Prepared in cooperation with the United States Geological Survey

Groundwater Exploration and Assessment in the Eastern Lowlands and Associated Highlands of the Ogaden Basin Area, Eastern Ethiopia: Phase 1 Final Technical Report

By Saud Amer, Alain Gachet, Wayne R. Belcher, James R. Bartolino, and Candice B. Hopkins

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per year (m^3/yr)	0.000811	acre-foot per year (acre-ft/yr)
liters per second (l/s)	15.8503	gallons per minute (gal/m)
	Transmissivity*	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)

*Transmissivity: The standard unit for transmissivity is cubic meter per day per square meter times meter of aquifer thickness [(m^3/d)/m^2] m. In this report, the mathematically reduced form, meter squared per day (m^2/d), is used for convenience.

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EXECUTIVE SUMMARY

This report describes the final technical results from Phase 1, a groundwater assessment for an area of 57,000 km^2 in the eastern lowlands and associated highlands, part of the Ogaden Basin of Ethiopia. Traditional hydrogeologic methods were used in selected areas identified by the WATEX© process. In this study we evaluated the groundwater resources of selected areas for sustainability, suitability for intended use, and possible measures for supply enhancement.

The results of this work are useful in the identification of sustainable, long-term groundwater supplies to enhance water resiliency and mitigate the effects of drought in the region. This information will assist the Government of Ethiopia (GOE) and the Somali National Regional State to manage and develop its groundwater resources in a sustainable manner, providing resiliency to the devastating effects of recurring drought. Results from this study can also directly support USAID's Water, Sanitation, and Hygiene, Transformation for Enhanced Resilience (WATER) project by helping the International Rescue Committee (IRC) increase accuracy for drilling potential high yield water wells.

Also a part of this study, training was provided to develop the capacity of Ethiopian scientists and engineers in groundwater assessment and development. Such development is furthered through interaction and cooperation with local, national, regional, and international entities.

The Phase 1 study area combines and builds upon the 16,323 km^2 ("Flemish") zone of the Upper Fafen-Jerer River system in the Somali Region of eastern Ethiopia with an additional 41,000 km^2 area south of the "Flemish" zone. Over the entire 57,000 km^2 Phase 1 study area, the WATEX© process was used to map all potential shallow alluvial groundwater, conductive fractures, and deep aquifer structures. In addition to these features, Phase 1 also mapped geological units and structures, soils, and potential recharge zones, thus enabling a full assessment of hydrogeology of the study area. The hydrogeology has been assessed in terms of potential storage capacity and recharge using precise geography.

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Phase I study results indicate that groundwater flow is strongly influenced by the physical framework of the system, which is characterized by aquifers, confining units, flow barriers, and other geologic structures. Much of the data from prior studies are not of high quality, which precludes mapping potentiometric surfaces. Phase 2 will help resolve these uncertainties. The wells drilled by USAID/IRC suggest that groundwater flows in a southeasterly direction.

The water-yielding zones in the Phase 1 study area are in the Jerer and Fafen Valleys, and consist primarily of unconsolidated alluvial deposits. Consolidated (bedrock) carbonate rocks and sandstones that underlie the unconsolidated alluvium or are exposed directly at the surface may be a source of water if the consolidated rocks are sufficiently fractured or have solution openings. Three principal lithologies form aquifers in the Phase 1 study area: carbonate-rocks, sandstones, and alluvial sediments.

Reported transmissivity of alluvium is about 45 meters squared per day (m^2/d). The combined Urandab, Hamanlei, and Adigrat Formations unit has an average transmissivity value of 75 m^2/d, with a range of 2 to 350 m^2/d. The single well completed in the granitic and metamorphic basement unit has a reported transmissivity of 116 m^2/d. Because this basement well produces water, it was probably drilled into either fractured or weathered basement rock that acts as a local aquifer.

In the Phase 1 study area, there are four main sources of recharge to the alluvial and bedrock (carbonates and sandstones) aquifers:

- Direct recharge to outcropping aquifers,
- Mountain-front recharge originating in the metamorphic highlands and Karamara Range,
- Recharge from rivers in the Jerer and Fafen Valleys, and
- Deep regional groundwater flow from the east (possibly including recharge from the Jessoma Formation sandstones exposed to the east).

Approximately 8.88 billion m^3 per year of precipitation falls on the outcropping area of the Jessoma Formation. The Jerer and Fafen Valleys received approximately 12.7 billion m^3per year of precipitation. To estimate groundwater recharge it is assumed that recharge from direct precipitation is between 3 and 10 percent. Using these end values, the alluvium and the bedrock aquifers beneath the Jerer and Fafen Valleys could receive between 380 million m^3 and 1,300 million m^3 of recharge from direct precipitation, while the Jessoma Formation could receive between 270 million m^3 and 890 million m^3.

A maximum of approximately 4.5 million m^3 of water is potentially recoverable from groundwater stored in the primary bedrock aquifers. The estimated maximum volume of potentially recoverable groundwater in alluvial aquifers is 460 million m^3. Applying an estimated specific yield of 0.1 means that as much as 46 million $m^3$of potentially recoverable water could be stored in the high-potential alluvial aquifer areas.

The perennial yield of the alluvium and bedrock aquifers beneath the Jerer and Fafen Valleys is estimated to be between 380 million $m^3$and 1,300 million m^3; the estimated perennial yield for the Jessoma Formation is estimated to be between 270 million m^3 and 890 million m^3per year. These estimated perennial yields are an order of magnitude larger or more than the estimates of potentially recoverable water in the aquifers. More accurate estimates of the perennial yield and aquifer hydraulic properties collected during a proposed Phase 2 would result in a better understanding of the sustainability of these water resources.

Most groundwater recharge probably originates as precipitation onto the northern metamorphic highlands, north of Jijiga. Water then runs off the relatively impermeable metamorphic rock and enters surface exposures of the Adigrat and Hamanlei Formations. Similarly, runoff from the relatively impermeable volcanic rocks of the Karamara Range also recharges the Adigrat and Hamanlei Formation aquifers. Groundwater flow in both valleys is to the south through the alluvial deposits, the Hamanlei Limestone, and Adigrat Sandstone. The rocks of the Karamara Ranges seem relatively impermeable in the north and more permeable to the south. The Karamara Range forms a barrier to the north, effectively blocking east to west flow, although some flow occurs to the east between the southern parts of the valleys. Some streamflow in the two rivers appears to recharge groundwater.

Eastern exposures of the Jessoma Formation probably receive some mountain front recharge as runoff enters the groundwater system from the sandstone to the west. Water also directly infiltrates into the sandstone body itself, but this recharge probably does not flow into the Hamanlei and Adigrat Formation aquifers because of a possible basal clay layer. If this clay is present, the Jessoma Formation may act as "stand-alone" aquifer. If there is no clay barrier, but rather a hydraulic connection with the primary Adigrat and Hamanlei Formation aquifers, then water from the Jessoma Formation also is a source of recharge to the primary aquifers to the west.

The present understanding of the hydrogeologic framework and groundwater flow system would be improved during a proposed Phase 2 effort.

The WATEX© process has demonstrated the ability to identify potential shallow and deep aquifers to within an accuracy of few meters. A comparison of the cost of drilling a productive well in the study area without using WATEX© to site a well and the cost of drilling a productive well in the study area using WATEX© to site a well highlights the importance of using WATEX© to locate select hydrogeologic features, such as depth to water and crystalline rock fractures, for groundwater exploration in undeveloped areas. The WATEX© process of siting wells has the potential to improve the efficiency and accuracy of borehole drilling from its current range (without using WATEX©) of 25 percent in the southern, dry Somali Region and 45 percent in the highlands, to (with WATEX©) 75 percent or more success rate of drilling productive wells.

Assuming factors of influence for wells sited with and without WATEX© are identical except for the drilling success rate, results show that WATEX© is cost effective if more than one productive well is needed in the southern, dry Somali Region, or if more than three productive wells are needed in the Highlands. Use of WATEX© for siting wells also saves time, which is important when working in an unsecure environment and (or) where there is an urgent need for water. Future drilling, therefore, is likely to benefit from siting boreholes using the WATEX© potential water map delivered as a product of Phase 1, which suggests numerous opportunities for potentially high yield boreholes within the study area.

The most significant hydrogeological structure identified by this work is the East Karamara aquifer structure on the eastern flanks of the Karamara Range, south of Jijiga. It lies at a depth of 50 to 700 m beneath the Jerer Valley, and is approximately 1 to 35 km wide and 200 km long. Use of the WATEX© process also allowed accurate mapping of a broad range of minor geologic features scattered over the study area. These structures include aquifers such as:

- Discontinuous alluvial aquifers (because these are apparently discontinuous, they would require further remote sensing- based geologic mapping before drilling).
- Aquifers of eolian origin that may potentially supply communities of several hundred persons.
- Perched aquifers of fluvial deposits sealed by basalts may be potentially productive.
- Potentially productive areas of bedrock fracturing. They may also indicate several hundred of meters deep potentially productive aquifers.

The maps and tools resulting from this study represent science-based information about groundwater resources, and have the potential to improve the lives of more than 5 million people *(*http://en.wikipedia.org/wiki/Somali_Region*)* who live in this semi-arid area with limited access to fresh water. A proposed Phase 2 of this project would further assist the GOE in exploration and mapping groundwater in the eastern lowlands and associated highlands of the Ogaden Basin area, and continue to build local capacity to ensure groundwater resources are developed and managed sustainably. By improving characterization of the groundwater resources and local groundwater science capacity, Phase 2 will contribute to pastoralists' household resiliency to drought by increasing their access to groundwater and by supporting the use of hydrologic science for sustainable management of water resources.

1. Introduction

This report describes a groundwater assessment for an area of 57,000 square kilometers (km^2) in the eastern lowlands and associated highlands, part of the Ogaden Basin in eastern Ethiopia. Traditional hydrogeologic methods were used in selected areas identified by WATEX© analysis. The WATEX© System (Gachet and Verjee, 2006) is an expert system that integrates remote sensing, geology, geophysics with a moisture algorithm; this System is discussed in section 4. This study evaluated the groundwater resources of selected areas for sustainability, suitability for intended use, and possible measures for supply enhancement. Sustainability and suitability of the groundwater supply were evaluated using remotely sensed derived products and available ancillary data, which were incorporated into a conceptual hydrogeologic model.

The results of this work are useful in the identification of sustainable, long-term groundwater supplies to enhance water resiliency and mitigate the effects of drought in the region. This hydrogeologic information can be used by the Government of Ethiopia (GOE) and the Somali National Regional State as a scientific basis for managing and developing its groundwater resources in a sustainable manner and provide resiliency to the devastating effects of recurring drought.

As part of this study, training was provided to local, national, and regional Ethiopian scientists and engineers to develop their capacity in groundwater assessment and development. Such development was furthered through support for and cooperation with international entities, such as International Rescue Committee (IRC), UNESCO, DFID, and JICA.

1.1. Background

The exploration and assessment of groundwater resources in the eastern lowlands and associated highlands, part of the Ogaden Basin in eastern Ethiopia (fig. 1), was a six-month project (January – June 2013) funded by the United States Agency for International

Development (USAID), Ethiopia Mission. The United States Geological Survey (USGS) is the participating agency on this project.

The USGS assisted USAID in implementing the project by:

- Using the Water Exploration (WATEX©) System to map potential groundwater resources and increase the drilling success rate in an area of 41,000 km^2;
- Conducting a hydrogeologic assessment in an area of 57,000 km^2, which includes a 16,000 km^2 area where WATEX© had previously been applied (the "Flemish" area); and Training staff from the Government of Ethiopia (GOE), universities, and nongovernmental organizations on hydrogeologic techniques and use of remotely sensed data.

The results from the USGS study can directly support USAID's Water, Sanitation, and Hygiene, Transformation for Enhanced Resilience (WATER) project by helping the IRC to increase its accuracy for drilling potential high yield water wells in a timely and cost effective manner. For the purpose of this study, a well yielding more than or equal to 1.5 l/s is considered a potential water supply well.

The following tasks were completed as part of this work:

- Analysis conducted with the WATEX© System;
- Fieldwork, verification, and training;
- Water-sample analysis; and
- Development of a hydrogeologic framework.

1.2. Purpose and scope

This report presents the final technical work from the Phase 1 study area (fig.1), linked with the "Flemish" area results from the 2012 survey of the Jerer and Fafen Valleys. The body of the report presents an overview of the study area, geologic and structural framework, a description of the WATEX© System, a summary of the results of the WATEX© process, geochemistry results, and a summary of the hydrogeologic framework. Appendices include the detailed report on the WATEX© results, a list of the deliverables for the project, and a brief description of the capacity building conducted at Addis Ababa University and training in the Somali Region.

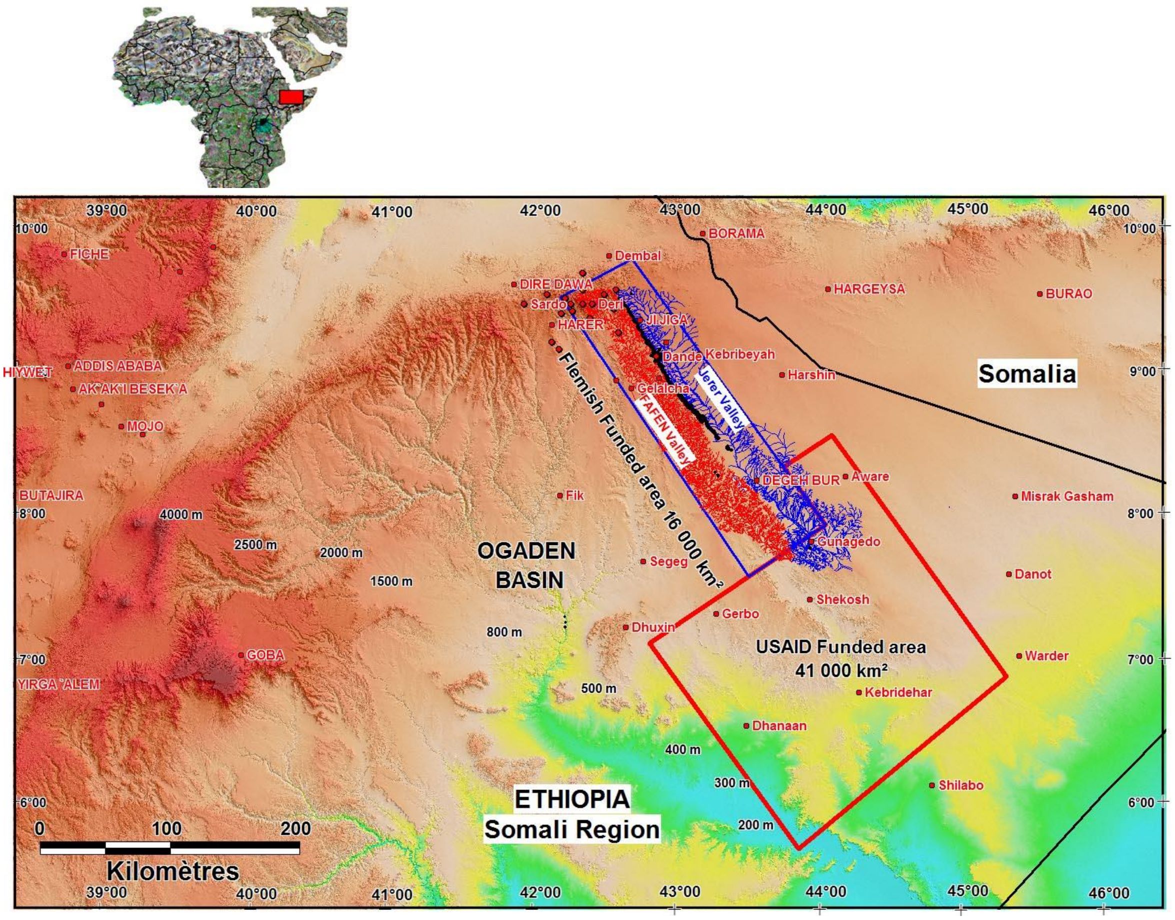

Figure 1. The Eastern lowlands and associated highlands of the Ogaden Basin area, eastern Ethiopia. Study area for Phase 1 includes both UNESCO Flemish area and USAID funded study area, a total of 57,000 km². The Karamara Range is shown as an area in black; the Karamara Range separates the Jerer Valley (shown in blue) and the Fafen Valley (shown in red). Black line indicates national boundary between Ethiopia and Somalia.

