Article

Climate resilient deep groundwater investigation and development in the Ogaden Jesoma sandstone aquifers of Somali Region, Ethiopia

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Abstract: Groundwater is the most extracted raw material in the world with global annual withdrawal rates of 800–1500 km^3/year. In East and Southern Africa, 70 % of the population are reliant on shallow groundwater as their primary drinking water source. With increased population growth, intensification of agriculture and industrialization, conflicting demands on groundwater present a challenge to achieve the Sustainable Development Goals (6,3,11,12,15). Between 2015 and 2018, the Horn of Africa was affected by a series of climatic induced events, namely *El Nino, La* Nina and the *Indian Ocean Diopole.* These events modified the variability of rainfall patterns and resulted in long periods of low rainfall, low recharge and high evapotranspiration. As a result, shallow aquifers in alluvial deposits of Somali region have low yields and produce brackish and saline water. That situation prompted humanitarian water professionals to finance the transportation of water from selected locations with high groundwater potential through water trucks to areas facing groundwater depletion and drought. To address this challenge, UNICEF explored alternative, sustainable deeper groundwater sources that could be extracted using solar water pumping technology for multi water use. This paper describes a three-phase methodology of deep groundwater development of wells in the Ogaden Jesoma sandstone aquifers of the Somali region of the Horn of Africa to a depth of 600 meters below ground level. The results concluded that the deep sandstone aquifer of Jesoma can provide fresh water with yields of 15 l/s to the local population of Somali region. to the study provided insights into deep groundwater identification and development as well as adaptive deep boreholes drilling as a source for climate resilient water supplies.

Keywords: Groundwater; Climate resilience; Deep wells, Deep aquifers, Drought, Somali, Ethiopia

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1. Introduction

The International Association of Hydrogeologists (IAH) estimate that global withdraws of groundwater have surpassed 900 km3/year in 2010, providing more than 36% of potable water-supply, 42% of water for irrigated agriculture and 24% of direct industrial water-supply [1]. Groundwater is now widely recognized as the most extracted raw material in the world with global annual withdrawal rates between of 800–1500 km^3/year [2,3]. Doll [4]states that 35% of the water consumed worldwide (4,300 km3/year during 1998–2002) is groundwater. Due to the over-reliance on groundwater there are conflicting demands for multiple uses and for achieving multiple

Sustainable Development Goals -SDGs (6, 3, 11, 12 and 15) [5]. The centrality of water to achieve the SDG targets is well acknowledged with groundwater being the primary water source.

In East and Southern Africa, 70 % of the population are reliant on shallow groundwater as their primary drinking water source [6]. This far higher than the global average which notes that 2.8 billion people (or approximately 40%) of the world's population are receiving their water supply from shallow groundwater [7]. In East and Southern Africa, the primary form of extraction of groundwater is through boreholes fitted with handpumps. Recent reviews of the level of functionality of handpumps indicate an increase in non-functionality of the technology due to lowering groundwater levels which are occurring because of changes in climatic patterns such as precipitation, evapotranspiration and groundwater recharge [8]. According to the IPCC WGII-AR5, *"Climate change will amplify existing stress on water availability in Africa."* This is particularly applicable in many African countries where extreme precipitation changes are aggravating the frequency of droughts and floods during the last 30 to 60 years. A further continued warming in the Indian-Pacific warm pool has also been shown to contribute to more frequent East African coastal flooding and inland droughts over the past 30 years during the spring and summer seasons [9].

Given that groundwater is the primary source of drinking water for the majority of Africa it is of paramount importance to understand how to identify and develop the "untapped" groundwater in a sustainable and cost-effective manner [10]. Earlier work in the Turkana region of Kenya by UNESCO identified the possible use of a technique termed WATEX (short for water exploration) for deep groundwater development. This technique was evaluated by IGRAC (International Groundwater Resources Assessment Centre) and it concluded that a lack of available information on the methodology was a limiting factor in supporting the studies' conclusions [11]. In Ethiopia, the WATEX approach was piloted in 2011 and modified by UNICEF using open source methods that are outlined in a three-phased methodology used in the Afar and Somali regions. The methodology uses a combination of remote sensing data, combined with ground truthing and appropriate deep groundwater drilling methods. This paper builds on the earlier [8] publication and provides a detailed case study of a deep well identified and drilled within the Jesoma sandstone formation of the Somali region in Ethiopia. This paper argues that development of deeper aquifers that are interconnected with surface and groundwater recharge zones is an effective solution in areas of Ethiopia affected by drought.

