

**GAROWE GROUNDWATER RESOURCES
PUNTLAND**
FED/2012/298-778
Implemented by Terre Solidali - EU funded



View of Jibagale flooding from plane

Geological - Hydrogeological - Geophysical Study

TECHNICAL REPORT

July 2014

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ACRONYMS AND ABBREVIATIONS

TS	Terre Solidali
Nuwaco	Garowe Water Agency
SWL	Static Water Level
WEC	Water Electrical Conductivity
$\mu\text{S}/\text{cm}$	micro-Siemens: unit of measurement of WEC
VES	Vertical Electrical Soundings
ρ	Electrical Resistivity
Ωm	Ohm x m: unit of measurement of the electrical resistivity
asl	above sea level
bgl	below ground level

1. SUMMARY

The present report describes the geological, hydrogeological and geophysical activities carried out in 2013-2014 by Terre Solidali, aiming at finding alternative ground water resources for the town of Garowe in the frame of the EU funded project **FED/2012/298-778**".

The studies have been executed by the following staff:

- Bruno Petrucci: senior geophysicist (TS consultant)
- Ahmed Mohamoud Adan: geologist and geophysicist (TS Puntland)
- Mohamed Jirde Mohamed: geologist and geophysicist (TS Somaliland)

The following activities have been carried out:

1. Base studies: previous geological, hydrogeological and geophysical studies have been reviewed, to get a preliminary knowledge of the area, where Terre Solidali had already carried out a preliminary study in 2011-2012, in the framework of a rural project funded by UNICEF
2. Remote Sensing: the satellite images of the area, available on Google Earth, have been studied and compared with the previous geological studies, to map the main geological, morphological and tectonic features. Thanks to this activity 3 investigation areas with agreeable geo-hydrological features were selected.
3. Geological survey: this activity was planned to verify on the ground the elaboration made by the remote sensing analysis.
4. Hydrogeological survey: the survey was carried out mainly on the Jibagale shallow wells field and on 4 private boreholes drilled in the area. Unfortunately the Nuwaco boreholes in town were not accessible and while trying to measure the water level in a borehole (Nuwaco-2) the dipmeter got stuck and had to be abandoned. The device was next recovered by Nuwaco. A shallow well was mapped near the village of Salaxley.
5. Geophysical survey: 60 VES distributed in 4 investigation areas have been carried out and interpreted.
6. Data interpretation and reporting: all the data have been interpreted and preliminary geological and hydrogeological models have been elaborated and the more suitable areas for groundwater research have been mapped.

The groundwater research in the Karkar region it is very difficult because of the geological structure. The Karkar Limestone which could theoretically constitute a good aquifer has a limited vertical extension and the town of Garowe is partly located on the outcropping Taleex Formation where both yields and water quality are very scarce. The groundwater research is complicated by the fact that any type of geophysical survey can do little to find out aquifers that are not spread horizontally but located in vertical (or sub-vertical) fractures. In such cases the survey findings have a statistical valence, which means that the investigation cannot detect exactly the water presence but only areas in which there are more chances to find possible aquifers (limestones as an example) but never certainties.

For this reason the geophysical survey has been mainly concentrated in areas where there are agreeable geological and hydraulic conditions and where the chances of widespread aquifers are high. In one of this areas (Salaxley) the survey had to be stopped for difficult relationship with the local authorities. Of the other areas investigated the **area 1** (Jibagale, about 20 km NE of the town) still presents the more agreeable conditions, confirmed by the geophysical survey. In the areas around the town there are less chances and, for the presence of the Taleex Formation at shallow depth under the town and outcropping upstream along the seasonal stream, the salinity is anyway very high.