2. Study Area

2.1. Geographic location

The Phase 1 study area covers about 57,000 km², although WATEX© was performed only for a 41,000 km² area as part of this study (fig. 1). Prior to this project, the Flemish Government funded a WATEX© survey for a 16,000 km² area (fig.1); the results of that prior WATEX© process are incorporated into this report to produce a hydrogeologic assessment for the entire 57,000 km2 study area.

The project area is located within the Somali National Regional State of Ethiopia. Jijiga, the capital of Somali National Regional State, is situated 630 kilometers (km) southeast of Addis Ababa (Addis Ababa not shown on fig. 1). The Fafen and Jerer River basins are elongated areas running NW-SE from the northernmost part of the study area for about 250km. The northern area is dominated by the narrow Karamara Range, which stretches along the NW-SE direction separating the Jerer Valley in the east from the Fafen Valley in the west (fig.1).

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2.2. Climate

The Fafen and Jerer River basins are adjacent to the Wabi Shebelle River basin. Precipitation and temperature data in the region are sparse, and were analyzed for all three river basins. The Fafen, Jerer and Wabi Shebelle River basins are characterized by a bimodal rainfall pattern with rainy and dry seasons. The north-western and eastern part of the Wabi Shebelle basin (around Jijiga) receive most of their rainfall during July, August and September associated with the northward passage of the Inter-Tropical Convergence Zone (ITCZ), known locally as Mahr season. From September to November, the ITCZ moves back in a southward direction, causing a rapid end to the rainy season during September and October. By December and January, the ITCZ moves further southwards into Kenya.

From about mid-March to May (the shorter rainy season, known locally as Belg season) the pressure system changes to warm, as moist and unstable air from the Indian Ocean moves in from the east and converges with a stable continental air mass from the Sahara high pressure cells.

Of note, the south-eastern part of the low lying areas of the Wabi Shebelle basin that is east of 42° and south of 8° (See Fig.1 around Degehabur, Gode, Kebridehare, and Kelafo) receives no rainfall in July and August and has two rainy seasons. The first is from March to May, and the second is from October to November. The March to May rains are caused by moisture from the Indian Ocean, while the October to November rains may be associated with the retreat of the ITCZ in a southward direction. Gachet (2013) includes maps showing average precipitation in January and August, and discussion of spatial variation of annual temperature range.

3. Geology

The descriptions below summarize the geology of the study area that was presented in Gachet (2013).

3.1. General geologic setting

Precambrian (mostly Archean) granite and metamorphic rocks dominate the basement rocks of Northern Somalia and southern “Bur” basements. The present sea-margins of Somalia, which is contiguous with Ethiopia (see fig. 1), began developing in late Paleozoic time as rift and pull-apart basins formed. These basins evolved intermittently over 150 million years until seafloor spreading commenced in the Late Jurassic, (Gachet, 2013).

At the initiation of seafloor spreading between West Gondwana (present-day Africa) and East Gondwana (present-day Madagascar, Seychelles, Greater India, Australia and Antarctica) at about 165 million years before present, sediment facies changed throughout the basins from dominantly continental to marine, with volcanism and normal faulting occurring at the same time. Thermal subsidence and mechanical (sediment) loading dominated margin evolution following margin breakup, and seafloor spreading ceased in the Western Somali Basin in early Cretaceous time. Vigorous ocean currents along the East African margin probably commenced in middle Cretaceous time, and widespread regional volcanism occurred in the late Cretaceous.

By the end of middle Jurassic time, oceanic crust separated Eastern Africa from Madagascar-Seychelles and the respective shorelines began to subside, leading to middle Jurassic-early Cretaceous marine transgression. The middle Cretaceous was a period of alternating transgression and regression phases with late Cretaceous-early Cretaceous transgression following. The early Oligocene was a quiet period of gentle sea-level decline (regression) marked by the absence of Oligocene sediments in some areas. Late Oligocene-Miocene sea-level rise (transgression) with accompanying tectonic movement followed. Subsequent regression established the present-day coastlines. In the south and east of the study area, the Precambrian basement rocks occur at the base of the late Paleozoic to early Mesozoic sediments overlain by Jurassic and Tertiary sedimentary rock successions.

These sedimentary successions are generally absent in other parts of Ethiopia. Apart from the sediments, sporadic Tertiary volcanic rocks occur overlying both the Mesozoic and Tertiary sedimentary rocks. Superficial sedimentary deposits, alluvial deposits in the major river valleys, colluvial deposits at the base of the ridges, and alluvial sediments on the plateaus/plains are not uncommon.

3.2. Stratigraphy

Most of the nomenclature used in the geologic classification of Ethiopia and Somalia were established by the previous geologists who assigned the name of the nearest town to the type of each formation (see the geological and hydrogeological maps of Ethiopia and oil exploration works published by Fugro Robertson Limited, 2007). The following stratigraphic units were used for the new geologic mapping (fig. 2). Table 1 presents the geologic units in the Phase 1 study area from the oldest on bottom to the youngest on top.

As there are no oil wells drilled in the study area, this Phase 1 study used a general chronostratigraphic description between West Ogaden and Somalia; namely, between Mandera, southwest of the study area in Ethiopia, and the Mudugh Coast, southeast of the study area. These show important stratigraphic variations.

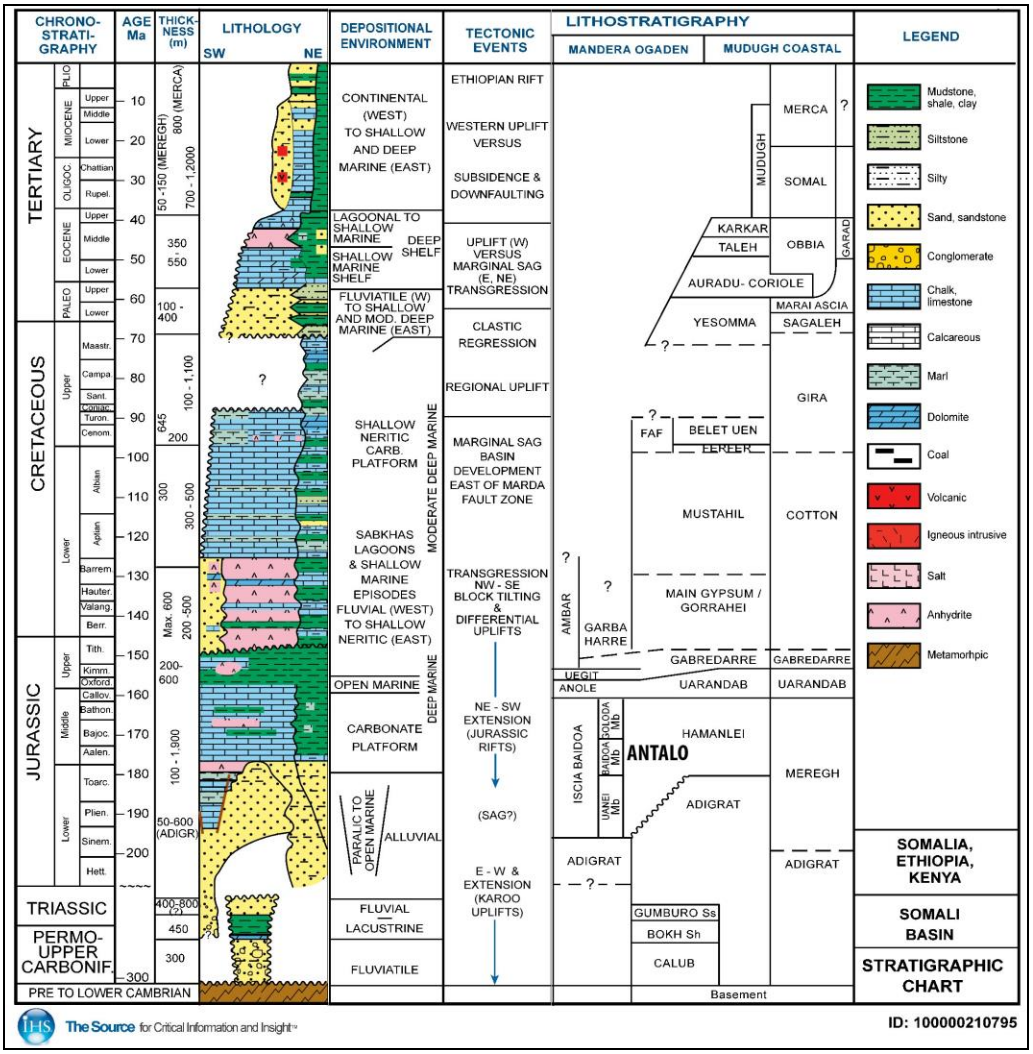

Figure 2. -- Lithostratigraphy and lithology between Mandera Ogaden in Ethiopia , South-West of the survey area, and Mudugh Basins in Somalia, South-East of the survey area (From Fugro Robertson Limited, 2007)

Table 1. Lithostratigraphic units present in the Phase 1 study area.

Name	Age	Description and lithology
Alluvial deposits on Basement complex	Quaternary	Weathered basement infilling streambeds made up of unconsolidated sediments originating from the upgradient metamorphic basement and Adigrat and Hamanlei Formations
Interfluvial volcanics	Tertiary	Paleo-river beds filled by basaltic lavas, and eroded after uplifting
Plateau Volcanics (basalts)	Tertiary (Oligocene)	Basaltic flows north of the study area, close to the Rift margin
Fissural Volcanics (basalts)	Tertiary (Eocene)	Fissured basalts outcropping along a visible trend of 130 km in the Karamara Range, most likely longer (250 km)
Auradu Formation	Paleocene-Oligocene	Finely crystalline, compact, hard, and usually tan to light-brown limestone with local thin gray shales; thickness up to 400-500 m in the western parts of study area
Jessoma Formation	Upper Cretaceous-Paleocene	Unconformably overlies the Belet Uen Formation; composed of red, brown, purple, and yellow sandstones; cross bedding is common and interpreted to be of fluvial (river) origin; loosely cemented fine to very coarse-grained sandstone with local gypsiferous beds at the base; unfossiliferous
Belet Uen Formation	Middle Cretaceous	Creamy to light grey limestones from neritic to locally reef origin, with intercalations of greenish grey glauconitic shales and green or brown sandstones, over a thickness from 87 to 232 m
Mustahil Formation	Lower Cretaceous	Shallow neritic carbonate platform transgressing over the Main Gypsum formation, with alternated limestones, sandstones and calcareous shale units. Thickness from 300 to 500 m
Main Gypsum-Gorrahei Formation	Upper Jurassic-Lower Cretaceous	Massive evaporite unit with gypsum, anhydrites, marls and dolomites, reaching thicknesses of 800 m in the survey area
Gabredare Formation	Upper Jurassic	Dark shale, calcareous shale, and gypsiferous limestone: upper 15 m fossiliferous, 20 m of thin-bedded alternating oolitic and shaly limestone with gypsum bearing shales, overlying 30 m of earthy ocher-colored limestones, 60 m of gypsum; 130 of finely crystalline, yellowish, partly oolitic limestone grading downward into 40 m of yellowish and gray marl containing flattened ammonite impressions
Urandab Formation	Upper Jurassic	Semi-regional shale made up of 55 m of gray, brown, and greenish gypsum-bearing shale intercalated with gray argillaceous limestone in the middle part, and similar shale in the lower 15 m;

		fossils common(abundant belemnites and ammonites). Thickness averaging 260 m in the survey area.
Hamanlei Formation	Middle Jurassic	Gypsum, limestone, dolomitic limestone, sandstone, shale, and calcareous shale; up to 250 m thick in study area.
Adigrat Formation	Lower Jurassic	Basal sands deposited during marine transgression; fine to coarse-grained, varicolored quartzitic, micaceous, cross-bedded, unfossiliferous sandstones, locally grading upward into sandy limestones with a commonly poorly cemented, but locally quartzitic, unfossiliferous; upper shale marks transition to Hamanlei Formation; thickness averaging 25 m in study area.
Basement Complex	Precambrian	Crystalline basement made of high-grade metamorphic rocks including granitic ortho-gneisses, quartzo-feldspathic and biotite gneisses, meta-gabbros, amphibolites and amphibole gneisses

3.3. Derived geologic map

Satellite-based derived information at a scale of 1:50,000 was used to improve the delineation of selected features of the existing geologic map of Ethiopia, at a scale of 1:2,000,000 (Kazmin, 1972), and to add new geologic and structural information, (fig. 3). Figure 4 presents the revised geologic map of the Phase 1 study area.

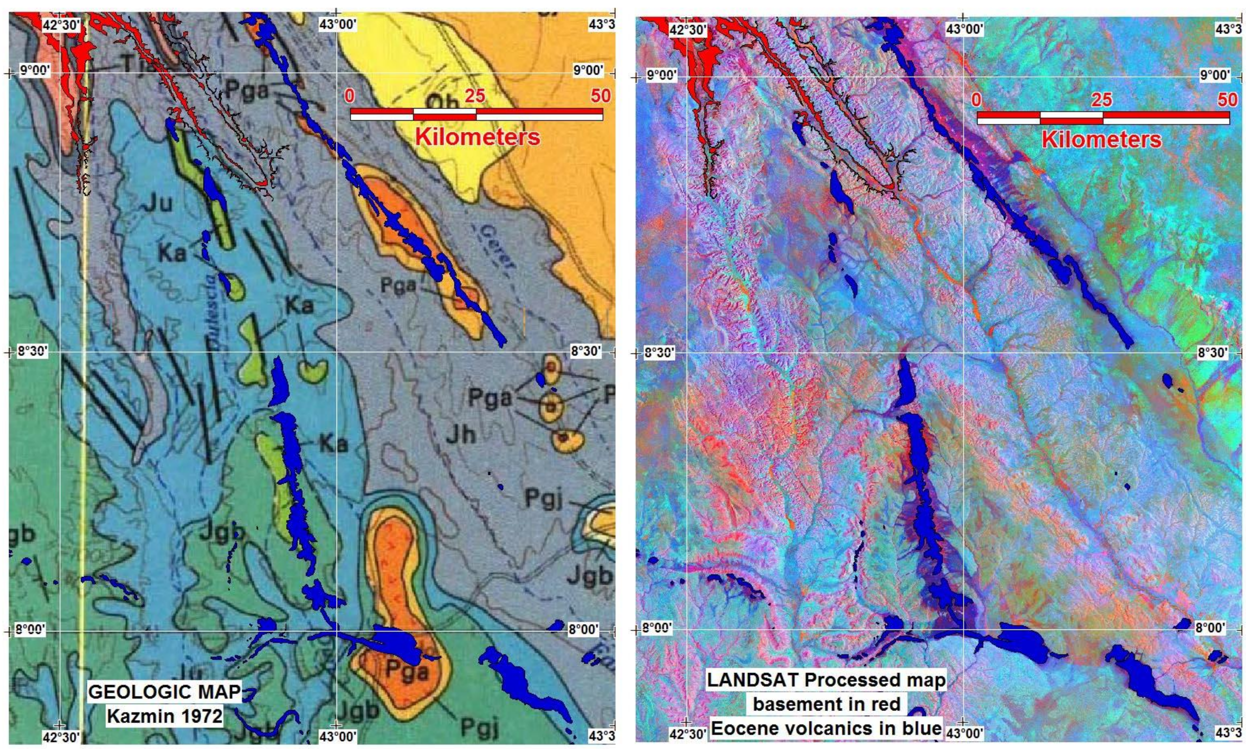

Figure 3. Comparison of published geologic map (left) with Landsat Sultan-processed image (right).

The signature of the Eocene basalts on the Landsat processed image coded in blue (fig. 3, right) and transferred onto the geological map (fig. 3, left). The signature of the basement on the Landsat image is coded in red (fig. 3, right) and transferred on the geological map (fig. 3, left), showing a shift to the east of several kilometers. Moreover, the geologic map shows a Lower Cretaceous clay, silts and sandstone unit (labelled Ka on fig. 3, left), which does not match the Eocene basalts signature on the Landsat Processed image (fig. 3, right).

