GROUNDWATER MAPPING 4 climate resilient WASH

May 29, 2020

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

Identifying the groundwater potential of 8 clusters

Project Summary Report RFP-S&L-2017-9137055




RESET · unicef for every child · Ministry of Water, Irrigation and Energy · ACACIA WATER · aquacon ENGINEERING PLC

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Executive summary

Acacia Water in collaboration with a local pool of experts has been tasked by UNICEF Ethiopia to conduct a groundwater mapping study (GW4E) to identify groundwater suitable locations for drilling 16 boreholes* in 8 clusters of the RESET II program. The goals of the project are to increase chances of finding enough and safe groundwater for fragile communities and ultimately improve livelihoods and fight poverty.

The RESET program areas encompass 41 water scarce woredas known to have complex hydrogeology. These woredas are grouped into 8 clusters spread over 5 regions. 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 drilling success rates in recent past. In addition, the widely dispersed communities and pastoral or semi pastoral livelihoods further complicated high WASH coverage and access in these areas.

The project team have improved and employed an integrated approach for groundwater survey to achieve the objectives of the project, based on an approach previously developed and tested by UNICEF. The method includes but was not limited to conventional and harmonized geological & hydrogeological mapping, geomorphological characterization, weighted overlay analyses, Remote Sensing and GIS application, geophysical surveys, hydrological application for recharge estimation, geochemistry and isotope hydrology application, statistical approaches for validation of overlay analysis and data integration through conceptual model development.

*During Phase 2 of the project, the number of boreholes has been increased from 16 to 20.

Colophon

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1 Introduction

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 deep 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/EU RESET II program contracted Acacia Water and a local team of experts to conduct a groundwater mapping study aiming at identifying drilling target sites for 16 boreholes in eight clusters of the RESET II program. The project is carried out in cooperation with the Ethiopian Ministry of Water, Irrigation and Energy.

By using a multi-layer analyses 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. Allocation of drilling sites is also supported by stakeholder's consultation and proximity to the community clusters.

This Project Summary Report presents an overview of the results achieved through the period of approximately 18 months (June 2018 – March 2020) and the deliverables produced by the team, in a nutshell.

In this report, we summarize all results obtained and already in more detail reported at the end of Inception Phase, Phase 1 and Phase 2. As for a good understanding and to keep this report a summary as intended, only few maps are provided as examples. The complete set of materials - final reports from all project phases, the geological and hydrogeological maps (1:50.000), the woredas groundwater suitability maps, the drilling maps (1:10.000), water demand and socio-economic maps, methodology training material, etc., are shared through the public accessible dissemination on-line platform.

To access the full data set, follow this link: http://gw4e.acaciadata.com/

1.1 Objectives and methods

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 improved methods that drilling success rates will be enhanced.

The following specific objectives were 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.

Methods

The approach and methods were developed and adjusted according to reality faced. Both logistics aspects such as access to the area and safety issues, as well as data availability, demographic density and geological characteristics have brought challenges to carrying out a standard methodology for all clusters and have therefore required for adjustments. Thus, methodology was slightly adapted for the different sites, as needed.

The methodology includes, but was not limited to geological and geomorphological characterization, hydrogeological surveying, Remote Sensing and GIS application, geophysical surveys, 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 project has been designed in 3 phases:

- Inception Phase (concluded in July 2018)
- Phase 1 (concluded in December 2018)
- Phase 2 (concluded at the end of 2019)

Figure 1 gives an overview of the steps followed such as to achieve the project goals.

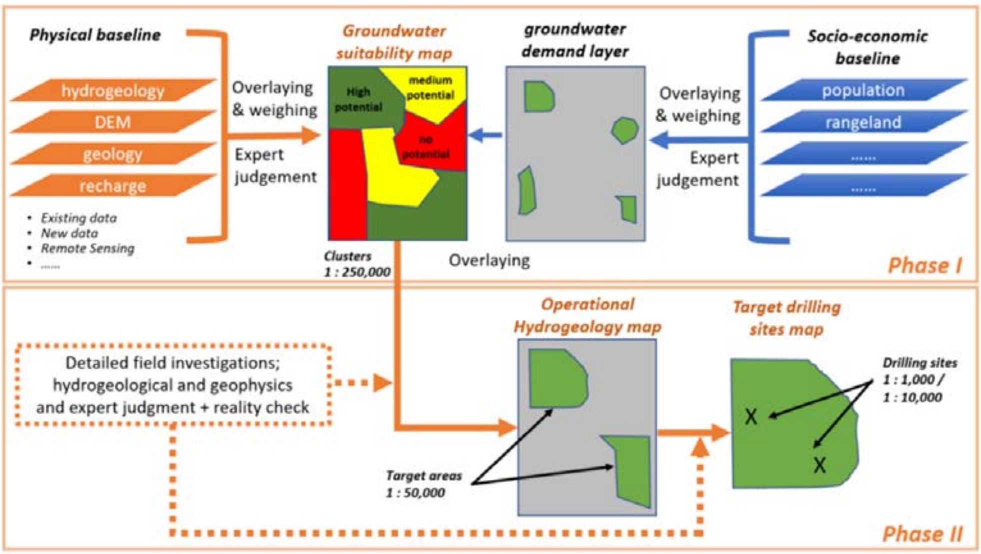

Figure 1. The project phases and its main deliverables.

1.2 Project phases and deliverables

During the Inception Phase work has been done to further develop and detail the proposed methodology and work plan. Our approach 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.

All these methods are going to be integrated and deployed according to the necessity and specific characteristics of each woredas. The methodology for Phases 1 and 2 has been further discussed and developed during the Inception Phase, among the project team and also with UNICEF. Nevertheless, adjustments might be needed in the course of the project implementation.

Several outputs are foreseen from the project activities. Some of them are diverging from the ToR, since some steps of the methodology have been adjusted and further developed. In Figure 2 the general project steps are presented. Some modification was necessary along the way to adjust to the project reality.

• Mobilization of teams, contract and logistics arrangements • Data collection and review • Data acquisition process (with EU-JRC) • Hydrogeological conceptual model of clusters • Data gaps identification • Inception report writing and review • Inception workshop	**Inception Phase (1 month)**
• Remote sensing (RS) data acquisition and preparation with EU-JRC • RS data processing and preparation input layers for overlay analysis • Familiarization filed visit to the cluster areas • Water points inventory and Water quality survey • Setting overlay analysis criteria & weighing criteria • Harmonized geological maps (1:50,000) • Peer review meeting • Water balance studies and recharge estimations per clusters • Overlay analysis, field work data integration and interpretation • Preparation Groundwater Suitability maps (woreda level) • Ground truthing and validation of the Groundwater Suitability maps • Dissemination workshop	**Phase 1 (6 months)**
• Phase 1 report writing and submission	
• RS image acquisition and processing for target areas (with JRC) • Reality check with regional stakeholders • Selection of target areas • Detailed hydrogeological (field) survey at the selected target areas • Isotope sampling & analyses of target areas • Hydrogeologic operational maps (1:50,000) • Detailed geophysical (field) survey • Geophysical data processing, analyses and integration • Analyses and selection of the 16 target sites for drilling • Validation of selected target sites • Preparation target drilling sites maps (1:1,000 / 1:10,000) • Dissemination workshop	**Phase 2 (12 months)**
• Phase 2 report writing and submission	

Figure 2. Project steps following the methodology, designed by the Acacia Water team

1.3 Organization

The first weeks were used to get the team in place and integrate the working program. All partner's roles have been refined and consolidated during the Inception Phase:

1.3.1 Acacia Water bv

Acacia Water is leading the partnership in deploying international experience in groundwater investigation and mapping through the use of remote sensing, data management modelling, and in the application of a range of geophysical methods. This role shall enable the identification of the groundwater potential and propose locations for implementing wells based on a strong technical methodology. Acacia is responsible for the project management (content and financial), reporting and the formal communication with the client.

Two local independent professionals are hired to coordinate the work at national level: Dr. Seifu Kebede and Mr. Abebe Ketema.

1.3.2 Aquacon Engineering plc

Aquacon is providing local support on hydrogeological assessments, groundwater mapping, water resources assessment and monitoring, geophysical measurements, and plays a role in the later phases of development and monitoring.