2. GEOLOGICAL FEATURES

In the area surrounding the town as well as in most of the Karkar region there are 3 main units outcropping or at shallow depth:

- The alluvial deposits of quaternary age are mainly present in the Nugal valley (QaN) and in the minor affluent valleys (Qa). These deposits are mainly constituted by fine deposits (from fine sand to clay) with minor sandy layers, mostly present in the upper part of the seasonal streams. Because of the outcropping of the Taleex formation, often Gypsum crystals are present in the alluvium and sometimes the deposits are covered by gypsum crusts. The thickness, at least in the affluent valleys in the study area, never exceeds 10 m.
- Karkar Limestones (EK): it is the most widespread unit in the area south and eastward of the town. The unit is made by limestones and marly limestones in the upper section, and by marls and marly limestones with small lenses of gypsum crystals in the lower section (Middle-Upper Eocene). In the study area the thickness of this formation may vary from few meters (near the Taleex formation outcrops) to few dozen meters. Probably it increases up to 200-250 m (which is the full thickness estimated of the formation) on the plateau south-eastward of the town.
- Taleex formation (ET): is a formation of evaporitic nature in which prevail gypsum and anhydrites with minor dolomitic limestones and clays (Lower-Middle Eocene). It outcrops west of the town up to and beyond the town of Laas Canood. The thickness of the Taleex formation is variable and can reach up to 500 m.