Note that some geologic details present on the Landsat image are not presented on the geologic map. With the georeferenced information available from the Shuttle Radar Topography Mission (SRTM) data (Rodriguez and others, 2005), the precision is reduced to 30 m from several hundred meters or few kilometers on the geological map.

Beside more detailed and accurate new geological map, several other important features have been revealed such as three major N140°-160° elongated shear fracture zones known as the Marda Fault System, which have a major role in groundwater circulation from the water harvesting area of the highlands in the north, to the low plains of Ogaden Basin in the south.

The elongated fissural basaltic dike of the Karamara Range operates as a hydraulic barrier to groundwater flow, with a tight separation between the groundwater recharged within the Jerer watershed and the Fafen watershed.The Marda Fault System appears to generate major prospective areas for groundwater assessment.

Another major fracture system oriented N 60°, called the **North Shillabo Half Graben,** is filled with Korahe Gypsum which contributes to sealing the aquifers south of the 7^{th} parallel. These two major structural trends, the Marda Fault System and the Shillabo Half Graben, were mapped in 2006 (Fugro Robertson Limited, 2007).

Field trips in Jijiga and the Upper Fafen Valley have validated the new additions made to the existing geologic map. Due to security considerations, project staff were not authorized to travel to the southern part of the study area to ground truth. More field measurements of hydraulic head and other hydrogeologic properties are needed to improve upon this conceptual model of groundwater flow.

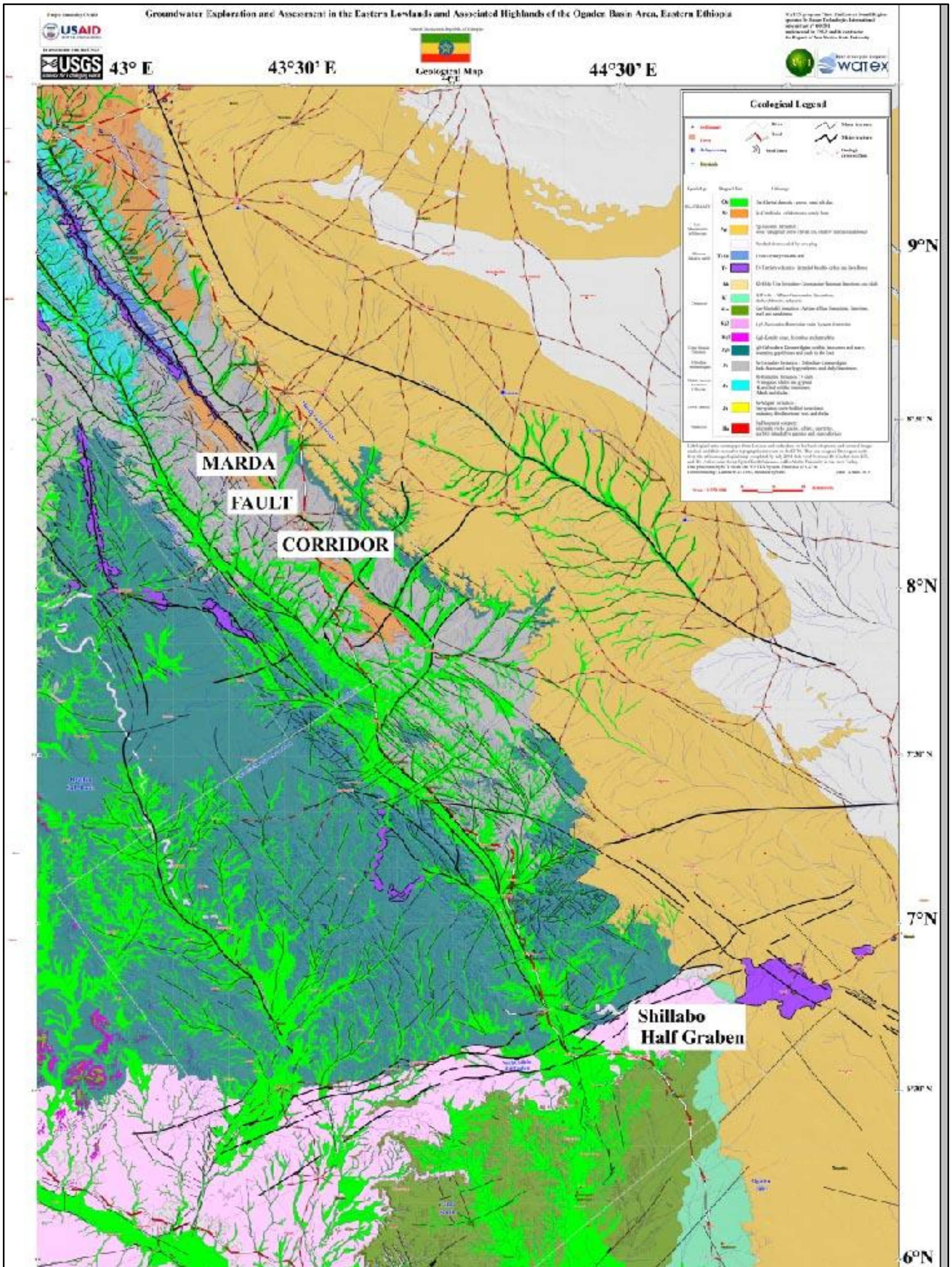

Figure 4. Revised geologic and structural map of the Ogaden Basin Area, Eastern Ethiopia based on processed Landsat 7 images (Sultan Processed), radar, SRTM and WATEX© Processed image. Digital map is presented at 1:250,000.

3.4. Geologic structure

The geologic structure of the study area is described in Gachet (2013). The following sections provide a summary description of the geologic structure.

3.4.1. General setting

Beginning in the late Cretaceous, uplift and fracturing occurred in northeast Africa resulting in: (1) regression of the Mesozoic sea and deposition of Cretaceous- to Tertiary-aged sedimentary rocks in the eastern Ogaden Basin (sandstones of the Jessoma Formation and limestones of the Auradu Formation), (2) eruption of flood basalts and subsequent volcanism forming the Ethiopian highland plateaus (such as the Jima basaltic magmas injected along the Karamara Range in early Eocene time), and (3) development of the East African rift systems including the Main Ethiopian rift, the Gulf of Aden, and the Red Sea rift. These events, accompanied by intense fracturing along the shear-distensive corridor of the Marda Fault System and tectonic uplift, caused major effects on erosion and sedimentation dynamics.

The Marda Fault System is a major continental structure that affects the survey area along a northwest-southeast oriented trend that extends from the northeastern Ogaden for about 900 km across the Belet Uen area in Somalia. The formation of the Marda Fault System down-warped the eastern Ogaden Basin in coastal Somalia and thus changed the pattern of sedimentation; it is also the apparent boundary between Mesozoic and Tertiary sedimentary deposits in the Ogaden Basin. The Marda Fault System is presumed to be a Precambrian structure later reactivated during Tertiary time. The Marda Fault System (fig. 4, fig. 5) played a major role in the development of surface-water drainages and the recharge of deeper aquifers. It has received little attention because it is too shallow for oil exploration and too deep for traditional hydrogeologic surveys; thus we emphasize the Marda Fault System in the current report.

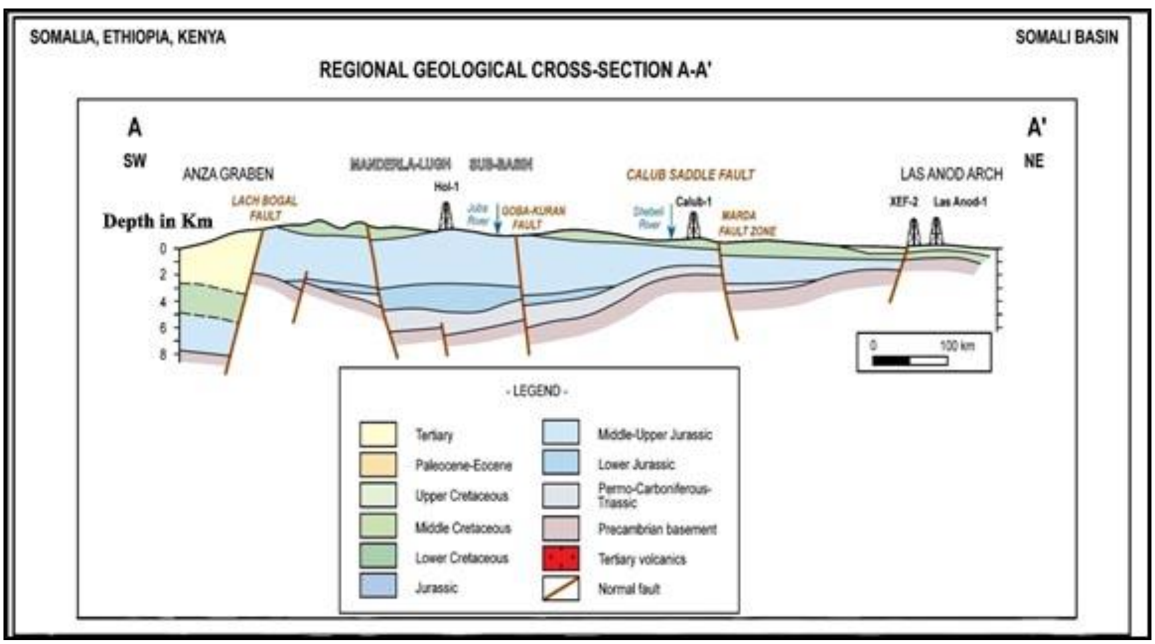

Figure 5. Cross section illustrating the southern part of the Marda Fault System between the oil wells of Calub-1, XEF-2, and Las Anod, outside of the current study area (see Sestini 1993 from IHS Petroconsultants in Fugro Robertson Limited, 2007).

3.4.2. Lineament (fracture) Analysis

Among thousands of fracture traces extracted from radar imagery, the SRTM, and the slope map, the main fracture traces have been selected to illustrate the structural type that is affecting the entire area. It appears that the major N 140°-160° pattern of elongated fractures known as the Marda Fault System, is the result of three major shear structures called ”flower structures”. They each control a distinctive watershed and thus have a major influence on groundwater flow drainage patterns (fig. 6):

- Flower structure 1, in ***red***, controls the Uardere watershed;
- Flower structure 2, in ***blue***, controls the Jerer watershed; and
- Flower structure 3, in ***yellow***, controls the Fafen watershed.

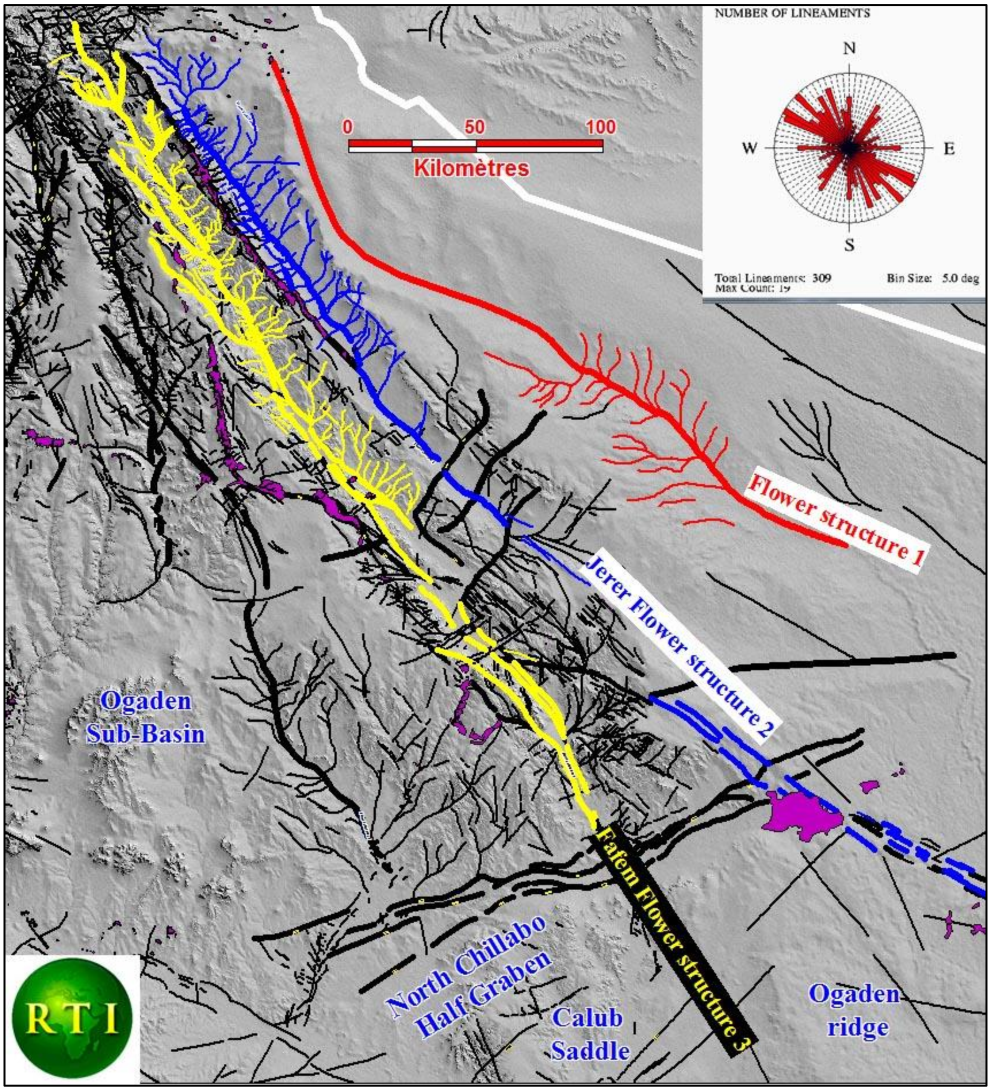

Figure 6. SRTM shaded image with detailed fracture patterns on the survey area. Geologic structure has strong control on drainage patterns.

The Jerer and Fafen watersheds are separated by the Karamara Range, an elongated basaltic dike (purple on fig. 6), that operates as a groundwater-flow barrier that separates groundwater in the Jerer and the Fafen watersheds, a concept that is supported by sparse measurements of hydraulic head. Because of this, the Marda Fault System is a promising area for groundwater assessment.

Nearly 200 km downstream from their origins, these two watersheds are dislocated by N. 45°-60° E. trending major fracture zone whose presence were identified using remotely sensed data. Groundwater flows along these fractures in the southern part of the Fafen Valley. More study is needed to confirm this conceptual model of groundwater flow.

The block diagram (fig. 7) illustrates flower structure 2 (blue on fig. 6), which controls the Jerer watershed, and flower structure 3 (yellow on fig. 6), which controls the Fafen watershed.

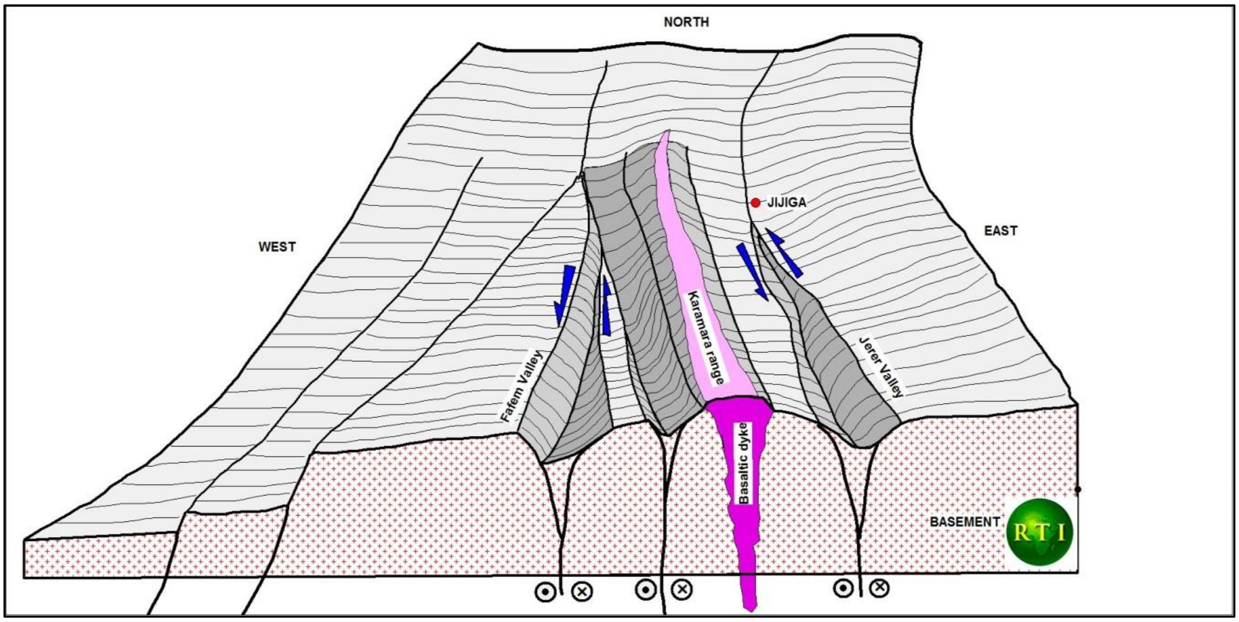

Figure 7. Schematic block diagram illustrating flower structures 2 and 3, for Jerer Valley and Fafen Valley. Not to scale. The grey lines suggest likely surface morphology of the basement.