2. Materials and Methods

The study area covers the drought-affected Gashamo district located in the Somali region of Eastern Ethiopia bordering Somaliland (Figure 1). Gashamo is an area in the Ogden Sedimentary Basin located in the southeastern part of Ethiopia that covers about 350,000 km^2 and has a population of 145,000. The basin is underlain by very thick succession of Late Paleozoic, Mesozoic and Cenozoic (Tertiary) sedimentary rocks. It is characterized by flat to undulating plain geomorphology, where the surface geology is Mesozoic sedimentary deposit with a thickness that varies from less than 200 to more than 1000 meters. The population of Gashamo are reliant on collecting rainwater from birkas or hafir dams which is only available during the short rains. As result, communities migrate to other areas or rely on water being tankered by the Government and UNICEF from more than 40 kms away.

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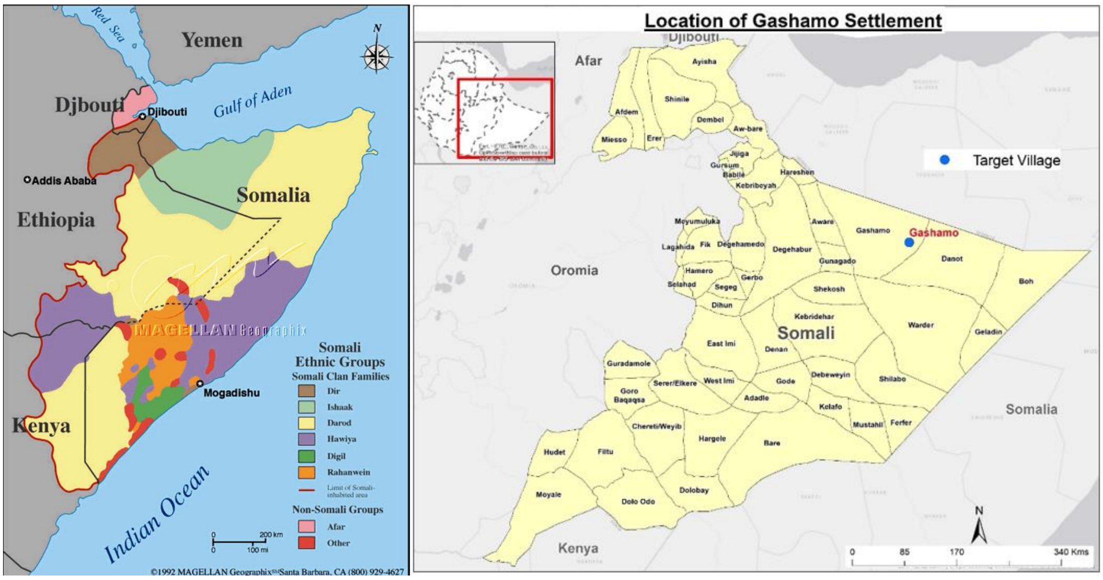

Figure 1. Location of the study region

The project followed a three-phased approach to identify the most promising site for drilling. Remote sensing, ground truthing and geophysical surveys that enabled to determine well drilling sites in the Jessoma sandstone aquifer of the Gashamo district. Due to the limited number of test wells andthe lack of deep groundwater investigation data in the study area, UNICEF initiated a deep groundwater survey in the area using the three-phase methodology outlined in [8]. This methodology consists of an overlay analysis of different groundwater relevant information (derived from remote sensing products, existing maps and report and geophysical survey) in a meaningful way to create a groundwater potential map that allow identifying areas of high probability of groundwater occurrence for drilling of productive boreholes. The remote sensing-derived thematic layers obtained through a collaboration with the EU-JRC (European Union Joint Research Centre) was validated with field hydrogeological and geophysical survey. Specific spots were identified for further geophysical survey using vertical electrical sounding and profiling to understand the underground lithology and water bearing formations.

