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TESI DI LAUREA TRIENNALE

IN

SCIENZE GEOLOGICHE

GROUNDWATER AND GEOLOGICAL ASSESSMENT IN ERITREA:

A COOPERATION PROJECT IN ADEMZEMAT VILLAGE (ASMARA DISTRICT).

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Thesis Index

Abstract:

Il seguente lavoro si inserisce nell’ambito di un progetto di cooperazione,la cui finalità è quella di fornire una risorsa d’acqua pulita per il villaggio di Admzemat, situato nell’altipiano Eritreo. Lo studio condotto vuole definire l’assetto geologico ed idrogeologico dell’area dove si trova il villaggio, in modo da fornire uno studio preliminare su cui basare i successivi sviluppi del progetto. A tale scopo, è stato necessario affrontare un inquadramento generale dell’altopiano Eritreo, seguito da un’analisi da remoto di immagini satellitari e da uno studio di campagna. Alla luce di quanto acquisito è stata presa visione dei dati prodotti durante un’indagine geofisica dell’Aprile 2010. In particolare si è cercato di analizzare la potenzialità del sito che, durante la geofisica del 2010, è stato indicato come punto di trivellazione per un nuovo pozzo.

Introduction

Eritrea is located in the North-East side of Africa (12°20'–17°50' N latitude and 36°30'–43°00' E longitude), belonging to the so call "*Horn of Africa*" (Fig.1). The country presents a total extension of 125.700 Km² and it is eastern bordered for more than 1000 km by the Red sea cost.

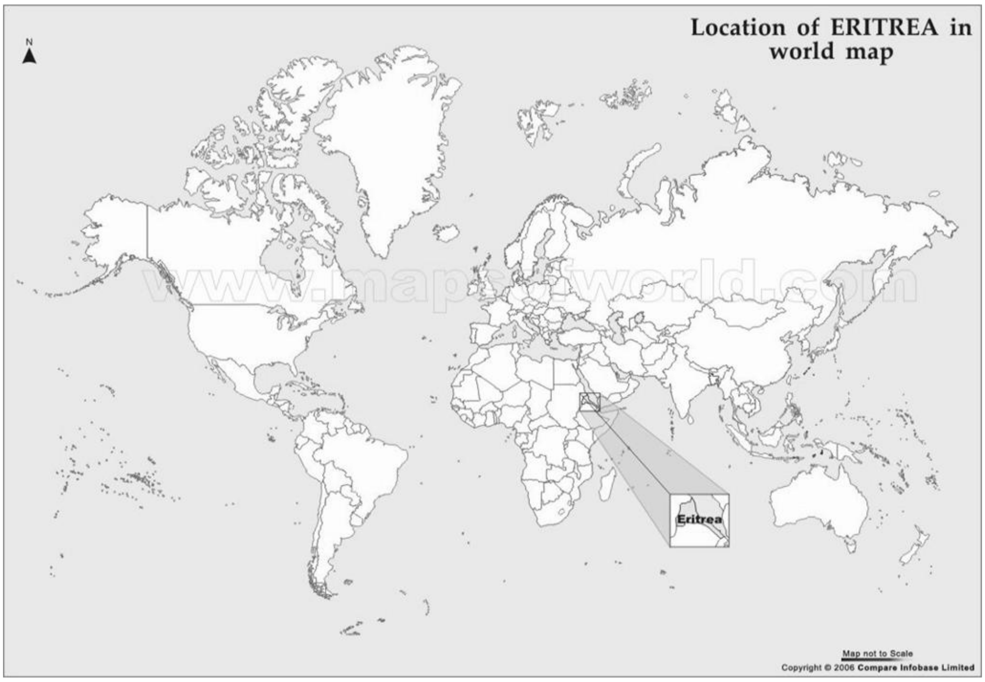


Figura 1: Eritrea Location (www.mapsofworld.com)

The semi-arid climate of the country is characterized by long dry periods, short and stormy rainy season and great variability in rainfall from year to year, as result rivers and stream present a seasonal flow. Surface water can not be considered a reliable source of potable water during the entire year period. The lack in adequate potable water supply sources is one of the main problems of Eritrea, especially in the rural areas. People living there collect water from ponds, channels, hand dug wells, and springs, that are barren during the dry season and located far away from the village. Hence, groundwater can be considered the main fresh water source for drinking and domestic uses.

The Eritrean Government is cooperating with different NGO to provide safe and adequate water supply systems to the rural communities. The present work is part of a cooperation project involving three principal actors: the Eritrean Administration of Zoba Maekel region, the population of Ademzemat village (located in the Zoba Maekel) and the Italian Onlus Bashù. The project started in 2010 and in November 2010 the Italian region of Veneto approved a founding , that will cover 50% of the costs. This work wants to define the geological and hydrogeological setting of the village area. We analyze the principal characteristics that influence the groundwater occurrence, in order to contribute to this project, which aim is to provide a reliable water supply source for Ademzemat village population.

1.WATER SUPPLY PROBLEM

Water is the most widely distributed substance on our planet. It is available everywhere and plays a vital role in both the environment and human life. Quantity of fresh water available is variable from region to region, according to different climates and to seasonal or inter-annual variations. Most developed countries have artificially overcome this natural variability by supply infrastructure to assure reliable sources, although at high cost and often with negative impacts. Many less developed countries, and some developed countries, are now finding difficulties in satisfy the ever increasing demands from demographic, economic and climatic pressures *(UN-Water ,2008).* In addition to problems of water quantity there are also problems of water quality. Pollution of water sources is reducing the amount of fresh water. Climate change is also impacting fresh water availability in both quantity and quality: temperatures are rising and precipitation patterns are changing. In many regions demand is increasing as a result of agricultural and industrial expansion, population growth and other demographic changes (in particular urbanization). All these environmental factors: climate change, increased population and water degradation contribute to water scarcity. The image below (Fig. 2) shows the World water supply coverage. Africa and Asia are the continents with the most critical situation in term of water accessibility.

In Africa the water provision is one of the bigger problem. Water pollution, dry season length and inadequate resources administration are causes of this critical situation. Figure 3A shows as in the 2000 Africa had a total water supply coverage of 62%. The situation was much worse in rural areas, where the coverage was only 47%, compared with 85% coverage in urban areas *(WHO, 2000)*. Figure 3B shows African water supply coverage. Few countries have more than 90% water supply coverage, instead ten African countries have less than 50% coverage. In the image Eritrea displays a water supply coverage between 26% and 50%. A jointed monitoring program of UNICEF and WHO states that the percentage of rural people with access to improved water sources was 39% in 1990 and 57% in 2004 *(UNICEF/WHO, 2006)*. Less favorable data are reported in a study carried out in 2003, that sets the proportion of the rural population whit access to a water source at 21% *(WRD, 2003).*

In the rural area of Eritrea women are appointed to collect water from channels, ponds, hand dug wells, and springs, that are usually located far away from the village. They spend many hours to carry, filter and boil the water, preventing their education. Moreover, the consumption of insane water causes the diffusion of water-related illnesses, such as diarrhea, that represents one of the principal causes of infantile mortality.

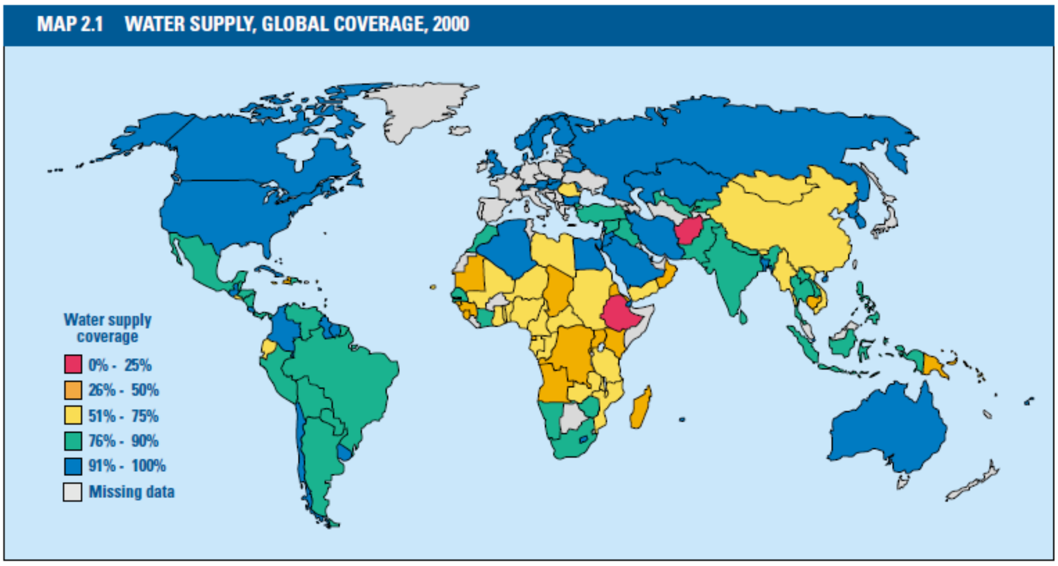


Figure 2: Word water supply coverage (WHO, 2000)

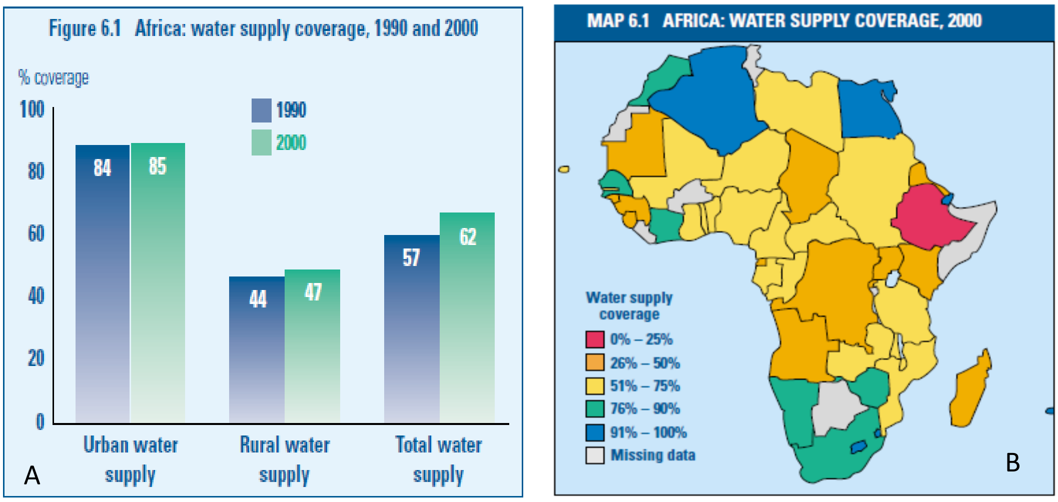


Figure 3: African water supply coverage (WHO, 2000)

2. WATER RESOURCES IN ERITREA

2.1 Hydrological Setting:

According to the definition given by *Lloyd (1986*), Eritrean climate can be considered of semi-arid nature. Locally it changes from hot arid climate, in the coastal plain, to temperate sub humid climate in isolate areas within the eastern highland escarpment.

Annual rainfall ranges from less than 50 mm on the eastern lowland regions to little more than 700 mm on the highland region. The average annual precipitation amount around the capital is about 520 mm/yr, with variation between 300 mm and 600 mm *(Estifanos, 2005).*

More than 65 % of the annual precipitation occurs during the months of July and August (Fig.4). Potential evapotranspiration rate is very high compared to the precipitation amount, it can reach about 1600 mm on annual basis (*Estifanos, 2005*). Eritrea experiences high temperatures since it is located in the sub-tropical latitudes of the Northern Hemisphere. However, temperatures are highly influenced by local topography. Altitude is the major factor in determining the temperature and rainfall (Fig.5). The minimum and maximum mean annual temperatures are 3° and 28° in the highland and 20° and 48° in the lowlands (*WRD data base*).