The professionals engaged in this project are also engaged in collecting the large amount of data and information necessary for carrying out the technical assessment.

Furthermore, Aquacon is providing logistical support for the team in organizing field work, and provides local expertise on hydrogeology, geology, geomorphology and geophysics.

1.3.3 Engaged professionals

The following personnel have been engaged in the project activities as the 'core-team' (Table 1).

Table 1. Overview personnel engaged in the GW4E project (core-team)

Name	Position	Tasks
Dr. Arjen de Vries	Project manager	project management (organizational and financial) and contacts with UNICEF, the Peer Review Committee, EU-JRC and other stakeholders
Dr. Jacobus Groen	Resident international project leader and Senior hydrogeologist / hydrogeochemistry	Senior international expert for geology, hydrogeology, hydro-geochemistry geophysics. International consultant for the training and manpower development.
Dr. Seifu Kebede	Senior Hydrogeologist and national team leader	Data integration and conceptual model development, methodology design, guiding field data acquisition and water point inventory works. Water quality and isotope hydrology survey supervision and integration in the hydrogeological models.
Mr Abebe Ketema	Senior Hydrogeologist and	Senior hydrogeology expert: data integration, methodology design and

Name	Position	Tasks
	National Project Manager	guiding field data acquisition by all experts, guiding water point inventor works, designing and validation of GIS overlay analysis, Geophysics data integration into the overlay analysis and in phase II reports, project management
Mr. Theo Kleinendorst	Senior remote sensing and GIS expert	Guide the team in remote sensing and satellite image processing and the validation of the weighting criteria for the GIS overlay analyses, Building data sharing webtool and capacity building of local professionals.
Dr. Asfawossen Asrat	Geologist	Harmonization of geological maps, production of geological cross sections, production of geological maps at all the scales, and quality control of geology maps that shall be used in the various analyses in this work.
Mrs. Daniela Benedicto van Dalen	Project management and hydrogeologist	Assist in project management tasks such as producing deliverables, help the team meeting deadlines, organizing meetings, keep track of changes in the proposed methodology, etc.
Dr Tilahun Azagegn	Project Hydrogeologist	Field hydrogeology mapping, advisory service on drilling related matters
Mr. Asaminew Gebeyehu	GIS expert	Map production
Dr Shimelis Feseha	Senior Geophysicist	Geophysics data collection, integration and interpretation
Mrs. Marie Hurlimann	Water governance expert	Stakeholder mapping, capacity assessment and guidance of the dissemination of the project's results to the local authorities and non-governmental organizations.
Mrs. Anouk Gevaert	Remote sensing and GIS specialist	Preparation and analysis of the remote sensing data for the overlay analysis in the Phase 1 of the project. In addition, help prepare and co-taught the capacity building workshop held in August 2019.

Additional specific support has been provided by:
Dr Gadissa Deyasa: Field water data collection for isotope and chemical tests
Dr Tesfamichael: WETSPSS recharge estimation

The GW4E project carried out several activities in the field, which started immediately after the Inception workshop. Several other professionals were engaged from this point on, and were organized in crews for the job, associated to each specific cluster. In Table 2 one can find the crew organized for the job, associated to each specific cluster.

Table 2. Overview personnel to be engaged on Phase 1 and 2 in the field work activities

Name	Profession	Assignment region	Cluster nr.
Dr Gadissa Deyasa	Hydrogeologist	Amhara	1
Addis Hailu	Hydrogeologist	Amhara	1
Addis Hailu	Hydrogeologist	Amhara	1
Hailemichael Kebede	Hydrogeologist	Oromiya	5
Nafyad Serre	Geologist	Somali	4
Tadesse Bersisa	Hydrogeologist	Oromiya	6
Ahmed Tahir	Hydrogeologist	Somali	3
Takele Workiye	Geologist	Afar	2
Yosef Lamore	Hydrogeologist	SNNPR	7&8

1.4 Geographic location

The project areas encompass 41 water scarce woredas known to have complex hydrogeology manifested by low and indirect recharge, rugged topography, too low yielding shallow groundwaters, high salinity groundwaters, etc. The widely dispersed communities and pastoral or semi pastoral livelihoods further complicated high WASH coverage and access in these areas.

In total, 39 woredas are prioritized and grouped in 8 clusters spread over 5 regions. In each of the 8 clusters, 2 target sites were selected for in-depth assessment and identification of 16 drilling sites. Due to the limited groundwater potential in clusters 1 and 8, it has been decided upon augmenting the amount of target sites in these clusters. A total of boreholes has been increased in these clusters from 2 to 4, totalizing 20 boreholes for the entire project. In Table 3 the priority of interventions and the 8 selected clusters are presented. In Figure 3 the localization of cluster is given.

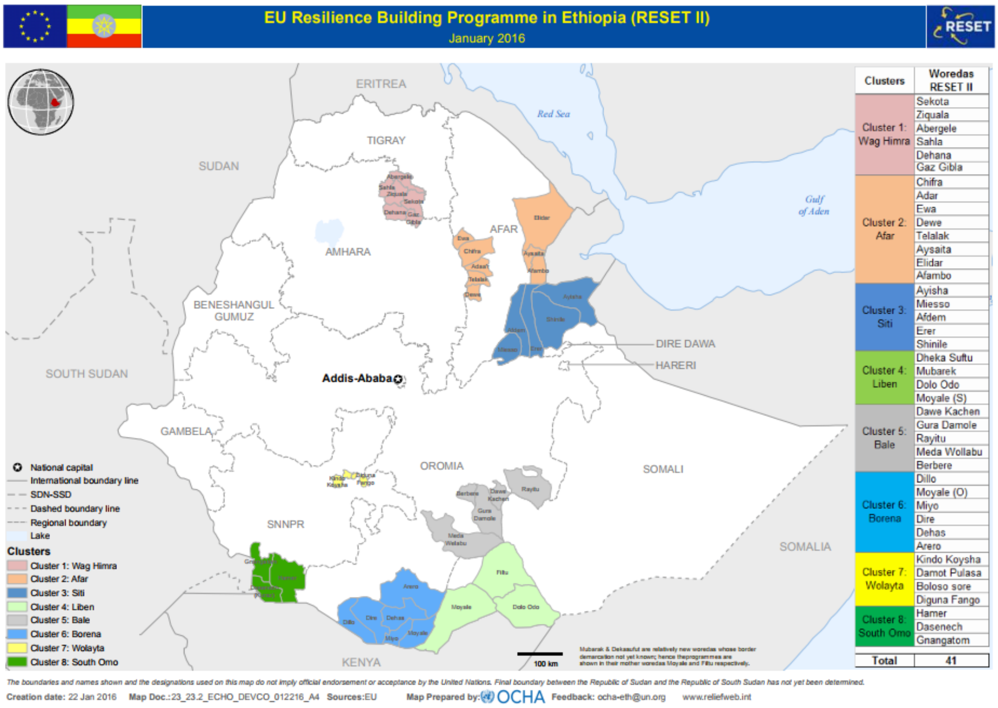

Figure 3. Map of the 8 clusters. Woredas not shown are Mubarek and Deka Suftu Woreda in Liben.

Table 3. Summary of priority and target sites per woredas

Cluster	Region	Zone	Woreda	Priority	Target sites
1	Amhara	Wag Himra	6	1	4
2	Afar	Zone 1,4,5	7	3	2
3	Somali	Siti	4	1	2
4	Somali	Liben	4	2	2
5	Oromia	Bale	5	2	2
6	Oromia	Borena	6	1	2
7	SNNP	Wolayta	4	3	2
8	SNNP	South Omo	3	3	4
Total			**39**		**20**

1.5 Data sources

An inventory of the pertinent references has been made. A List of Geological Maps, Explanatory Notes, Hydrogeological Maps, Technical Reports and Scientific Literature is compiled per cluster. More than 200 reports, maps and published materials have been collected and used for the project analyses.

The available references, we present then into three sections:

A. 1:250.000 Scale Geological Maps and Explanatory notes
B. Other geological maps and accompanying reports of various scales covering parts of some or more of the project areas
C. List of pertinent reports

Most relevant remote sensing data and global datasets were gathered in preparation for the overlay analysis including the processed data from EU-JRC, the European Commission's Joint Research Centre: SRTM datasets and soil moisture. For several layers, such as precipitation, evaporation, soil moisture, vegetation and land-use, the changes over time are most essential. For these layers, the long-term average, significant trend, standard deviation and seasonality was determined using statistical methods. Table 4 and 4a give an overview of the collected data sources.

