Research Paper

Three-phase approach to improve deep groundwater supply availability in the Elidar district of Afar region of Ethiopia

S. Godfrey and G. Hailemichael

ABSTRACT

This study provides new evidence on the effectiveness of a combined remote sensing and hydrogeological investigation method for deep groundwater development in complex geologic and geomorphologic situations in Ethiopia. The study was undertaken in the Elidar district of the Afar region of Northern Ethiopia. Due to the water availability and vegetation in this district, the majority of the population (total population of 79,000 people and 647,000 head of cattle) are dependent on pastoralist livelihoods. The current ratio of available water supply facilities to number of beneficiaries is 1:2,323 people and 1:19,029 head of cattle. A joint UNICEF-UNESCO groundwater investigation pilot project with the objective of improving drilling success rates in the Elidar district considered a three-phase approach. In phase 1 and 2, an overlay method was developed that combined data from radar, optical remote sensing and ground measurement (geology, hydrogeology, hydrology, hydro-meteorology, and geophysics). The overlay model identified the most promising site to undertake well drilling, considering a probability of drilling wells with sufficient amount of water and permissible water quality (defined as $Q = >2$ L/s and EC $< 2{,}000$ μms/cm²). In phase 3, three production boreholes were drilled and the results showed a 92% accuracy against the overlay model.

Key words | deep groundwater, Ethiopia, geophysical survey, hydrogeology, radar and optical remote sensing

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INTRODUCTION

Ethiopia is renowned for being the 'water tower of Africa' due to the presence of three principal drainage systems feeding the Blue and White Nile, which originate in the Ethiopian central highlands (Arsano & Tamrat 2005; Teklu *et al.* 2015). Despite this acknowledgement, there are limited data on Ethiopian hydrogeology. Deyassa *et al.* (2014) state that a comprehensive model that explains the hydrogeological set-up and genesis of basement aquifers in Ethiopia does not exist in the international literature (Cherenet 1993; Deyassa *et al.* 2014). This is due to the diversity of aquifer systems, which are described in detail in Kebede (2012). The most widely used map is at a scale of 1:2,000,000 (EIGS 1993, 1996). The major reason for the limited data relates to the vast landmass, complex geological variations and inaccessibility of lowland areas due to political insecurity. Ayenew *et al.* (2008) characterized the physiology of Ethiopia as a 'high-altitude volcanic plateau tapering into rift valley and peripheral lowlands' (Ayenew *et al.* 2008, p. 97). This is depicted in Figure 1.

The most geologically complex zone of the country is the north-eastern Afar region, which is characterized by a highly variant hydrogeology and physiology. The topography of Afar ranges from the upper Rift Valley at an altitude of more than 2,000 m above sea level to the Danakil Depression, which is 120 m below sea level. In between, there are vast areas of the Melka–Sedi–Amibara zone in

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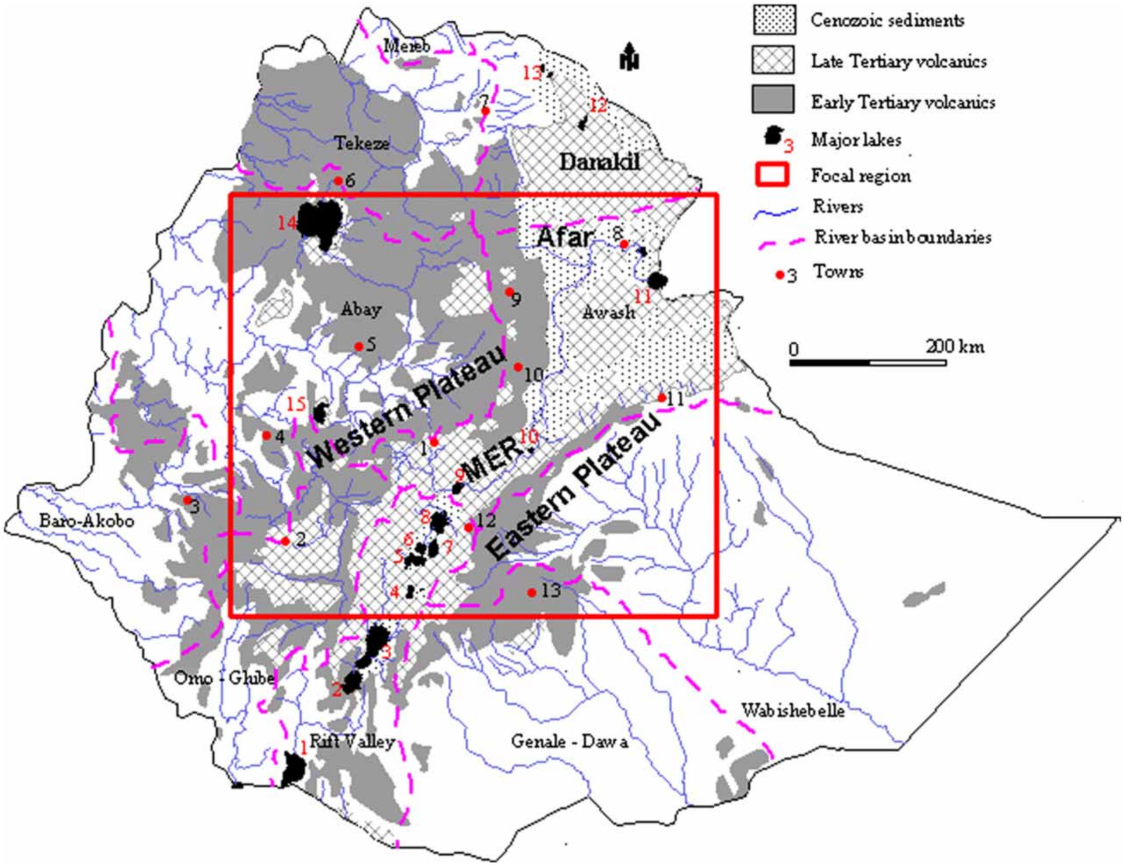