4. WATEX© (WATerEXploration) Process

The WATEX© process is a geo-scanner designed to detect potential aquifers by indicating buried moisture as bright areas on processed imagery. This system integrates remote sensing (hyper-frequencies and optical frequencies), geophysical and conventional hydrogeologic assessment techniques, and geographic information systems. It has been used to map and assess potential alluvial aquifers, conductive fractures, and deep aquifers in a wide range of situations, including conflict zones, emergencies, and early recovery situations and has been applied successfully in several parts of the world since 2004 for groundwater exploration. WATEX© image processing is a based on a new algorithm for soil moisture detection, (Gachet, 2013).

The WATEX© process is an expert system which integrates, beside the WATEX© image, optical and radar remote sensing, geologic and geomorphologic data, climatological data, SRTM, and several other derived products and ancillary data (Gachet, 2008; Gachet and Verjee, 2006). Geophysical information is also used whenever available such as gravimetric, magnetism, and seismic data from oil companies, and all existing water and oil wells information from GIS databases (provided by IHS-Geneva in Fugro Robertson Limited, 2007). The output of the algorithm is then interpreted by experts and a map of potential water-well drill sites is inferred and generated as a final product to aid drilling companies to more accurately locate productive water boreholes. The work and results presented in this section are covered in more detail in Gachet (2013).

4.1. WATEX© methodology

The WATEX© System methodology is a multi-step process. The first phase of analysis maps features that directly or indirectly affect the likelihood of finding large, renewable aquifers. Such features relate to the geologic context, weathering processes, vegetation cover, watershed boundaries, precipitation, slope values, and river profiles (in order to estimate the energy level of sediment transport along wadis or other streambeds).

With this work, the following parameters are considered (described in detail below):(1) the size and shape of the WATEX© brightness anomaly, (2) the area of the watershed upstream available for aquifer recharge, (3) geology of the aquifer, (4) major fault structures, and (5) riverbed slope and structural dip. Once these five parameters are obtained it is possible to detect and make an overall assessment of the most promising aquifers.

To evaluate the suitability of areas for the establishment of settlements, the WATEX© process also considers the proximity of existing cattle ranching, good soils and crop farming, and indigenous settlement. This part of the analysis prioritizes sites that are close to roads, agricultural land, and wood fuel sources; environmental impact studies are also essential to assess sustainability. Aquifers with a high suitability are then examined to ensure close proximity to a suitable well location, because RTI recommends that new settlements be within 500 meters of at least one well (The Sphere Project, 2004).

4.1.1. Size and shape of the WATEX© bright anomaly

For alluvial aquifers the size of the radar anomaly is an indicator of the volume of water in storage. For the current study, only radar anomalies with a minimum area of 120,000 square meters (m^2) were considered. This minimum area indicates potential alluvial aquifers that could sustain communities of 20,000 persons per year.

Without further analysis it is almost impossible to know if anomalies are associated with subsurface reservoirs or with surface moisture in clays or silts. Additionally, saturated fractures absorb and reflect microwave signals differently from unsaturated fractures, and fractures traces that appear on WATEX© images with a white and bright tonality indicate that they are conducting groundwater. When located in a sedimentary environment these fractures infer the presence of deeper and more prolific aquifers in certain geologic and structural conditions. For example, discharging fractures can be important indicators of deeper artesian aquifers. However, these fractures may also be drilled to access shallow groundwater, (Gachet, 2013).

4.1.2 Amount of upstream watershed drainage

By definition, each potential target aquifer must also receive recharge. It is assumed that such recharge comes largely from upstream and up gradient watersheds that supply at least

100,000 cubic meters per year (m^3/yr) of recharge to the aquifer. Assuming that only 10 percent of the precipitation that falls in the watershed is recharged to the aquifer, at least 1 million m^3/yr of water must fall as precipitation. Further study is needed to characterize groundwater recharge and surface water – groundwater interaction.

4.1.3. Hydrogeologic Considerations

The geology of individual units influences how groundwater enters, flows through, and is stored within an aquifer. The potential for alluvial sediments to be aquifers depends on the properties of the sediments that comprise the aquifer; these properties include grain size and distribution, lithology, and stratigraphy. An example of geologic properties influencing groundwater flow and storage is weathering of basaltic rock – basaltic rock typically weathers to clay and colloids, reducing reservoir porosity and permeability. Alternatively, granitic rocks, quartzite, and sandstones can themselves store or can produce gravels that can store large volumes of water. Similarly, the primary (intergranular) or secondary (karst or solution) porosity of an aquifer depends on their geologic origin, structural history, and diagenesis through time. Careful mapping and understanding of the paleogeography and the geologic and structural context is crucial to understanding and assessing the hydrogeology.

4.1.4. Major fault structures

In the study area, the linear river system controlled by graben-like structures is likely to be 60 m to 90 m thick multi-layered aquifers, particularly when downstream of an area with sufficient recharge. The age of these structures is relevant in that the structures must be of sufficient age (several thousand years to millions of years) to allow adequate sediment accumulation to form regional aquifers.

4.1.5. Riverbed slope and structural dip

For alluvial aquifers, the optimal riverbed slope within wadis for sufficient vertical recharge ranges between 1 to 4 percent (Darfur calibration during the field works and drilling results from RTI 1995-1998). Very gentle or flat slopes (less than 1 percent) may allow clay or silt accumulation, thus limiting infiltration and thus recharge. Overly steep slopes (greater than 4 percent) may result in erosion and transport of gravels that are essential for recharge. The Jerer and Fafen Rivers have average slopes of 3.3 to 3.8 percent thus indicating that these river basins have potential for the recharge and storage of groundwater along their length (Gachet, 2004).

4.2. Summary of WATEX© results

For the Phase 1 study area, an additional 41,000 km^2 has been added as the southern continuation of the 16,323 km^2 ("Flemish") zone of the Upper Fafen-Jerer River system in the Somali Region of eastern Ethiopia (fig. 1). The WATEX© System was used to map all potential shallow alluvial groundwater, conductive fracture traces, and deep aquifer structures. In addition to these features, this study also mapped geological units and structures, soils, and potential recharge zones, thus enabling a full assessment of hydrogeology of the survey area. The hydrogeology has been assessed in terms of precise locations, potential storage capacity, and recharge.

4.2.1. East Karamara aquifer structure

A major finding of the WATEX© process is the identification and assessment of deep-seated aquifer structures. These structures have apparently not been described in previous literature.

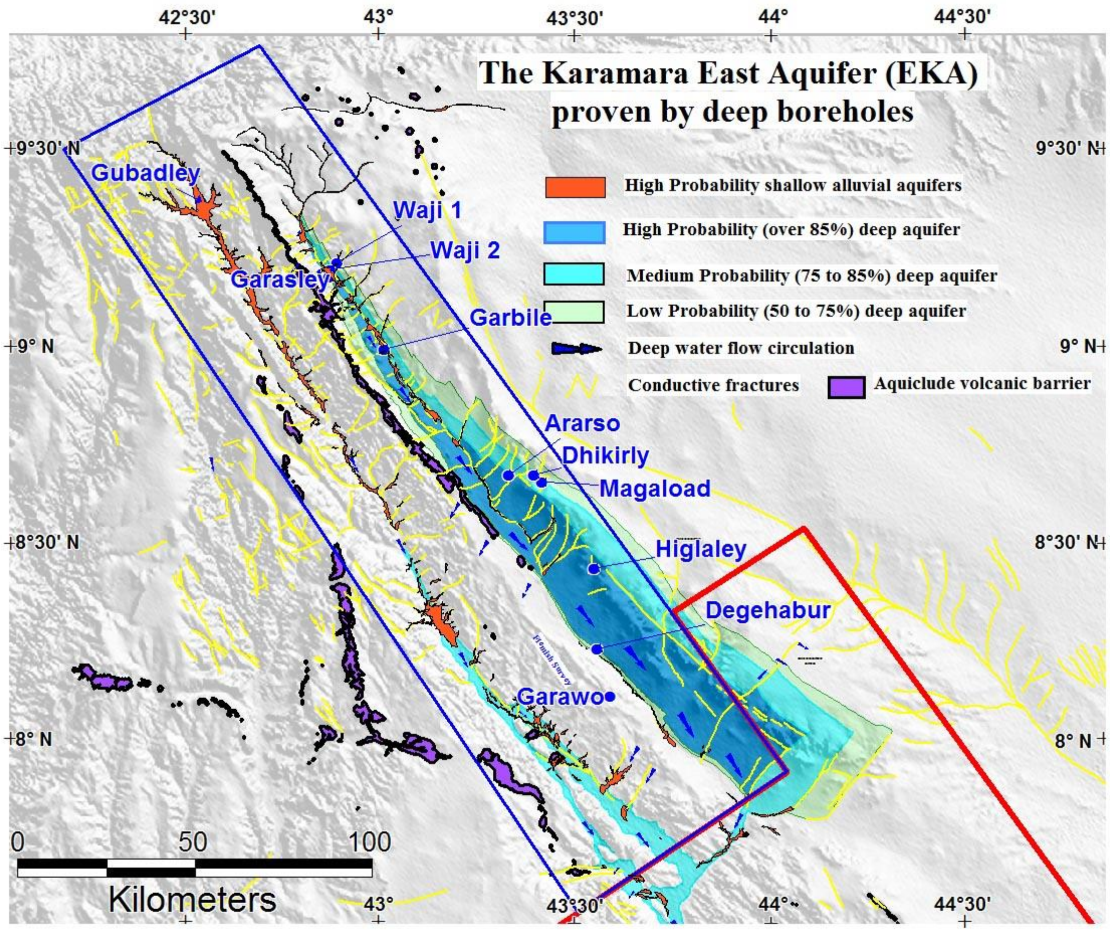

Figure 8. WATEX© mapping of the East Karamara aquifer structure at or near land surface, (Gachet, 2013). The aquifer extends in a southeasterly direction in the subsurface. Adigrat-Hamanlei groundwater flow direction is derived from a conceptual model of groundwater flow, which is based on sparse available data.

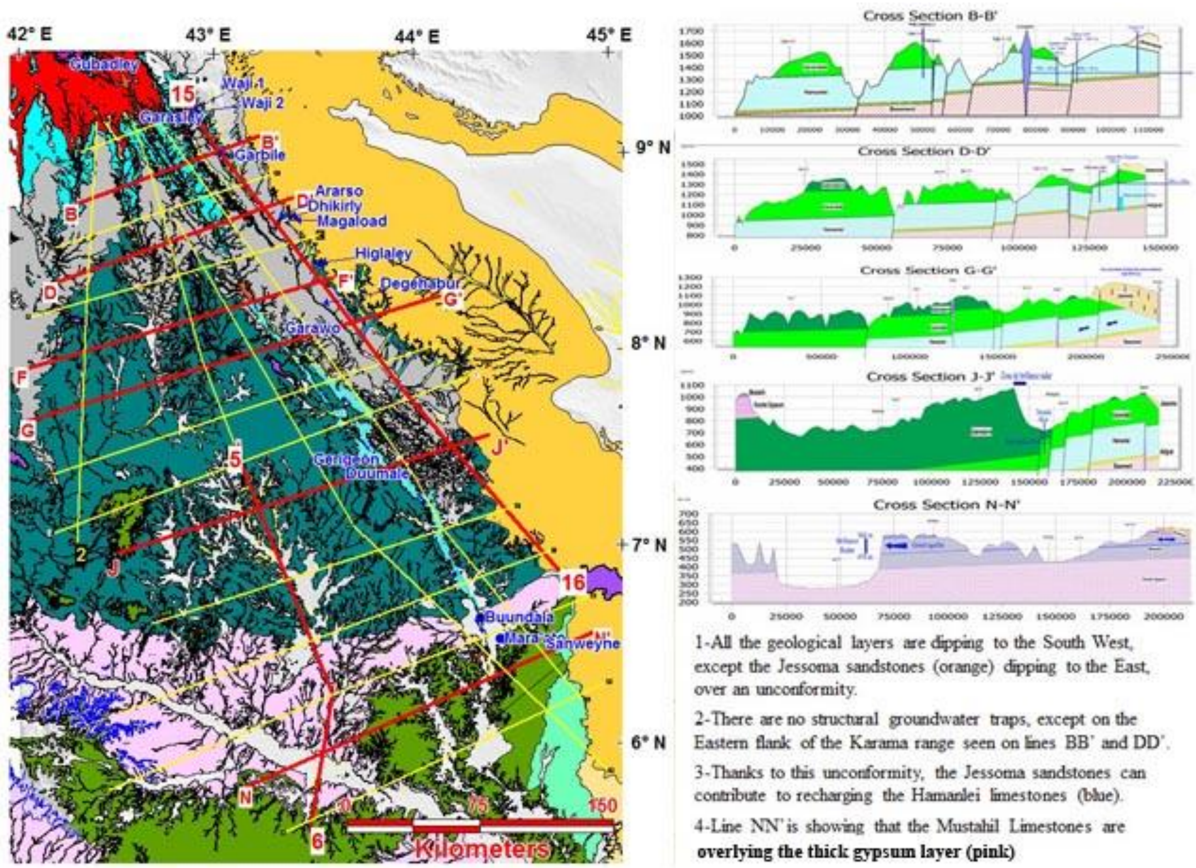

Figure 9. Cross sections constructed by Gachet (2013) depicting the East Karamara aquifer structure. Digital geologic map is presented at 1:200,000 scale.

The East Karamara aquifer (EKA) structure is a major structure east of the Karamara Range which may potentially store several billion m^3 of groundwater. It lies at a depth of 50 to 700 m below land surface along the Jerer Valley and ranges from 1 to 35 km wide and 200 km long. The structure is composed of the Hamanlei and Adigrat Formations. It is bounded by low permeability units of the basaltic Karamara Range to the west, uplifted granitic basement to the east, and vertically confined by the shales of the overlying Urandab Formation. Groundwater flow is to the southeast. The presence of confined conditions is highly probable in the southern half of the aquifer as indicated by the discharging fractures downstream. This prominent structure continues to the southwest, passes near Birkot, then along the Fafen Valley to a gypsum barrier that represents a major discontinuity in the hydrogeologic system of the study area.

The estimated storage capacity in cubic meters/volumes of the EKA structure was approximated with the rule of the thumb (Gachet, 2012) within a range from 2.7 to 30 billion m^3. Such a rough estimation is reflecting lack of data related to limited number of boreholes which should be regularly spread along 200 km. Each well should be carefully monitored by well loggers (yields, salinity, SWL, drawdown) and water dated to evaluate the rate of replenishment. Phase II will be necessary to ensure a broader WATEX coverage to better understand the replenishment process and implement the hydrogeologic model of such a large structure. This preliminary finding of a potentially productive hydrogeologic structure significantly raises the prospect for improving the livelihoods of the nearly 1 million people living in this water-scarce area, most of whom live in poverty and have limited access to basic services and clean water; further study is needed.