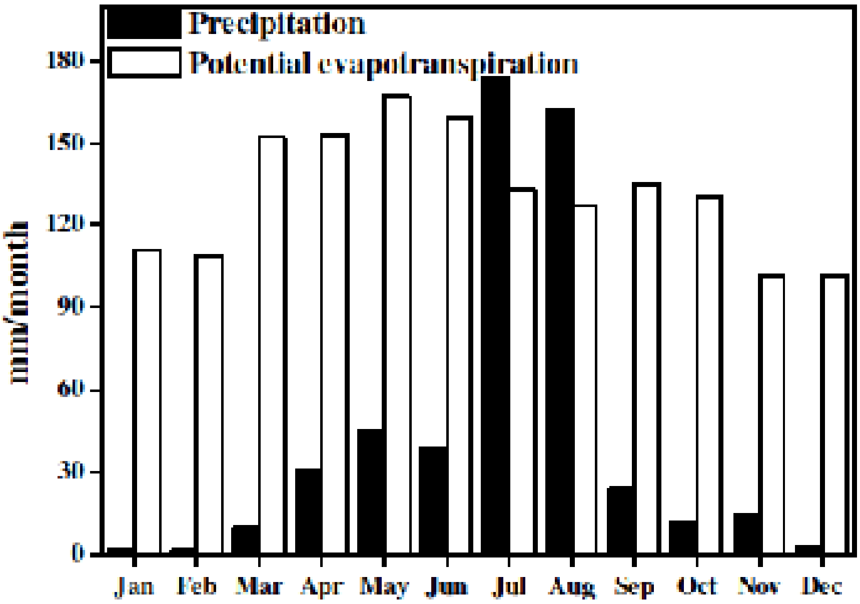


Figure 4. Monthly precipitation and potential evapotranspiration around Asmara (Estifanos, 2005).

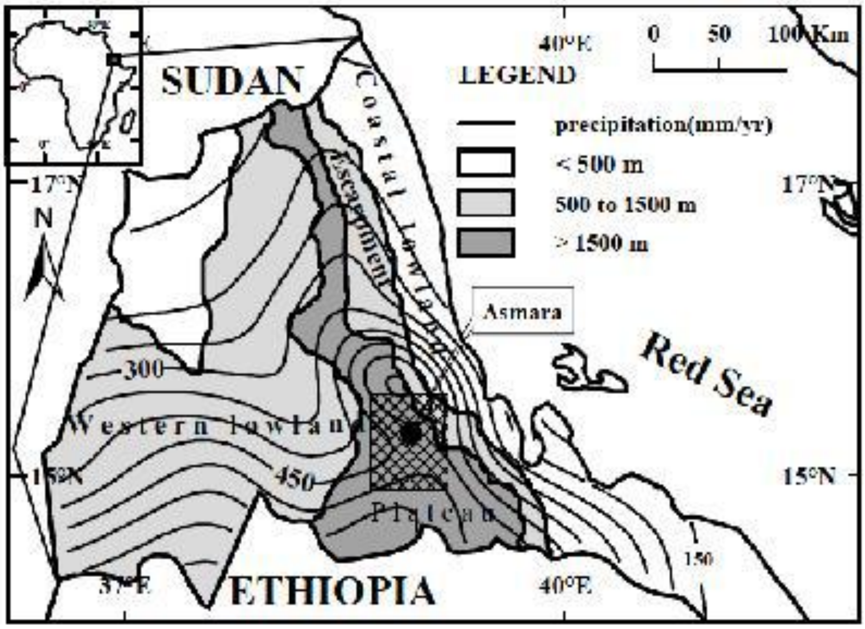


Figure 5: Map showing major morphological regions of Eritrea and annual rainfall distribution (Estifanos, 2005)

2.2 Geomorphological Settlement

Eritrean territory is divided in three morphological regions: the western lowland (500–1500 m), the central highland (1500–2500 m) and the eastern coastal lowland (0–1000 m), (Fig 6).

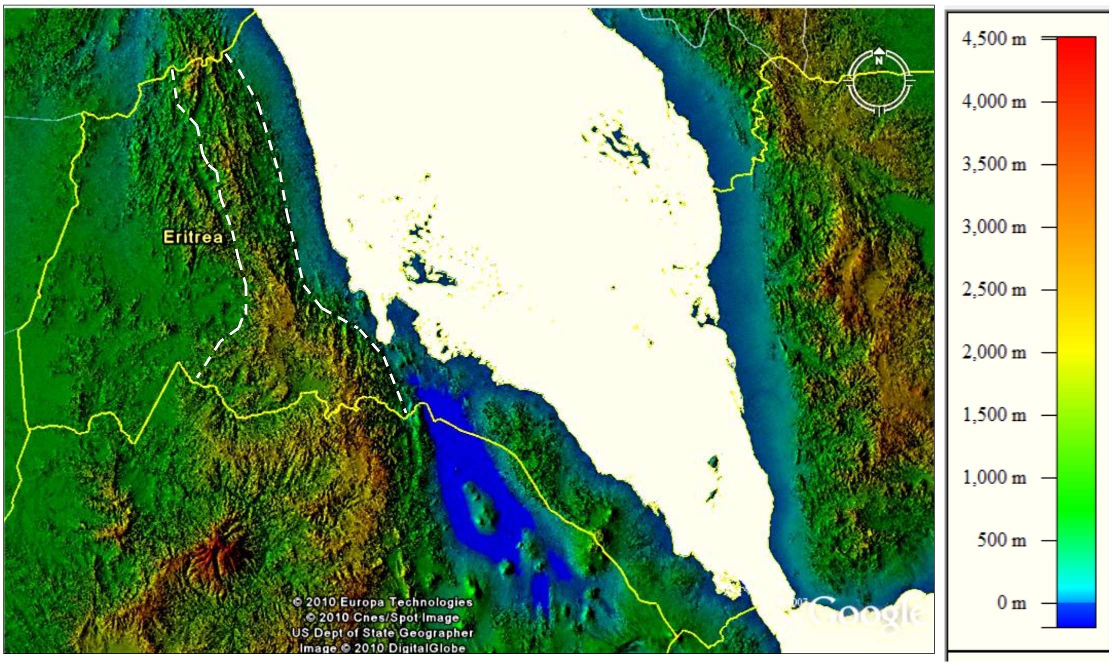


Figure 6: Three morphological regions of Eritrea (DEM downloaded from http://srtm.csi.cgiar.org/ and visualized in Google Earth).

The surface hydrology of Eritrea (Fig 7) is defined by three main drainage systems:

- The Mereb-Gash and Tekeze-Setit River systems, draining into the Nile River;
- The eastern escarpment and the Barka-Anseba River systems, draining into the Red Sea;
- The river systems of a narrow strip of land along the south-eastern border with Ethiopia, draining into the closed Danakil Basin.

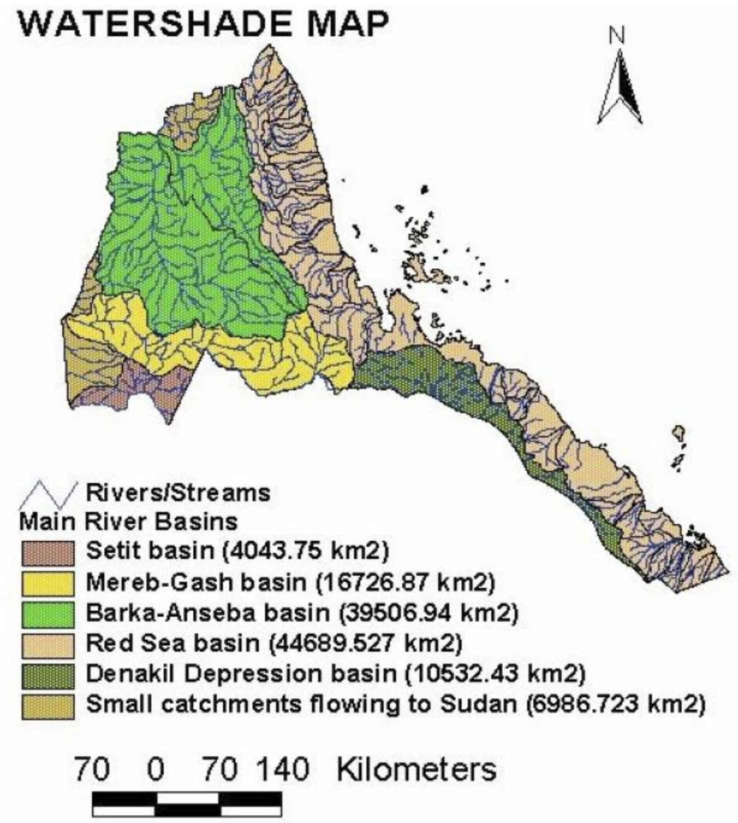


Figure 7: Main water shades in Eritrea (WRD database, 1997)

Except the Setit all other rivers and their tributaries are seasonal and intermittent.
Focusing on the highlands, the rugged morphology of this region, the lack of grass cover and the largely deforested terrains determine that most of the rain develops into flash floods causing severe soil erosion.

2.3 Geological Setting

Eritrea is characterized by an assemblage of Neoproterozoic terranes, involved in the Pan-African orogeny. These represent a metamorphic basement that has been covered by Tertiary to Recent volcanic rocks. Marine sediments of Mesozoic to Recent age are exposed in the coastal area of the country along the Red Sea (Fig.8). Since the Oligocene, the initial rifting and subsequent spreading along the Red Sea axis has been accompanied by the 3 km of uplift of the rift-shoulder, that created the present regional topography (Drury, 1994). Subsequently intense erosion has progressively stripped the Early Tertiary cover.

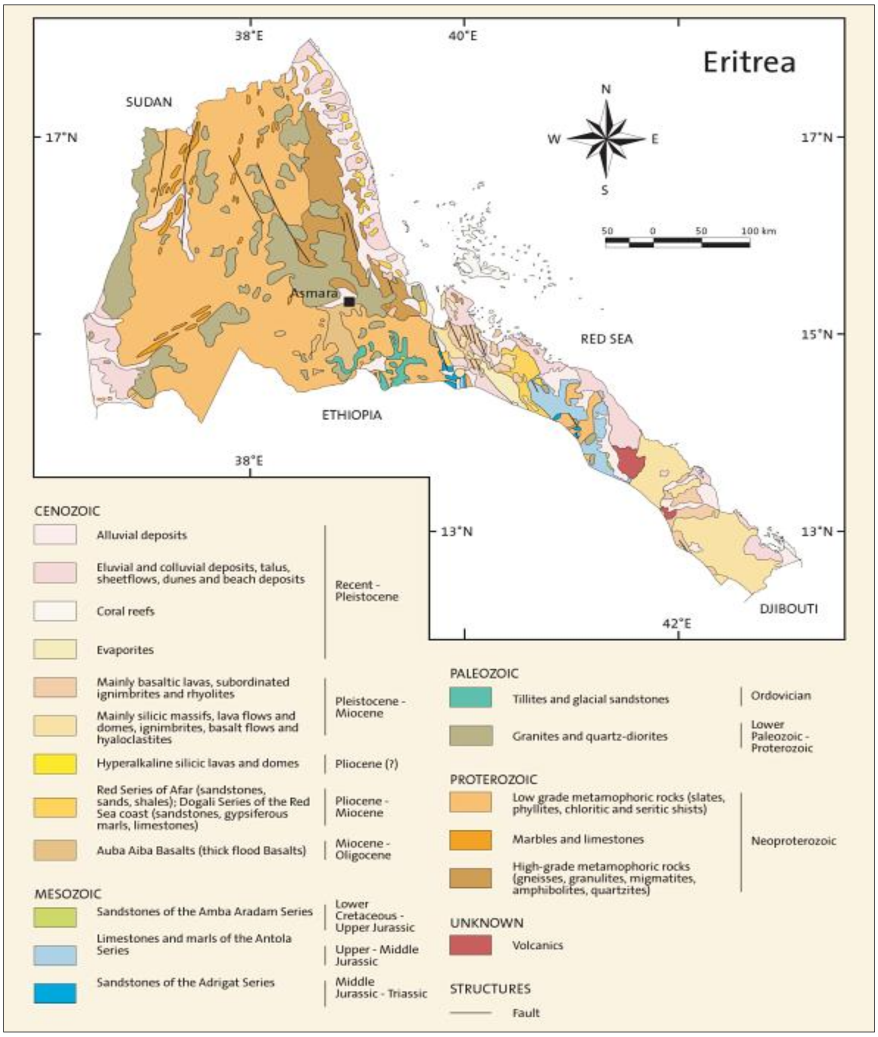


Figura 8: Geological map of Eritrea (Schluter, 2008)

Eritrean Neoproterozoic Terranes:

Eritrea lies at the axis of the northern part of the Neoproterozoic East African Orogen, and occupies one of the most southerly areas of the Arabian-Nubian Shield (ANS). The Neoproterozoic Arabian-Nubian Shield and the Mozambique belt together constitute the East African Orogen (EAO), that formed when the Mozambique Ocean closed as a result of the consolidation of East and West Gondwana. Lateral crustal growth through arc accretion has been proposed as the main mechanism for the evolution of the ANS, during Neoproterozoic time (Teklay, 2005). A first important study of Neoproterozoic terrane assemblages in Eritrea has been done by *Drury and de Souza Filho(1998).* The Authors define four large terranes, that are structurally and lithologically distinct (Fig.9). The Barka terrane is an upper amphibolite to granulite grade complex, characterized by multiply deformed gneisses, amphibolites, pelitic schists and orthoquartzites. The Hagar Terrane is dominated by supra-subduction zone volcanic rocks, but its western parts contain oceanic basalts, pelagic sediments and deformed basic-ultrabasic rocks. Parts of this tectonised ophiolite retain high P, low T assemblages, suggesting that the Barka western boundary was initiated as a subduction zone. The Adobha Abiy terrane extends as a narrow strip bounded by major shear zones throughout western Eritrea. It consists of metamorphosed clastic sedimentary rocks and marbles with metavolcanic rocks and syn-kinematic granitoids. The Nakfa terrane occupies more than half of the Neoproterozoic basement of Eritrea. It is composed of volcano-sedimentary rocks intruded by syn- and post-kinematic granitoids. The Nakfa terrane rocks are greenschist facies metamorphic rocks with dominantly steep fabrics.