Figure 1 | Location map showing the volcanic regions and major river basins (Ayenew *et al.* 2008).

the Middle Awash valley at 750 m above sea level (Ayenew 2007). Salinization of the groundwater aquifers is a major limitation to effective groundwater development in the Afar region, with the most affected area being the arid southern and eastern Afar region (Ayenew 2007). The study area for this paper is the Elidar district (located in the east of the Afar region). Elidar is characterized by grabens (100–200 m above sea level) with interspersed undulating forests (400 m above sea level). These physiological features are interspersed with acidic volcanic centres. The region experiences low rainfall, high evapotranspiration and average temperatures >40°C. Due to the vegetation in this district, the majority of the population (79,000 people and 647,000 head of cattle) are dependent on pastoralist livelihoods. The current ratio of water supplies is 1:2323 people and 1:19029 head of cattle.

Literature on the hydrogeology of Elidar has been limited to conventional resistivity techniques for shallow groundwater identification similar to those used by Arvidsson *et al.* (2011). Limited published investigations have been carried out with regard to the groundwater resources of Elidar, and they are predominantly related to the Afar depression and its inference on the groundwater potential of the Djibouti basin (Jalludin & Razack 2004). These conventional shallow groundwater investigation techniques have proved ineffective in locating groundwater in Elidar due to the depth of the groundwater occurrence. To overcome this limitation, the reviewed literature suggests the use of GIS and remote sensing tools to delineate deep water bearing zones (Dar *et al.* 2010). Studies by Magesh *et al.* (2011) note that these tools have wide application in the management of various natural resources, but are highly underutilized for deep groundwater mapping. They further state that a combination of remote sensing and 'ground trothing' is an effective way of delineating potential groundwater zones. This is evident in studies by Murthy (2000), Leblanc *et al.* (2003) and Tweed *et al.* (2007), who used remote sensing to increase the accuracy at a lower

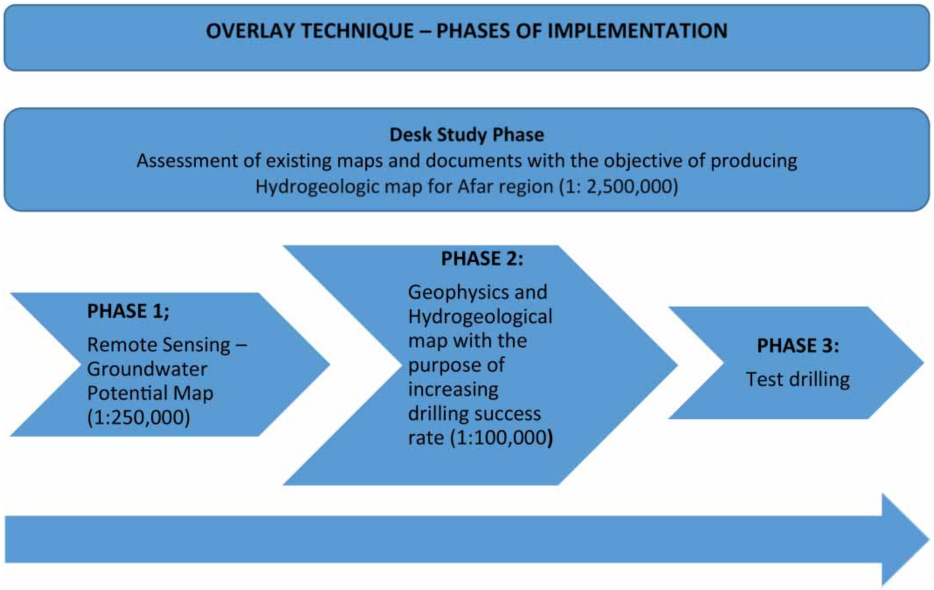

Figure 2 | Phases of implementation.

cost and quicker timeframe. In a recent World Bank review of *Earth Observation for Water Resources Management* (World Bank 2016), it is recommended to use remote sensing to provide fast and reliable information for water-related decision-making. Therefore, this paper presents the methods used from a combined remote sensing and ground trothing overlay method from the Afar region of Ethiopia.