It is well known that recharge of an aquifer refers to the infiltration of water from the unsaturated zone to the saturated zone which is dependent upon several factors such as topography, geological structures, drainage network, etc. [12] . Because these factors are interdependent, considering a single factor to explain the recharge process reduces the reliability of the estimates for a given region. Therefore, the adopted methodology is a based-on experts' judgement overlay of four aquifer recharge-related thematic layers, mainly geomorphology, drainage density, permeability of geological formations and lineament density (structural density). However, as each thematic layer influences differently the potential aquifer recharge, a weighting process was applied to consider the importance of each factor in relation to the other one [13]. Hence, the more a factor influences groundwater occurrence, the greater its relative importance resulting in a high weight [14]. The resulted groundwater potential map was then used to identify suitable locations for drilling successful wells and to determine the type of drilling technique and capacity required for drilling. Later, the input from these studies was used to develop the terms of reference, estimated bill of quantities, technical specification for the groundwater drilling engineering contract.

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3. Results

3.1. Hydrogeological conceptual model

The lithologic units identified in the Gashamo area consist of Tertiary Mesozoic sedimentary rocks with intercalation of sandstones, lime stones and gypsum which in general is named as "Jessoma sandstone". The identified formation consists of gray and multi-colored sandstone intercalated with multi-colored shale and lateritic layers. Tertiary Jessoma sandstone covers almost all Ogaden Basin including the project area and composed of poorly sorted and poorly consolidated sandstone. Two test wells had been drilled in this formation in 2015 and 2016, namely in Harshin and Yaole locations [15]. These well logs showed that the Jessoma sandstone thickness is variable and can range from 130 m below ground. The report also showed that the water quality in the upper layers from the test wells is brackish. Using the overlay methods outlined in [8], a conceptual model was developed and outlined in figure 2 below.

The conceptual model identified an absence of a retaining layer at shallow depth due to the high transmissivity of the sandstone formations. Recharge was noted to percolate deeper until it intercepts the underlying limestone or clay layers of the upper cretaceous formation. As per the interpretation outlined in figure 2, the water bearing layers are expected to be located between depths of 300 m to 450m below ground level.

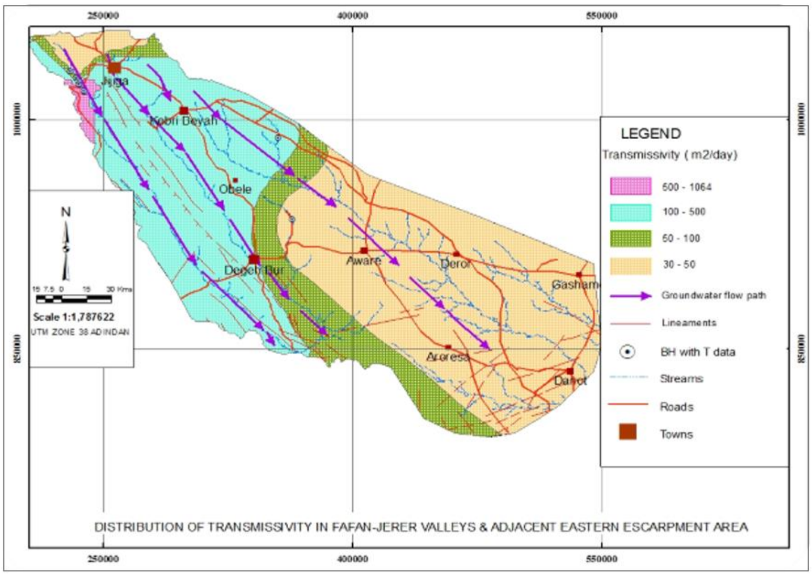

Figure 2. Hydrogeological conceptual model for Gasham

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3.2. Geophysical survey

The second phase of the methodology included confirmation of the hydrogeological model using field level Vertical Electrical Soundings (VES). Six Vertical Electrical Sounding (VES) tests were conducted along the west to east direction. The VES interpretation is outlined in table 1.

Table 1. Estimated water le vel depth and interpreted water quality condition from VES survey.