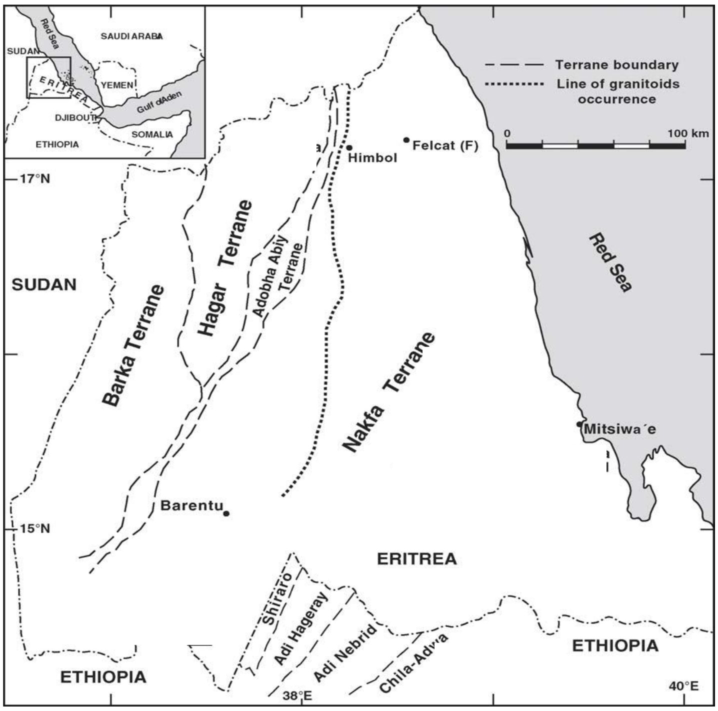


Figure 9: Simplified terrane map of Eritrea. (Teklay 2005)

Geological Setting of the Central Highlands of Eritrea:

The Neoproterozoic rocks in central Eritrea are part of the Nakfa terrane. The granitoid rocks, intruding the volcano-sedimentary sequence in the central highland, are described by *Salomon S. and Ghebreab W. (2006)* as granitoid varying from foliated porphyritic granite and granodiorite, syenite and diorite with local exposures of gabbros. Mesozoic sandstone and Cenozoic volcanic rocks (dominantly flows) lie unconformably over the volcano-sedimentary

sequences and the granitoid rocks of the Nakfa terranes . The contact between the basement and the base of the flood basalt pile is marked by a well-developed lateritic paleosol.
A lineament characterization study, by *Salomon S. and Ghebreab W. (2006),* analyzed the central highlands of Eritrea using Landsat TM data. The Authors defined six lineaments sets trending N–S, NNE–SSW, NE–SW, ENE–WSW, WNW–ESE and NW–SE. Their field studies, together with remote sensing analysis, indicate that most of the lineaments are extensional fractures, that correspond to either dykes emplacement or normal faults. Most of these were subsequently reactivated into strike-slip shear fractures. The NW–SE and NNE–SSW lineaments represent normal and dilatational fractures. The NNE–SSW trending lineaments constitute the most prominent dyke swarm, defined as the "Asmara dyke swarm" by Mohr (2001). The N–S and WNW–ESE lineaments form conjugate shear fractures. These shear fractures are older than another set of conjugate shear fractures, oriented NE–SW and ENE–WSW. The evolution of all these fractures is attributed to the Red Sea/Danakil rifting.

2.4 Hydrogeological Setting

Unconsolidated (alluvial deposits) and bedrock aquifers are both known in Eritrea. Unconsolidated aquifers are found over extensive areas in the eastern lowlands and coastal areas, but are limited to valleys of major stream systems in the rest of the country. Bedrock aquifers, consisting of weathered and fractured rock, comprise: fissured and jointed volcanic aquifers; fissured and karsic aquifers of consolidated sedimentary rocks, evaporite deposits and marbles; fissured aquifers of the crystalline metamorphic basement rocks and associated intrusive rocks. The bedrock aquifers have wide distribution throughout much of the central highlands and western lowland (Fig.10).

A report regarding the hydrogeological aspects of major fractures in Eritrea by *Drury et al (2001)* defines that the 60% of Eritrea is directly underlain by crystalline Precambrian basement. Most of the basement lithologies are aquicludes, with exception of steeply dipping, thin marble layers. In zones of intense ductile strain or late brittle faulting, the marble layers develop secondary permeability. They are targets for small scale supplies of potable water. In areas underlain by basement, other aquifers are active alluvium and regolith.

Palasozoic and Mesozoic sediments occurring in broad sedimentary basins of Tigray and Afar-Danakil contain a number of carbonate and clastic aquifers of various ages. These aquifers are absent from most of Eritrea.

The sequence of Mid-Oligocene flood basalts contains a number of pervasively rotted flows and interflow clastic sediments that are excellent high-yielding aquifers. They host perched water tables and a variety of potential supplies ponded by later igneous dykes and faulting against a basement. Intense erosion had progressively stripped the early Tertiary cover, leaving only a few isolated outliers. The largest of these, from Asmara to Adi Quala.

Later sedimentary cover, restricted to the evolving Red Sea Basin in the coastal lowlands and Danakil Depression, defined the Miocene to Pliocene Red Series. These strata offer little groundwater potential. The Red Series was involved in an episode of extensional tectonics, which produced the rise of the core complexes of basement. Its unconformable sedimentary cover of Pliocene to Recent offers some groundwater potential in coastal areas.

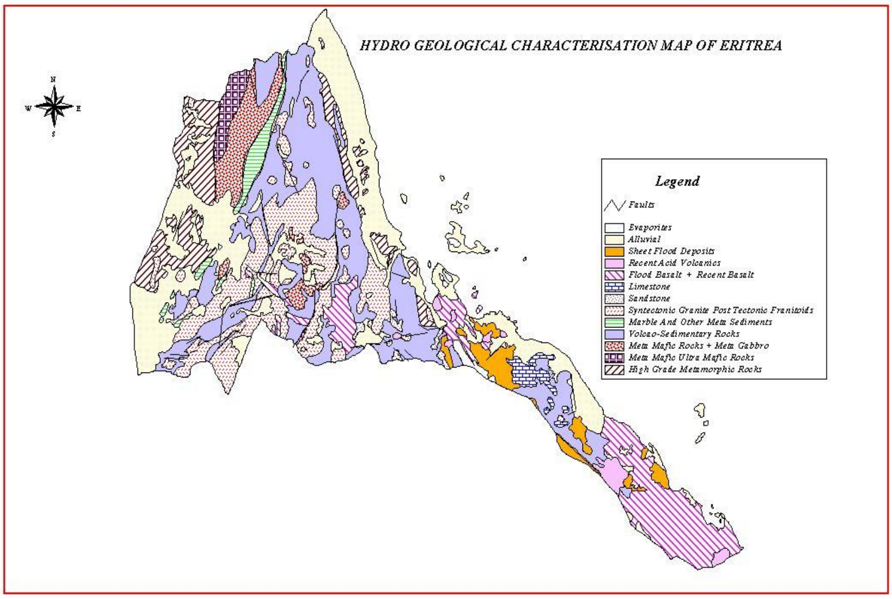


Figure 10: Hydrogeological map of Eritrea (WRD)

3. CASE STUDY: ADEMZEMAT VILLAGE

3.1 Introduction

3.1.1 Village location and accessibility

Ademzemat village is located in the Zoba Maekel Administration Region, under Galanefhi Sub Zoba. It is located about 14 km south of Asmara (Fig.11). The road from Asmara to Ademzemat is a combination of asphalt (11km) and weathered gravel road (last 3 km). Based on the general geographical classification of Eritrea the village could be categorized under the central and northern highlands of Eritrea.

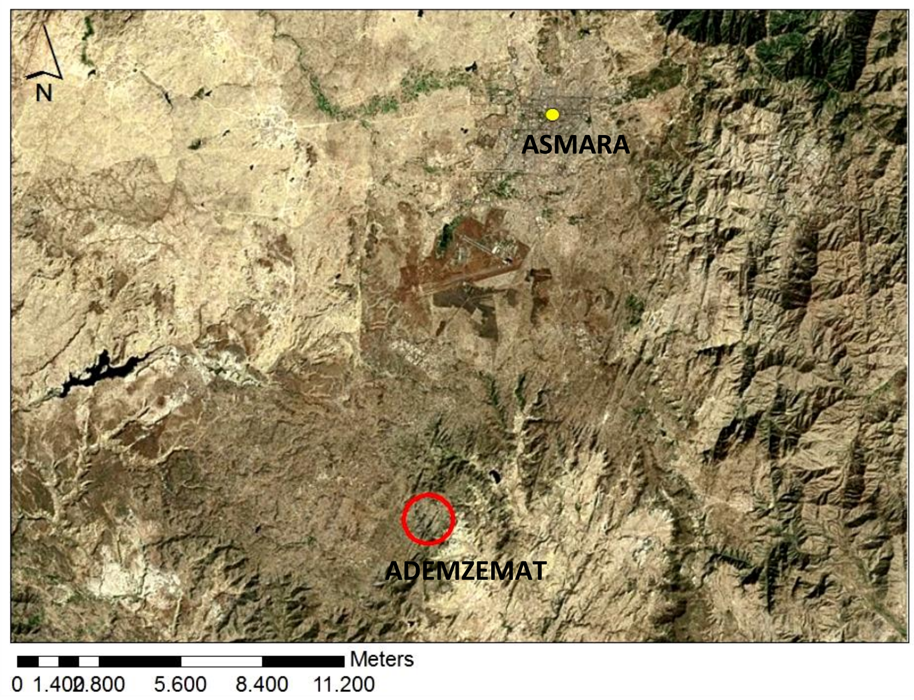


Figure 11: Ademzemate village location (Bing Maps).

3.1.2 Water Supply Project

The population of Ademzemat village is about 811 individuals and 162 households. Most of the villagers are farmer and live with crop and livestock production and selling. Along time different kind of water sources have been developed in the village (Fig.12).

The Eritrean Red Cross built a small dam on the west side of the village. However, the reduced dimension of the dam catchment area does not allow a sufficient and prolonged water storage. The dam is filled during the rainy season (June to September) and it provides water only until January. Due to poor sanitation condition, the water from the dam is used mainly for irrigation. Moreover, the villagers built an hand-dug well, 3,5m depth, which catches the runoff water during the rainy season. Another project was carried out in 2009, a borehole was drilled with a depth of 41m and an hand pomp Indian Mark II was installed. Currently the yield of this borehole results to be very limited (almost 20 l per week), probably because the borehole intercepted a perched aquifer layer that exhausted its reservoir in a small time. The borehole was located downstream refer to the dam building, this can be another factor that, associated with the small dimension of the recharging basin, explains this extremely low yield. Currently the main water supply for the village are truck hauling from Asmara. The water tariff is of 8 or 9 Nakfa per barrel, which represent a great economical effort for the community.