MATERIALS AND METHODS

During phase 1, groundwater potential estimates were calculated by overlaying data from radar and optical remote sensing in maps of 1:100,000 scale. In phase 2, all existing information (geology, hydrogeology, hydrology, hydro-meteorology, geophysics) were gathered and a base map of 1:250,000 was developed. The overlay model developed based on the findings of phase 1 and 2 studies identified the most promising site to undertake well drilling considering a probability of drilling wells with a sufficient amount of water and permissible water quality (defined as $Q = >2$ L/s and $EC < 2{,}000$ μms/cm²). The study was undertaken in the Elidar woreda (district). Elidar woreda (district) is located in the north-eastern region of Afar. It has an area of approximately 13,119 km^2, is bounded in the north by Afdera woreda, in the west by Dubti, in the northeast by the international border with Eritrea and in the southeast by Djibouti. To reduce the probability of dry or negative boreholes, this study followed the three phases outlined in Figure 2.

Table 1 | Remote sensing source and resolution

Source	Resolution	Data
ASTER VNIR	15 m	
Landsat -5-7-8, ASTER SWIR	30 m	Vegetation indices like MODIS, Landsat, can provide an indication of the water availability at the rooting depth, which may stretch to slightly larger depths, but still remain an indication of only the shallowest presence of soil moisture
SRTM	90 m	
MODIS	250 m	
ENVISAT ASAR	1,000 m	
AMSR-E, SMOS	>1,000 m	Soil moisture information derived from satellite data (AMSR-E, SMOS and ASAT) provides information about the water availability in the first (tens of) centimetres of the soil
TRMM, ARC-2	0.25 degree, 0.1 degree	(TRMM and ARC-2) a full map and the temporal variance of the precipitation over the area is obtained

Table 2 | Definition of remote sensing data sources and platforms

Source	Translation
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
VNIR	Visible and near infrared
Landsat -5-7-8	Continuous acquisition of satellite imagery of earth (versions 5, 7 and 8)
SWIR	Silicon wafer inspection with laser induced photoluminescence
SRTM	Shuttle Radar Topography Mission
MODIS	Moderate-Resolution Imaging Spectro-radiometer
ENVISAT	Environmental Satellite
ASAR	Advanced Synthetic Aperture Radar
AMSR-E	Advanced Microwave Scanning Radiometer – Earth Observing System
SMOS	Soil Moisture and Ocean Salinity
TRMM	Tropical Rainfall Measuring Mission
ARC-2	Advanced Room Correction-System 2

Remote sensing data

In phase 1, the groundwater analysis (GwA) methodology developed by Acacia Water was used to develop the groundwater potential maps (Acacia 2014). The Acacia GwA is designed to give 'an indication of the areas with the highest potential for fresh groundwater occurrence' (Acacia 2014). First, data from a range of satellite data sources were compiled. These included from SRTM, MODIS, TRMM, LANDSAT, AMSR-E, SMOS, RADAR-SAT 2, Google Earth and Data Phase 1. The specificity of these data was used at varying depths depending on the strength of the satellite imagery. Table 1 compares the penetration data (resolution) from the different satellites, while definitions of remote sensing data sources and platforms are indicated in Table 2.

Data from these sources were combined with precipitation, evapotranspiration, soil moisture, geology,