No.	NAME	X	Y	Z	Estimated SWL, (meter)	Aquifer Resistivity (Ωm)	Remark
1	VES-1	45.11	7.89	739.17	292.7	9.4	Kayder labile (site) - Probably fresh
2	VES-2	45.17	7.95	723.00	287.8	6.4	Probably brackish
3	VES-3	45.35	8.12	790.59	349.1	3.7	Anamadobe (site) - Brackish
4	VES-4	45.44	8.16	763.94	360.4	12.1	Most probably fresh
5	VES-5	45.69	8.26	818.95	358.0	22.7	Fresh
6	VES-6 (calibration)	45.92	8.36	721.00	314.3	14.8	Fresh as per Balijano well water quality data EC=1310 mS/cm

The results of the VES indicated that groundwater generally occurs at depths below 300 m depth in the Auradu limestone and 450 m to 500 m depth in the Jessoma sandstone. In Urandeb formation the quality of water becomes more saline with increasing depth even at shallower depth below 35 m the groundwater quality is highly deteriorated. Based on the combination of the conceptual model and the VES readings, the study observed that the Gashamo site is composed of highly permeable tertiary sedimentary formations dominantly composed of poorly sorted and poorly consolidated sandstone. The regional groundwater flow in the area is from northwest to southeast which could most probably controlled by the piezometric level of Indian Ocean. The groundwater in the area is deep mainly caused by high permeability of the unconsolidated sedimentary – sandstone (main aquifer) and the groundwater flow that is discharged to the Indian Ocean and controls. This is certified by the available information from the available test borehole data where the static water level (SWL) is 324 m below the ground surface, the average regional hydraulic gradient is calculated to be 0.000941.

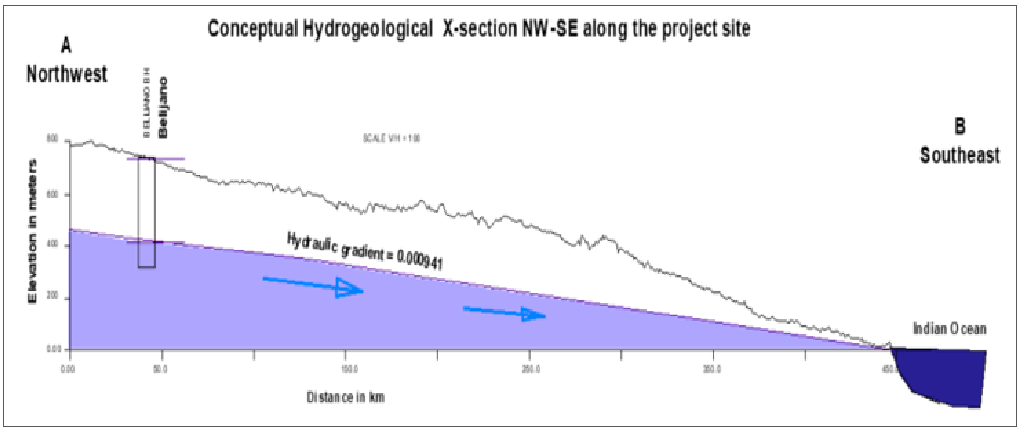

Figure 3. Conceptual model of the lithologic formation

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The groundwater level depth along the transect (Gashamo area) is estimated based on the hydraulic gradient and vertical electrical sounding interpretation. The conceptual hydrogeological x-section indicate a high probability of deep water that may be brackish due to the gypsum in the aquifer. For drilling purpose, the VES site 5 was selected as the specific site for well siting at a depth of 600 m. Resistivity readings were taken during the drilling to interpolate the electrical conductivity of the well and its potential to produce saline or brackish water. The results from this study are outline in the figure 4 and they showed a gradual increase of resistivity meaning the presence of a fresh water with lower conductivity.