With additional work and data from new boreholes, including well logs, the understanding and refinement of the hydrogeologic framework will continue to improve. Among the most important information needed to improve the hydrogeologic framework is the analysis of existing seismic data (not accessible during Phase 1) and the collection of improved rainfall and evapotranspiration data using new meteorological stations well distributed within the watershed boundaries. In this region, where most known sedimentary aquifers are uplifted tabular plateaus, the identification of the East Karamara aquifer opens the possibility of finding similar structures in the Somali region in particular and in the Horn of Africa in general.

4.2.2. Other features

In addition to the East Karamara aquifer (EKA), the WATEX© process accurately mapped a broad range of minor geologic features and aquifers scattered throughout the study area such as:

- Discontinuous alluvial aquifers which have been completely mapped and integrated into the GENS,
- Aquifers of eolian origin that may potentially supply communities of several hundred persons,
- Perched aquifers of fluvial deposits and sealed by basalts that may be productive, and
- Potentially productive areas of bedrock fracturing that may also indicate deeper potentially productive aquifers.

A more detailed discussion of these features may be found in Gachet (2012).

5. GEOCHEMISTRY

5.1. Available Information from Reports and UNESCO Database

Of the 75 reports on geology, geophysics, groundwater, water-quality, and water resources in Ethiopia that were supplied to the USGS, 38 reports contain water-quality information. The type and amount of water-quality information available varies from report to report. Most reports present major findings from water-quality analyses, such as water-type information, comparisons of samples with water-quality standards, and discussions of geologic influences on water chemistry.

Information from these reports is valuable in understanding the geochemistry of groundwater in Ethiopia. However, the information contained in these reports is difficult to synthesize into a workable database for several reasons. The majority of reports do not provide the original analytical data and/or sufficient location data needed for interpretation. Analytical and collection techniques are rarely mentioned and detection limits and analytical methods vary by report. The majority of water-quality data also lack collection dates and metadata such as well depth and completion that are needed for interpretation.

The UNESCO database provides water-quality data for 379 groundwater samples that were collected and analyzed over an unspecified time period. In general, this database contains adequate location and water-quality information for interpretation. Cation-anion balance (or charge balance error) is the percent difference between total cation and anion charges for a sample. In water with specific conductance greater than 100 µS/cm as was generally found here, if the ion balance is not within 10 percent, then either non-analyzed constituents are present in the water or errors occurred during sampling or analysis. The majority of the analyses in the UNESCO database had acceptable ion balances, which indicates that the database is suitable for some level of interpretation with some degree of quality assurance needed for quantitative analysis of the data.

5.2. Findings from Previous Reports

Previous reports present a variety of water-quality information and interpretations about various influences on water quality and its suitability for drinking and irrigation. Some analytical results describe localized water-quality issues, such as elevated fluoride, chloride, nitrate, and sulfate concentrations and the presence of bacteria (such as fecal coliform). Concentrations of some analytes, such as nitrate and fluoride, exceeded World Health Organization standards and may be indicative of regional water-quality issues such as elevated concentrations of nutrients.

Water type, as determined by the concentration of dominant ions in solution, can be used to interpret geochemical processes that affect water quality. One method of determining water type is to plot analytical results on a Piper (or trilinear) diagram: water type is determined by where an analysis plots on the diagram. Groundwater analyses from various reports and the UNESCO database were plotted on a Piper diagram to determine water type (fig. 10). Geochemical processes that control dominant ions in solution include dissolution of minerals by groundwater and the presence of groundwater from different sources of recharge. Such interpretations of water type and geologic controls on water quality will be used in Phase 2 interpretation of geochemical data.

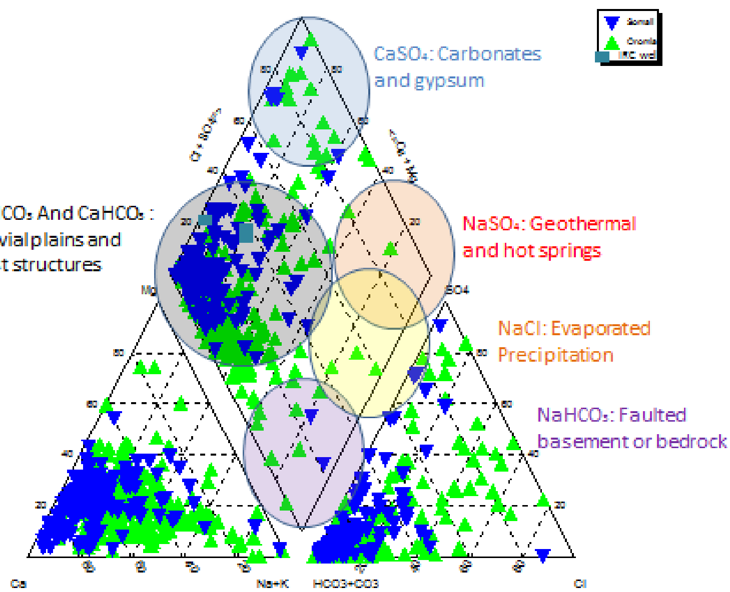

Figure 10. Piper diagram with UNESCO data and geochemical interpretations from previous reports.

5.3. Findings from country-wide database

A database was compiled from water-quality data presented in various reports and the UNESCO database. This newly compiled database includes analytical data, location information, and dates of collection (if available). Sampling locations include other areas of Ethiopia but provide a baseline set of water-quality data that can be used for interpretation of geochemical influences on groundwater.

For example, data from the UNESCO database was plotted in a Giggenbach triangle, a tool used to interpret water-rock interaction (fig.11). This simple plot shows that most of the samples collected as part of the UNESCO study have not undergone significant water-rock interaction.

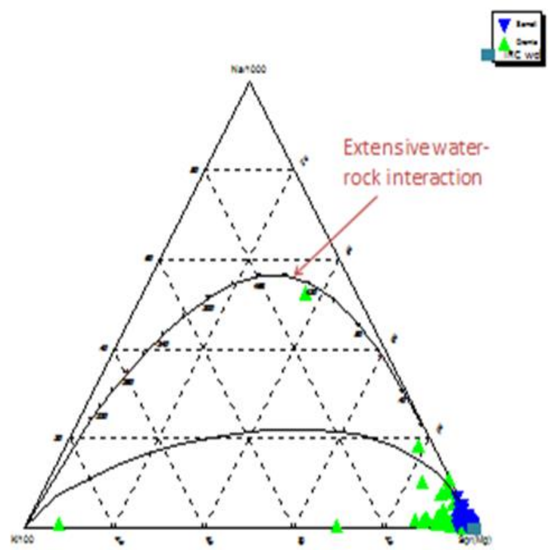

Figure 11. Giggenbach triangle of UNESCO data.

5.4. Analytical results from USAID wells drilled by IRC

Water samples were collected in June 2013 from the USAID/IRC wells at Araso, Garawo, and Degehabur. The Araso sample was analyzed for stable oxygen isotopes and all three samples were analyzed for tritium. Groundwater samples were not analyzed for deuterium, but such analysis would be useful in future sampling.

Although it is difficult to use one sample to interpret sources of recharge, the oxygen-18 value of the Araso sample was compared to local meteoric water lines to provide additional insight. Many factors can affect the isotopic composition of a sample and this interpretation is made with the assumption that no fractionation has occurred since recharge. The oxygen-18 value of 2.1 percent suggests a mixing of waters of different origins. While the isotopic signature resembles the meteoric water line representing monsoonal precipitation originating in the South Indian Ocean, , its relatively heavy signature probably suggests a mixture with a second source of water. This second source of water resembles precipitation that originated in a wetter, cooler climate, possibly in the past (at least 10,000 years before present).When the Giggenbach triangle plot described in the previous section (fig. 11) is considered, the most likely explanation is a mixture of older water and water more recently recharged.

The tritium analysis was determined for the three samples (Ararso, Garawo, and Degehabur) by the Addis Ababa University Department of Earth Science Isotope Hydrology Laboratory using electrolytic enrichment and liquid scintillation decay counting.

Samples from Ararso, Degehabur, and Garawo had activities of 2.47, 1.97, and 1.55 +/- 0.5 tritium units (TUs), respectively. No detection limit was reported with the test results. These data indicate that there is detectable tritium, indicating that some portion of groundwater was recharged within the last 50 to 60 years (possibly decayed bomb-pulse tritium from the 1950s to 1960s). Because atmospheric tritium from natural, cosmogenic sources can be up to 10 TUs (Clark and Fritz, 1997), it is difficult to assess the source of tritium (cosmogenic versus bomb-pulse tritium) at such low activity levels. Analysis of the tritium/helium-3 ratio, though very difficult, would allow for differentiation of the two sources thus refining recharge timing estimates, and will be considered for further study

A possible interpretation of these analytical results is that the water reflects a local, recently (50-60 years) recharged source of water. Another interpretation is that a sample is a mixture of regional and local water sources in a regional aquifer containing older water. If any water was recharged to the regional aquifer through the limestone, the presence of younger water would be expected due to short residence time in the carbonate-rock aquifer. Our conclusion, based on these limited data, is that the Ararso and Degehabur wells data (with higher TU activities) suggest that they are drilled within the regional aquifer structure, which probably receives more direct recharge from precipitation than the Garawo well (with a lower TU activity) that is drilled on the margin of the regional aquifer structure.

6. HYDROGEOLOGIC FRAMEWORK

Phase 1 study results indicate that groundwater flow is strongly influenced by the physical framework of the system, which is characterized by aquifers, confining units, and flow barriers. Groundwater flows through a diverse assemblage of rocks and sediments in the region, and geologic structures exert significant control on groundwater movement as well.

This section describes the development of a hydrogeologic framework of the combined "Flemish" and Phase 1 study areas, largely based on the work of RTI. The hydrogeology is based on review and interpretation of existing and new surface geology and structure, available drillers' logs for wells and boreholes, previous investigations, and data collected at wells. The description of the hydrogeologic framework includes RTI's production of an updated digital geologic map of the study area(s), RTI's hydrogeologic cross sections, descriptions of the hydrogeologic units, estimates of hydraulic conductivity of the primary aquifers, and an estimate of the capacity of the primary aquifers.

Additionally, various reports on the hydrogeology of Ethiopia were examined, and GIS data (cultural, geology, and hydrology) and water-level and water-quality data were compiled, as described in the following section.

6.1. Water-level information

Water-level data were compiled from UNESCO and IRC. As in any project, the compilation and quality assurance of data is a time consuming task. The quality of data, even the basic borehole information presented by UNESCO, is difficult to assess. For instance, geographic locations are uncertain because coordinate systems are neither consistent nor identified, coordinates do not match well logs, or the coordinates do not fall within the area the well is identified as being in.

Locations of wells in the UNESCO database are suspect because it is a simple compilation with little quality assurance (Dr. Seifu Kebede, Professor of Earth Science, University of Addis Ababa, Ethiopia, oral commun., 2013). Some well locations plot in other parts of the world; many plot in Ethiopia but are outside the UNESCO study area (fig. 12). Because of this, the authors were not able to construct credible water-level surface maps. Similarly, water-quality data is difficult to interpret because of the well location issues.

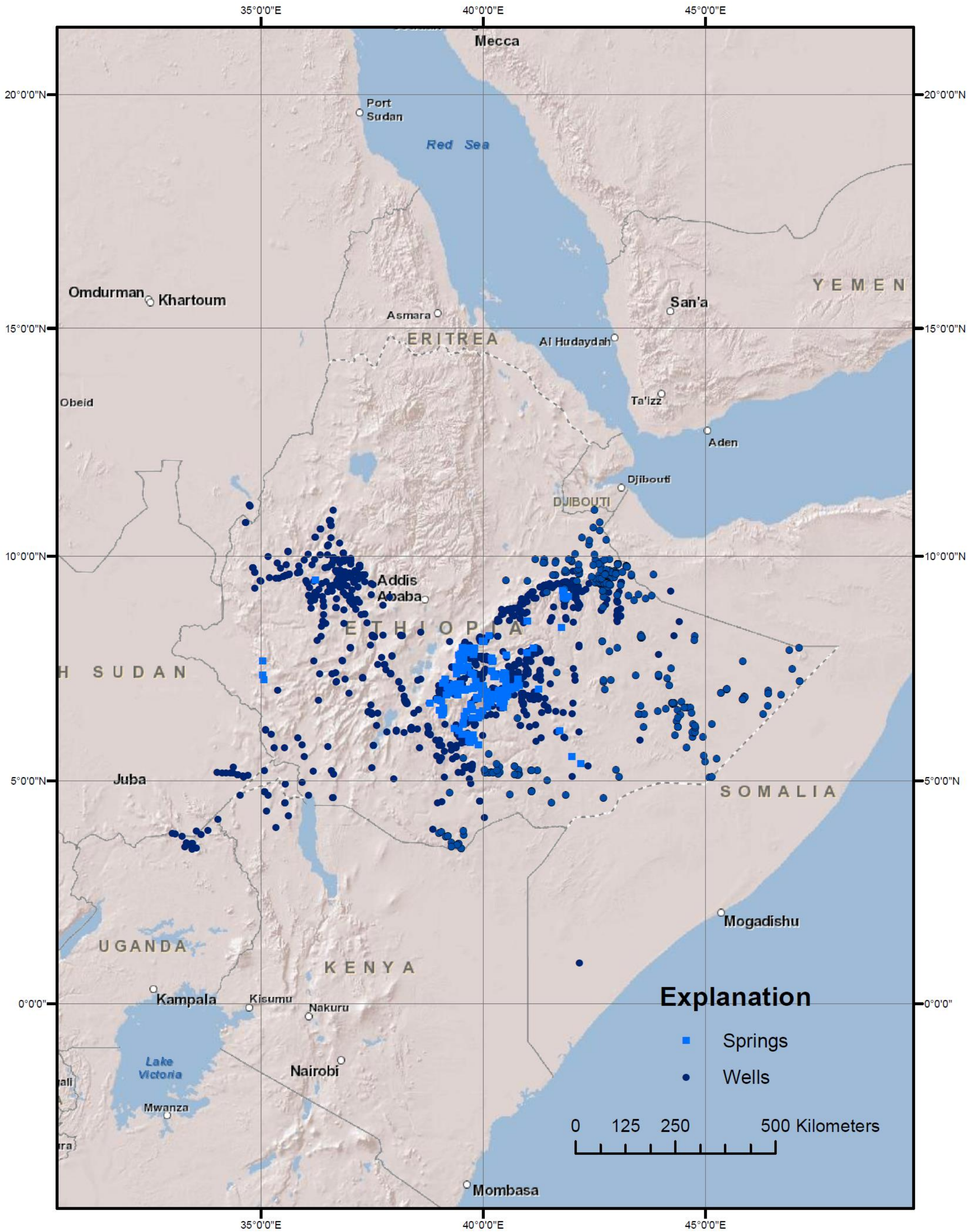

Figure 12. Well/ borehole and spring locations from the UNESCO database.

Figure 13 shows water levels in USAID wells drilled in the Phase 1 study area by the International Rescue Committee, written commun., 2013. These data were surveyed by IRC using a global positioning system, and are thought to be reliable. Groundwater-level altitudes in these and other wells drilled within the Phase 1 study area are lower in both the Fafen and Jerer Valleys to the south, which may suggest a general south to southeast groundwater-flow direction trending down the valleys (fig.13, table 2).Because of the geologic and structural complexity in this area, sparse measurements, and potential error in determination of the land-surface altitude, there is a large degree of uncertainty as to whether all of these groundwater levels represent a single surface. For example, laterally discontinuous and fractured basalt underlies the Karamara Range. Differences in the water table on either side of the Range may suggest no lateral flow through the basaltic dike. More boreholes and associated geology and water-level measurements in Phase 2 will help to assess the effect of the Karamara Range on groundwater flow.