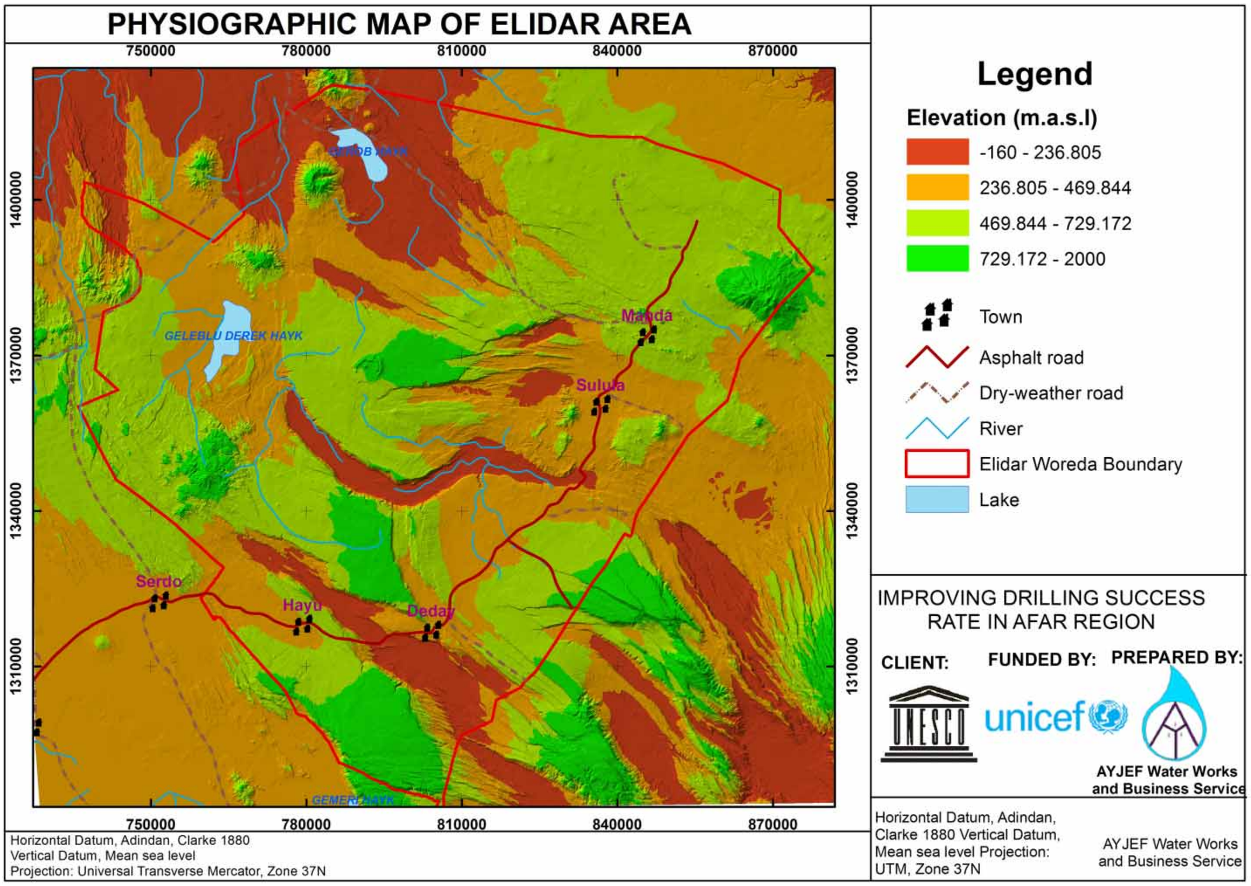

Figure 3 | Physiographic map of Elidar woreda and location of main population centres.

geo-morphology, land use and existing well analysis to provide a S-GwA (shallow groundwater analysis) and D-GwA (deep groundwater analysis) conceptual model. These were presented as infiltration zones, accumulation zones and were based on the TRMM system. This system uses precipitation radar (PR), Microwave Imager (TMI) and Visible and Infrared Scanner (VIRS), Clouds and the Earth's Radiant Energy Sensor (CERES) and a Lightning Imaging Sensor (LIS) to estimate the precipitation. This estimate is merged with NOAA, GMS, GOES and Meteosat data to produce merged 3-hourly precipitation datasets in a 0.25×0.25 degree grid (dataset 3B42). The ARC-2 system uses inputs from two sources:

(1) 3-hourly geostationary infrared (IR) data centred over Africa from the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT);
(2) quality-controlled Global Telecommunication System (GTS) gauge observations reporting 24-hour rainfall accumulations over Africa.

Results of the remote sensing analysis are presented in 1:250,000 scale maps. A description of the district's characteristics is outlined in Figure 3. The principal points of population settlement are on the asphalt road from Serdo to Manda and onwards to Bure and the Eritrean border. Elevations vary within the district from 2,000 m above sea level to −272 m below sea level.

Hydrogeology and geology

In phase 2, UNICEF Ethiopia contracted a consortium led by UNESCO and other private consultancy firms to undertake a field hydrogeological study that included a water point inventory, water quality survey, groundwater