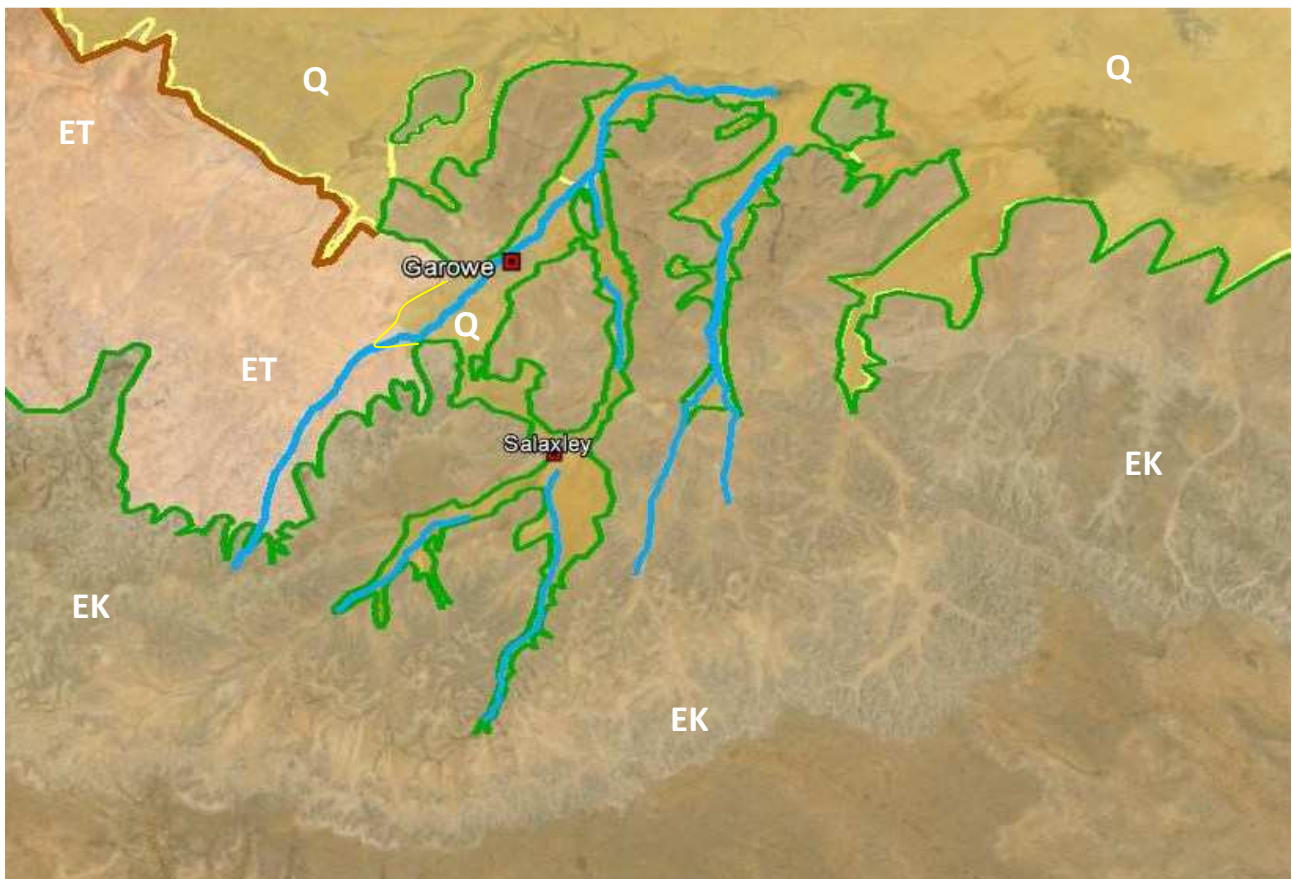


Figure 1 – Geological Map – Q: alluvial deposits – EK: Karkar limestones – ET: Taleex Formation

Anticipating the results of the geophysical survey, it seems that between the outcropping limestones of the Karkar formation and the evaporites of the Taleex (visible at depth as resistive terrains), there is a

transitional unit made by marls, marly limestones, sand and clay which cannot be directly identified as the lower section of the Karkar formation.

From the tectonic point of view, the enlarged study area is characterized by the structure of the Nugaal Valley (northward of the area surrounding Garowe), probably a tectonic trench on which northern side there is a horst with outcropping Auradu Limestones, from the stratigraphic point of view, normally below the Taleex Formation. In the area directly surrounding Garowe there are not clearly visible tectonic features. Notice that in the remote sensing analysis carried out by SWALIM in 2011-12 some geological faults have been hypothesized in the study area, but during the present study have not been found evidences or morphological features to justify such tectonic structures.

3. MORPHOLOGICAL AND HYDROLOGICAL FEATURES

In the area surrounding the town there are 4 hydrological basin with different features, converging in the area of Jibagale.

- Togga Garowe (Gar-1) has a very defined course, normally limited by (more or less) high banks. Only at Jibagale, the course disappears for a section of about 2 km where there are dozens of shallow wells. The valley of Gar-1 extends for about 35 km from the southern plateau edge to the confluence with Gar-2. The total surface of the basin is about 450 km². Along a section of almost 20 km, upstream of Garoowe, the stream mostly runs on outcropping Taleex formations (gypsum and anhydrite).