Table 4. Databases and data collected for the overlay analyses.

Layer	Data Source	Type
1. Groundwater	MoWIE, Others	Water points, WQ
2. Hydrometeorology	MoWIE NMSA	River flow records Rainfall Evaporation Temperature Relative humidity
3. Maps and Reports	GSE, AAU, MoWIE, Others	Geological and hydrogeological maps and reports

Table 4a. overview data collected for the overlay analyses

Layer	Source	Resolution		Availability	Phase
		Spatial	**Temporal**		
Precipitation	GPM	0.1 degree	2014-2018	Available	1,2
	TRMM	0.25 degree	1998-2018	Available	1,2
Surface reflectance	MODIS MOD09	500m	Dec 2017	Available	1
	Landsat-8	30m	Dec 2017	Available	1
	Sentinel-2	15m		JRC	2
NDVI	MODIS MOD13	250m	2000-2018, 16 days	Available	1

Layer	Source	Resolution		Availability	Phase
	Landsat-8	30m	Dec 2017	processing	1,2
	Sentinel-2	15m	tbd	JRC	2
Landcover + dynamics	MODIS MOD12	500m	2001-2012, yearly	JRC	1
Evapotranspiration	MODIS MOD16	500m	2000-2016 (8 days)	Available	1,2
Structural lineaments	SRTMGL1	30m	2014	JRC	1
	Landsat-8	30m	Dec 2017	JRC	1
	Sentinel-2	15m	tbd	JRC	2
Surface geology	Landsat-8	30m	Dec 2017	JRC	1
	Sentinel-2	15m	tbd	JRC	2
Elevation	SRTMGL1	30m	2014	Available	1,2
Flow accumulation	SRTMGL1	30m	2014	JRC	1,2
TWI	SRTMGL1	30m	2014	JRC	1,2
Slope	SRTMGL1	30m	2014	JRC	1,2
Catchments	SRTMGL1	30m	2014	JRC	1,2
Drainage network	SRTMGL1	30m	2014	JRC	1,2
Soil moisture	GLEAM	0.25 degree	2003-2015	processing	1
	SMAP/Sentinel-1	1000m	2017, daily	JRC	1
	SMAP/Sentinel-1/Sentinel-2	100m	tbd	JRC	2

2 Outputs

2.1 Field visits and woreda water points inventory

A field inventory was carried out simultaneously to the operational area familiarization field visit. During the field visits, essential information about 653 existing water points lying within the cluster boundaries was collected. The distribution of the water points is given in Figure 4.

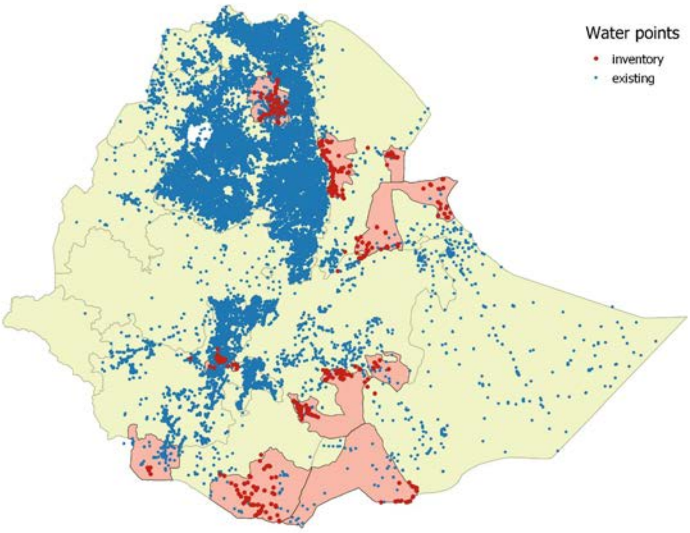

Figure 4. Water point locations

2.2 Weighting criteria

The weights of the criteria or map layers for the overlay analysis are non-unique and vary from one hydrogeological environment (or conceptual model) to another. The detailing of the criteria weighting factors that is commonly agreed upon were set during a peer review committee meeting held in Addis on September 6th, 2018). The criteria set up with the Saaty methodology[1].

Results

Apart from the average weights also the minimum and maximum values were calculated. These minimum and maximum values were the basis for a sensitivity analysis on the mapped groundwater suitability zones (see 2.4). The overall conclusion from the discussion, after presenting the results of the Saaty questionnaires, was that the average weights of the 5 criteria are logical and applicable to the overlay analysis. Another conclusion is that the large variance of some weights was due to the fact that the

[1] The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then.

hydrogeological environment of some clusters is not well known and/or that some attendees personally did not known the area well. The variance (difference between max and min weigths) will be used as a basis for the sensitvity analysis. In Table 5 the calculated factors are given as determined during the workshop in Addis.

Table 5. Weighting factors for the overlay analysis based on Saaty questionnaires.

	Cluster 1, Wag Himra (3 resp.)			Cluster 2, Afar (Chifra/Aysayta) (5 resp.)		
Criteria	Average	Minimum	Maximum	Average	Minimum	Maximum
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
	Cluster 3 Sitti (4 resp.)			Cluster 4 Liben (5 resp.)		
	Average	Minimum	Maximum	Average	Minimum	Maximum
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
	Cluster 5 Bale (4 resp.)			Cluster 6 Borena (8 resp.)		
	Average	Minimum	Maximum	Average	Minimum	Maximum
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
	Cluster 7 Wolayta (4 resp.)			Cluster 8 South Omo (6 resp.)		
	Average	Minimum	Maximum	Average	Minimum	Maximum
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

2.3 Harmonized geological maps

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 maps was a complicated undertaking, approached in 7 steps (more details in Phase 1 report, example Figure 5 for Cluster 1 - Wag Himra):

1. Searching, sorting, and systematization of structural and geological data;
2. compiling, digitizing and harmonizing existing geological maps of the area;
3. Tracing of major faults and lineaments from spatial imageries and geo maps;
4. Preparation of geomorphological maps;
5. Finalize the geological, structural and geomorphological maps and the associated geological cross-sections;
6. Preparation of detailed explanatory note of the geological map;
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.