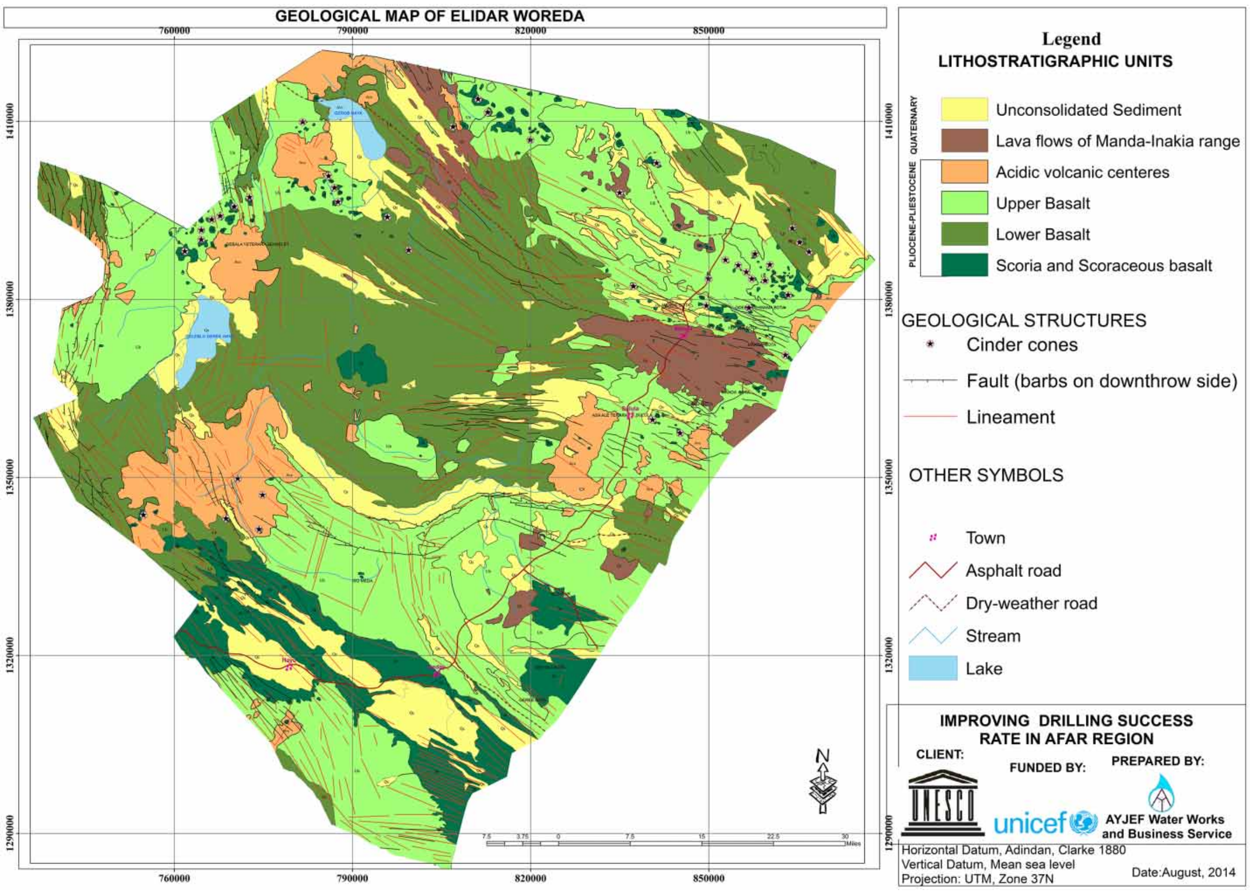

Figure 4 | Geological map of Elidar woreda.

recharge estimation and geophysical investigations at the 'high potential sites' identified by the remote sensing technology. Resistivity surveys were undertaken using the vertical electrical sounding technique. The WDJD-3 digital Earth resistivity meter was used to undertake the field work with a Schlumberger electrode configuration with a maximum half-current electrode spacing (AB/2) of between 330 m and 500 m. The results were plotted on a log–log plot of apparent resistivity versus half the current electrode spacing. Additionally, 50 water quality samples were collected and analysed to determine the hydrogeochemical characteristics of the district. Also, data were collected on the meteorology, rainfall, precipitation and evapotranspiration. The geology of the Elidar district was mapped using the existing data from the EIGS (1993, 1996) (Figure 4). Unconsolidated sediments were identified along the principal asphalt road where demand from the population was at its highest.

Water quality samples collected from the 50 sites were plotted using a box and whisker diagram (Figure 5). Results indicate TDS and conductivity levels of between 400 and 2,240 μms/cm² are of greatest concern.

The data were then combined using an expert judgement overlay method. Reference was made to Malezewski (1999) and Minor *et al.* (2007) to define the weightings. The study divided the overlay into four main parameters: geology (k), geomorphology, groundwater recharge potential and structural density. The assumptions for each of these factors included:

(1) Geology: General permeability, primary permeability (pore spaces) or regional permeability are associated with average jointing and fracturing. The storage capacity depends on pore spaces, and the movement depends on permeability resulting from interconnected weathering and cooling joints and rock mineral assemblage openings. Water storage or yield potentially increases with increasing general permeability.
(2) Geomorphology: Water storage or yield potentials increase with a decrease in slope steepness. Groundwater storage is poor over mountainous and steep slope areas.
(3) Groundwater recharge: Groundwater potential increases with the increase in recharge potential, and the rate of infiltration controls recharge potential.

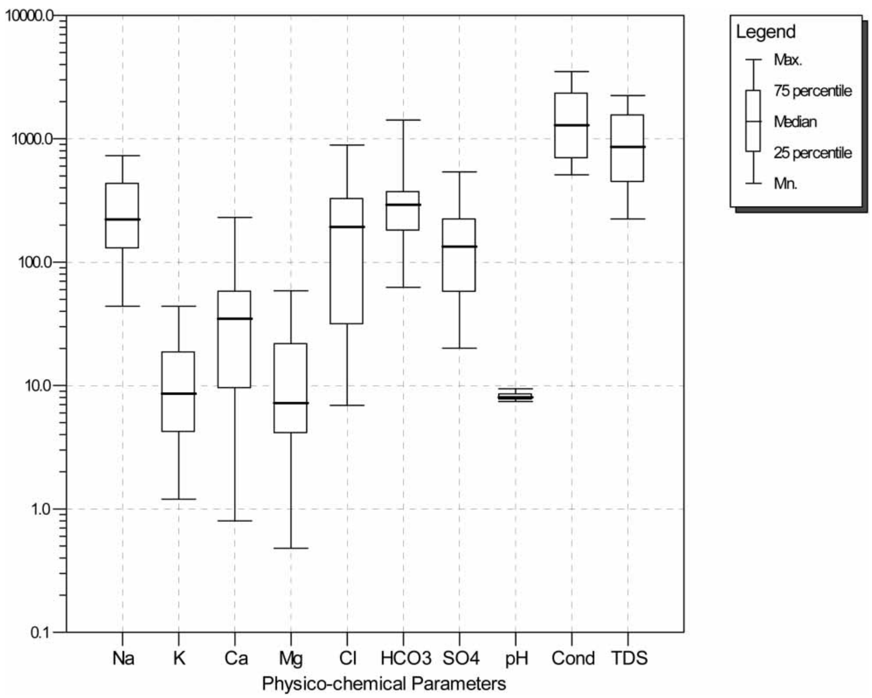

Figure 5 | Box and whisker plot of water samples from Elidar woreda.