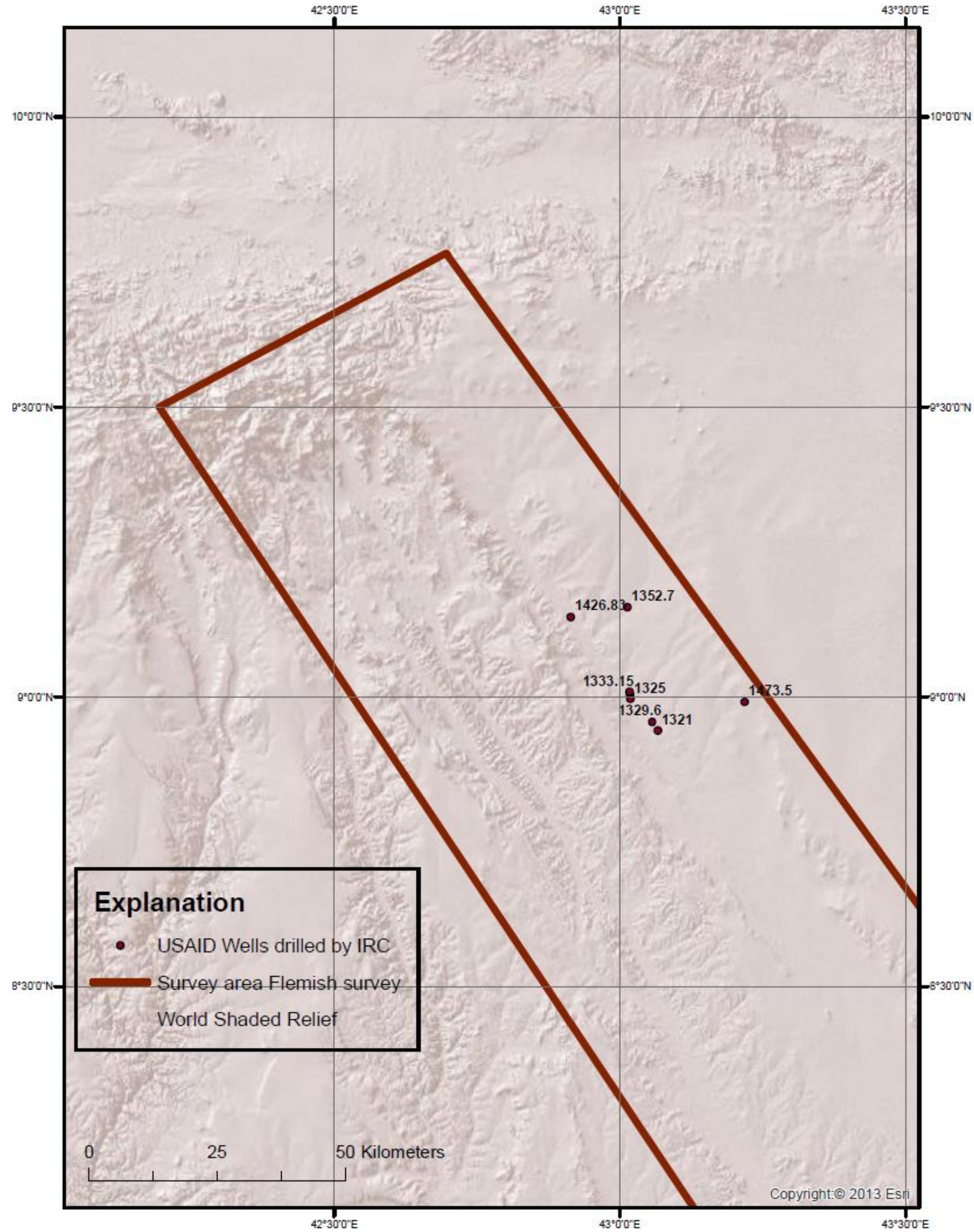

Figure 13. Water levels data from USAID/IRC wells drilled in the northern Jerer Valley. Note that groundwater altitudes suggest groundwater flow to the south and east.

Table 2. USAID wells drilled by IRC in the Jerer Valley [m, meters; amsl, above mean sea level]

Borehole name	Latitude (WGS 1984)	Longitude(WGS 1984)	Land surface elevation (m, amsl)	Well depth (m)	Depth to water (m)	Water level altitude (m, amsl)
Adaley	42.9142	9.13799	1,508	230	81.1	1,426
Aranadka	43.2180	8.99081	1,600	292	126	1,473
Dhurwaale 2	43.0665	8.94171	1,420	254	99	1,321
Harre 2	43.0132	9.15464	1,560	259	207	1,352
Qaaxo (EB1)	43.0175	9.00326	1,412	200	83.8	1,328
Qaaxo (EB2)	43.0167	9.00826	1,417	177	83.8	1,333
Qaaxo (PB1)	43.0181	8.99614	1,410	186	85	1,325
Xaaxi	43.0570	8.95642	1,424	250	94.4	1,329

6.2. Hydrogeologic units

The rocks and deposits forming the hydrogeologic framework for a groundwater flow system are termed hydrogeologic units. A hydrogeologic unit has considerable lateral extent and has reasonably distinct hydrologic properties because of its physical (geological and structural) characteristics. An aquifer is “a geologic unit that can store and transmit water at rates fast enough to supply reasonable amounts to wells” (Fetter, 2001, p. 95).The water-yielding materials in the Phase 1 study area are in the Jerer and Fafen Valleys, and consist primarily of unconsolidated alluvial deposits. Consolidated (bedrock) carbonate rocks and sandstones that underlie the unconsolidated alluvium or are exposed directly at the surface may be a source of water if the consolidated rocks are sufficiently fractured or have solution openings. Three principle rock types form aquifers in the Phase 1 study area: carbonate, sandstone, and alluvial sediments. Table 3 presents the lithostratigraphic units classified as aquifers or confining units. The primary bedrock aquifers are found in the Hamanlei and Adigrat Formations (highlighted in Table 3).

Table 3. Description of major hydrogeologic units in the Phase 1 study area.

Lithostrati-graphic Unit	Description	Hydrogeologic Unit classification	Comments
Alluvial deposits and volcanic rocks	Unconsolidated basin-filling deposits and surface volcanic flows	Aquifer	Volcanics may serve as aquifers where fractured or scoriaceous; where dense and unfractured as confining units
Karamara volcanics	Tertiary-aged basalts	Barrier in north, leaky in the south	Where unfractured in the north of the study area they act as a confining unit or a barrier to flow where they extend above land surface
Jessoma Formation	Cretaceous-Tertiary sandstones	Aquifer	May contain a lower confining unit; serves as a major recharge area on the eastern edge of study area
Mustahil Limestone	Cretaceous carbonate rocks and alternating sandstones	Aquifer	--
Korahe Formation	Cretaceous gypsum and shales	Confining unit/barrier	--
Urandab Formation	Jurassic shales and mudstones	Confining unit	Main confining unit above the Hamanlei Formation aquifers
Hamanlei Formation	Jurassic carbonate rocks	Aquifer	High-quality aquifers due to karstification; surface exposures act as recharge zones
Adigrat Formation	Triassic-Jurassic sandstone	Aquifer	Good-quality aquifers; surface exposures act as recharge zones in the northern part of the survey area
Basement	Crystalline metamorphic rocks	Impermeable basement(unless weathered)	Base of probable aquifers

The cross sections from Gachet (2013) were scaled and oriented in three-dimensional (3D) space (fig.14) to:

- Assess the spatial relationships of the sections where they intersect, and
- View the spatial relationships of the hydrogeologic units as related to hydrologic information.

A "proof-of-concept" of the utility of a 3D hydrogeologic framework model was constructed using only cross section data for a limited number of hydrogeologic units in the northern part of the Phase 1 study area. This was done due to time and data constraints during Phase 1. Phase 2 will improve upon this conceptual model. Figure 14 shows the location of data digitized from the cross sections and the resulting hydrogeologic framework model. This visualization is schematic only since it was not constructed using all available data sets; notably, this framework model from Phase 1 does not incorporate topography, well data, or geologic structures. Furthermore, it represents only three of the hydrogeologic units: Adigrat and Hamanlei Formation aquifers and the Urandab Formation confining unit.

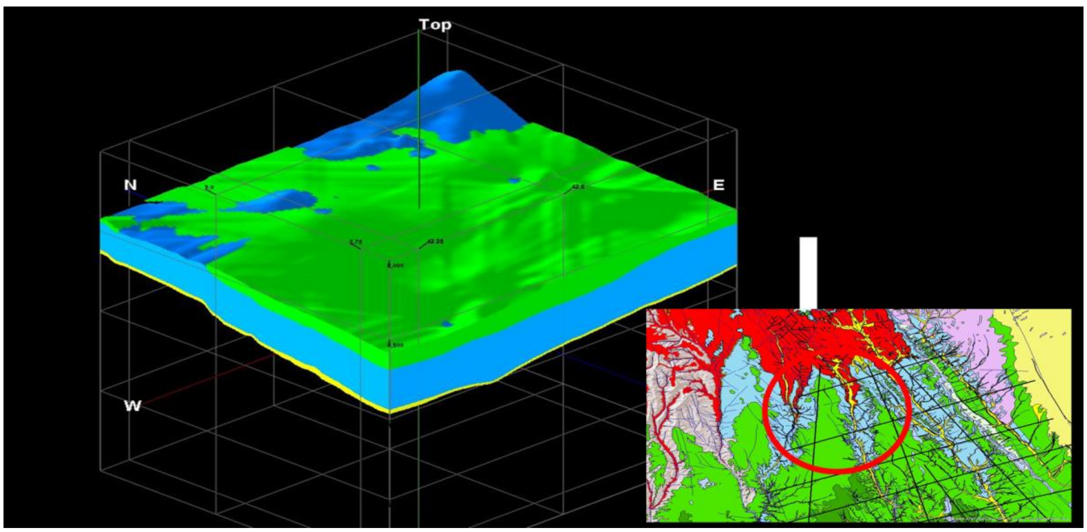

Figure 14. Proof-of-concept of a 3D digital hydrogeologic framework model of the northwestern part of the Phase 1 study area for the Adigrat Formation (yellow), Hamanlei Formation (blue), and Urandab Formation (green) using limited data (cross-sections from Gachet, 2013).

6.3. Hydraulic properties of primary aquifers

Transmissivity is a measure of how much water can be transmitted to a well and is determined from aquifer tests. Without knowing aquifer thickness transmissivity values are relative—larger values indicate more prolific aquifers. Table 4 presents geologic and hydraulic property (transmissivity) information for selected wells that occur in the western Jerer Valley near Jijiga. Wells listed in Appendix 1A of OWWDSE (2007) that possessed location, elevation, total depth, lithology/geologic unit, depth, and transmissivity estimates were included in table 4. Only wells completed in alluvium, limestone (by combining the Urandab, Hamanlei, and Adigrat Formations into one unit), and basement were included. The reported alluvium transmissivity values are about 45 meters squared per day (m^2/d).The combined Urandab, Hamanlei, and Adigrat Formations unit have an average transmissivity value of 75 m^2/d with a range of 2 to 350 m^2/d. The single local well in table 4 completed in the granitic and metamorphic basement unit has a reported transmissivity of 116 m^2/d. It should be noted that because this basement well produces water, it was probably drilled into either fractured or weathered basement that acts as a local aquifer.

Table 4. Well descriptions and reported hydraulic properties for wells in the western Jerer Valley near Jijiga (after Appendix 1A in Oromia Water Works Design and Supervision Enterprise, 2007). [m, meters; m^2/d, square meters per day; Qa, Quaternary alluvium; gt, granite; Ju, Urandab Formation; Jh, Hamanlei Formation; Ja, Adigrat Formation; Pc, Precambrian metamorphic rock]

	UTM Coordinates (Zone 38)						
Well Name	**Easting (m)**	**Northing (m)**	**Elevation (m)**	**Depth (m)**	**Lithology/ Geologic Unit**	**Depth to Water (m)**	**Transmissivity (m2/day)**
Finkile (BH 003/96)	831588	1047473	2032	85	Alluvium and fractured volcanics (Qa+gt)	1.45	44
Kernesa (HBF BH OO1)	832232	1048013	2032	51	Alluvium and basement (Qa+gt)	0.84	45
Medega	844295	981360	1533	254	Limestone (Ju+Jh+Ja)	209.15	4
Fechatu	843638	997249	1688	150	Limestone (Ju+Jh+Ja)	78.14	2
Woter BH-1	804025	1035400	2040	84.5	Limestone (Ju+Jh+Ja)	7.5	350
Burka ella	757500	1030000	2000	120	Limestone(Ju+Jh+Ja)	21.4	15
Setewake nisa	775181	949598	1400	221	Limestone (Ju+Jh+Ja)	6	4
Kito well	863450	1025000	1600	51	Granite (Pc+gt)	3.8	117

6.4. Water budget for the Groundwater System

A basic way to evaluate the occurrence and movement of groundwater in an aquifer system is to develop a groundwater budget that accounts for inflows (recharge) and outflows (discharge) to the aquifer system (Laczniak and others, 2008) (fig. 16). A preliminary groundwater budget is developed to evaluate the balance between flow into and flow out of a groundwater system. This preliminary groundwater budget will be further studied in Phase 2. The introduction of pumping from the flow system initially decreases hydraulic heads and ultimately affects one or more flow components by decreasing natural discharge, increasing recharge, and/or removing groundwater from aquifer storage leading to water-level declines (San Juan and others, 2010).

The primary components of a regional groundwater budget are:

- Natural discharge (evapotranspiration and spring flow);
- Pumpage;
- Recharge from direct precipitation, overland flow, and streamflow; and
- Subsurface flow into and out of an area (estimated by using Darcy calculations or existing water budgets).

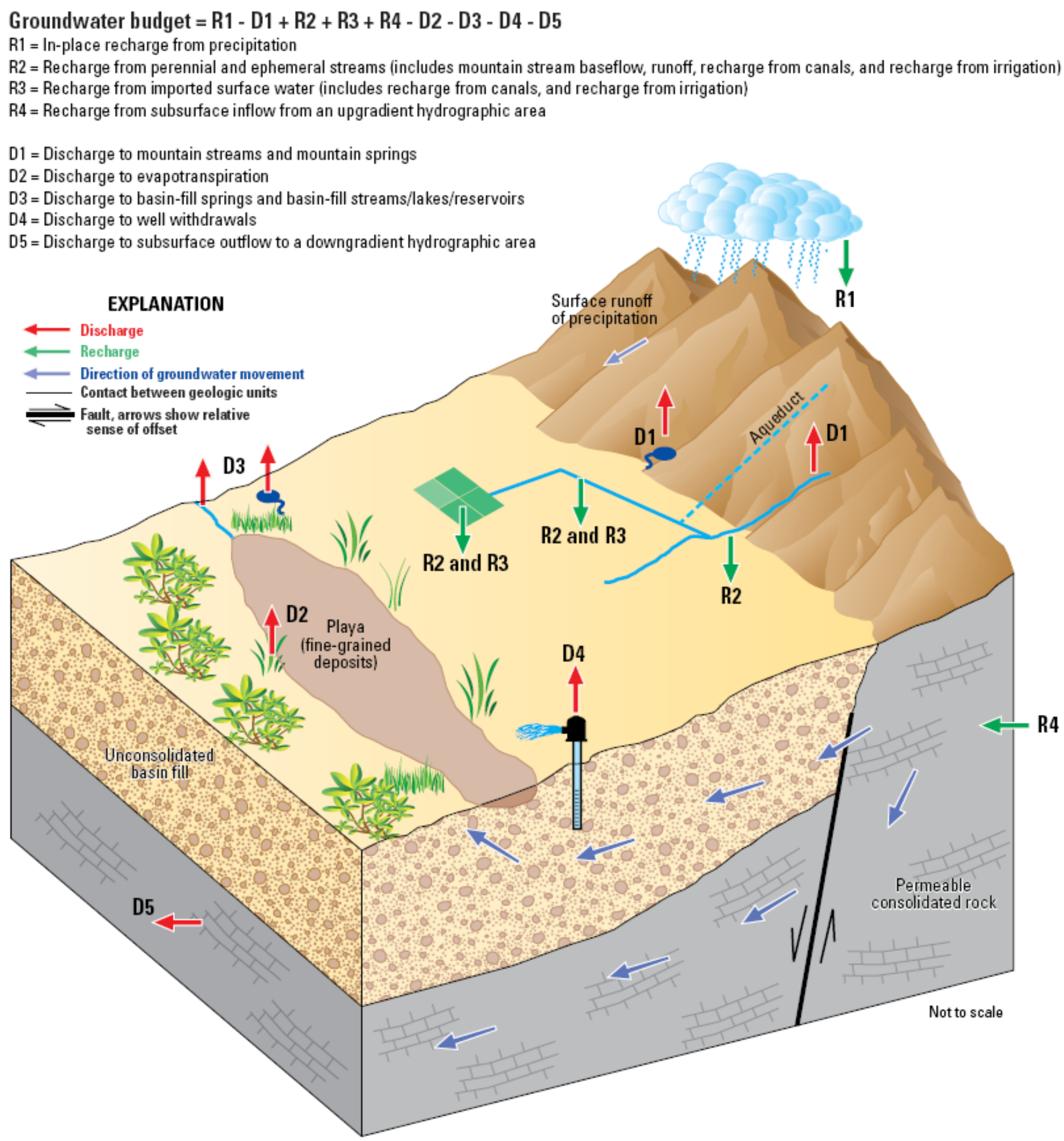

Figure 15. Schematic of groundwater-budget components (from Heilweil and Brooks, 2011, p. 77).