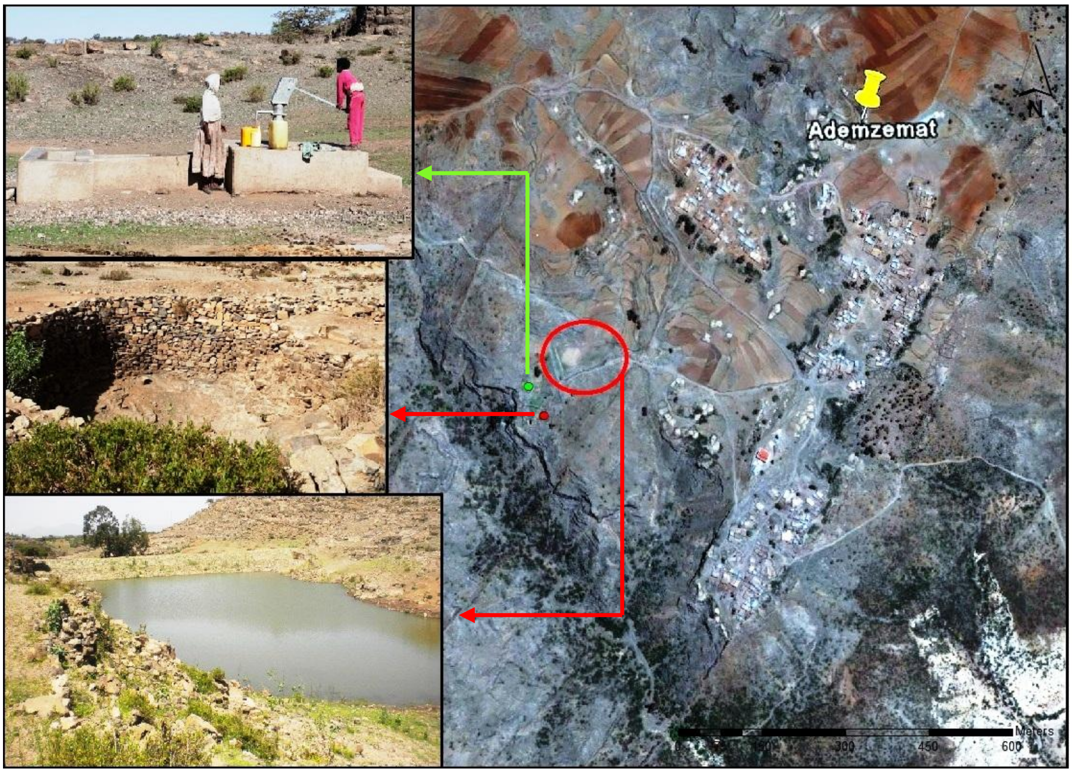


Figure 12: Ademzemat village and the existing water supply systems.

The existing water supply systems in Ademzemat village can be considered inadequate and insufficient to supply the village demand. The project supported by Bashù Onlus, in cooperation with the local region of Zoba Maekel and the villagers, has the aim to provide a source of clean and drinkable water for the village. The water source provide by the project should have an adequate production for at least 20 year, considering the population growth. This to sustain the cost of the project itself. The project plane presents the following steps:

- A previous characterization of the geology and hydrogeology of the village area will be carried out. This characterization will help to define the sites where conduct the geophysical survey.
- The analysis of the area and the geophysical survey will provide a complete overview of the hydrogeological setting of the area. If the more favorable option for water supply is the drilling of a borehole, the geophysical survey will orient the location of the borehole.

- The drilling will be carried out. If this operation succeed and the well has a good yield, on the borehole will be installed an electrical pump, powered by solar panels. The pump will carry the water from the well to the village.
- The water will be stored in a reservoir near the village. The area in which the reservoir will be cited is higher than the rest of the village (Fig.13). This fact allows the water to flow from the reservoir to the public fountain simply for gravity.
- Both connections between the pump and the reservoir and from the reservoir to the fountains will consist of a pipe running inside a channel excavated on the ground surface.
- The constructions will be carried out by the villagers and managed by the water committee with the supervision of the local Onlus representative.
- The water committee consists in six people representing all the village habitants. It will manage all the project steps, including the financial aspects and the final administration of the new supply system.
- Training in water sanitation and management will be organize for the village population, in order to enable them to develop a self administration of the resource.

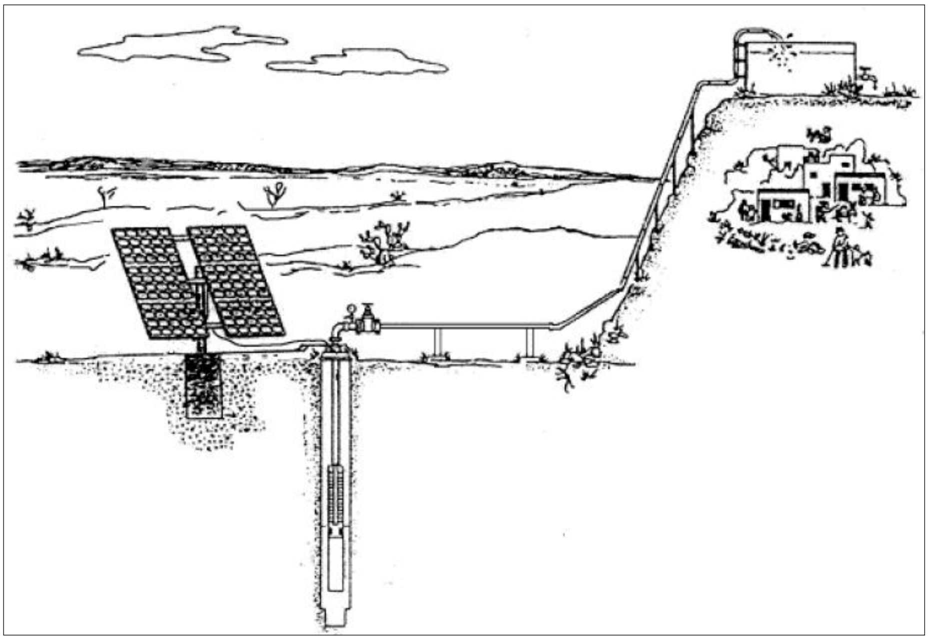


Figure 13: Project outline scheme

3.2 Geomorphology

The village is located on the top of a cliff and the average topographic elevation is about 2350m. The South and East sides of the village are bounded by steep cliffs, while the West side space on a wide flat area (Fig.14). These cliffs have an high of about 200 m. The one on the East side of the village is related to the presence of a basaltic dyke. The village was built along this volcanic structure, and some of the houses are cited behind the dyke itself. The area is crossed by several dykes; when exposed this features form crests and ridges. The cliff on the West side represents a deep stream valley intersected almost perpendicularly by dykes.

In the area most of the streams drain towards South East, with a seasonal and intermitted flow. Generally we can recognize an association between the main geological structures in the area and the drainage pattern. The lack in vegetation and the rugged landscape lead to severe soil erosion due to water flash flood, during the rainy season.

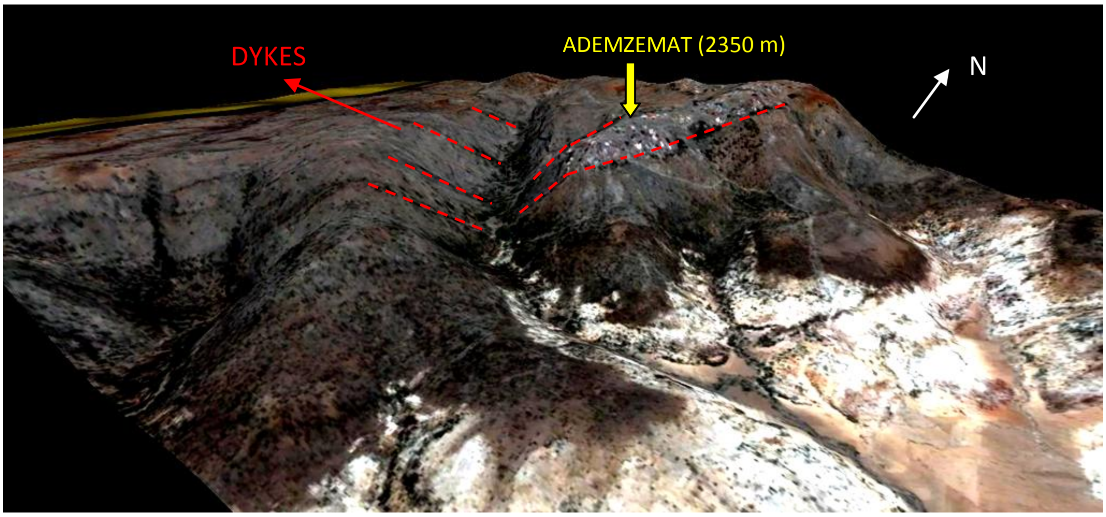
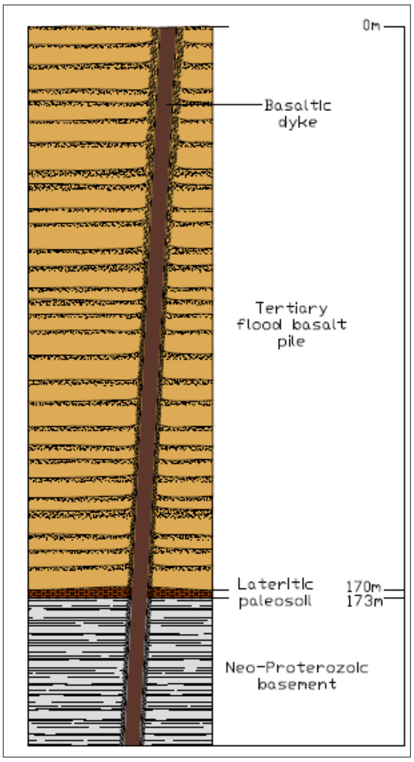


Figure 14: 3D view of Ademzemat. Using Global Mapper v11.00,Google Earth image and DEM, downloaded from http://srtm.csi.cgiar.org/, were combined.

3.3 Geological Analysis

The area is characterized by two formations: Tertiary Basalt, defined by a pile of sub-horizontal lava flows, and Neoproterozoic Metamorphic Basement. The contact between them is underlined by lateritic paleosoil, formed during the basement exposure. The remote sensing analysis and field study are reported in the following sections.

Figure 15: Schematic section showing the Lithological units of the study area.



3.3.1 Remote Sensing Analysis

The aim of our remote sensing study was to map the main lithologies and principal lineaments. According with O'Leary et al. (1976) a lineament is a mappable simple or composited linear features of a surface, whose part are aligned in a rectilinear or slightly curvilinear array, which differs distinctly from the patterns of adjacent features and which presumably reflects a subsurface phenomenon.

The characterization of geological lineaments and lithological contacts is relevant because, as reported in several hydrogeological studies of the surrounding area, the main aquifers are localized in weathered and fractured bedrock or associated to the Tertiary unconformity between the flood basalt pile and the lateritic paleosoil. Moreover the major fractures act as principal collector and conduit for groundwater.

The remote sensing investigation was based on:

Google Earth (GE) images

From Google Earth software we got the detailed images of the area, that presumably are multispectral Ikonos image with a resolution of 3 m. Using Arc Gis 9.3.1 we emphasized the data with the histogram equalization stretch. This allowed us to recognize the contact between different lithologies and detect even the barely visible lineaments.

Hence, the GE images resulted particularly useful to:

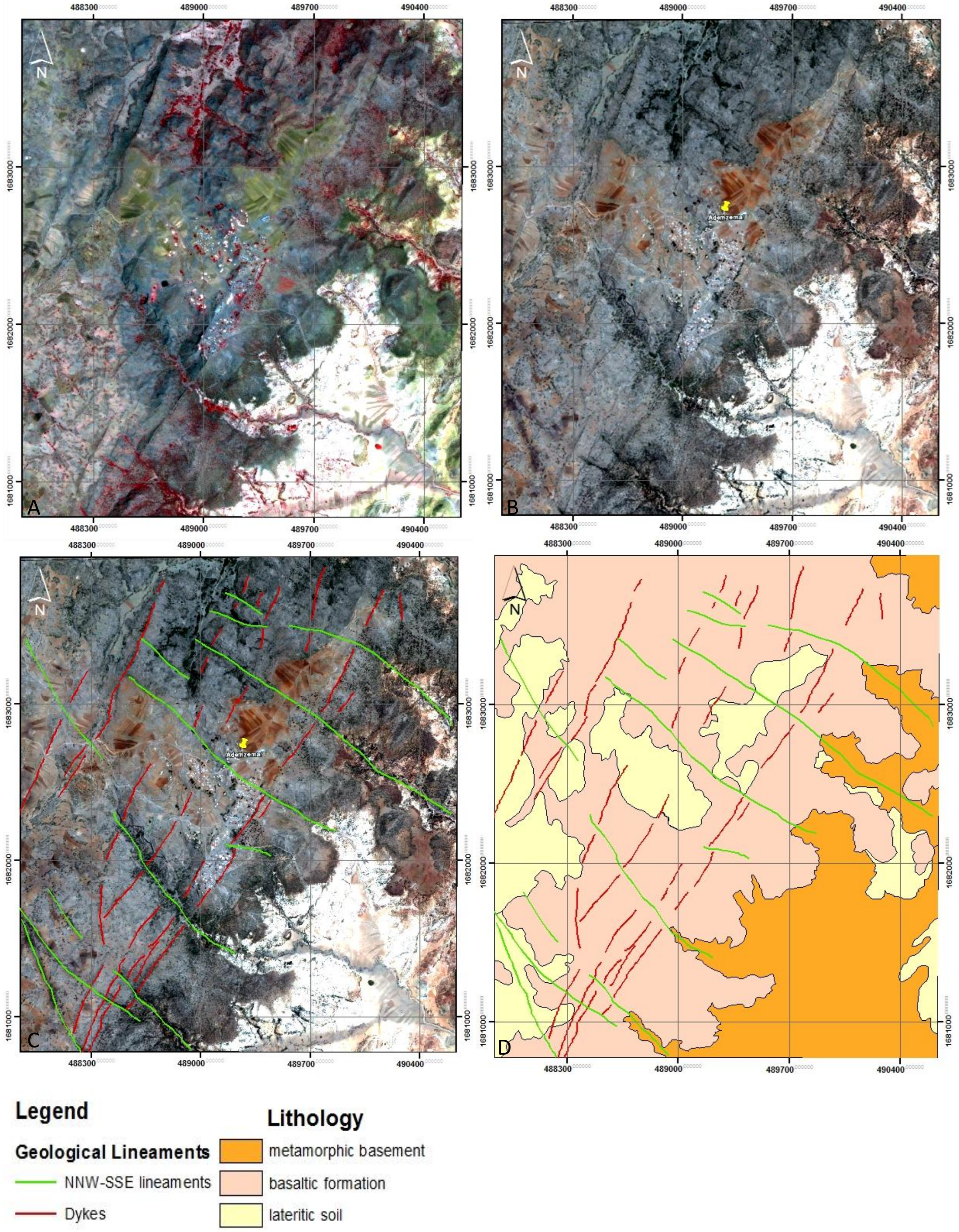
- localize the existing water supply systems for the village and identify other man-made objects.
- define geological lineaments, such as dykes and major faults.
- define the lithological contact between different formations.
- observe the landforms and the geomorphological setting of the area.