Table 3 | Overlay method weightings

Layer	Parameter	Factor weight	Class and class weight 1	2	3	4
1	Geomorphology	0.3	Flat low lying grabens 50	Gentle to flat horst 30	Gentle to steep horst 15	Steep and mountainous 5
2	Drainage/drainage density	0.25	High 70	Moderate 30		
3	Hydrogeology/permeability	0.23	High 60	Low to moderate 35	Aquiclude 5	
4	Structure/structural density	0.22	Major (regional) 55	Moderate 25	Local 15	Poor 5
	Total	1	58.4	30.05	8.95	2.6
	Classification		High	Moderate	Low to moderate	Low

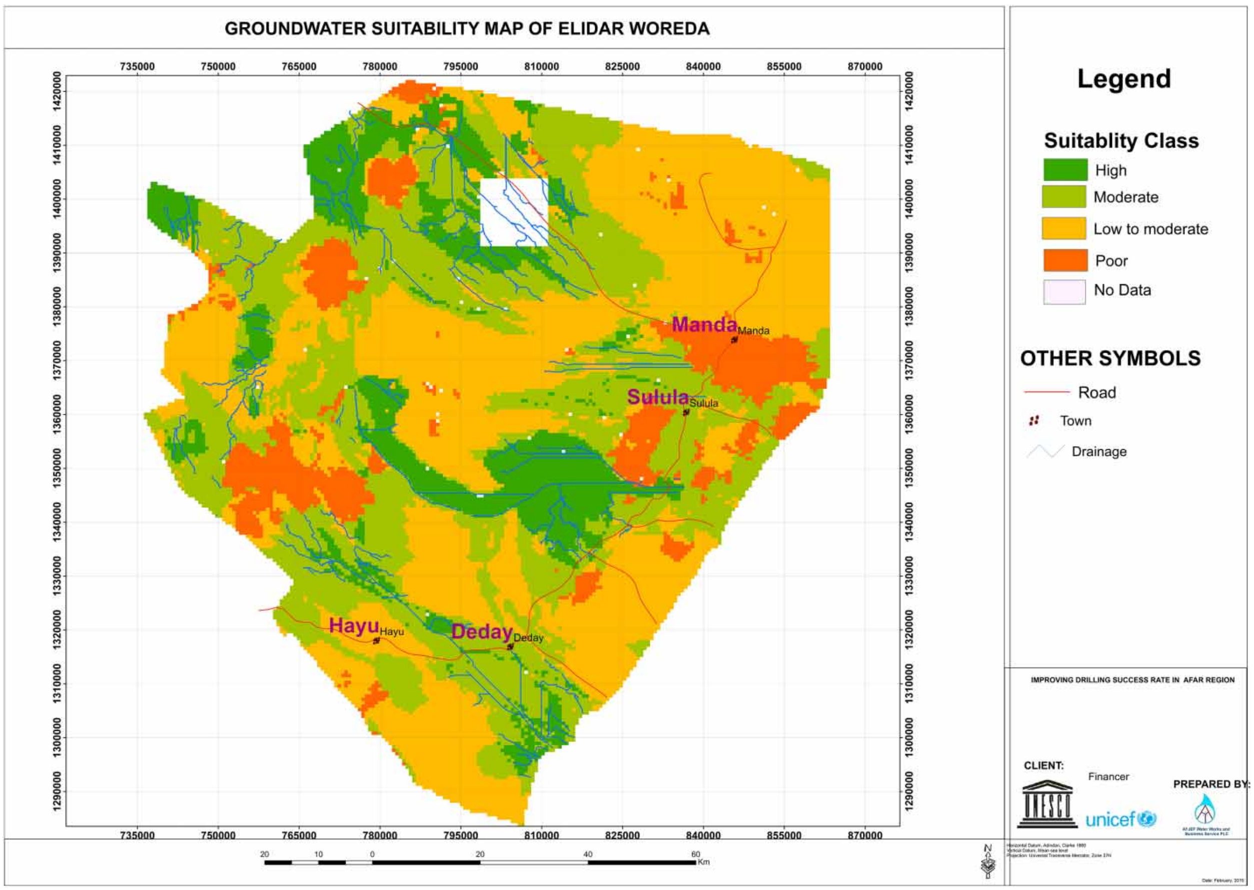

Figure 6 | Groundwater suitability map of Elidar woreda.