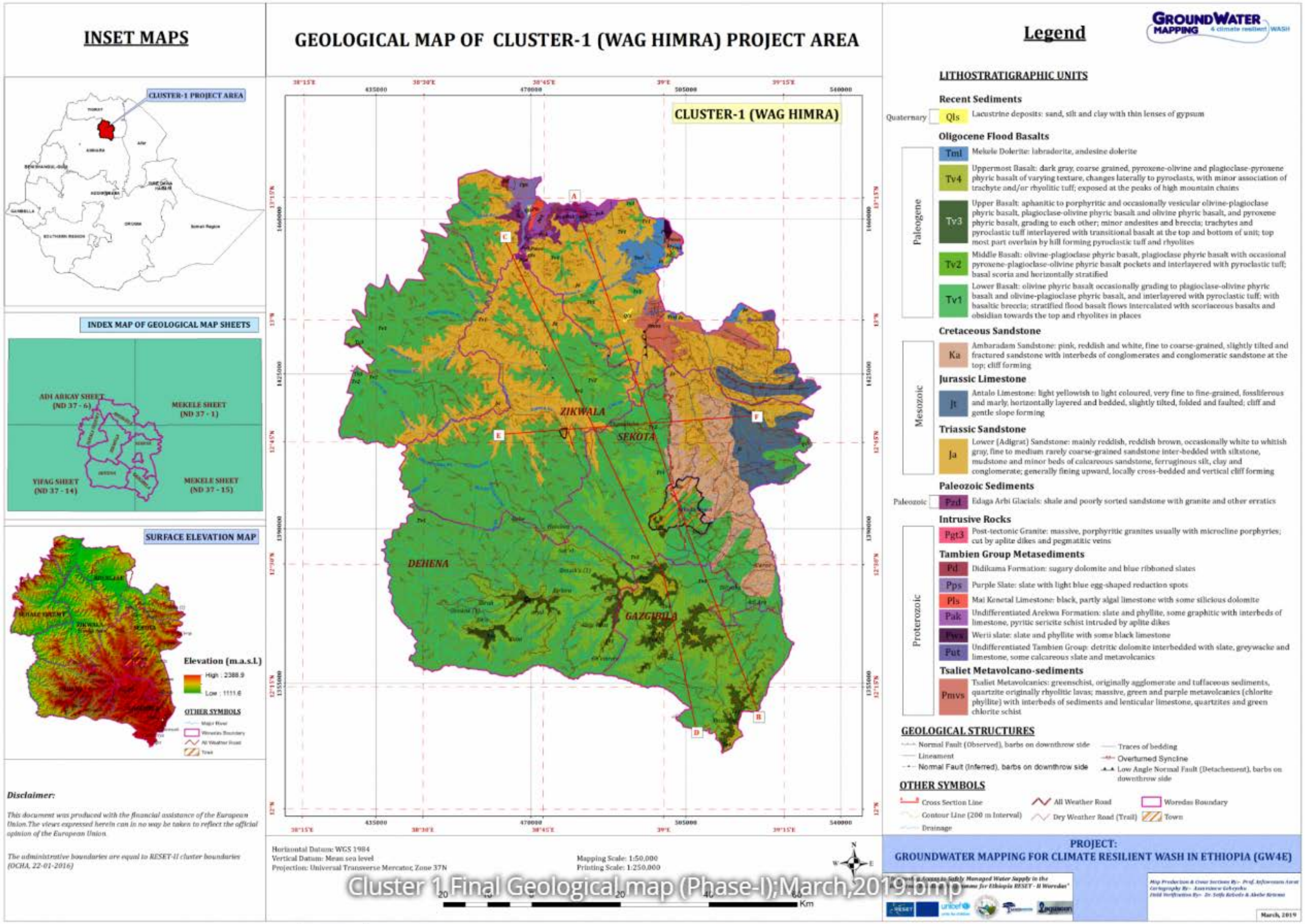

Figure 5. Geological Map of Cluster 1 (Wag Himra) project area. Full set of geological maps available in the dissemination tool.

2.4 Overlay analysis & Groundwater Suitability maps production

The groundwater suitability is calculated as a normalized, weighted sum of the overlay layers per cluster. The delineation of the suitability zones strictly depends on the rating and scoring of five parameters: lithology, structures, slope, recharge, and land use land cover. The overlay layers are calculated by recoding the input layers using their respective score tables. The entire process is automated in QGIS through a python processing script. The layers and suitability scores are colored with the same color scheme: from red (low score) to blue (high score). In Table 6 an overview of the used RS data for the overlay analyses is provided.

Table 6. Remote Sensing data sources for the overlay analyses

Theme	Source	Spatial res.	Temporal res.	Time intev.	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	month	2000-2014	Yes	JRC
Multiple	HydroSHEDS	1 km	n/a	20007	No	JRC

Sensitivity analysis

During the September 2018 workshop, the peer review committee assigned a set of weights for the overlay layers. 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.

Validation

Two types of validation were applied: firstly, the results of the overlay analysis (suitability maps) compared to the inventory data (653 waterpoints) and previously existing data (2102 waterpoints) was not conclusive. 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. 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. The conclusions draw during the field visits were individually discussed in report Phase 1.

A couple of the Suitability maps can be found in Figure 6. Low suitability is displayed in red colour, high suitability in blue. Intermediate values range from orange, to yellow and green. In brown a new class, unsuitable for groundwater abstraction.

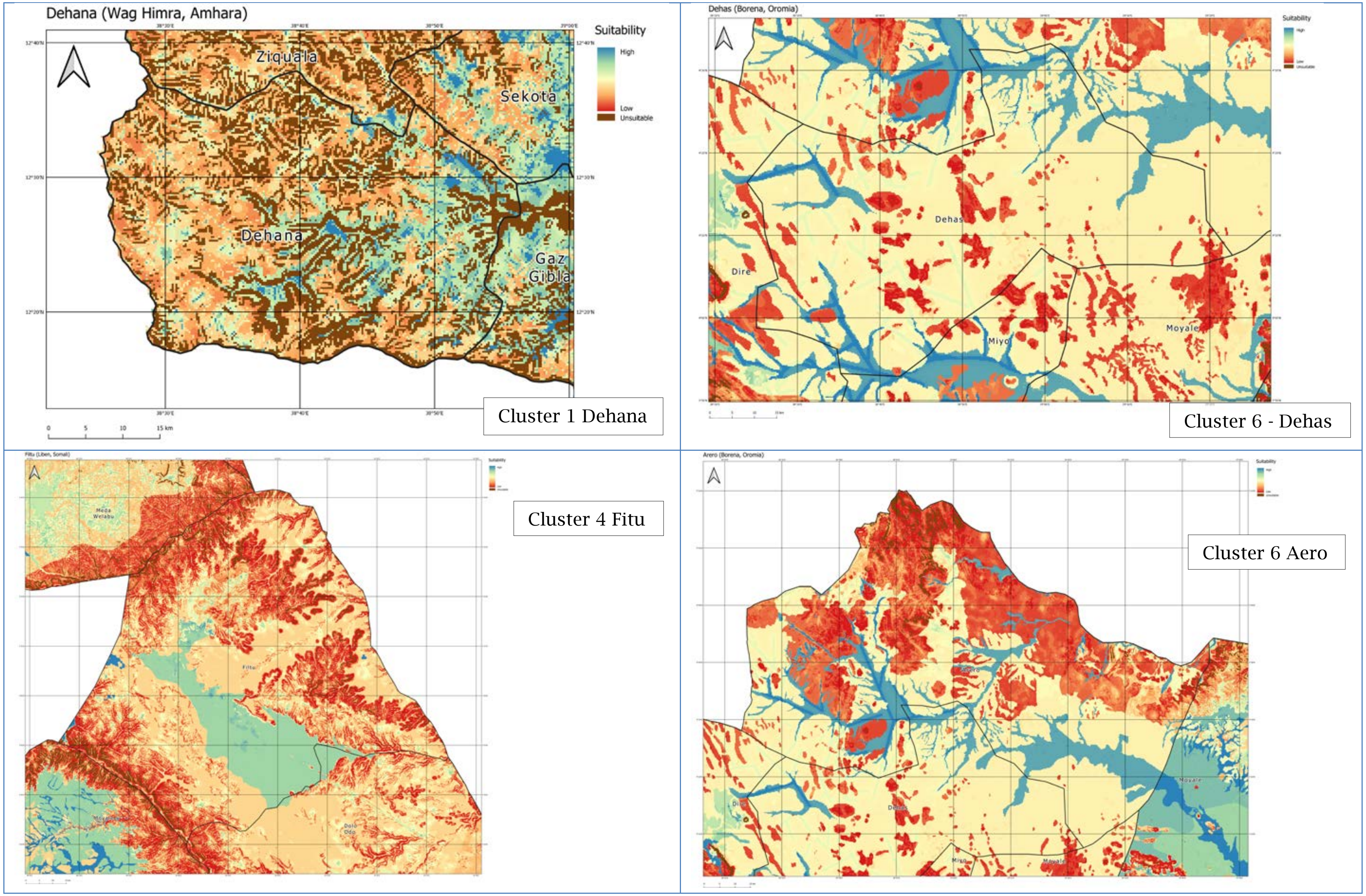

Figure 6. Few examples of the Woredas Suitability Maps of cluster 1 – Dehana, cluster 4 – Fitu and clusters 6 – Dehas & Aero

2.5 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.

Population density of the kebeles is expressed as the number of total inhabitants in 2019 per km^2. 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.

Domestic water demand maps

Domestic water demand in m^3 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.

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.

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. 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.

2.6 Hydrogeological conceptual models and cross sections

Existing evidence (geology, hydrogeology) has been used to improve and further develop the hydrogeological conceptual models, including aspects such as groundwater recharge, occurrence and flow. The conceptual models were fully presented in Annex 3 of report Phase 1. In Figure 7 an example is given from cluster 2 Afar – cross section E-F.

Groundwater flows from south to north, recharge comes from losing 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 foothills of the mountains in the south. Decrease in yields and increase in salinity further north and east limits the groundwater potential in these zones.