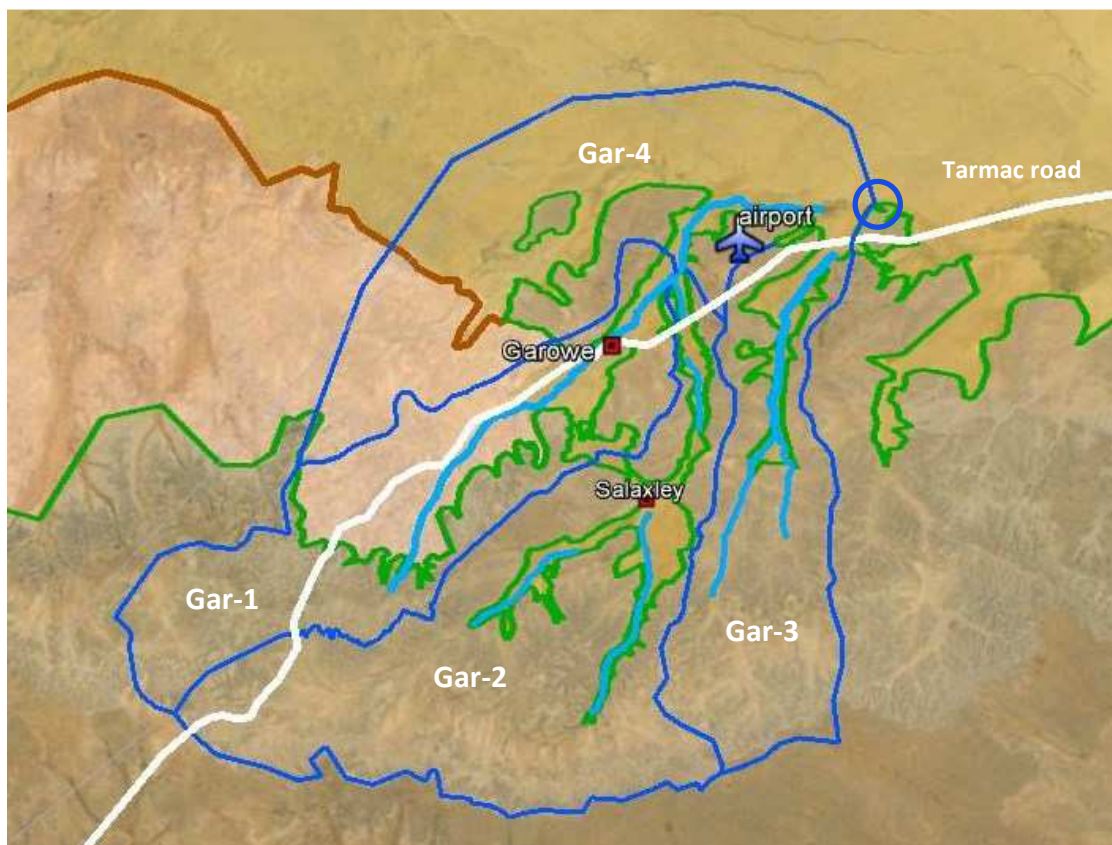


Figure 2 – hydrological basins (blue) and main streams (cyan) – blue circle: streams confluence

- The Salaxley valley (Gar-2) hosts a drainage line which is divided in five sectors, three of which are characterized by a clearly defined course and two by dispersion areas in which the courses spread their flows on flat plains. The last downstream section, is well defined and ends in the course of Gar-1, about 5.5 km NE-ward of the edge of the town. It is strongly suspected that the areas where

the courses disappear are areas of higher infiltration with the formation of shallow aquifers, which water table should be below 10 m bgl. The whole valley is about 57 km long from the plateau edge to the confluence with Gar-1 and for the whole length is cut inside the Karkar formation. The basin extension is 600 km².

- The third toga, Gar-3, which ends in the flat area near Iskufaruran (km 22 of the tarmac road to Bosaso), has a well defined course along the whole valley length. The valley is 42 km long (from the plateau edge to Iskufaruran) and it is cut only in the Karkar formation (like Gar-2). The terminal section, at Iskufaruran, has the same characteristics of the other areas in which the drainage line is absent. For this area too, there is the suspicion of a strong infiltration. This valley show similar features to that of Gar-2, but it is farther from the town and for this reason less interesting for the present study. The total basin surface is 350 km².
- At the confluence of the basin Gar-1 and 3 (Jibagale area) ends a further basin contiguous to Gar-1 NE-ward (called Gar-4). The basin extends at lower elevations, partly on the Taleex outcrop partly on the alluvial deposits at the edge of the Nugaal Valley. This basin adds a further surface of about 480 km² to the whole surface of the three above described basins, with which the total surface reaches about 1900 km².

4. HYDROGEOLOGICAL FRAMEWORK

4.1 AQUIFERS FEATURES

In the area surrounding Garowe there are 3 aquifers:

