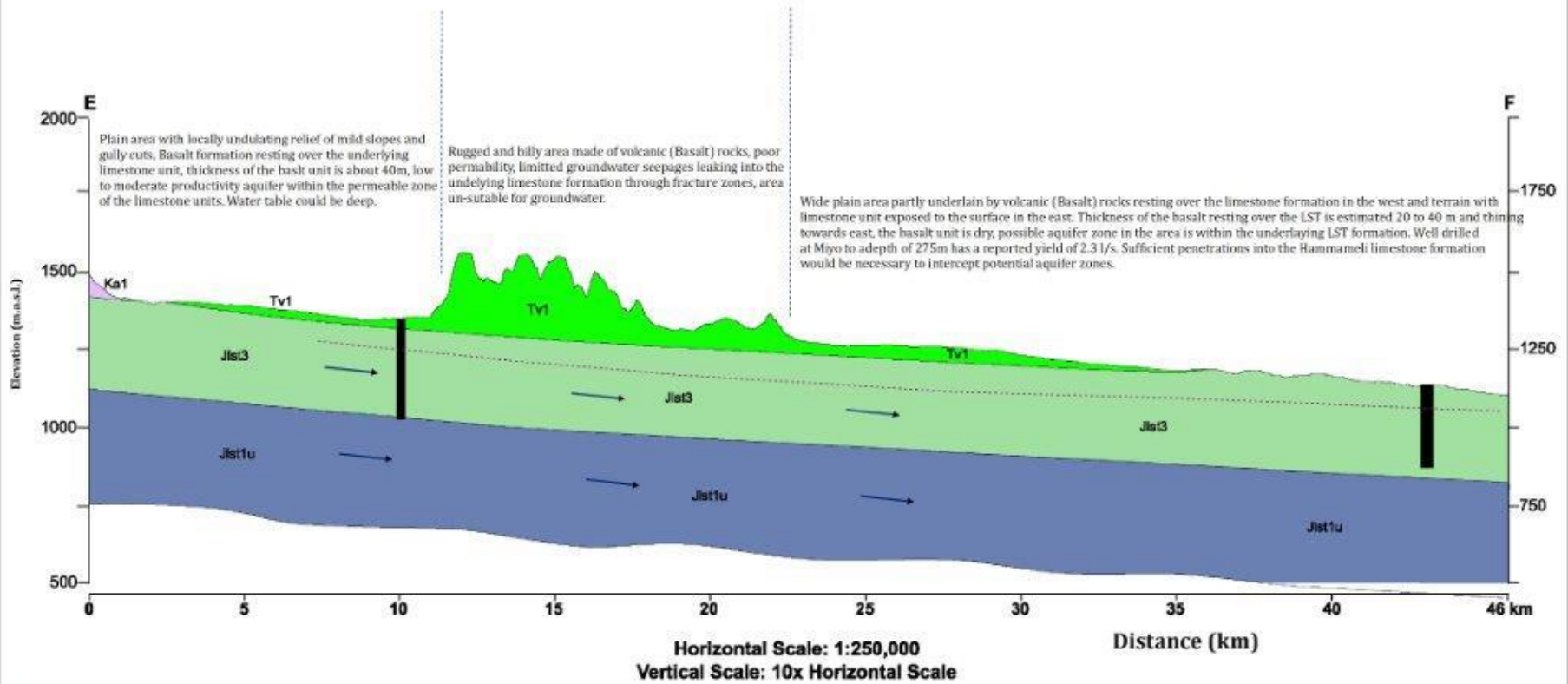
GEOLOGICAL STRUCTURES

- Lineament

OTHER SYMBOLS

- Shallow well
- Groundwater Flow Direction

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-5 (BALE) - SECTION "E - F"