(4) Structure: Secondary permeability along geological structures, generally considered as water bearing. The higher the structural density, the higher the water bearing capacity.

To assign weightings to each of these assumptions, an expert group consultation was held and the following expert judgement weightings were agreed (Table 3).

Topographical data and geomorphological maps were developed. Results of the hydrogeology and geology maps were presented as 1:100,000 scale maps.

Test drilling

In phase 3, groundwater suitability zones were identified from the remote sensing and the hydrogeology/geology maps. A probability model was then presented. To stress test the model, UNICEF contracted a private drilling company to drill four production boreholes in the high probability zones. An average success rate of 75% was applied to the contract. The contract was awarded to drill the four boreholes selected from the list of most feasible sites identified from a combined study of phase 1 and 2. In the contract, UNICEF agreed to pay for a maximum of three out of the four boreholes (assuming at least a 75% success rate) that are successful in striking water of acceptable quantity and quality as predefined in the contract agreement ($Q > 2$ L/s and with acceptable water quality). Any additional borehole drilled would be the liability of the contractor. Turnkey contracting was used following the FIDIC procurement rules of the National Competitive Bidding (NCB) procedures of the Government of Ethiopia Procurement Proclamation. Payment for positive boreholes was used as an incentive to reduce the

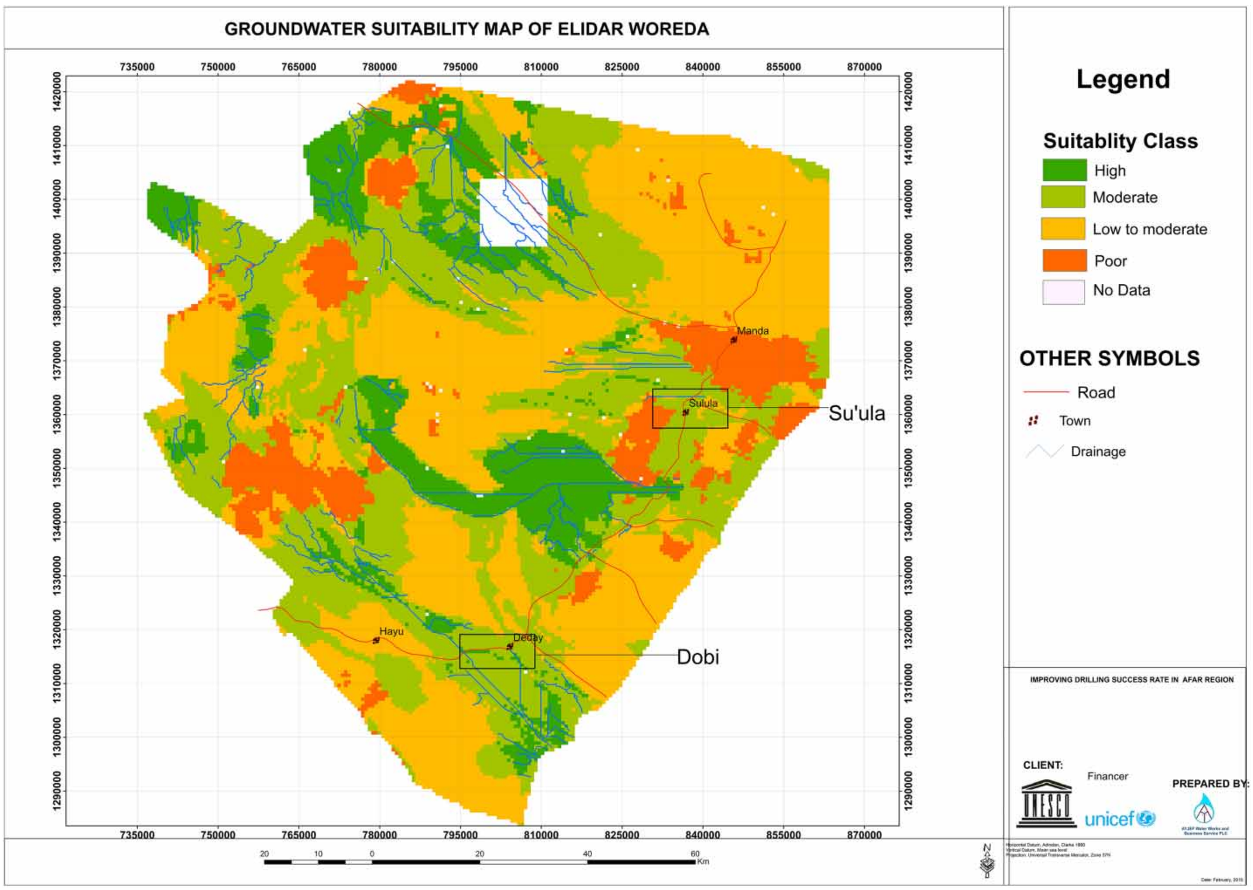

Figure 7 | Zones of 'high' probability of groundwater occurrence along the road.