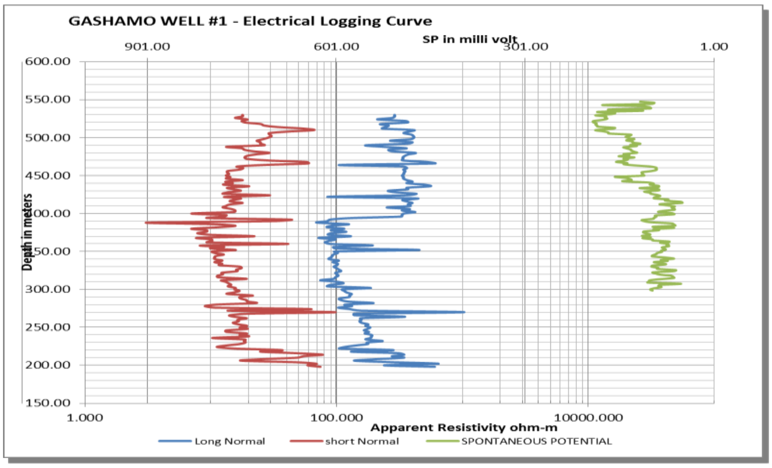

Figure 4. Electrical logging of well 1

3.3. Test borehole drilling

Based on the conceptual model of the lithologic formation and the geophysical survey, the study concluded that the most climate resilient water supply solution in the Gashamo district is deep drilling of groundwater from the sandstone/limestone aquifer. To drill through the tertiary sedimentary formations in Gashamo characterized by unconsolidated sandstone with intercalations of soft formation (clay), a mud rotary drilling method that uses reverse circulation was deployed. Due to the geologic nature of the area, the lithologic formation alternated between soft (collapsible), soft (not collapsible), medium, slightly hard and hard formations. Reverse circulation method was employed using tri-cone bits designed for soft formations, but these had a slow rate of penetration even when applied with bentonite clay to avoid collapse. This technique consumed more than 20,000 liters of water per day but was the only means to stabilize the well during construction. As predicted by the hydrogeological conceptual model and the geophysical study, the well drilled at 600 m depth was productive and it provides fresh and non-brackish water.

The static water level was estimated from both the rims of water marks on the drill pipes, the interpretation of the electrical logging and a change in water temperature from the surface temperature of 42^{o}C. A constant rate pumping test of thirty-six hours was undertaken at a rate of 4.5 liters/sec using a hot water pump due to the increase in deep groundwater temperatures. The hot water (at least 50°C) pump was installed at a position of 423 meters and the discharge from the well was measured from 4.5 liters per second. 63 mm medium class stainless steel riser pipes were used for test pumping due to the temperature of the water using specific design of thread shape and depth to withstand the load and vibration of the pump and the riser pipe itself. The pipes were also further welded to make sure they did not disconnect in the well. The pumping test concluded that the static and dynamic water levels were found to be respectively 381 and 385.21 meters below ground and indicated a drawdown of 4.21 meters as outlined in figure 5.

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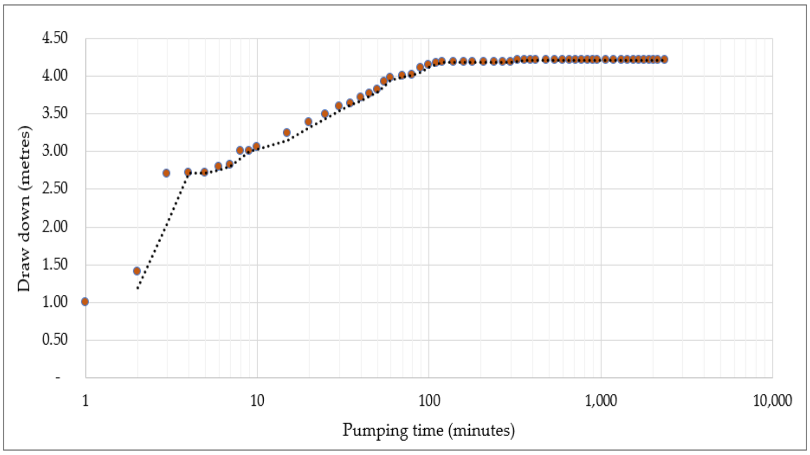

Figure 5. Constant rate test drawdown curve

After the constant rate pumping test of 36 hours, the pump is shut-off and recovery test was conducted. The water level stabilized after only sixty minutes to a water level of 381.02 meters which is only 0.2 meters lower than the static water level. This rapid recovery time and low decrease in the water level is synonymous of a high transmissivity aquifer. Based on the pumping test and empirical calculations, an estimated pumping yield of 15 liters/seconds was determined for this deep well (figure 6).