SPOT image

The analyzed Spot image belongs to the SPOT 5 series, that are characterized by a resolution of 10 m pixel. As for the GE images also the SPOT one has been analyzed with Arc Gis 9.3.1, but all its bands were enhanced using a linear stretch at 2 Standard Deviations. The interpretation was carried out using a 321-RGB false color composite. The analysis of this imagine resulted particularly useful to identity the distribution of vegetation, that in the used RGB is represented in red color, and to map different lithological units, with particular regard to the Quaternary lateritic soil (displaying a dark green color). In addition, the synoptic view of the 60 x 60 Km Spot scene enabled us to evaluate the regional extension and importance of each mapped feature.

The result of the remote sensing analysis is shown in Figure 16. The contact between the Basaltic Formation and the underlying Metamorphic Basement is distinctly visible; its geometry let us associate it to sub-horizontal contact. The principal geological lineaments of the area are sub-parallel vertical dykes, showing a NNE-SSW trend, representing a unique dyke swarm of regional relevance. Moreover, it is notable a strong parallelism among river valleys, that are characterized by a general NW-SE orientation. The dykes intersecting these features appear to be often interrupted and, in places, displaced. It is very likely that the valleys were excavated within weaker and fractured zones, associated to faults. Therefore two principal lineament sets are distinguished in the area: NNE-SSW trending dykes and NW-SE faults. These sets are associated to normal and dilatational fractures by *Salomon S. and Ghebreab W. (2006).* The same authors consider the prominent NNE–SSW dyke swarm older than the NW-SE fault system. This is confirmed by the analysis of the study area. The presence in the area of two intersecting lineament sets is relevant in term of groundwater potential, especially at the intersection points.

Figure 16: A SPOT5 image of the study area; B GE image of the study area; C GE image of the study area with lineaments interpretation; D Geological map of the study area elaborated with ArcGis 9.3.1.



3.3.2 Field Study

The aim of field study was to characterize the lithologies of the area, in order to define their features or characteristics that appear to be crucial for groundwater storage and circulation. Moreover, the field work gave us the opportunity to verify the nature of the features detected during the remote sensing analysis. Quaternary deposits and principal lithologies encountered were:

Quaternary Deposits

Black cotton soil of Quaternary formation is exposed with a thickness ranging from 0.5ms to 2 ms . This soil is the physical and chemical weathering product of the basaltic flow. Besides thick clay soil of lateritic origin was also observed. Thin alluvial (gravel) deposits of basaltic origin are exposed in the river bed.

Tertiary Basalt

The basaltic unit crops out on the top of both ridges that bound the village, it displays a pile of several sub-horizontal lava flows. Generally in Eritrea the maximum preserved thickness of the flood basalt pile is around 250 m *(Mohr, 2001*), in the village area the preserved pile thickness is about 170 m. Each flow presents a thick of 2 to 5 m, in which two different parts can be recognize (Fig.17A). The base of each flow is represented by massive basalt, that can be described as a black or dark grey, massive and fine grained mafic rock. The upper part of each lava flow appear to be vesicular due to processes of gas escape, during the magma cooling (Fig. 17B). The vesicles show zeolite filling the spaces. The vesicular basalt presents high porosity but low permeability. There is no contacts between the vesicles, that appear to be isolated in the basaltic groundmass. Moreover the vesicles filling reduce the porosity itself. On the Contrary, if the vesicular part result to be fractured or weathered it can constitute highly permeable aquifer layer.

Along the lava pile the contact between two different flows is usually defined by a reddish horizon (Fig.18A). This can be considered the result of a “backing effect” due to the incoming hot lava flow on the older and cooler one. This difference in temperature allow the “backing” of the upper part of the existing flow. In addition, this contact can also be associated to weathering processes. Each lava flow knew a period of surface exposure before to be covered by a new flow. According to the time of exposure each flow can develop different grade of alteration, that results in this reddish contact. If this horizon between flows is well developed, it can became significant in term of water conduction.

On the top of the cliffs the exposed sections of the basaltic unit appear to be weathered as result of exposure to the sub-aerial conditions; here spheroidal weathering is dominant (Fig.18B). Generally the degree of weathering ranging from fresh to highly weathered.

In the exposed basaltic sections two sets of minor fractures were defined:

- Sub-vertical minor fractures strike N-S (270-85), with an opening of about 0.5cm and quartz filling. The continuity of the set fractures varies from 1 to 5 m and the spacing varies from 10cm to 1m.
- Sub-vertical minor fractures strike NNE-SSE (175-90), appear to be filled with products of basalt alteration. The presence of weathered basalt along these fracture allows us to suppose that they acted as water conduits.

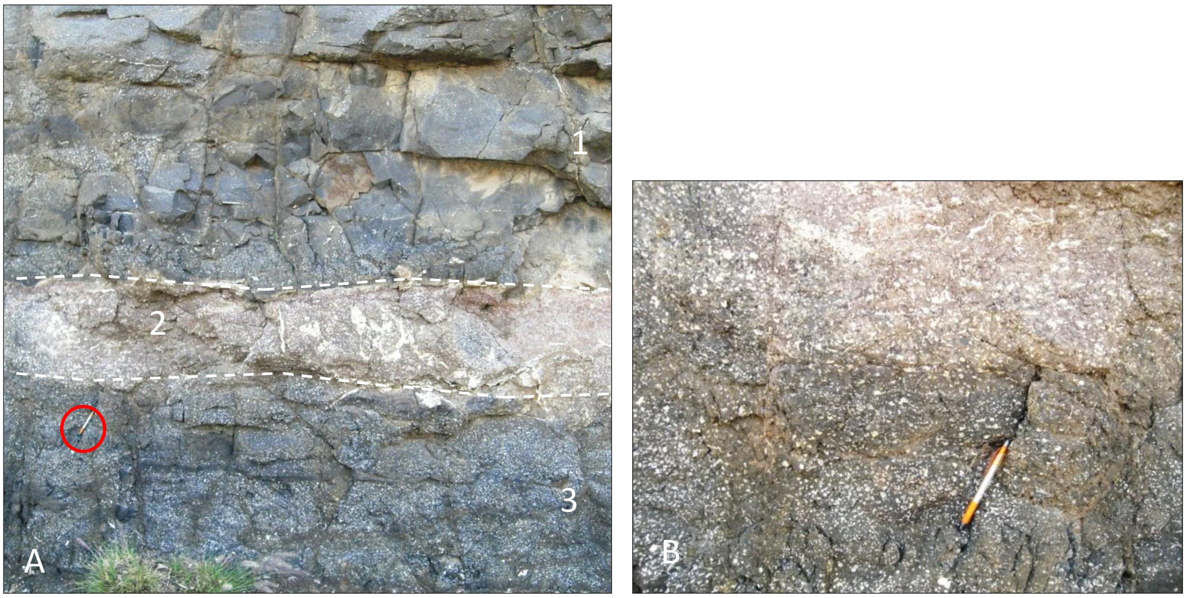


Figure 17: A Section of Basaltic flows that shows: massive basalt (1), reddish contact between flows (2) and vesicular basalt (3).Scale in the red circle. B Vesicular parts of basaltic flow.

Weathered and fractured basalt is expected to be potential aquifer in the area. Despite that, we have to note that the basaltic layers shows different fracturing and weathering degree. Moreover, there are same adverse factors reducing the groundwater circulation within the analyzed basaltic formation. The clayey materials produced by the basalt alteration, if collected into fractures, can reduce the secondary permeability of the formation. In addition, the presence of minerals filling fractures represents fluid circulation, but are currently sealing the fractures them self.

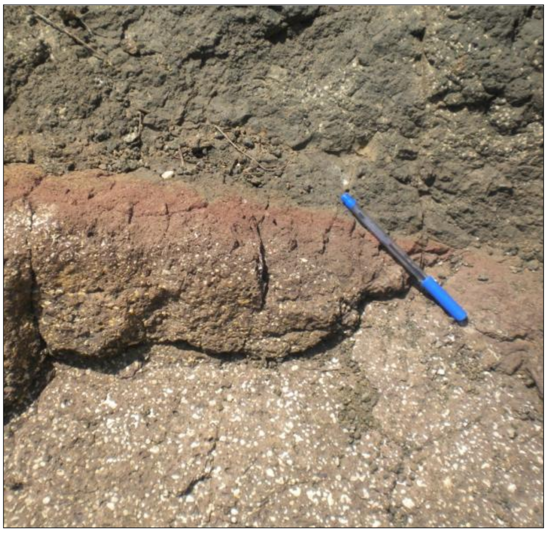


Figure 18A: Red horizon between lava flows.

Figure 18B: Spheroidal weathering in basalt.

Neoproterozoic Basement and Lateritic paleosoil

In the study area the upper part of the Neoproterozoic basement is defined by a lateric paleosoil. It developed during the surface exposure of the metamorphic basement, occurred among the Cretaceous-Eocene interval (Mohr, 2001). A lateritic soil is a surface formation rich in iron and aluminium. It develops in hot and wet tropical areas due to intensive and long weathering of the underlying parent rock. In the study area this lateritic paleosoil defines the contact between the flood basalt pile and the underlying Neoproterozoic basement (Fig.19). It typically displays as a red to dark brown cemented horizon showing circular pisolides, formed as the result of high degree of lateritization (Fig.20A). The thickness of lateritic horizon in the area ranges from less than one meter to few meters. Because of its composition, this lateritic paleosoil can be considered as an impermeable layer, allowing groundwater accumulation. Beneath the lateritic paleosoil, the regolith displays white color and massive structure. Due to the high degree of alteration it was difficult to discern the structures and compositions present in the rock of the study area. Observing a road-cut section exposed 4 km south to the village, it was possible to recognize highly foliated rocks, typical of metamorphic basement (Fig.20B). The Geological map of Eritrea, reported in the Geological Atlas of Africa by Schluter, (2008), describe the basement underlying the study area as low grade metamorphic rocks (slate, phyllites, chloritic and seritic shists).