- The shallow aquifer is hosted in recent alluvial deposits (T. Garowe, T. Salaxley, T. Iskufaruran, called in this report Gar-1, 2, 3). This aquifer contains water of different quality. While Gar-1, before entering in the town, runs on the Taleex formation, and enriches in the salts from the melting of the calcium sulphate, the other two courses run only on the Karkar formation and, during flows, bring only fresh water. The wells field of Jibagale contain water with a WEC of 2500 $\mu\text{S}/\text{cm}$ and it is located after the confluence of Gar-1 and 2, at the confluence with Gar-3. A shallow well mapped near Salaxley had the same WEC. It is to outline that near the town the same shallow aquifer of T. Garowe has a much higher salinity that causes WEC values up to more than 4000 $\mu\text{S}/\text{cm}$. This fact is probably due to the presence of the Taleex formation all along the upper part of the course. The other two courses (Gar-2 and 3) running more quite exclusively on the Karkar formation can contribute at Jibagale with running water of a better quality. In the figure XXX of the Annex C is shown the distribution of the WEC of the shallow wells at Jibagale.
- Below the recent alluvial there is a transitional formation which overlies the evaporitic section of the Taleex. The transitional section is characterized by rare pure limestone layers, interbedded between marls and clay with gypsum more in sparse crystals than in layers. This formation may host aquifers of limited yield (normally ranging between 2 and 5 l/sec) in the limestone layers. The water conductivity is normally higher than in the shallow aquifer, but also lower of the overlain deep aquifer. Near Jibagale the WEC is lower than in the boreholes drilled near (or in) the town, probably because there the intermediate aquifer is partly recharged by the shallow one. The boreholes south of the stream showed a fair diminution of the conductivity after the last important flood of October. In the borehole Jiba-2, 400 m northward of the stream, the WEC remained constant (about 3700 $\mu\text{S}/\text{cm}$) but the SWL raised above the ground level (when it was not in production water flowed outside of the hole). In the town, the borehole GTZ 1, drilled in the 80ies and tapping the intermediate aquifer, had a WEC of 3500 $\mu\text{S}/\text{cm}$ (now is abandoned). The borehole GTZ II, still active (in the present work re-named Nuwaco 1), reached the evaporites of the Taleex and has a much higher WEC (4400). The borehole Nuwaco 2, the only one presently with a WEC below 4000 $\mu\text{S}/\text{cm}$ seems to have a depth less than 100 m. The transition section normally reaches depths ranging from 50 to 100 m bgl. In synthesis we think that where this aquifer is recharged by water running on the Taleex formation the salt content is higher of the section of the aquifer recharged by water running on alluvium or limestones of the Karkar formation.

- The deeper aquifer is hosted in the Taleex formation which is mainly made by gypsum, anhydrite, rare limestones and marls. In this unit it is possible to find higher yields but with a very high saline content (WEC > 4000 $\mu\text{S}/\text{cm}$). The borehole Nuwaco 3, drilled more than 200 m has a WEC of 5300 $\mu\text{S}/\text{cm}$. Many boreholes tapped in this unit tend to dry up or to recharge too slowly to constitute suitable permanent sources. In this formation the water circulation occurs in fractures or cavities and the water bearing section is usually more wide in vertical direction than in the horizontal.

4.2 WATER POINTS

The water supply of the town is managed by the Nuwaco company. The company manages presently four active boreholes, one drilled long time ago by GTZ and three new, all in the eastern sector of the town. Nuwaco is not very active in the monitoring and all the wells are not accessible to the dipmeter. Production data are available only for the boreholes 1 and 4.