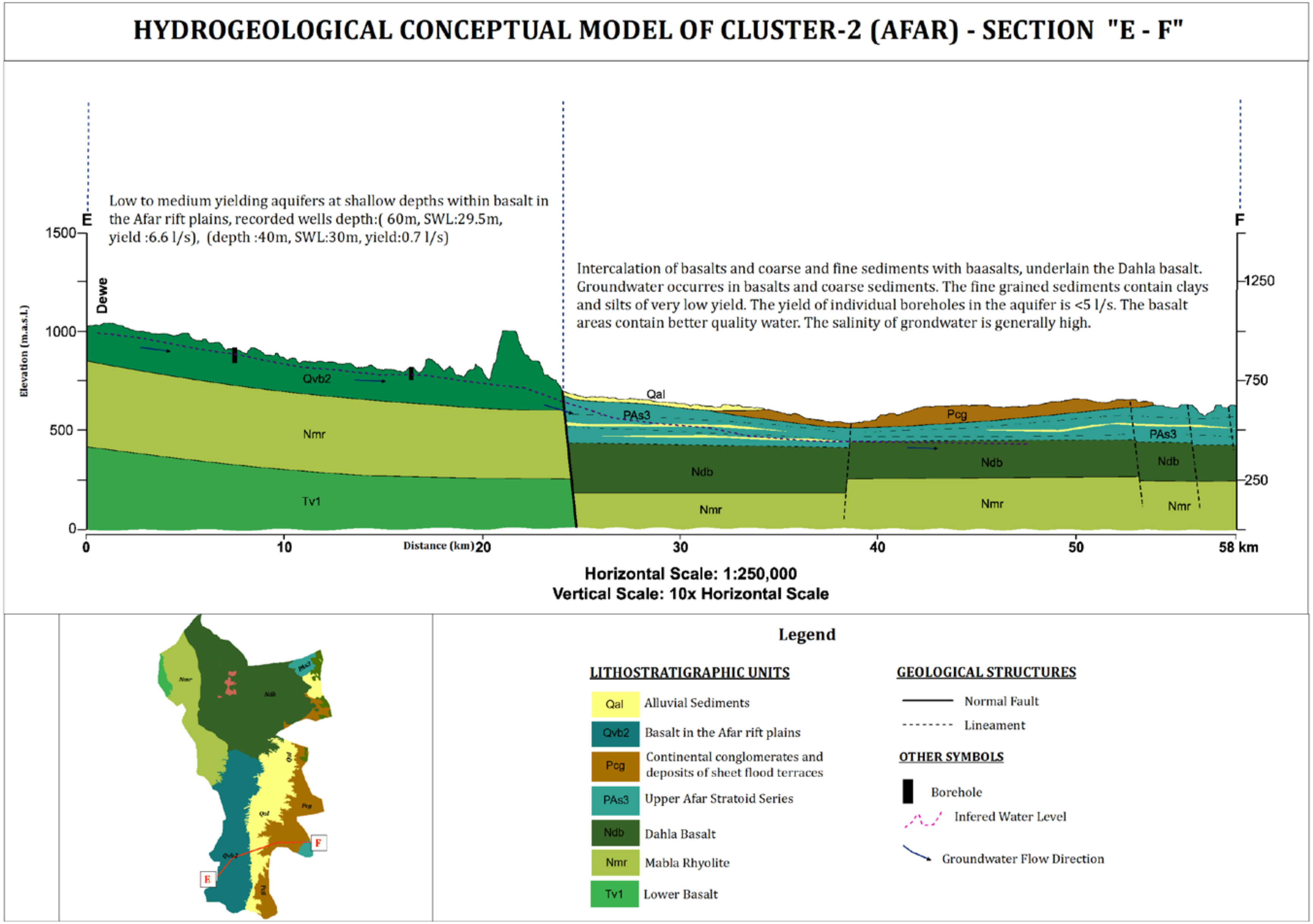

Figure 7. Hydrogeological conceptual model of Cluster 3 (Siti) – cross section E-F. Full set of cross sections available in the dissemination tool.

2.7 Zonal consultation meetings

The geological, groundwater suitability, water demand and socio-economic maps formed the basis for the zonal consultation meetings in the individual cluster areas. In these meetings, stakeholders representing NGOs, zonal and regional water bureaus and woreda representatives participated. During the meetings the groundwater suitability maps, as well as the water demand and socio-economic maps were presented and explained. The participants were requested to discuss into groups, water scarcity situation the zones or clusters and to produce a list of 10 high priority kebeles or villages located in areas with a moderate to high groundwater suitability.

Table 7. Overview of priority Kabele and Target area map ID

Woreda		Kebele	Kebele nr.	1:50,000 map target area	
				Map nr	Map name
Cluster 1 Wag Himra					
	Sekota	Feya	13	1238B4	Sirel
	Sekota	Tiya	56	1239A3	Sekota
Cluster 2 Afar					
	Adar	Hado (Silunahedo)	42	1140C2	Elwiha
	Dewe	Helbi (Halbina Senkokor)	88	1040A2	Ogoli
Cluster 3 Sitti					
	Erar	Erar		0941A4	Erer
	Afdem	Hawanile		0941A1	Asbuli
Cluster 4 Liben					
	Mubarak	Mubarak		0439D4	Gendede
	Deka Suftu	Deka Suftu		0539D4	Hogobe
Cluster 5 Bale					
	Dawe Qachen	Dibe Mole	52	0640B2	Sof Umer
	Raitu	Kere Tule	74	0741C3	Kere Tule
Cluster 6 Borena					
	Dire	Goray	59	0437D1	Dilo
	Moyale	Guchi	38	0338B2	Erder
Cluster 7 Wolayta					
	Bolossa Sore	Legama	15	0737D3	Shone
	Damot Pulasa	Waeitea Belaka	77	0737D4	Shone
Cluster 8 South Omo					
	Hamer	Mrsha	1	0436A1	Omorate
	Hamer	Erbore	12	0436B2	Erbore

After a plenary session the final list of 10 priority kebeles was defined. Out of the list of priority kebeles the consultant from GW4E team selected the two - or sometimes three - kebeles (or villages) located in or near areas with a high groundwater suitability.

It is to be recalled that the groundwater suitability map, conducted under the Phase 1, classified the areas into suitability classes. The likelihood of encountering positive wells depends on the suitability classes delineated under the Phase 1 work and field checks during the ground truthing period. The suitability of the target areas has also been evaluated with respect to relative proximity to the target community, accessibility of the terrain as well as its conditions in terms avoiding potential conflict zones. Table 7 contains the list of two or three priority kebeles for the project clusters.

2.8 Groundwater quality assessment

Bellow a summary of the results found in the assessment of groundwater quality. Further detailed information is provided in the Technical Reports 4 and 7 – respectively Isotope application & Groundwater Quality under Annexes 1 and 4 of Phase 2 report.

2.8.1 Quality survey

Water quality survey has been conducted in the six target areas. The purpose of the water quality survey was to assess the suitability of the waters for drinking water uses and to determine the potential water quality problem that may be encountered in the target areas and in the proposed wells to be drilled.

The survey encompasses in situ measurement of water quality parameters (pH, electrical conductivity, and temperature). Water samples have been collected from all existing schemes (springs, HDWs, BHs) and were analyzed at the Water Works Supervision Enterprise Laboratory. The samples were analyzed for their major element (Ca++, Mg++, Na+, K+, HCO3-, CO3--, Cl-, SO4--, F-) and minor elements (Fe total and Mn total), using the Standard Methods of Water and Waste Water Measurement. The results for the chemical composition are fully presented in Phase 2 report.

2.8.2 Isotope survey

An in-depth investigation of the stable isotope of water have been conducted under the Phase 2 of the current work for each of the clusters. Water isotopes analysis (namely δ 18O δ2H have been conducted on 153 water samples collected from six clusters. Figure 8 below shows the δ18O- δ2H plot of the samples along with the local meteoric water line. The local meteoric water line for Addis Ababa has been drawn from the monthly isotope recorded in rainfalls gathered from the IAEA/WMO station (1961-2015) in Addis Ababa. The equation of the local meteoric water line is given as δ2H = 7.2 δ 8O + 11.9.

There is no evidence for the presence of paleo waters in most of the waters, except in two deep boreholes obtained from the Waghmara target area.
In almost all cases the isotopic composition of the groundwaters mirror the isotopic composition of rains in the highlands of Ethiopia. This reveals that most of the sampled waters contain modern waters originating from modern/recent rains.