Figure 19:Contact between the Tertiary flood basalt pile and a colluvial deposit overlaying the lateritic paleosoil and Neoproterozoic basement. Outcrop on the road-cut to Mendefera

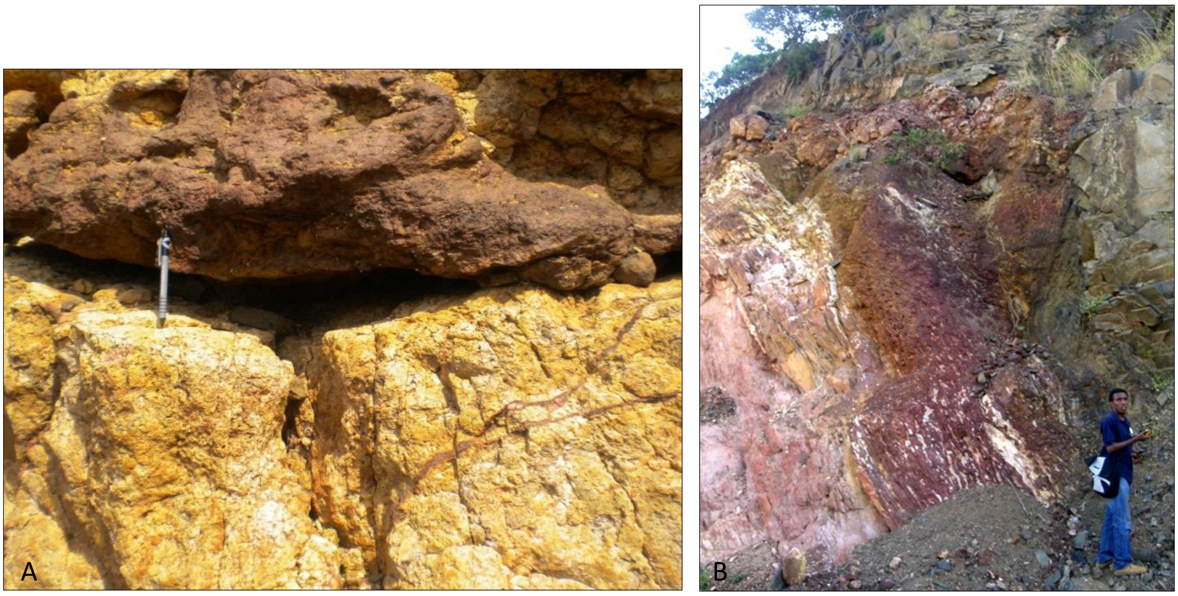


Figure 20: A Lateritic paleosoil and the regolith beneath in the village area. B Section on the road to Mendefera showing the basement foliation sub-parallel to the dyke intrusion.

The principal structure define in the area during the field study were:

NNE-SSW Dyke Swarm

According to *Salomon S. and Ghebreab W. (2006)* , in the central highland of Eritrea there are six sets of basaltic to doleritic dyke swarms, the most prominent set strikes NNE–SSW. Other sets are N–S, NNW–SSE, NW–SE, WNW–ESE, NE–SW and ENE–WSW in strike. All sets of dyke swarms intrude the Neoproterozoic basement rocks and the overlying Cenozoic basaltic flows (Fig.21A). The dykes observed during our field study belong to the most prominent system of intrusion of the central highland, reported as the “Asmara dyke swarm” by Mohr (2001). According to the Author the Asmara dykes represented a off-rift injection oblique to the Afar/Red Sea basin (trending NNW-SSE), that runs for at least 50 km with a width of 7km. The dykes intrusion is generally near-identical to the structural disposition of the basement schists/gneisses. These basaltic dykes are considered to be feeders of the upper part of the regional flood basalt pile.

In the study area, where exposed at the surface, the basaltic dykes form crests or ridges as a regular wall-like features. Dykes strike NNE-SSW and their dips are sub-vertical. They present a width ranging from less than 1 m to 5 m. From remote sensing analysis their spacing appears to vary from some tens of meters to more than one hundred meters; their length can be traced from few meters to hundreds of meters. In the village area the dykes cut the entire lava pile. In same case they present visible chilled margins and the hostrock appear to be brecciated for some centimeters out from the contact with the dyke. The dykes core is characterized by variable degree of fracturing. Three sets of joints are recognizable within the exposed dykes, with the following orientation: (350-05), (052-80), (285-85). The spacing of each set varies from less than 1 m to 2m. Therefore the dykes appear to be divided in several isolated blocks of variable dimension (Fig.21B). The opening of each set varies from few centimeters up to 30 centimeters, these spaces are in part filled with basaltic fragments.

The presence of this dyke swarm deeply affected the groundwater assessment of the study area. The dykes may have hydrogeological significance as either barriers to subsurface flow or zones of water conduction inside the country rocks, along their shattered margin or their internal fractures. When the dykes show multiple injections, with the outer part (first injection) presenting columnar joints (Fig. 22), they might be considered as water conduits. If we consider the dykes having a barrier effect, when they cut streams valleys we might consider them as natural dams for the groundwater flow. To conclude, the groundwater occurrence in the area will be driven by the interaction between the NNE-SSW dykes and the NW-SE faults system, detected during the remote sensing analysis.

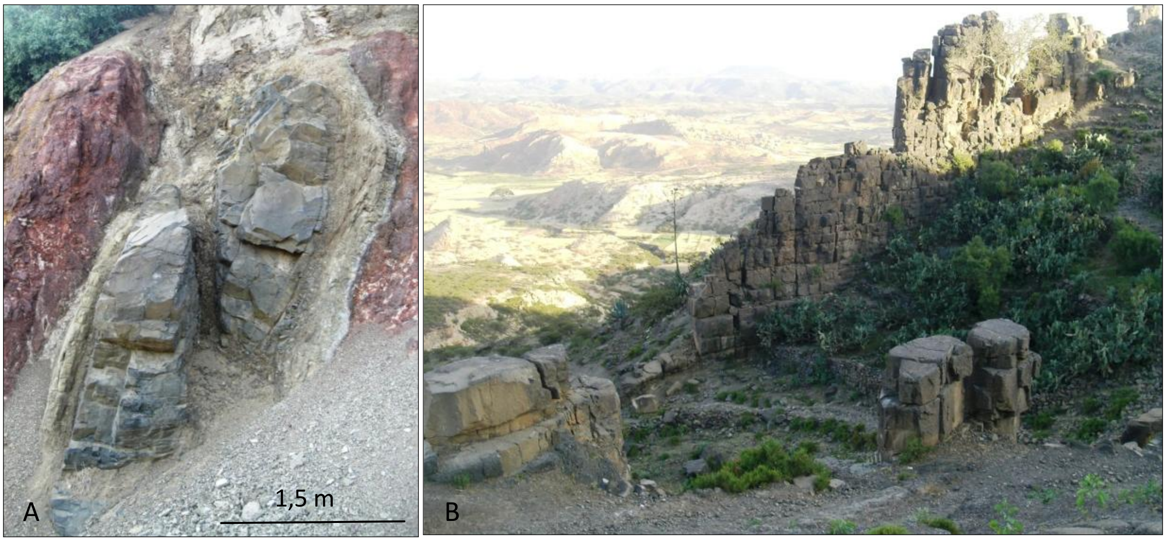


Figure 21: A. Dyke intruding the Neoproterozoic Basement, cropping on a section along the road to Mendefera. B. Basaltic Dykes intruding the lava pile, showing the internal sets of fractures. The dykes in the picture are the two parts of the same intrusion cut and shifted along a NW-SE fault.

Figure 22: Columnar joints of a dyke showing multiple injections.

3.4 Hydrogeological setting

Generally in the Eritrean central highland, weathered and fractured basaltic rocks, Tertiary unconformity plane (between the basement and the basaltic flows) and junction of joint planes are considered to be important in term of groundwater storage potential. In addition the points where the dikes cut the main recharging stream are considered as potential sites.

According to *Estifanos (2005)*, although the basaltic aquifers have small extension, they show relatively high capacity as compared to granitic and metamorphic rocks. This fact due to their primary porosity, the presence of multiple stratification and the grade of weathering and fracturing developed.

According *Tesfaslasie (2003)*, in bedrock aquifers, the principal factor controlling the groundwater occurrence and flow is the existence and density of geological structure. The complex nature of such structures is the main problem encountered during assessment of groundwater resources and siting of production wells.

3.4.1 Groundwater assessment

According to Estifanos (2005), in arid and semi-arid areas, assessment of groundwater recharge is one of the key challenges to determine the sustainable yield of aquifers, because of the small amount of recharge rates in comparison with average annual rainfall and evapotranspiration. The Author proposed the use of chloride mass balance method to estimate groundwater recharge for bedrock aquifers in the Eritrean Highland. Figure 23 shows the results of this study, according with which the groundwater recharge in basalt is about 6% (almost 31mm/yr for the annual precipitation amount of 520 mm).

The significance of groundwater as potential resources for usage in the area is related to the amount of recharge that is occurring as well as factors that affect the water quality within the aquifers. In the highland the chemistry of groundwater is controlled by bedrock. A study of the chemical quality of groundwater resources in Eritrea was conducted by Zerai (1996).

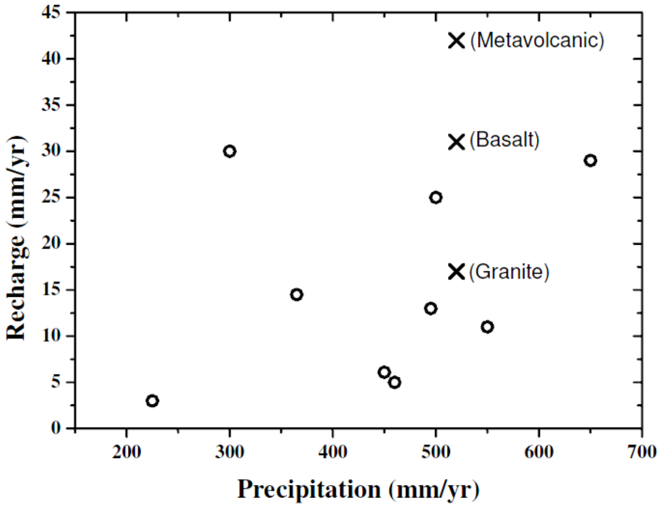


Figure 23: Recharge estimates from different localities and bedrock types by using chloride mass balance. Cross mark represents Estifanos (2005) calculation.

According to the Author, Eritrea can be divided into three regions based on water quality. For the Eritrean Highlands and western lowlands the Author defines a good groundwater quality, except where sewage contamination around Asmara produces high nitrate concentrations in some wells. The waters, with electrical conductivity values ~1 mS /cm, hardness values of 50-100 mg/l, are soft to slightly hard and predominantly of Ca-Mg-HCO type.

Another study considering the groundwater quality of Eritrean aquifers is by Estifanos (2005). On the Piper diagram (Fig.24) are plotted water compositions from different bedrock types. The Piper plot by Estifanos confirms a composition of Ca-Mg HCO type for metavolcano-sedimentary rocks and basalt; with the Metavolcanic rocks giving a water more rich in Ca^{2+} and Mg^{2+}, while the proportion of Mg^{2+} is higher for the basaltic rocks.

During the hydrogeological characterization of the village area finalized to identify the sites for the geophysical survey of 2007, same quality parameters were measured: for the village dug-well, with a depth of 3.5 m were measured SWL of 2.5 m, Ph of 6.5 and total hardness of 240 mg/l; for the borehole drilled in 2006 for the near village of Sela'edaero, with a depth of 50 m and a yield of 0.8 l/s, a total hardness of 200 mg/l was measured. The parameters measured during the survey can not be considered representative of the water quality in the study area. Despite the bibliographic studies give a good quality for the groundwater in the central highland, a better characterization is required, particularly to assess water quality in the perspective of a drinking water use.

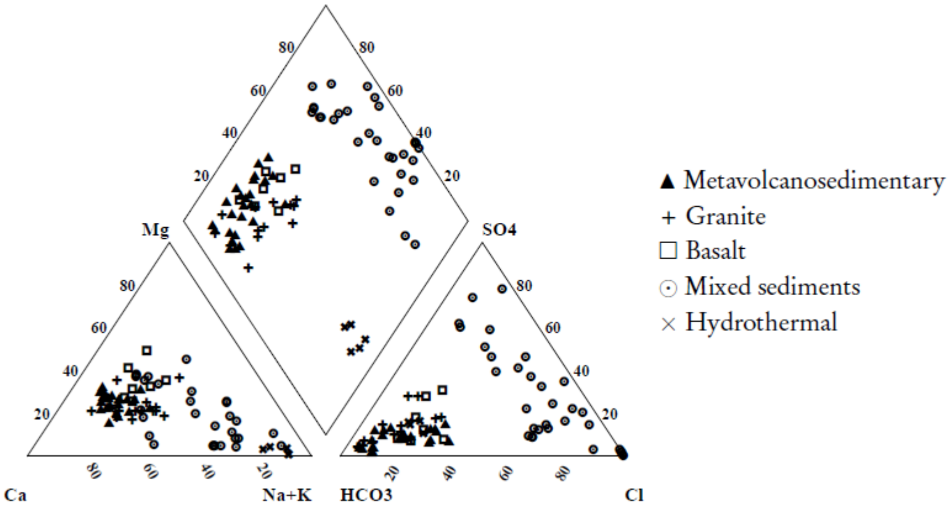


Figure 24: Piper plot diagram for water samples from different rock sources (Estifanos 2005)

3.4.2 Geophysical Survey

A first geophysical survey in the village area was conducted during 2007, by Dr. Abrham Fishatsion. It resulted in the drilling of a borehole where was installed an hand-pomp. This project failed and the well is currently provide only 20 liters per week. A more recent geophysical survey was carried out during April 2010, by same consultant, in order to define a proper site where drill a new borehole. Three potential sites were selected and in each site one electrical profile and two VES were conducted (Fig.23).