Legend

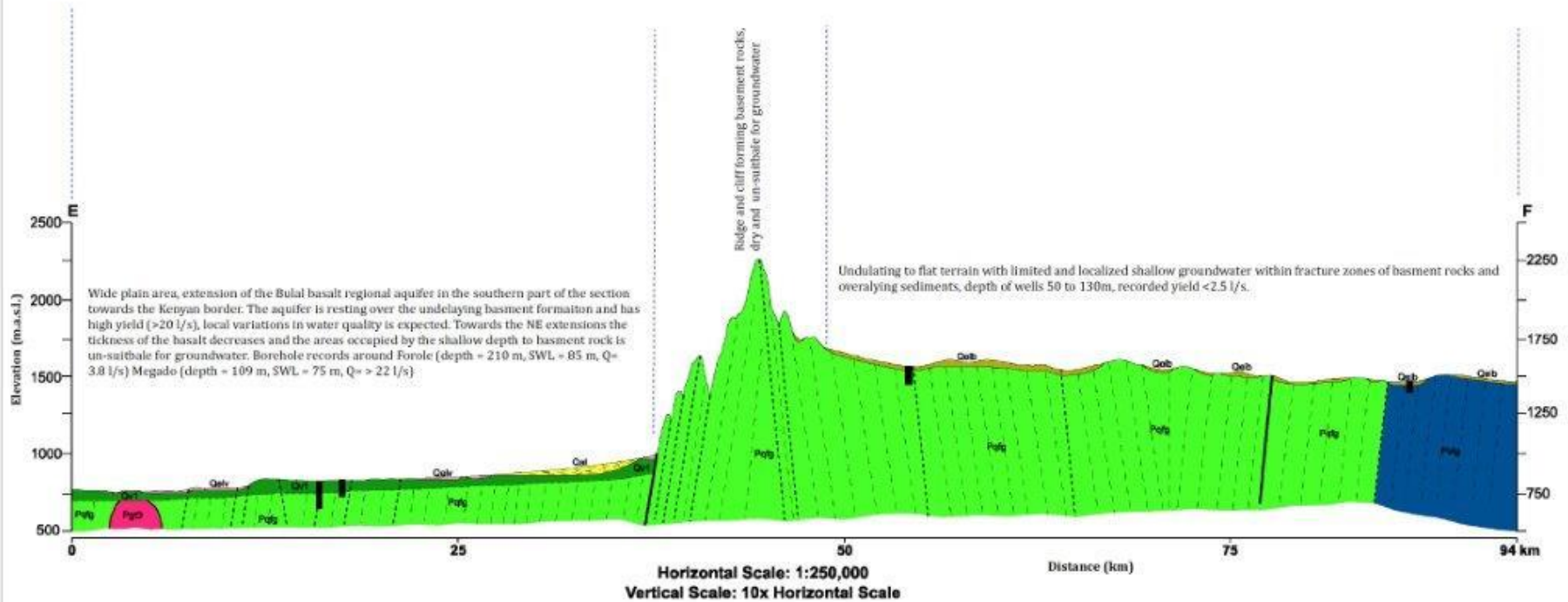
LITHOSTRATIGRAPHIC UNITS

- Tv1 Lower Basalt
- Ka1 Sandstone fine to medium grained
- Jla3 Limestone member 3: intercalation of oolitic and fossiliferous limestone
- Jst1u Upper Hamannell Limestone

OTHER SYMBOLS

- Borehole
- Inferred Groundwater Level
- Groundwater Flow Direction

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-6 (BORENA) - SECTION "E - F"



Legend

LITHOSTRATIGRAPHIC UNITS

- Qal Alluvial Sediments
- Qelv Eluvial deposit over volcanic bedrock
- Qelb Eluvial deposit over the metamorphic basement bedrock
- Qv1 Dark grey to black, vesicular scoraceous basalt
- Pgtb Post-tectonic granite
- Pqtg Quartzofeldspathic gneiss
- Pvg Augen granitic gneiss & biotite bearing quartzofeldspathic gneiss