6.4.1. Recharge estimates

In the Phase 1 study area, there are four main sources of recharge to the alluvial and bedrock (carbonates and sandstones) aquifers:

- Direct recharge to outcropping aquifers,
- Mountain-front recharge originating in the metamorphic highlands and Karamara Range,
- Recharge from rivers in the Jerer and Fafen Valleys, and
- Deep regional groundwater flow from the east (possibly including recharge from the Jessoma Formation sandstones exposed to the east).

Precipitation that does not infiltrate into the subsurface or is not consumed by evapotranspiration and sublimation in the metamorphic highlands and the Karamara Range becomes runoff. The majority of this runoff flows into the heads of the Fafen and Jerer Valleys (in the case of the metamorphic highlands) and the margins of these valleys (from the Karamara Range). Part of this runoff recharges the unconsolidated alluvial deposits as infiltration along the highland margins, beneath stream channels, irrigation canals, and irrigated fields (fig. 16l Heilweil and Brooks, 2011). Recharge from runoff occurs predominantly through coarser deposits along the margins of each basin.

The Fafen and Jerer Rivers, which flow from the metamorphic highlands through their respective valleys on either side of the Karamara Range, lose water to infiltration. They are completely dry in the southern part of the study area. This surface water is lost to irrigation, evapotranspiration, and as recharge to the alluvium and bedrock aquifers. As noted in the "WATEX© Process" section, several lineaments have been identified that possess a water signature. In the dry environment of the Phase 1 study area these water-bearing fractures could indicate recharge paths to deeper aquifers. It is inferred that the water not lost to evapotranspiration or anthropogenic uses may recharge the deeper aquifers through these fractures or faults.

Direct recharge to the sandstone is limited to the Jessoma Formation to the east of the study area. This hydrogeologic unit may not be directly connected to the regional groundwater-flow system. It is possible that a low-permeability layer may be present at the base of the sandstone that may isolate it from the Hamanlei and Adigrat Formation aquifers (which it uncomfortably overlies). If so, the Jessoma Formation aquifer is hydraulically isolated from regional hydrogeological processes thus affecting recharge, groundwater levels, and water quality; based on the current understanding this seems unlikely. Phase 2 will allow a better understanding of the relation between these units.

Figure 58 in Gachet (2013) shows a qualitative map of recharge potential in the Phase 1 study area, with most of this representing recharge directly on outcropping aquifers (valley alluvium, sandstones, and carbonate rocks).Approximately 8.88 billion m^3 per year of precipitation falls on the outcropping area of the Jessoma Formation. The Jerer and Fafen Valleys received approximately 12.7 billion m^3per year of precipitation. This estimate is based on interpolation among observed precipitation at four stations (Gachet, 2013). In order to estimate groundwater recharge it is assumed that recharge from direct precipitation is between 3 and 10 percent. Using these end values, the alluvium and the bedrock aquifers beneath the Jerer and Fafen Valleys could receive between an estimated 380 million m^3 and 1,300 million m^3 of recharge from direct precipitation, while the Jessoma Formation could receive between an estimated 270 million m^3 and 890 million m^3 (Gachet, 2013).

6.4.2. Volume of potentially recoverable groundwater

To assess a volume of water that can potentially be recovered from an aquifer, a storativity value is required. Storativity (or storage coefficient) is the volume of water released from storage per unit surface area of a confined aquifer per unit drop in water level (Fetter, 2001, p. 559).The equivalent concept of specific yield is used for unconfined aquifers and is the ratio of the volume of water that drains from a rock due to gravity (Fetter, 2001, p. 78). The potential volume of groundwater able to be pumped from an aquifer is obtained by multiplying aquifer volume by either the storativity or specific yield.

Using the areas of the Hamanlei Formation and Adigrat Formation aquifers presented in figure 81 of Gachet (2013), the total area of the combined Hamanlei and Adigrat units that have a high probability of obtaining usable water is approximately 5,250 km^2. By assuming a thickness of 250 m for the Hamanlei Formation and 25 m for the Adigrat Formation (table 1), as observed during the ground truth survey of 2011 and confirmed by boreholes tied to the Landsat imagery interpretation, an estimated total volume of approximately 1,500 million m^3 is obtained.

Because there are no known storativity values for either the Hamanlei or Adigrat Formations, values from similar carbonate-rock aquifers in the Great Basin region of Nevada are used to estimate potentially recoverable water. Belcher and others (2001, p. 19) reported a mean value of 0.003 for storativity in regional carbonate-rock aquifers of southern Nevada. Multiplying this value by aquifer volume gives an upper bound estimate of approximately 4.5 million m^3 of potentially recoverable water stored in the primary bedrock aquifers.

Similarly, figure 63 in Gachet (2013) shows alluvial aquifers in the Fafen and Jerer Valleys as having 460 km^2 of WATEX©-identified high potential aquifer area. Assuming an average alluvium thickness of 5m, the resulting volume of maximum potentially recoverable water is 460 million m^3.The application of a specific yield of 0.1 yields 46 million $m^3$of potentially recoverable water stored in the high-potential alluvial aquifer areas (Gachet, 2013, p. 65). Climatic changes and contamination are not considered in this study, and warrant further study.

6.5. Perennial yield

Perennial yield (also known as safe yield) is “the amount of water which can be withdrawn from an aquifer annually without producing an undesired result” (Todd, 1959).Obviously, undesired effects must be defined, especially if based on economic factors. Conkling (1946) defined undesirable effects as:

- Pumpage that exceeds average annual recharge,
- Decline of the water table so that the cost of pumping exceeds an economic threshold, and
- Decline of the water table enough that water quality in produced water declines.

Other possible effects include reduction of surface-water flows and subsidence. Although some critics argue that any groundwater withdrawal will have adverse effects over some period of time and thus reject the concept of perennial or safe yield, the concept remains useful if for no other reason than to provide a long-term view of how groundwater resources will be developed and managed (Bartolino, 2009).

For the purpose of this report, the perennial yield (the amount of water that could be pumped from an aquifer over the long-term without undesired effects) is taken as equivalent to the amount of recharge. Using the values given above in the “Recharge values” section, the perennial yield of the alluvium and bedrock aquifers beneath the Jerer and Fafen Valleys is estimated to be between 380 million $m^3$and 1,300 million m^3; the estimated perennial yield for the Jessoma Formation is estimated to be between 270 million m^3 and 890 millionm^3per year. It should be noted that these estimated perennial yields are an order of magnitude larger or more than the estimates of potentially recoverable water in the aquifers. Better estimates of the perennial yield (based on improved estimates of recharge) and hydraulic properties of the aquifers (from additional aquifer tests) during Phase 2would aid in a better understanding of the sustainability of the water resources in the Phase 1 area.

6.6. Summary description of the hydrogeologic framework

Figure 17 presents a schematic of the groundwater flow system in the Phase 1 study area. Most groundwater recharge probably originates as precipitation onto the northern metamorphic highlands (north of Jijiga). It then runs off the relatively impermeable metamorphic rock and enters surface exposures of the Adigrat and Hamanlei Formations. Similarly, runoff from the relatively impermeable volcanic rocks of the Karamara Range also recharges the primary Adigrat and Hamanlei Formation aquifers. Groundwater flow in both valleys is to the south through the alluvial deposits, the Hamanlei Limestone, and Adigrat Sandstone. The rocks of the Karamara Ranges seem relatively impermeable in the north and less so to the south; Phase 2 study will allow a better assessment of this. The Karamara range forms a barrier, effectively blocking east to west flow, although some flow occurs to the east between the southern parts of the valleys. Apart from evaporative losses, at least some streamflow in the two rivers appears to recharge to groundwater as discharge decreases downstream to the south.

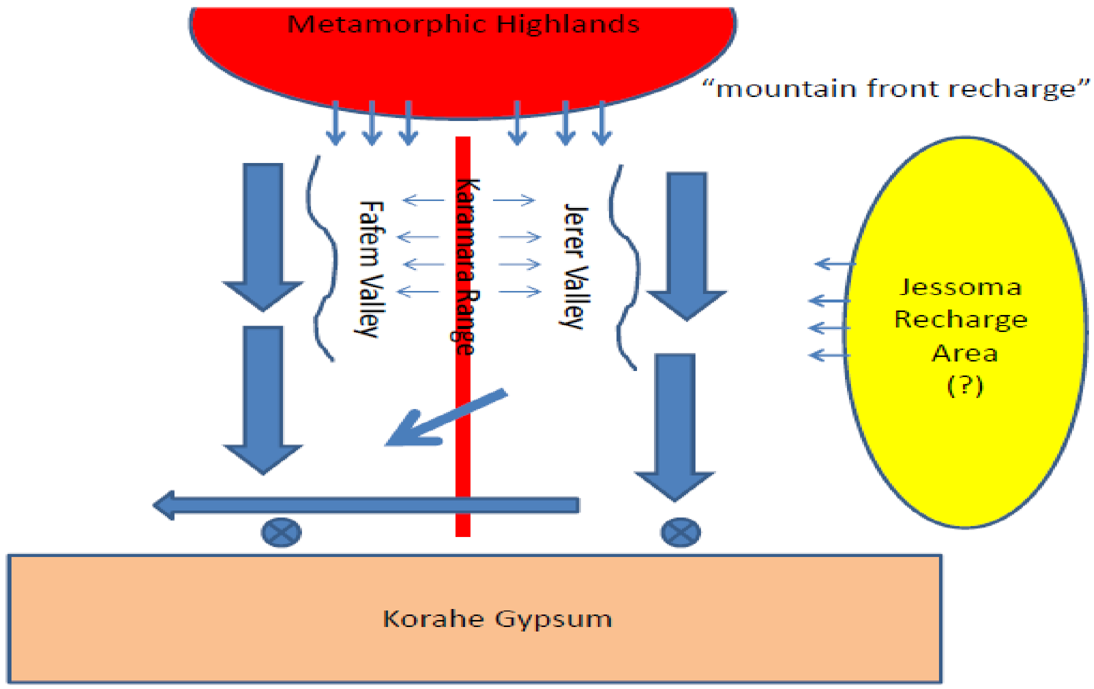

Figure 16. Schematic diagram of hydrogeologic framework for Phase 1 study area. Thick arrows represent general groundwater flow direction. Thin arrows represent components of groundwater recharge. Width of arrows represents general amount of flow.

Eastern exposures of the Jessoma Formation probably receive some mountain front recharge as runoff enters the groundwater system from the sandstone to the west. Water also directly infiltrates into the sandstone body itself, but this recharge probably does not flow into the Hamanlei and Adigrat Formation aquifers because of a possible basal clay layer. If this clay is present, the Jessoma Formation may act as "stand-alone" aquifer. If there is hydraulic connection with the primary Adigrat Formation and Hamanlei Formation aquifers and no clay layer, then water from the Jessoma Formation also is a source of recharge to the primary aquifers to the west.

7. Analysis of drilling success for USAID wells

Figure 18 is a map showing the East Karamara aquifer structure with the locations of USAID wells drilled by IRC. The East Karamara aquifer structure (figs. 8 and 9) located on the eastern flanks of the Karamara Range, about 3 km southeast of Jijiga, has been successfully drilled by 3 IRC boreholes (fig. 18): (1) Garbile borehole drilled by IRC in 2010; (2) Ararso borehole drilled by IRC in 2013; and (3) Degenbur borehole drilled by IRC in 2013. The figure shows that, excepting Garasley and Garawo boreholes which are located outside the East Karamara aquifer structure, all the wells drilled into the East Karamara aquifer structure fall within the predicted high potential zones of WATEX© and produce drinkable water with yields over 4 liters/sec.

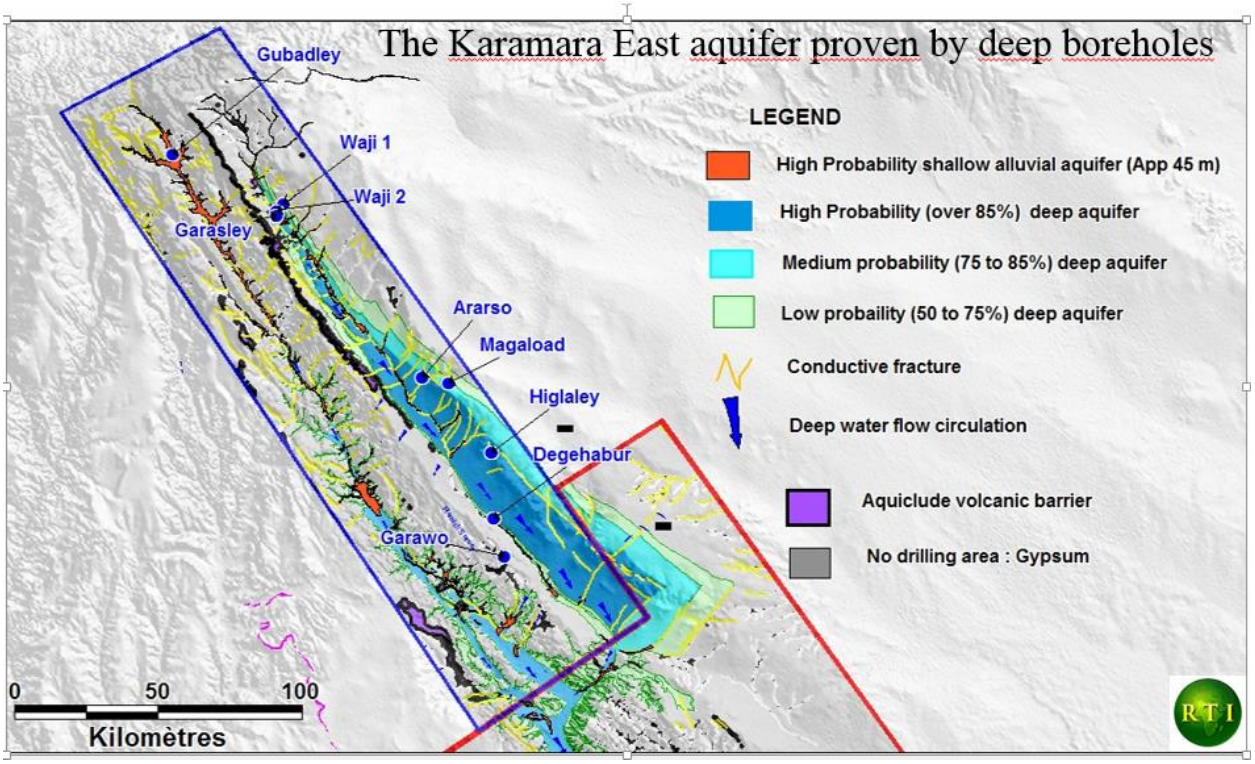

Figure 17. The East Karamara aquifer and USAID wells drilled by IRC, (from Gachet, 2013).

7.1. Economic analysis of well success rates

Table 5 presents the well drilling success rate predicted by the WATEX© process as of May 2014. Average well drilling success (hitting usable quantities of groundwater) rate is between 25 percent in arid areas of Somali Region of Ethiopia and 45 percent in the most favorable case in the highlands of Ethiopia (Tesfaye Tedessa, Director Groundwater Study Development Management Directorate, oral commun., June 2013). Table 5 shows that the use of the WATEX© method could boost well drilling success rates to 80 percent or greater. It should be noted that since none of the wells were actually sited using the WATEX© recommendations, these results confirm and constitute an independent verification of the WATEX© results. However, the WATEX potential water map delivered for phase 1 provides numerous other opportunities for drilling successful and potentially high yield boreholes within the study area. This provides a great economic value for future drilling projects by GOE, NGOs, and donor organizations.