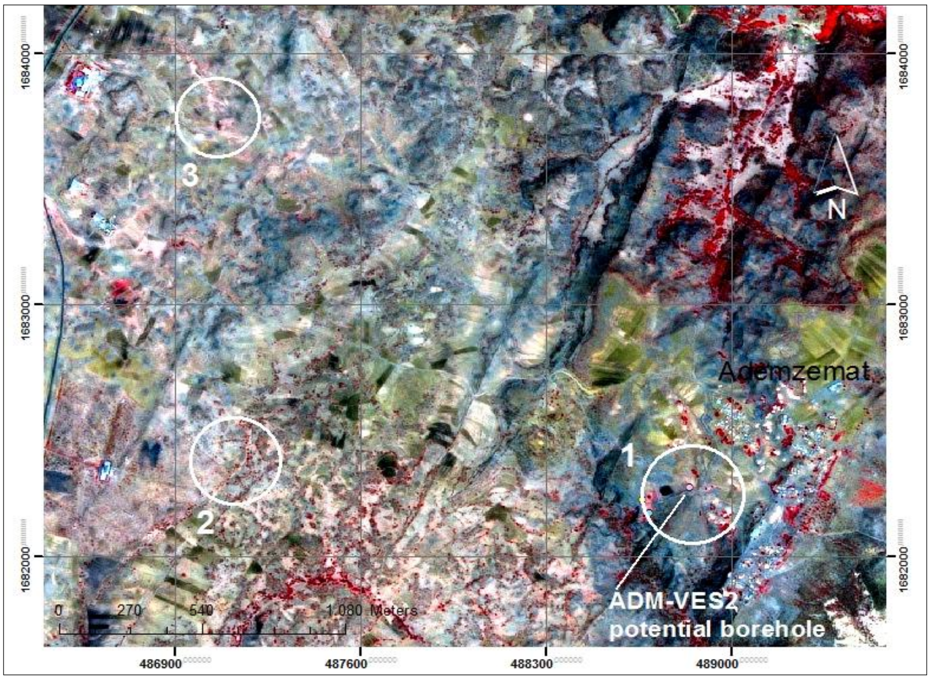


Figure 23: Ademzemat, Geophysical survey 2010, investigated sites location.

The configuration used for the electrical vertical soundings was Shlumberger array, with a max AB/2 ranging from 100 to 160 meters. The configuration used for electrical profiling was the Wenner array. A quantitative interpretation of the obtained data was elaborated using an inversion software, that allowed to create a subsurface geoelectrical sections with layer resistivity and its thickness. We report bellow only the Profile and the VES conduced in Site 1, located around the micro dam area. This area was selected as the recommended drilling site. To characterize the potential aquifer layer a profile lines having an observation point of 5 m interval and three penetration depths of 20, 40 and 60 meters was conducted (Fig.24). The obtained resistivity curve shows two segments. The first segment characterizes relatively by lower resistive zones can be interpreted as weathered basalt and associated fractured zone. The second segment is a more resistive region, that might be interpreted as massive basaltic environment. Based on the outcome of the result two VES (ADM-VES1 and ADM-VES2) were conducted in this site.

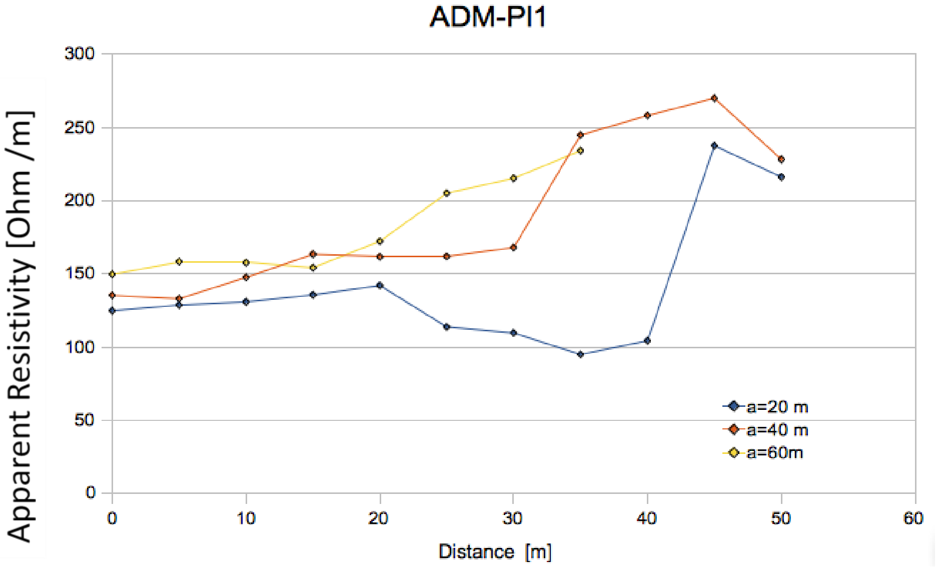
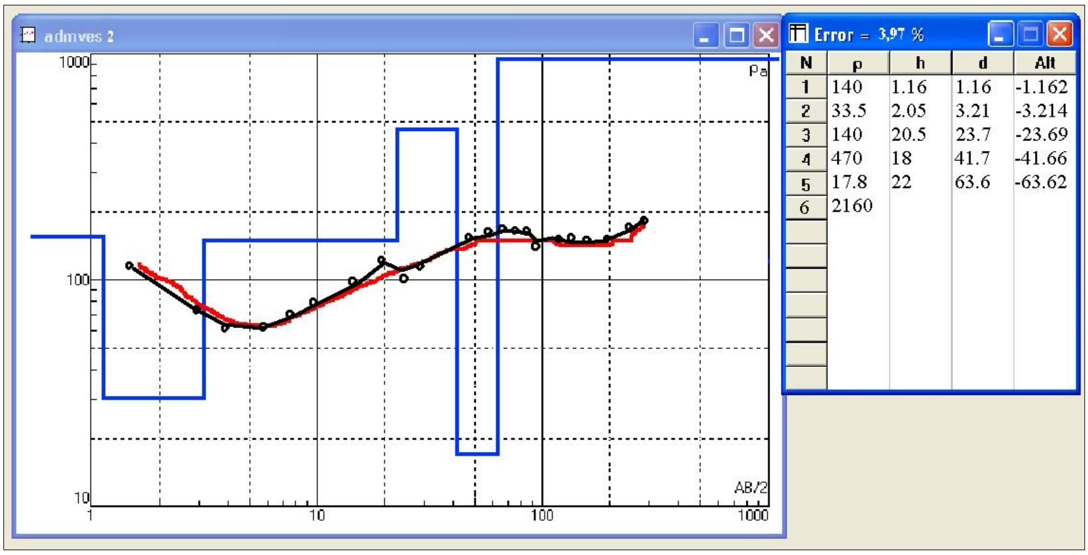


Figure 24 Ademzemat, Geophysical survey 2010, Profile 1

ADM-VES2 was the vertical electrical sounding that defined the potential aquifer layer. This VES point has been carried out in the dam area with an azimuth east to west.

Based on the conducted VES survey a model with six geo-electric layers was elaborated (Fig.25). The top layer, with a resistivity value of 140 Ω m and thickness of 1.16 m belongs to top soil. It is underlain by weathered basaltic layer having an resistivity of 33.5 Ω m and a thickness of 2.05 m. The third layer, interpreted as slightly fractured basalt, has a resistivity of 140 Ω m and a thickness of 20.5 m. The fourth layer is associated with massive basaltic layer (probably a dyke) having an resistivity of 470 Ω m and a thickness of 18m. The fifth layer shows a resistivity of 17.8 Ω m and a thickness of 22m. The last layer is related to massive basalt. The fifth layer was interpreted to be water bearing and associated to saturated basalt.



Error = 3,97 %

N	ρ	h	d	Alt
1	140	1.16	1.16	-1.162
2	33.5	2.05	3.21	-3.214
3	140	20.5	23.7	-23.69
4	470	18	41.7	-41.66
5	17.8	22	63.6	-63.62
6	2160			

Figure 25: Ademzemat, Geophysical survey 2010, VES 2

This geophysical survey allowed the Author to affirm that the area is characterized by various basalt layers. The basalts showed various degree of weathering and fractured zones. The existing NE-SE running basalt dykes did not show potential aquifer layer in the area. The Author, supported by knowledge of the area and bibliography, supposed that potential aquifer layers are related to fractured basalt. The geophysical survey of April 2010 defined as potential borehole the ADM-VES2 (488838,1682274) with expected low resistivity layer between 20 to 50m and expected aquifer zones between 20 and 38m. Recommended maximum drilling depth is about 50 m.

3.4.3 Basin Analysis

Different factors are usually considered during a basin analysis: current and future population of the village, water demand, rainfall data and basin characteristics. We conducted a simplified analysis because of the lack of high resolution data, joined with the small dimension of the considered basin.

The number of Ademzemat current population is about 811 people. Considering the estimate of a 3% growth rate per year (*WHO, 2000*), the population has been expected to amount to 1465 people in twenty years.

Considering the increase of population number and the growth of the water consumption in twenty years (at least 15 liters per person per day), the water consumption has been calculated to be 8020 m^3 on annual basis. This is the annual water demand in twenty years. Currently the water consumption rate is estimated to be 1,5 liters per person per day. This estimate is based on the WEDC guidelines, considering the villages supplied by hand pumps. The current annual water demand is calculated to be 444 m^3 on annual basis.

The nearest meteorological station for Ademzemat village is Asmara (14km to the North). According to the station data, the annual average temperature varies between 8,7°C and 23,6°C and the annual average rainfall from 335 to 642mm (W R D database from 2002 to 2006). In our calculation we considered the average annual precipitation referred to the capital, that is about 520 mm/yr (*Estifanos 2005*).

This analysis considered the hydrological basin that recharges the future borehole, located by 2010 geophysical survey results (ADM-VES2). The basin area was traced in ArcMap (Fig.26), with the visual support of a topographic map and DEM , overlaying to the Spot image. Therefore, using ArcMap was possible to calculate the area of the basin projected on a flat surface. The results showed that the basin area has an extension of 156120 m^2.

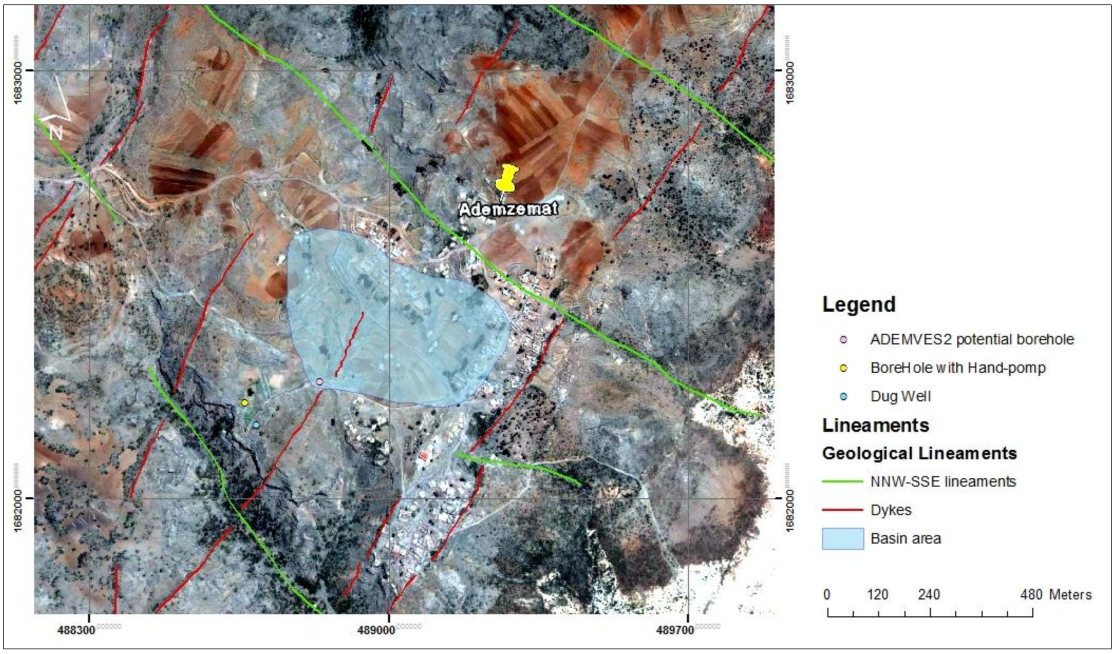


Figure 26 Hydrological basin area.