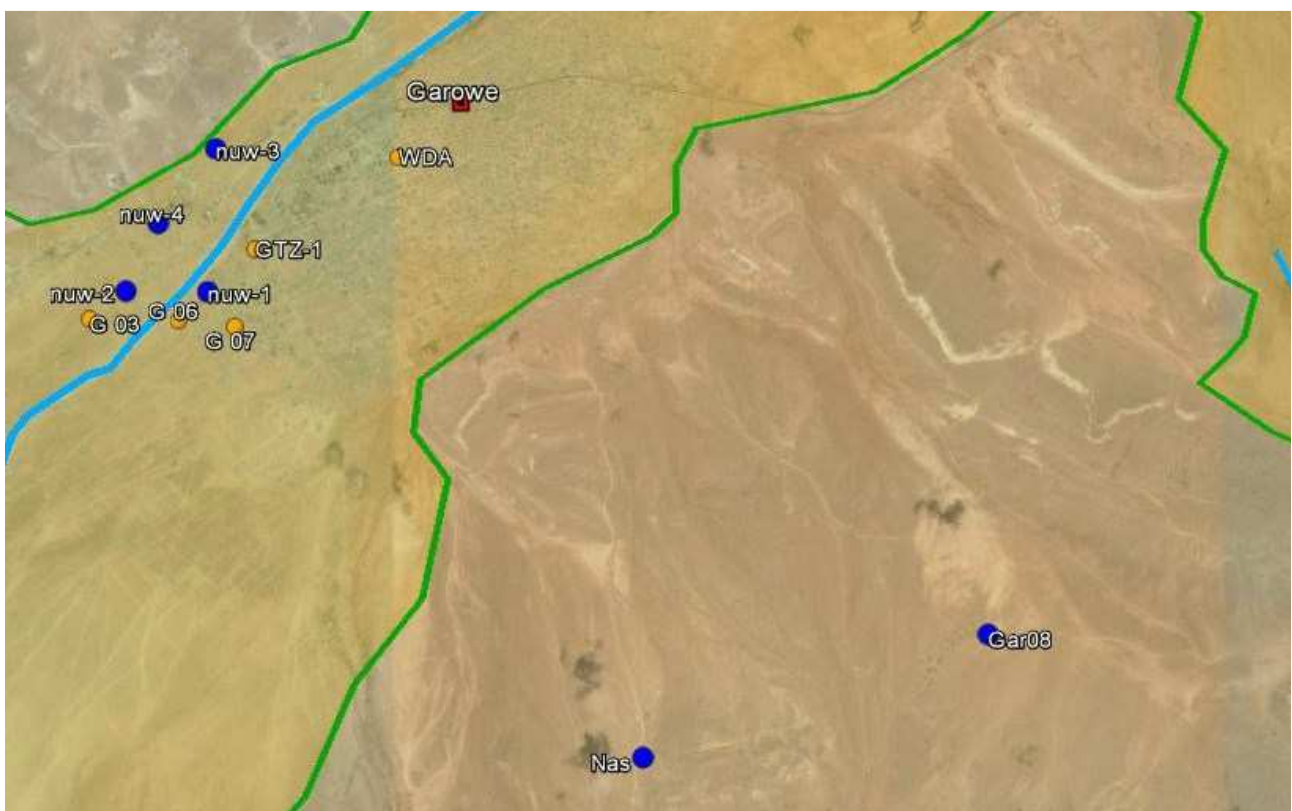


Figure 3 – Garowe active (blue circles) and abandoned (orange) boreholes

In the table 1 are listed public and private boreholes in the town surroundings, while the map with the location of the boreholes and shallow wells at Jibagale is shown in the Annex C.

From the table, among other data, it is possible to see the relationship between depth and WEC as a salinity indicator: boreholes Nuw-3, Gar-8 and Nas (Nasablood) are deeper (285, 200 and 253 m bgl) and have higher WEC values: 5350, 8000 and 4980 $\mu\text{S}/\text{cm}$. The borehole Nuw-3 has also the lowest production among the Nuwaco boreholes. During the last visit (May 2014), while pumping with a yield of about 15 m^3/hour , the DWL was dropping with a rate of 1 m per minute.

The data outlined in yellow are considered not sure, while the water levels outlined in grey are dynamic.