GEOLOGICAL STRUCTURES

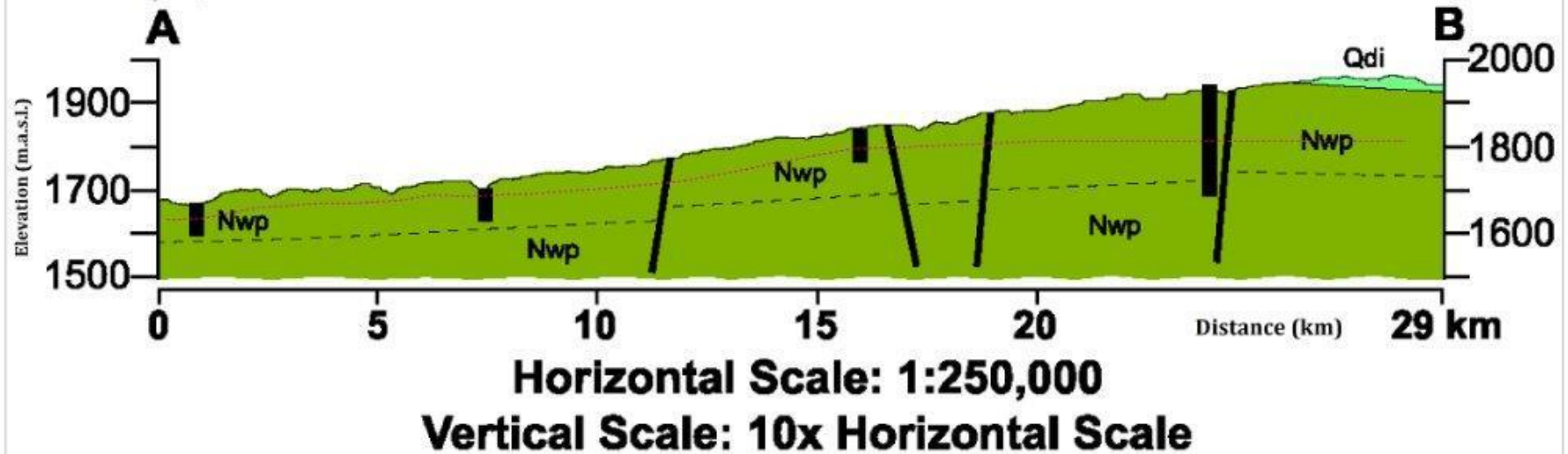
- Normal Fault
- Lineament

OTHER SYMBOLS

- Borehole

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-7(WOLAYTA) - SECTION "A - B"

Lithology is mainly composed of tuff, ignimbrites, Rhyolites and minor basalts of the Nazreth group. Tuffs are predominant. Groundwater occurs in fracture ignimbrites in the minor basalt intercalations. Individual well yields are less than 3 l/s in general. But locally yields can reach 8 l/s when fracture zones in ignimbrites are encountered. Best sites could be the basalt layer underlying the Nazreth series rocks. Thickness of the Nazreth series reaches up to 300m. The rocks underlying the Nazreth series could be a good target for deep borehole sitting. In the Nazreth series, shallow Boreholes are common, SWL varies from 14 to 69m. Well depth vary from 30 to 200m. Groundwater occurs in semi-confined conditions.



LITHOSTRATIGRAPHIC UNITS

- Qdi Ignimbrites, tuffs, water-lain pyroclastics, occasional lacustrine beds
- Nwp Nazreth Group: alkaline and peralkaline rhyolitic flows intercalated with lapilli tuffs