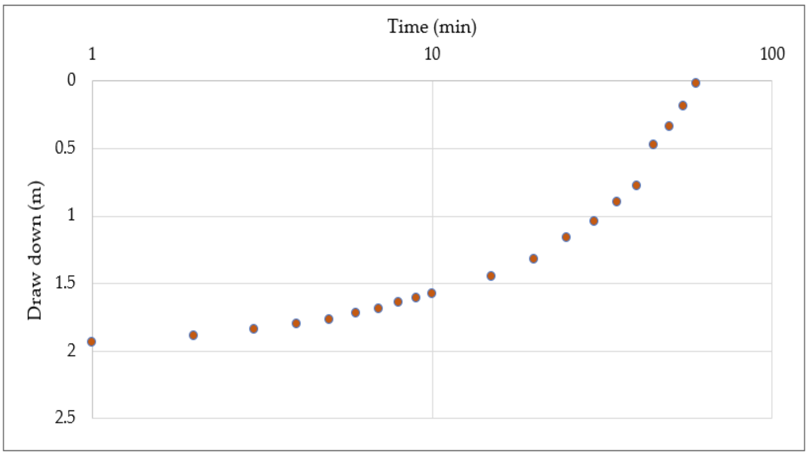

Figure 6. Recovery test drawdown curve

4. Discussion

This paper complements the results of previous drilling studies undertaken in Eastern Ethiopia in shallow aquifers. It argues that from an economic perspective it is Value For Money (VfM) to invest in deeper aquifer exploration and from an environmental perspective it is not damaging to the broader eco system.

Economically, this paper argues that an initial CAPEX (Capital Expenditure) investment in deeper aquifers provides a more resilient water source. During the *El Nino* drought, water engineers and water sector planners explored the use of on plot desalinization plants to extract brackish shallow groundwater and treat and pump it for domestic and agricultural use. The energy demand to ensure efficient operation of the plants, combined with high levels of calcification, precluded the use of solar water pumping and solar energy and resulted in the installation of diesel generator systems. A Value for Money (VfM) analysis revealed that the operation cost of the generators was potentially harmful

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for the environment and resulted in high water tariffs which made the water unaffordable for domestic use.

Environmentally, this paper supports earlier studies from the Elidar district of the Afar region of Ethiopia which showed that shallow wells located in alluvial deposits (Dobi 1 and 2) produced brackish and saline water [8]. The Elidar wells were noted to not only have challenges in water quality but also of water quantity (3 l/s). The challenges in the water quantity and quality could be explained by the fact that the region of Elidar experienced low rainfall and elevated temperatures and due to high evapotranspiration and that the shallow aquifers are at risk of salinization. However, it also demonstrates the vulnerability of the shallow aquifers to surface-groundwater interactions which is resulting in both geo chemical contamination and potential microbial contamination from surface run off in areas with limited sanitation. Furthermore, isotope analysis of shallow aquifers in Ethiopia support earlier studies by [16] in the Gidabo basin of Ethiopia which note the complex nature of the aquifer systems and distinct difference between the shallow and deep groundwater flows. They used $\delta^{18}O$ and $\delta^{2}H$ values to estimate the age of the groundwater and they concluded that there is a direct relationship between the deep groundwater flows and rainfall patterns. Therefore, a systematic understanding of deep lithology was undertaken using appropriate hydrogeological investigations. The conceptual model of lithological formation and the geophysical survey concluded that the most climate-resilient water supply solution in the Gashamo district is to drill in the deep sandstone/limestone aquifer.

Deep drilling results have shown that the Jessoma sandstone formation can provide fresh water with yields of 15 l/s. The presence of quaternary deposits makes this Jessoma sandstone formation an exploitable high potential aquifer, especially in its deep part which is characterized by cherty limestone limited by impermeable layers. The exploitation of this deep aquifer of sandstone can provide water to the local population and improve the equitable access to safe and clean drinking water in the drought-affected areas of the Somali region. However, Appropriate integrated water resources management is required to ensure that deeper boreholes are not over pumped and do not result in either surface to groundwater contamination or over extraction.

Constraints in deep aquifer exploitation include the lack of deep well drilling capacity within the Ethiopian drilling sector. A lack of experienced deep drilling capacity could result in the loss of drilling tools, finance and time. Lessons learnt indicated the need to invest in reverse circulation drilling to avoid well collapse.

5. Conclusions

The study supports the three-phased approach and emphasizes the need for a systematic understanding of the lithology with appropriate hydrogeologic investigation, pre-drilling arrangement, contract management activities, comprehensive drilling supervision, backup support from project management and strict project monitoring activities. The high CAPEX cost is necessary to successfully complete the drilling in a place where water is scarce. The study concludes that the Jessoma sandstone formation can provide fresh water with yields of 15 l/s. The presence of quaternary deposits makes the Jessoma sandstone formation an exploitable high potential aquifer, especially in its deep part which is characterized by cherty limestone limited by impermeable layers. This paper contributes to improve the equitable access to safe and clean drinking water for the local population of the drought-affected region of Somali and to the broader Somaliland region. The paper provides a clear justification for investment in "resilient" water solutions that provide water throughout the year without requiring supplementary emergency water trucking.

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