The basin analysis considered all the infiltrated water as water which recharge the studied aquifer. This is an approximate estimation but, due to the few data available, it was no possible to be more precise. Given these assumptions was possible to make an estimation of the rain falling inside the basin. Basin area [m^2] x Precipitation [m] = Volume of waterfall [m$_3$]: (156120 m^2) x (0.520 m) = 81182 m^3

This value represents the volume of water falling in the borehole recharge area during each year.

Estifanos (2005) estimates that the groundwater recharge rate for fractured basaltic aquifer is almost 6%. Considering the volume of rainfall fallen in one year in the analyzed basin, as 81182 m^3, and the 6% of this volume as the infiltration rate, we calculated the infiltration, that resulted in 4870 m^3. This value represents the recharge rate for the considered hydrological basin. Comparing this result with the future water consumption of 8020 m^3, calculated considering the population and consumption growth in twenty years, it is clear that the hydrological basin recharging the borehole has not the extension required to provide an adequate amount of water. The basin annual recharge rate appears to be higher than the actual water demand of 444,02 m^3/yr. We have to consider that the actual water demand considers a use of 1,5l per person per day, that is an extremely low value and represents only the drinking water.

The presence of geological structures in the area leads us to suppose that the hydrological basin, considered during our analysis, can result different from the hydrogeological one. The considered basin area is characterized by the presence of NNE-SSW basaltic dykes and NW-SE faults system. As visible in Figure 26, the potential borehole is located laterally to one of these dykes. Therefore appears crucial to understand if the dykes act as barriers to subsurface flow or as zones of water conduction inside the country rocks. To determine that many factors must be considered. The presence of joint sets interesting the dykes core represent a favorable factor to define these feature as zones of water conduction. However, we can not determine if this fracturing interests pervasively all the dyke structures or if is only affecting its shallower part, as consequence of different cooling processes due to different depth and temperature of the intruded rocks. The general observation of the study area shows that the dykes intruding the deeper part of the sequence are more massive. This fact leads to associate the dykes to a barrier effect, especially at depth. However, we must consider that the hostrock are usually brecciated out to the dykes margins; this is emphasized in the lateritized part of the basement. Therefore we have to consider that, even though the dykes appear massive, the fracturing of the hostrock, due to the dykes intrusion, can act as groundwater conduit.

The complexity of factors leading the hydrological significance of the basaltic dykes does not allow us to determine a unique result. The geophysical survey of 2010 affirms that the basaltic dykes cutting the basin area don't show potential aquifer layers. Figure 27 shows the extension of the hydrogeological basin considering the dyke having a barrier effect, the calculated area result in 60425 m². In that hypothesis the hydrogeological basin appears to have a smaller extension, and therefore a smaller recharge, than the hydrological one. The volume of water falling in this reduced basin during the year is calculated to be 31421 m³, while its annual recharge rate is 1885 m³. This represents the most unfavorable hypothesis, considering the dyke having a completely barrier effect. Generally it is more likely that the dykes show a barrier effect only at depth where they might be less fractured.

Other geological structures affecting the basin area are the NW-SE lineaments. These features were associated to weaker and fractured zones during the geomorphological analysis of the village area. Hence, they can be considered as zones of groundwater conduction. The selected site for the borehole drilling is localized almost at the intersection point among the dyke and the continuation of a NW-SE trending fault (Fig.27). This feature was identify during the remote sensing analysis and field study, because it coincides with a stream valley that cut and dislocates dyke structures. If the interpretation, that gives the structure continuation towards NW, is correct, the location defined for the future borehole appears to be favorable in finding groundwater. The borehole will be cited on a fractured and consequently more permeable zone, that might act as drainage axis for the groundwater flow. Hence, according to the importance of this structure in terms of groundwater conduction, the hydrogeological basin recharging the borehole can be considerably different from the hydrological one. The most favorable hypothesis is to consider both the dykes and the NW-SE faults as zone of groundwater conduction.

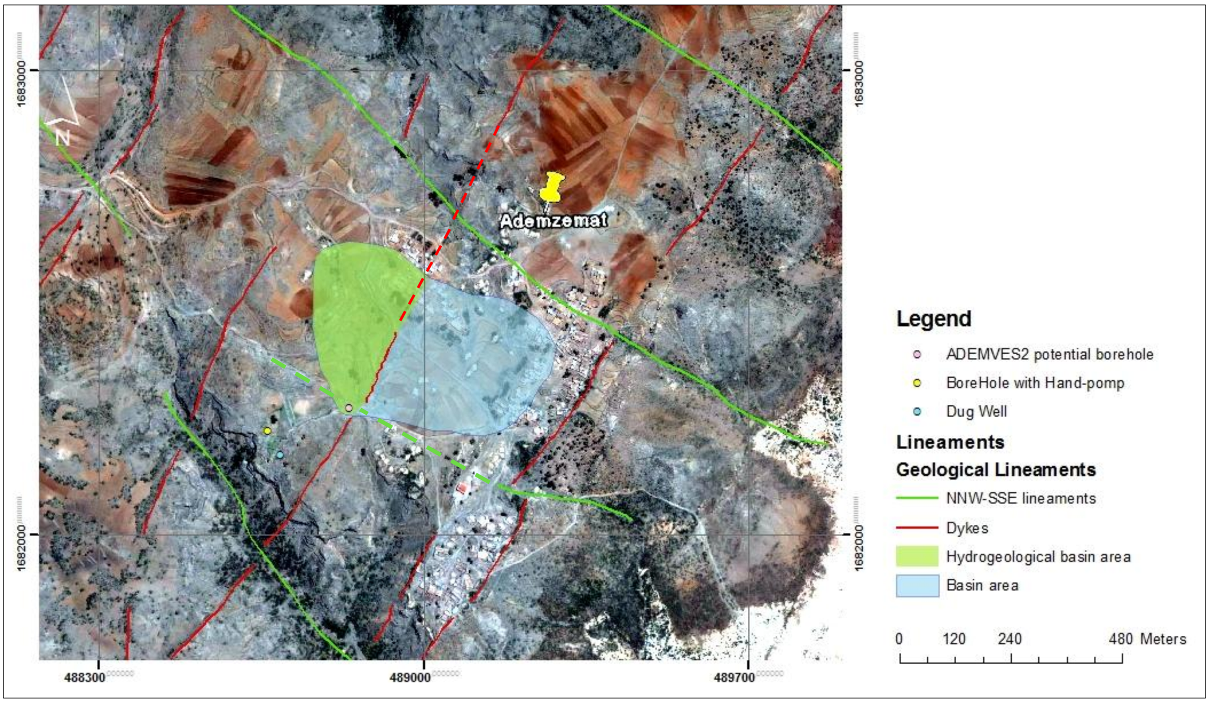


Figure 27 Hydrogeological basin area, considering dykes having a barrier effect to groundwater flow.

4. DISCUSSION AND FINAL REMARKS

This work wanted to contribute to the cooperation project aimed to provide a reliable source of fresh water for Ademzemat village. In this perspective we analyzed various factors concerning groundwater occurrence in the area, with particular regard to assess the site selected for the new borehole, during the geophysical survey of 2010.

The village area appears to be bounded by steep cliffs. Hence, during the rainy season, the runoff water develops in flash flood, with the result of a reduced water infiltration. The flat area that extends to the west side of the village is more favorable to water infiltration.

The main aquifers in the area are supposed to be within weathered and fractured bedrocks, or at the unconformity plane between the flood basalt pile and the Neoproterozoic basement, with the lateritic paleosoil that acts as impermeable layer. The presence of multiple stratification, primary porosity and fractured and weathered layers define the Tertiary basaltic unit as the more favorable bedrock for the aquifers of the area.

The basin recharging the selected site for the new borehole has not the extension required to provide the water demand amount, defined for the village in twenty years. Despite that, the groundwater occurrence in the area is deeply affected by the presence of geological structures: NNE-SSW basaltic dykes and NW-SE faults system. Hence, the hydrological basin, considered during our analysis can present relevant differences compared to the hydrogeological one. While the NW-SE faults are supposed to be zones of groundwater conduction, the dykes can act both as conductive zones or barriers to groundwater flow. Figure 28 shows the relation between present and future annual water demand for the village and dimension of the hydrological basin.

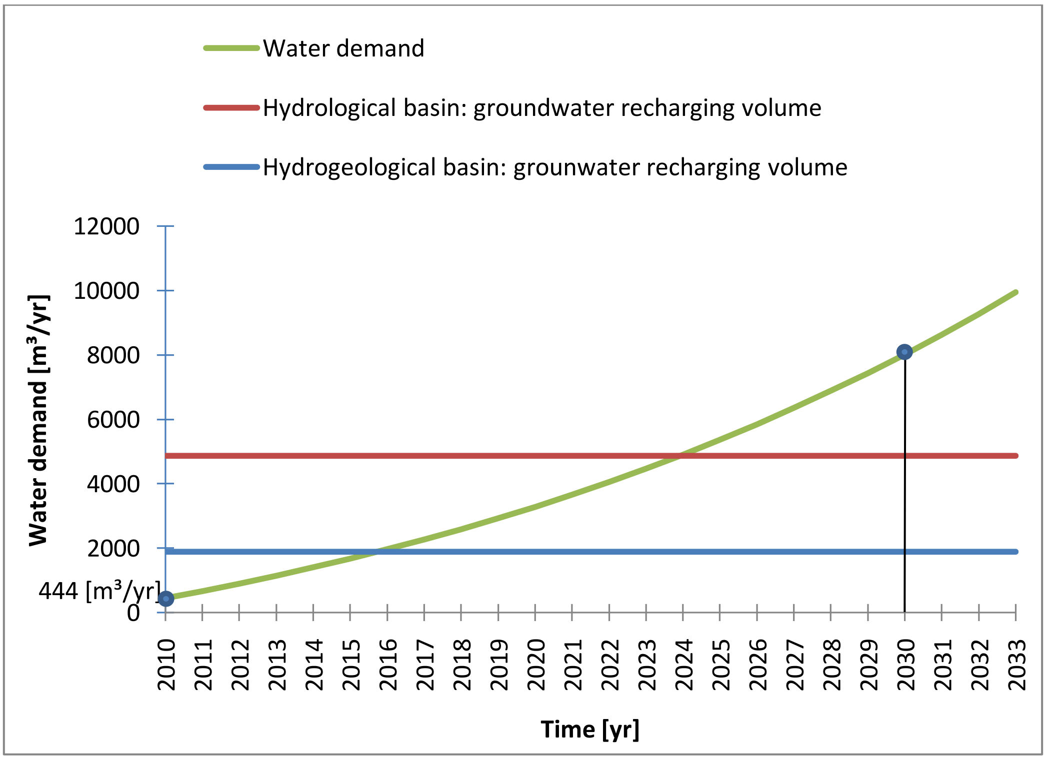


Figure 28: Increase of water demand with time and annual groundwater recharging volume for the hydrological basin and hydrogeological basing (considering dyke having barrier effect).

The remote sensing interpretation shows that the selected site for the future borehole lies at the intersection point among a basaltic dyke and a NW-SE trending fault. This presumably assure the location of the borehole on an highly fractured and consequently permeable zone. Despite that, to better understand the hydrogeological significance of the basaltic dykes, NW-

SE faults and their interaction we suggest to complete the geophysical survey with ERT . This technique will give a 2D resistivity section, where the role of sub-vertical structure might be clearly visible. In addition, we have to consider that the location for the future borehole was cited near to the village. This represents a favorable factor in terms of water transport and construction of the water supply system. Despite that, in our case the near location of the borehole means a small extent of the recharging basin. Over a more complete geophysical survey, we suggest to consider a different location of the borehole related to a more extended hydrological basin. This option might combine a higher recharge rate, giving by a larger basin, with the occurrence of tectonical elements, representing zones of water conduction. Moving the borehole location to a wider basin means to cite the well far from the village. If the topographic gradient from the well to the village exceeds 50 m we have to consider the realization of a system with several storage points, longer connecting piping and loss of hydraulic load. This involve major building and maintenance costs and risks for water quality preservation. The water stored in the surface reservoirs is exposed to high temperatures that can determine a raise in their bacteriological content.

The work conducted encountered difficulties in terms of finding available and reliable data and accessing to the sites of interest. Despite that, we believe that define the hydrogeological assessment of the area represents a fundamental stage, that can prevent the failure of the well drilling, that usually means the failure of the entire project.

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