Legend

GEOLOGICAL STRUCTURES

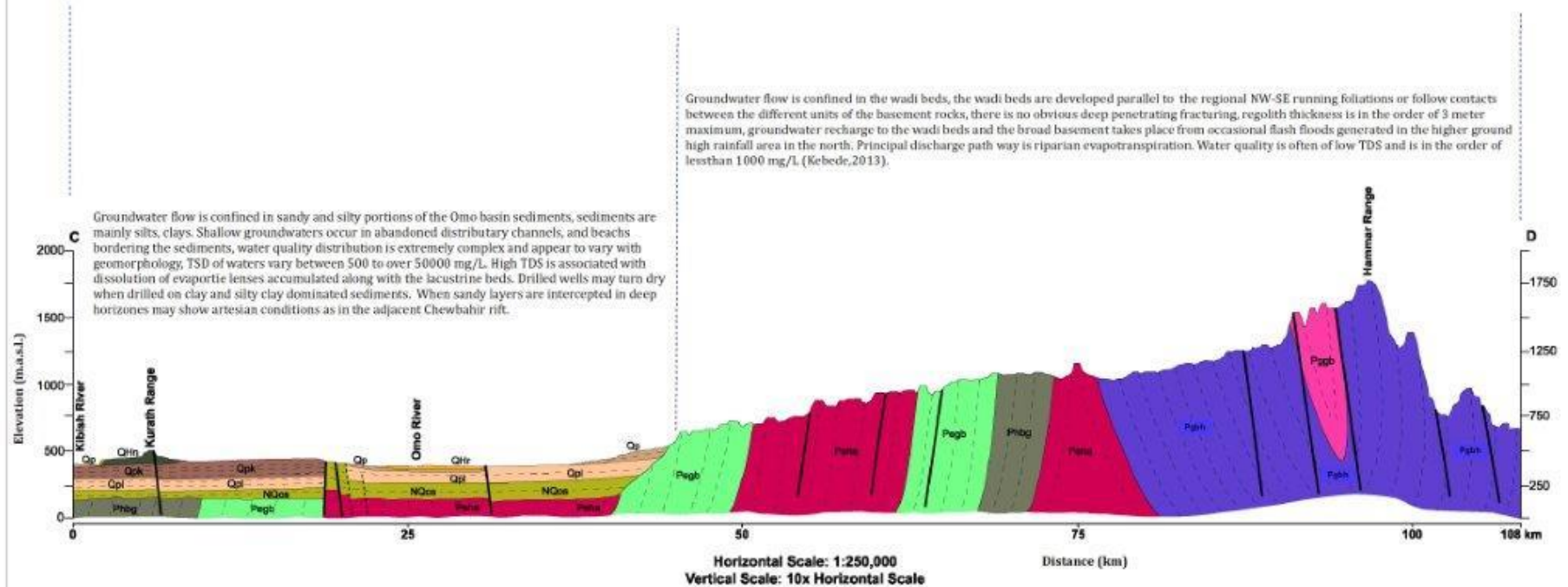
— Normal Fault

OTHER SYMBOLS

■ Borehole

- - - Static Water Level

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CLUSTER-8 (SOUTH OMO) - SECTION "C - D"



LITHOSTRATIGRAPHIC UNITS

- Qhr Fluvatile sand, silt
- Qhk Nakwa Formation
- Qp Undifferentiated alluvial, fluvatile and lacustrine sediments
- Qpk Kibish Formation
- Qpl Lacustrine silt, clay
- NQos Shungura Formation
- Pgbg Undivided gniess
- Pgh Granulite facies equivalent of the undivided gniess
- Pgg Metasedimentary gniess
- Pgh Granulite facies metasedimentary gniess
- Pgh Layered mafic gniess and amphibolite

Legend

GEOLOGICAL STRUCTURES

- Normal Fault
- Lineament

Annex 4

Technical report 1 GW4 WASH Ethiopia

Annex 5

Technical report 2 GW4 WASH Ethiopia

Annex 6

Technical report 3 Classes and scores

Annex 7

Harmonized geological maps of EU RESET II clusters

Annex 8

Groundwater suitability maps of EU RESET II clusters

Annex 9

Socio-economy maps of the EU RESET II clusters

Annex 10

Water demand maps of the EU RESET II clusters

Annex 11
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