In Omo, Afar and the lowland Woredas of Bale, a strong enrichment of the isotopes (along the local evaporation line) have been observed. This can relate to the recharge mechanism which is probably dominated by flush floods taking place at mountain fronts upstream the sampling points. Two deep boreholes supplying the town of Sekota show the most depleted values which are dissimilar to the signal of any modern rains. This may be an evidence for the presence slow moving fossil waters in the aquifers that hold these waters.

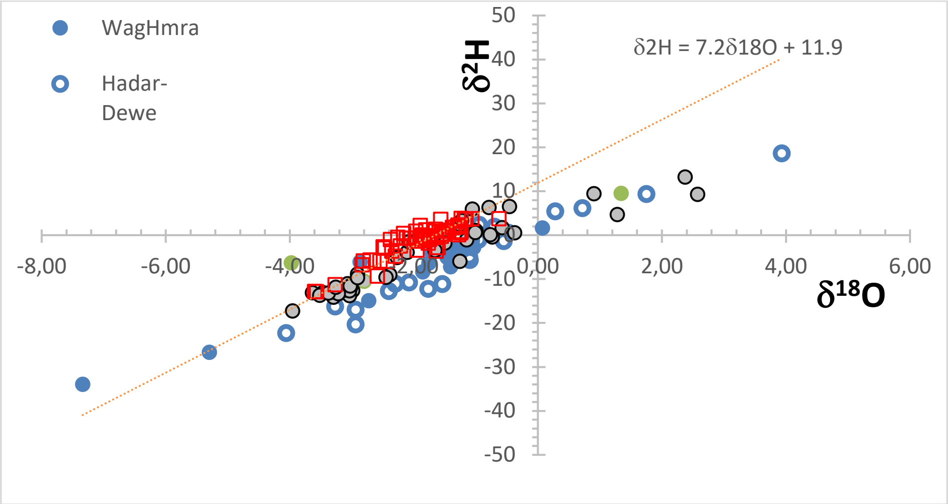

Figure 8. The δ18O- δ2H plot of water schemes from the target areas.

2.9 Geophysical survey

Geophysical investigations device mapping the subsurface variations of some diagnostic physical parameters such as magnetic property and electrical resistivity. The systematic variations in these parameters usually reflect variations in lithology and/or geo-structural setup of the subsurface formations. The methods help to delineate boundaries between residual soils, weathered and fresh rock.

The principal objective of the geophysical survey is delineating prospective zones for groundwater production and come up with the most suitable spots for 16 wells – objective of the project. This can be done through collecting fundamental subsurface information enabling to assess the general geological, hydrogeological and litho-structural setup and identifying potential aquifers.

For assessing the clusters of GW4E, several integrated geophysical investigations were carried out in the selected woredas, specifically, Vertical Electrical Sounding (VES), 2D Electrical Resistivity Tomography (ERT) and Total Magnetic Field (TMF) mapping. Within the framework of this general objective, comprised geo-electrical and geomagnetic methods were also conducted to achieve the following specific objectives:

- Examine the variations in the diagnostic physical parameters (electrical resistivity & magnetic susceptibility) of each lithological layer constituting the geological sections beneath the target areas.
- Estimate depths to the likely aquifer beds.
- Delineate zones of peculiar physical responses (anomalies) which may indicate presence of any possible geological structures (faults, fractures or any weak zones) that may serve as conduits
- Under favourable circumstances, obtaining indications on water quality (Salinity).

The results of the geophysical survey are integrated in the selections of the drilling sites (presented in section 2.12 of this report). The full survey is reported in Technical Report 6 – Geophysical Survey, published under Annex 3 of Phase 2 report.

2.10 Water balance studies

In order to get insight into the sustainability of the UNICEF wells, water balance studies have been carried out by the University of Mekkele in collaboration with Acacia Water. For the studies grid-based data were used from satellite images and global data sets.

With the help of the WetSpass code, runoff, evapotranspiration and groundwater recharge were determined for certain study areas and micro catchments around the target areas for the well siting.

The study has been carried out in two stages. The first and major part of the study, focused on relatively large study areas and catchments or micro catchment in or near the kebeles, selected during the zonal consultation meetings. The catchments enclosed the target areas for the well siting studies. Some target areas and catchments are located outside the beneficiary kebeles due to the suitability classification.

A sustainability check has been carried out by comparing water balances and notably groundwater recharge against the projected groundwater abstractions. The study applied the rule of thumb that groundwater abstraction should not exceed 50 % of the renewable groundwater (or groundwater recharge) minus the present abstractions in a catchment.

In the final stage of the project the actual well sites were defined. Some of the wells were sited outside the micro catchments delineated in the first study. Therefore, the catchments were redefined, and a second series of water balance studies were carried out using the grid-based data of the initial study.

2.11 Hydrogeological operational maps 1:50,000

Updated and harmonized hydrogeological operational map on 1:50,000 scale have been prepared to the identified target areas. For each cluster, the detailed mapping has been made for the target areas and surroundings encompassing the identified potential areas for groundwater development to supply the communities.

The basis for the hydrogeological operational map is the harmonized geological map prepared for the project at the same scale (1:50,000) added by topo-sheets, water points inventory data and water quality information. The main map is also supported by other groundwater related small scale thematic maps, providing additional information. These are rainfall, recharge, and geomorphology/elevation maps.

For the purpose of maintaining consistency in the mapping activity and for ease of future use, the mapping has been done on the basis of the national gridded 1:50,000 top map of the country for parts representing the selected target areas falling within the project boundary area.

The hydrogeological maps depict the occurrence and distribution of water bearing formations (aquifers) and associated groundwater information. With the support of field observations, ground checks and utilization of existing data, the rock units over the mapped area have been classified according to their hydraulic properties, mode of occurrence and productivity levels. In Figure 14 an example is given of one of these maps – Cluster 6 Goray.