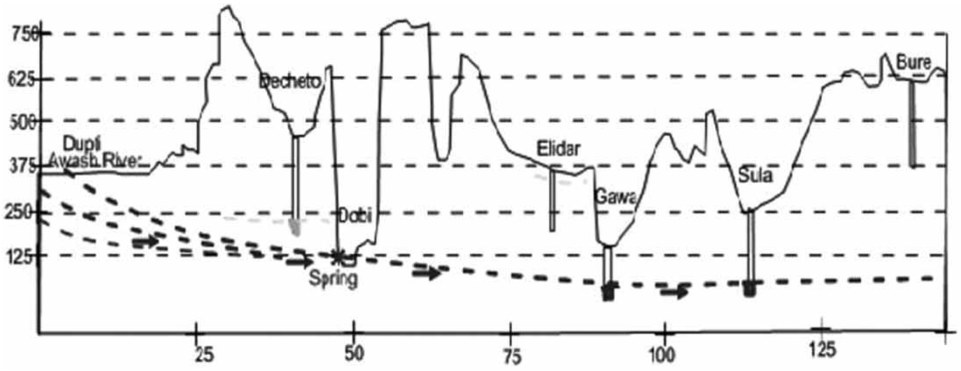

Figure 8 | Depth versus altitude conceptual model.

potential number of abandoned or negative boreholes during the drilling process.

RESULTS

The overlay map produced as a result of this study is outlined in Figure 6, where weightage was given based on expert judgement for each of these categories.

Using the weightages, the district was divided into four groundwater probability zones (high, medium, low to moderate and low). Figure 7 indicates the location of the major asphalt road running from west to north east of the district and connecting the road to Eritrea and Djibouti with the region's capital (Semera). The sedentary majority of the population of the district live along this road. The model identified two zones of 'high' probability of groundwater occurrence along the road. These are marked in boxes in Figure 7, and are Dobi and Suula villages.

To further understand the potential required depths for improving drilling success rates in Dobi and Suula, the GWA conceptual model outlined in Figure 5 was produced. Figure 8 compares data from phase 1 and 2 of the investigation with existing borehole logs. The X axis is in km and demonstrates the distance from the district border to the location of the sites, and the Y axis indicates the mountain topography measured as metres above sea level. Using this conceptual model, estimations of both the probability of

Table 4 | Recommended drilling depths from GWA model

	Location		
Description	**Dobe 1**	**Dobe 2**	**Suula 1**
Recommended water strike depth (from GWA)	110 m a.s.l.	110 m a.s.l.	88 m a.s.l.
Actual water level after drilling	113 m a.s.l.	116 m a.s.l.	98 m a.s.l.
Recommended water quality (from GWA)	1,900 μS/cm	1,800 μS/cm	1,000 μS/cm
Actual water quality (after drilling)	7,000 μS/cm	3,000 μS/cm	1,900 μS/cm
SWL (m b.g.l)	3	2.5	207
DD (m b.g.l)			112.4
DWL (m b.g.l)			219.4
Yield (L/s)	10	3	3.9
Water quality	Not acceptable	Acceptable	Acceptable
Aquifer type	Alluvial deposit	Alluvial deposit	Fractured basalt and scoria
Remark	Compressor test	Compressor test	Test pumping undertaken

striking fresh groundwater from the lateral recharge from the highland region, combined with an approximation of borehole depths, can be ascertained.

The D-GWa and the S-GWa model estimates that boreholes will need to be drilled in Suula from 250 m above sea level to 88 m above sea level to ensure a borehole would strike water. The depth in Dobi will need to be from 120 m above sea level to 110 m above sea level to ensure access to a fresh water lens.

Table 4 compares the recommended drilling depths from the GWA model with the actual drilling depths achieved in phase 3 of the test drilling.

The drilling campaign was undertaken between September and December 2015. In phase 3, three production boreholes were drilled and the results showed a 92% accuracy against the overlay model.

CONCLUSION

In conclusion, this study provided a comprehensive understanding of the hydrogeology of the area that assured the drilling of productive wells. Each of the three phases of the study complemented each other. The remote sensing information helped to trace lineaments and provided a combination of high probability correlations for the identification of groundwater suitability zones. Field hydrogeological and geophysical surveys were used to verify the remote sensing study and identify suitable locations for drilling successful wells of acceptable groundwater quantity and quality (phase 2). As part of the field hydrogeological study, thorough investigation of existing groundwater outlets (springs, wells) was very useful to build the conceptual model and to verify groundwater occurrence at shallow and deep depths. The hydrogeological study was further enhanced from field checks of existing lithology and structures, analysis of information gathered from water wells and collection and verification of water quality data. Daily supervision of drilling works was required to ensure required drill depths and well construction were carried out as per the predefined design and locations. Analysis of drilling logs, test pumping results and water quality data helped to verify results of the first two phase studies and was used as an input to design the water supply system (phase 3).

However, it should be understood that, despite the positive implications of the three-phase approach, the availability of potential groundwater resources does not necessarily coincide with the settlement pattern of people. A phase (4) of the study to combine potential groundwater sites with socio-economic and demographic data should be considered in future studies. This would ensure that the groundwater is economically utilized to benefit people living within or in the surrounding areas of the identified potential sites.

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