Table 5. Drilling results to date with respect WATEX© recommendations.

Site	Recommended by WATEX	Results and remarks	Discharge L/sec	Water producing	Depth of well (m)	Static water level (m)
Gubadley	Yes	Positive (discharge of 5 l/sec)	8	Yes	74	5.74
Waji 1	No	Dry	NA	No	120	NA
Waji 2	Yes	Positive	2.8	Yes	126	69.7
Gerasley	Yes	Dry	NA	No	138	NA
Garawo	No	Positive but very low yield	1.2	Yes	210	90
Degehabur Town	No	Positive	2.5	Yes	45	18.62
Araso	Yes	Positive	2	Yes	420	184
Maglaad	Yes	Positive	3	Yes	450	250
Higlaley	Yes	Failed due to drilling complications	NA	not counted	317	NA
Duumale	Yes	Positive	5	Yes	180	80
Buundada 1	Yes	Recommended because sustainable but quality questionable; low yielding	1.1	Yes	31	7.6
Buundada 2	Yes	Adequate yield with pump	6	Yes	21	5.5
Sanweyne	No recommendation given (see tabl5 in USGS final report)	Failed due to drilling complications	NA	not counted	120	NA
Garigeon	Yes	Positive	2.5	Yes	250	110
Mara'ato	No	Dry		No		
Dhikirley	Yes	Drilled for SRSWB in 2010; identified as potential site on WATEX map	2	Yes	380	180
Garbile	Yes	Drilled for IRC in 2010; identified as potential site on WATEX map	4	Yes	200	89.26

7.3 Cost/benefit analysis for the WATEX© Process

A comparison was made of the cost of drilling a productive well in the study area without using the WATEX© process to site a well and the cost of drilling a productive well in the study area using the WATEX© process to site a well. Factors of influence for wells sited with and without the WATEX© process are assumed to be identical except for the drilling success rate, or the probability of drilling a well that produces water. The following simplifying assumptions have been made:

1. The probability that a drilled well is productive if the well is in the southern, dry Somali Region, sited without using WATEX© is 0.25.
2. The probability that a drilled well is productive if the well is in the Highlands sited without using WATEX© is 0.45.

3. The probability that a drilled well is productive if the well was sited anywhere in the study area using WATEX© is 0.80.
4. Well depth is 200m.
5. Cost to drill a well is $600/m.
6. The opportunity cost of spending time to drill unproductive wells is not considered.
7. Economic and environmental externalities of drilling a well are not considered.
8. Cost of performing the WATEX© in the study area is $410,000.

The cost of drilling N productive well without using WATEX© in the southern, dry Somali Region is:

$$\begin{aligned} c_S(N) &= \$120{,}000\left(\frac{1}{0.25}\right) N \\ &= \$480{,}000\, N \end{aligned}$$

The cost of drilling N productive wells without using WATEX© in the Highlands is:

$$\begin{aligned} c_H(N) &= \$120{,}000\left(\frac{1}{0.45}\right) N \\ &= \$267{,}000\, N \end{aligned}$$

The cost of drilling N productive wells using WATEX© throughout the study area is:

$$\begin{aligned} c_W(N) &= \$410{,}000 + \$120{,}000\left(\frac{1}{0.80}\right) N \\ &= \$410{,}000 + \$150{,}000\, N \end{aligned}$$

Figure 19 shows a comparison of costs of drilling N productive wells with and without using WATEX© to site wells. The vertical difference between lines represents the difference in cost between the methods. Results highlight the importance of using WATEX© to locate select hydrogeologic features, such as depth to water and crystalline rock fractures, for groundwater exploration in undeveloped areas. WATEX© is cost effective if more than one productive well is needed in the southern, dry Somali Region, or if more than three productive wells are needed in the Highlands.

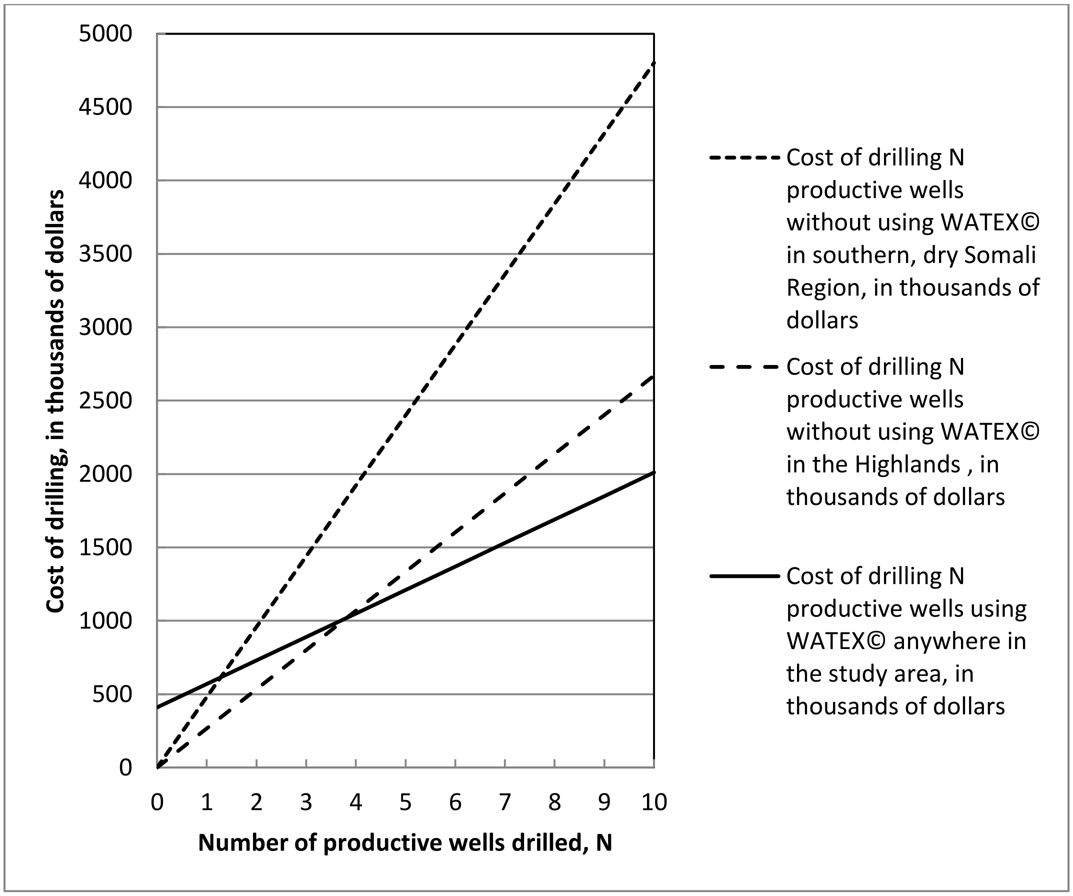

Figure 18. Graph comparing costs of drilling N productive wells with and without using WATEX© to site wells in the southern, dry Somali Region and the Highlands.

For example, the cost of drilling two productive wells without using WATEX© in the Somali Region and the Highlands, respectively, is $960,000 and $534,000; the cost of drilling two productive wells anywhere in the study area using WATEX© is $730,000. The cost of drilling four productive wells without using WATEX© in the Somali Region and the Highlands, respectively, is $1,920,000 and $1,068,000; the cost of drilling four productive wells anywhere in the study area using WATEX© is $1,010,000. The cost savings of WATEX© continues to increase as more productive wells are drilled; $2,890,000 is saved if 10 productive wells are needed in the Somali Region, and $760,000 is saved if 10 productive wells are needed in the Highlands.

Use of WATEX© for siting wells also saves time, which is important when working in an unsecure environment and (or) where there is an urgent need for water. The maps and tools resulting from this study, including new information about groundwater resources, have the potential to improve the lives of more than 5 million people (http://en.wikipedia.org/wiki/Somali_Region) who live in this semi-arid area with limited access to basic services and clean water. The number of people benefiting from WATEX©, that is, receiving water supply from wells sited using WATEX©, is directly related to the number of productive wells sited using WATEX© in either the Somali Region or the Highlands.

8. Summary and suggestions for future work

The work described here will improve knowledge of the location, quality, and volume of groundwater resources and allows increased efficiency in the siting and drilling of boreholes for humanitarian assistance programs in pastoral areas, while also enabling the GOE to make better-informed water resources decisions. The maps and tools resulting from this study, including new information about groundwater resources, have the potential to improve the lives of more than 5 million people who live in this semi-arid area with limited access to basic services and clean water.

8.1. Summary of results

The most significant hydrogeological structure identified by this work is the East Karamara aquifer on the eastern flanks of the Karamara Range, south of Jijiga. It lies at a depth of 50 to 700 m beneath the Jerer Valley. It is approximately 1 to 35 km in width and 200 km in length. This southwest-trending structure continues past the confluence of the Jerer and Fafen Valleys near Birkot to a regional flow barrier composed of gypsum and other evaporites.

Use of the WATEX© process allowed accurate mapping of a broad range of minor geologic features scattered over the study area. These structures include aquifers such as:

- Discontinuous alluvial aquifers (which appear to be discontinuous and would require further remote sensing- based geologic mapping before drilling).
- Aquifers of eolian origin that may potentially supply communities of several hundred persons.
- Perched aquifers of fluvial deposits sealed by basalts may be potentially productive.
- Potentially productive areas of bedrock fracturing. They may also indicate several hundred of meters deep potentially productive aquifers.

The WATEX© process has demonstrated the ability to identify potential shallow and deep aquifers to within an accuracy of few meters. Application of this approach to previously sited boreholes verifies its utility. It has the potential to improve the efficiency and accuracy of borehole drilling from its current range of 25 percent, in the dry context of Somali Region, to 45 percent, in the favorable context of the highlands, to 75 percent 66 percent or potentially more.

8.2. Applications implementation

The purpose of the USGS Phase 1 and Phase 2 work is to assist the Government of Ethiopia exploring and mapping the groundwater potential in the eastern lowlands and associated highlands of the Ogaden Basin area and build local capacity to ensure groundwater resources are developed and managed sustainably. The specific objective is to increase pastoralists' household resiliency to droughts and related shocks by increasing access to and utilization of water resources.

In practice this translates to increasing access to clean and sustainable water supplies by successfully completing wells. The WATEX© process aids the expert hydrologist in identifying areas with greater potential for siting productive wells. The Drilling Handbooks and Groundwater Exploration Navigation System (GENS) allow specific and accurate siting by drilling personnel. This siting process can reduce the number of unsuccessful boreholes, which can reduce drilling costs. These potential cost savings can be used to allow the completion of more wells.

The hydrogeologic framework evaluates the groundwater resources of selected areas for sustainability, suitability for potable supply, and possible measures for supply enhancement. It also iteratively informs the WATEX© analysis which in turn continues improvement of the hydrogeologic framework.

8.3. Recommendations for future work

The objective of Phase 2 is to map, characterize, and assess groundwater resources in the eastern lowlands and associated highlands of Ethiopia in an area of 393,900 km^2. Phase 2 consists of three components: (A) WATEX© process, (B) hydrogeological assessment, and (C) capacity building.

Phase 2 will build on Phase 1 results and contribute to further refinement of the hydrogeologic understanding of the Ogaden Basin. Analysis of the larger study area will enhance the regional understanding of groundwater-flow processes and the water budget. Based on the current understanding of hydrogeologic conditions in the Phase 1 study area, several specific recommendations are suggested for Phase 2.

8.3.1. Recharge estimates

The assumed 3 to 10 percent values used in the "Recharge Estimates" section can be improved by the measurement of surface permeability in different locations in order to capture the heterogeneity of a hydrogeologic unit. This spatially varying permeability can be easily and quickly be estimated using field-based "Bottomless Bucket" method (Nimmo and others, 2009; Mirus and Perkins, 2012) (fig. 19); this method is a type of falling-head permeameter test, which intended to be used for Phase 2. The resulting values can then be used to estimate infiltration and recharge. However, it is likely that recharge will be overestimated using this method. The significant heterogeneity within the Ogaden renders this method appropriate because a larger number of quick and approximate measurements is more useful than a smaller number of more-precise measurements. Furthermore, the apparatus is composed of readily available easily reparable materials.

Figure 19. Bottomless bucket method setup for a location in the Mojave Desert, USA. The photograph illustrates the simple equipment (a bucket with the bottom cut out), stopwatch, and ruler (not shown) to measure the declining water level in the bucket. These values are used to estimate the surface permeability of the unit. These values, in turn, can be used to estimate recharge.

8.3.2. Volumetric analysis and visualization of the hydrogeologic framework

In order to more accurately assess aquifer volume material and estimate available water, a 3D digital hydrogeologic framework model could be constructed from available hydrogeologic data. This technique has been successfully applied in other regional groundwater systems such as the Death Valley regional ground-water flow system in Belcher and Sweetkind (2010). The geometric representation of the hydrogeology can also serve as the basis and precursor for a numerical groundwater-flow model. Such a hydrogeologic framework model also aids in the visualization of aquifer systems, particularly for demonstrating concepts to non-technical audiences. An example of such a hydrogeologic framework model was described in the "Hydrogeologic units" section above.

8.3.3. Hydraulic properties

For a more accurate estimate of potential aquifer storage, values for the hydraulic properties of each of the hydrogeologic units will be needed. Some of these values can only be obtained from multi-well aquifer tests, which require an observation well near the pumping well. Other techniques for obtaining hydraulic properties such as the use of air permeameters can also be investigated for their applicability to the study area.

Until multi-well aquifer tests can be performed, some of these values may be estimated from properly conducted single-well pumping tests. The UNESCO compilation has such data and estimated values and can serve as a starting point for this task. However, single-well pumping tests should be conducted on each well drilled by USAID. Time-drawdown data from these tests are useful in assessing the hydraulic characteristics of various aquifers.

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Appendices

Appendix 1: List of products delivered

With this report, the following Phase 1 products have been delivered to USAID. This technical (final) report is the last item on the list; all other products were delivered to USAID in 2013.

- Series of maps, including water potential, recharge and soil;
- GIS database;
- Metadata for all the data generated;
- Two portable drives contain all maps, information and remotely sensed data used for this study;
- Two Groundwater Electronic Navigation System (GENS) devices;
- One week GENS training;
- Drilling handbook;
- Progress report;
- Technical (final) report.

Appendix 2: Capacity building

Three classes were taught for capacity building in Ethiopia: remote sensing application for water resources, groundwater field techniques and project management, and estimation of aquifer properties using single- and multiple-well aquifer tests:

1. **Remote sensing applications for water resources**: This introduced a tool to characterize and track changes in natural resources as well as human activities. The course focused on the following topics:

   a review of introduction to the physics of remote sensing

   introduction to satellite data search site

   overview of spectral channel uses

   exercises of application of remote sensing to natural resources

2. Groundwater field techniques and project management: This course combined lectures and field exercises on the principles and techniques for collecting and recording basic groundwater data at wells and springs, drilling and well construction basics, and introductory project management. Topics included water-level measurement, use of GPS, the recording of data on ENGDA or ENGWIS field forms, drilling techniques, well construction, and basic project management and cost estimation.

3. Estimation of aquifer properties using single- and multiple-well aquifer tests: An emphasis was placed on the fundamental concepts of aquifer-system responses to imposed hydraulic stresses. The focus was less on the theoretical aspects of aquifer-hydraulic responses and more on the applied, practical aspects of analyzing and interpreting results. Expected ranges of aquifer properties were presented. Field conditions and limitations were considered for measuring water-level and discharge data. Classroom and field exercises included the techniques and analysis of single-well and multiple-well tests. Theoretical responses from confined and unconfined aquifers were applied to estimate hydraulic properties such as permeability and storage properties of the aquifer systems.

These courses were taught on February 4 through 8, 2013, by the USGS, in cooperation with USAID, DFID, and UNESCO. The classes were taught by Drs. Saud Amer, James Bartolino, and Wayne Belcher, respectively. The courses were taught at the School of Earth Sciences at Addis Ababa University.