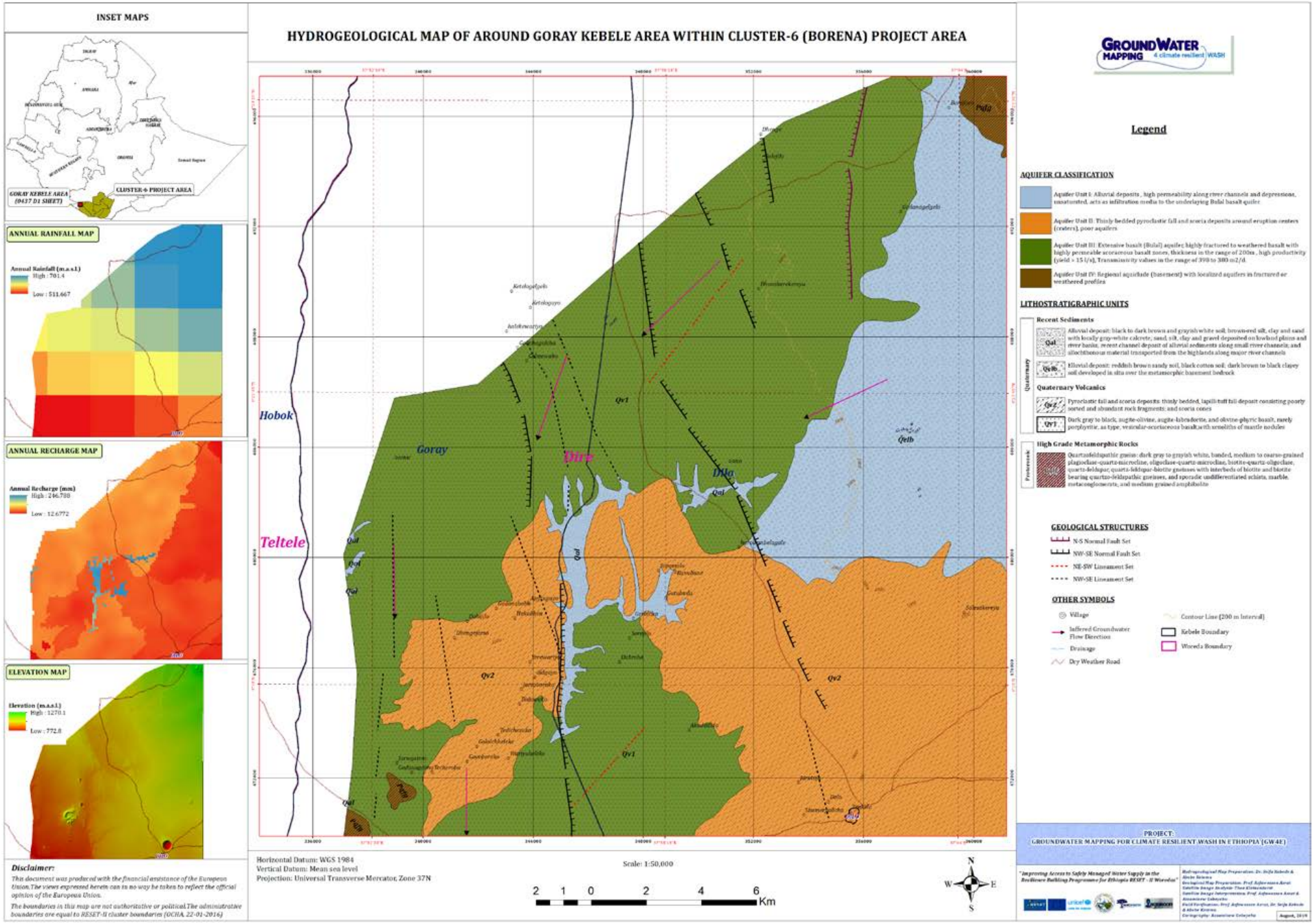

Figure 9. Hydrogeological Operational Map Cluster 6 – Goray area (1:50,000). Full set of cross sections available in the dissemination tool.

2.12 Drilling site maps 1:10,000 (well siting in target areas)

GW4E team selected two priority kebeles for each cluster out of the priority kebeles identified during the zonal consultation meetings (generally 10 were selected during the meetings). In some cases, a "spare" extra third kebele was selected in case further detailed investigations may prove to be difficult in some area (more details in Annex 2 of Phase 2 report). The priority kebeles were selected on the basis of the groundwater suitability maps of the various clusters. Afterwards target areas were chosen for the detailed investigations (geophysics, water sampling and hydrogeological reconnaissance). The target areas are located in or near the priority kebeles depending on the groundwater suitability and accessibility of the terrain

The final selection of well sites has been made based on multiple criteria including- geology, stratigraphy, structures, geophysics (VES, and magnetics), field observation, inspection of success and failure of previously drilled wells (conducted during water point inventory and later), groundwater recharge conditions, and anticipated groundwater quality issues that were in-depth assessed during this project. The selected sites also account for proximity to the kebele as well as appropriateness for multi community schemes development (e.g. potential yield, location in higher area for gravity schemes). The merits for the selection of individual sites are given in the sections below.

In general, not one but three well sites have been determined for each kebele. The spare ones may be needed in case there are unexpected obstacles. Only for the Feya kebele in Wag Himra and the Mrsha kebele in South Omo, three sites have been chosen, which probably have to be drilled all three as capacities of the individual wells are expected to be too low to meet the water demand of the MVS scheme.

In the following sections, a table is provided for each cluster containing the borehole information of the selected drilling sites. In Figure 15 an example is given of an operational drilling map – Cluster 7 – Wolayta. In Table 8 an overview of the selected drilling sites and coordinates is given.

Table 8. Overview of drilling sites Kabele and priorities

Cluster	Target Area	Target Kebele	Priority	VES Reference	Coordinate (WGS84)	
					X	Y
Cluster 1 (Waghimra)	C1A3	Feya	1	V38	496024	1401809
			2	V37	496153	1402301
			3	V32	496944	1402632
	C1A5	Tiya	1	V57	510635	1382304
			2	V56	509942	1382227
			3	V53	510488	1382930
Cluster 2 (Afar)	C2A1-2	Halbina	1	V8	637211	1195484
			2	V1	640779	1192460
			3	V5	638317	1196015
	C2A2	Silindaho	1	V10	638119	1262345
			2	V16	637157	1261925
			3	V12	636860	1262764

Cluster	Target Area	Target Kebele	Priority	VES Reference	Coordinate (WGS84)	
					X	Y
Cluster 3 (Siti)	C3	Erer	1	VES4	762810	1063480
			2	VES8	761459	1066169
			3	VES24	764365	1063108
	C3	Hawanile	1	VES1	738950	1090795
			2	VES2	740052	1090263
			3	VES3	741028	1089672
Cluster 4 (Liben)	C4	Mubarek	1	V5 & V2	603825	440610
			2	V3	608485	448650
			3	V5	606069	449275
	C4	Deka Suftu	1	V8	602093	575063
			2	V1	604118	576836
			3	V6	595180	576055
Cluster 5 (Bale)	C5A1	Dibe Mole	1	V29	700282	746695
			2	V28	701077	746195
			3	V27	701430	747304
	C5A6	Kere Tule	1	V36	725266	778555
			2	V38	724831	780055
			3	V31	724787	775392
Cluster 6 (Borena)	C6A2	Goray	1	V25	342225	477981
			2	V6	344768	476467
			3	V10	348665	476547
	C6A5	Guchi	1	V3	496916	424688
			2	V2	497889	423263
			3	V1	496823	424481
Cluster 7 (Wolayta)	C7A1	Legama	1	V30	363242	778520
			2	V4	360895	781411
			3	V15	361489	778524
	C7A3	Waeitea	1	V35	377248	774230
			2	V45	376154	775695
			3	V49	375520	776210
Cluster 8 (South Omo)	C8A2	Mirsha	1	V21	185009	544761
			2	V19	182599	543733
			3	V20	185427	541259
	C8A3&A4	Erbore	1	V3	256660	554387
			2	V1	252233	555099
			3	V21	251907	534566

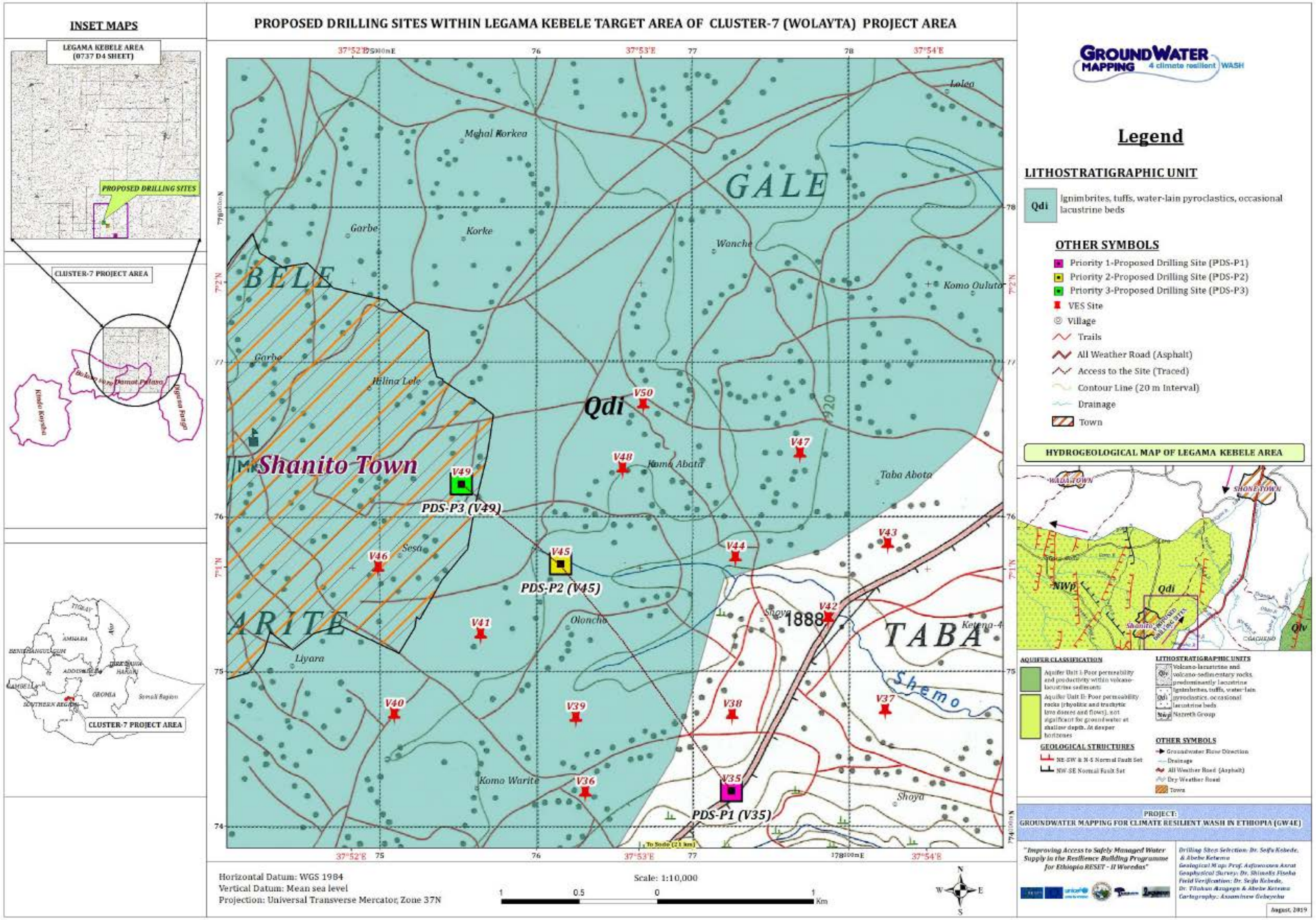

Figure 10. Drilling site map for Cluster 7 (1:10,000). Full set of cross sections available in the dissemination tool.

2.13 Groundwater Mapping Methodology Training

The Groundwater mapping training took place from 19 – 23 August 2019 in the Africa Centre of Excellence for Water Management on the campus of Addis Ababa University. The course was attended by 16 participants from the Ministry of Water, Irrigation and Energy, UNICEF main office, UNICEF field offices and the Regional Water Bureaus.

During the training, 14 participants learned how to prepare groundwater suitability maps and how to combine the results of this analysis with other socio-economic and other data in well siting studies. The training was divided into two main parts: Part 1- Overlay analyses and Suitability Map; Part 2- Well sitting.

At the end of the course participants discussed the way forward, covering topics including well design and monitoring approaches. During the evaluation of the training, participants indicated that they consider the topics that were covered to be very important and relevant to their work. Participants were especially enthusiastic about the practical nature of the training and the extensive coverage of what had been done in the project until the date of the training. Despite having different backgrounds and experience levels at the start of the training, participants concluded that they intend to apply the knowledge and skills gained during the training in their work in the future.

2.14 Dissemination web-tool

All spatial data such as maps, GIS layers and imagery are stored in a PostGIS database. The entire database is available on a CD-ROM and will be shared with MoWIE. To facilitate dissemination and the project's results can also be accessed through a web application, WMS service and ftp server.

The urls for dissemination are given in Table 9:

Table 9. Overview urls for dissemination

Name	url
Main website	https://gw4e.acaciadata.com
WMS capabilities document	https://gis.acaciadata.com/?map=/project/unicef/clusters.qgs&service=WMS&request=GetCapabilities
FTP server	http://cloud.acaciadata.com

The main website is the starting point for the dissemination. The site contains an interactive map viewer that can be used to share relevant maps and GIS layers of the project. The home page contains download links for:

Phase 1:

- Final report of phase 1
- Harmonized geological maps 1:250,000
- Conceptual models 1:250,000
- Socio-economic maps 1:250,000
- Water demand maps 1:250,000
- Suitability maps 1:250,000 per woreda
- Suitability maps 1:250,000 per cluster
- Inventory data

Phase 2:

- Final report Phase 2
- Operational hydrogeological maps 1:50,000
- Drilling site maps 1:10,000

The WMS capabilities document in Table 9 describes the WMS service of the project. The service publishes all relevant layers though an OGC WMS service that can be accessed by any modern GIS software package with an internet connection.

3 Final remarks

3.1 Lessons learned

This paragraph contains a summary of the capitalization chapter in Phase 2 report (chapter 8). Executive consultant consortium consisting AQUACON, local experts and Acacia Water formed a good and efficient team. The project benefited from the good cooperation and frequent communication with UNICEF, as project mandator and MoWIE as main Ethiopian counterpart and hosting organization.

Throughout the project communication and consultation with local stakeholders like NGOs (RESET partners) and the regional and zonal water bureaus and woreda WASH departments proved to be essential. UNICEF regarded these as main clients, though they did not have a formal role. Expectations and obligations were not always well defined. It is recommended to define their roles and responsibilities more strictly in future TOR's and inception documents. This holds also for the allocation of budget to these organizations.

The goal of the GW4E project was clear: a new or more rational methodology for groundwater mapping and siting of boreholes and capacity development in this methodology. Looking back, we may conclude the GW4E project has achieved this goal although not always along the lines set out in the beginning.

With respect to the TOR and inception documents we recommend to better define notions like climate resilience, well depths, and sustainability. This sometimes led to confusion.

In the project document water demand and water delivery systems should be better geared to the various regions in Ethiopia. The project aimed at multi-village schemes, which are appropriate for densely populated areas with relatively large villages and sedentary farming communities. However, the situation in sparsely populated pastoralist areas with small villages and a high-water demand for livestock, which comprises a large part of the RESET II woredas, should also include other water delivery systems.

Field work was often hampered by unexpected security incidents leading to prolonged delays. For the consultant it was difficult to gather information or to take precautions. We recommend not to enter zones with persistent negative travel advice (according to most EU embassies), unless UNICEF or MoWIE can offer protection to consultants not native to these zones or allocate additional budget for them to take these measures. Training has been carried out through two courses, one organized by JRC and the final one organized by the GW4E team. In addition, on-the-job training was provided. The project has used many methodologies from traditional techniques to highly sophisticated ICT operations like overlay analysis. We recommend organizing separate courses for specific groups with specific capacities. For instance, training in overlay analysis is only effective and relevant to a few people. In some cases, it may be better to support them by scholarships. To consolidate their newly acquired knowledge we recommend assigning course participants to other similar projects.

The harmonized geological maps are crucial input for the overlay analysis. We strongly recommend continuing harmonization of the geological maps for the entire country (cooperation between Addis Ababa University and Geological Survey of Ethiopia). The groundwater suitability maps have proven to useful tools for many organizations. We recommend not to publish these maps as hard copies. Printing and distribution take a long time, and, in the end, maps may get out of print. Potential users are nowadays better served via a webservice system, enabling them to assemble their own maps and map attributes and print the maps. It is also easier to maintain and expand the system with new attributes.

In principle socio-economic and water demand maps are useful. The ones made for this project lacked recent information about population (based on 2007 census), the actual status of the WASH systems and, consequently, the actual water demand. If these data become available after the new upcoming census and the recent national WASH, these maps can be the basis for planning of water supply interventions even on kebele level. These socio-economic and water demand maps recommended above do not devalue the zonal consultations meetings. These proved to be very efficient in assessing the real need for water and the priority kebeles or villages. Not everything can be captured in statistics, especially the always ever-changing conflict zones.

3.2 Way forward

This project and also other projects prove that the overlay analysis technique as a fast and efficient tool in assessing the suitability for drilling wells on very small scale.

We recommend scaling up the basic mapping approach in this project to the entire country. In a sense we could regard this project as a large pilot. At the same time, we recommend widening the scope of water mapping to the entire water domain and IWRM.

Groundwater and groundwater management cannot be isolated from this. The basic data and information for the groundwater suitability mapping in this project is similar to what is needed for mapping of the entire water system and other water measures. We think of various water collection and delivery systems (shallow wells, sand dams, deep wells, dams), erosion control, flood prediction and protection, irrigation planning et cetera. On request of UNICEF the GW4E team has written a concept note on this topic (Annex 11, Phase 2 report).

For this national water mapping we advise to cooperate with the Geological Survey, the Central Statistical Agency, the Agricultural Transformation Agency (ATA) and the Land and Water Resource Center (LWRC) of the Addis Ababa University. ATA is presently carrying out groundwater mapping studies for small scale irrigation in Ethiopia. LWRC has a repository and website with basic information on land and water. It also has the required academic skills to develop and maintain the national land and water data base.

GroundWater Mapping 4 climate resilient WASH

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