Borehole	Latitude	Longitude	Elevation	Depth (m bgl)	yield (m ³ /hour)	production (m ³ /day)	pumping time (hours)	SWL (m bgl)	WEC (μS/cm)
Nuw-1	8.39523	49.47059	476.0		27	648	24		4450
Nuw-2	8.39524	48.46555	475.0	100	23	322	14		3800
Nuw-3	8.40381	48.47109	473.0	285	15	?	?	80	5350
Nuw-4	8.39937	48.46751	472.0	105	45	1080	24	19.76	4360
Jiba-1	8.48830	48.62397	399.0	70				4.9	3640
Jiba-2	8.50183	48.62425	398.0	100	8	32	4	0.0	3720
Jiba-3	8.49261	48.62270	399.0				6	16.55	3680
Jiba-4	8.50545	48.64076	396.0			20		4.7	4980
Gar-8	8.37444	48.51845	481.0	200				27.5	8000
Nas	8.36702	48.49729	495.0	253	30	30		29.7	4460

Table 1 – public and private boreholes location and hydrogeological data (May 2014)

4.3 BASIN BALANCE

On the base of the data of the previous chapterS and of the rainfall data from the SWALIM data base a tentative balance of the whole basin has been tried.

The average of the rainfall data in the last 5 years is about 200 mm/year, while the historical data of the stations of Qardho, Galkayo and Laas Canood is about 140 mm/year. On the base of these data an average value of 150 mm/years has been selected.

The total surface of the four basins, all converging in the area of Jibagale has been calculated in 1900 km².

The infiltration volume has been calculated with two coefficient: the first, regarding the direct infiltration has been estimated 2%; the second, considering the infiltration rate of the floods on the seasonal streambeds has been estimated 5%. The rate of the runoff on the total rainfall volume has been estimated 30%. Assuming these parameters the total volume of groundwater that infiltrates per year is 10 millions of m³, which divided on 365 days is about 27.000 m³/day.

The data are listed in the following table.

basin area (km ²)	1900	1.9E+09	m ²
rainfall (mm/year)	150	0.15	m/year
total rain volume		2.85E+08	m ³ /year
runoff	30%	8.6E+07	m ³ /year
direct infiltration	2%	5.7E+06	m ³ /year
infiltration from run-off	5%	4.3E+06	m ³ /year
total available groundwater		1.0E+07	m ³ /year
		2.7E+04	m ³ /day

Table 2 – hydrogeological balance

Notice that applying the same parameters to the basin upstream of the town of Garowe (about 400 km²), the available underground water volume reduces to about 4300 m³/day.

The daily volume supplied to the town from Nuwaco is estimated 2200-2300 m³/day, to which has to be added the volume extracted by the shallow wells on which is difficult to make an estimate, that could be roughly between 500 and 1000 m³/day.

With all the limits that such type of balance implies, because of the imprecision of the coefficients and extracted volumes estimate, it is to outline that the volume of water presently consumed in town is very

close to the estimated available volume in the town area. On the other hand, on the whole hydraulic basin, converging at Jibagale, it is expected a much higher groundwater volume.

5. GEOPHYSICAL SURVEY

5.1 METHODOLOGY

The geophysical methodology more appropriate, given the geological conditions of the area, is the geo-electrical survey by VES. This methodology allows the detection of successions of units of wide horizontal extension and sharp vertical limits. In the study area the VES methodology was thought agreeable to detect the limits between the alluvial and the transitional formations and between the latter and the overlain Taleex formation. This methodology can give useful information, about the thickness of the first two units (alluvial and transitional) and their composition, in terms of abundance or scarcity of deposits with low permeability, such as clays and marls, negative for the groundwater research.

This type of survey can give little information (or nothing at all) about the characteristics of the deep Taleex unit, except the depth of the top of the gypsum-anhydrite series (resistive with regard to the transitional series), because it is unable to detect the presence of vertical fractures or cavities at depth above 100 m of depth. No other investigation method can find out this type of deep anomalies, unless for wide fractures fields associated to important geological faults.

For this reason TS proposed to concentrate the investigation in the areas of supposed high infiltration where both, the shallow aquifer and the intermediate one can be recharged by the stream flows and floods. The target areas suggested were the following:

1. Junction area of Jibagale extended few kilometers upstream
2. Lower courses of toggas Gar-1 and 2 up to their confluence
3. Valley of T. Gar-2, in the section near Salaxley
4. Valley of T. Garowe in the town surroundings

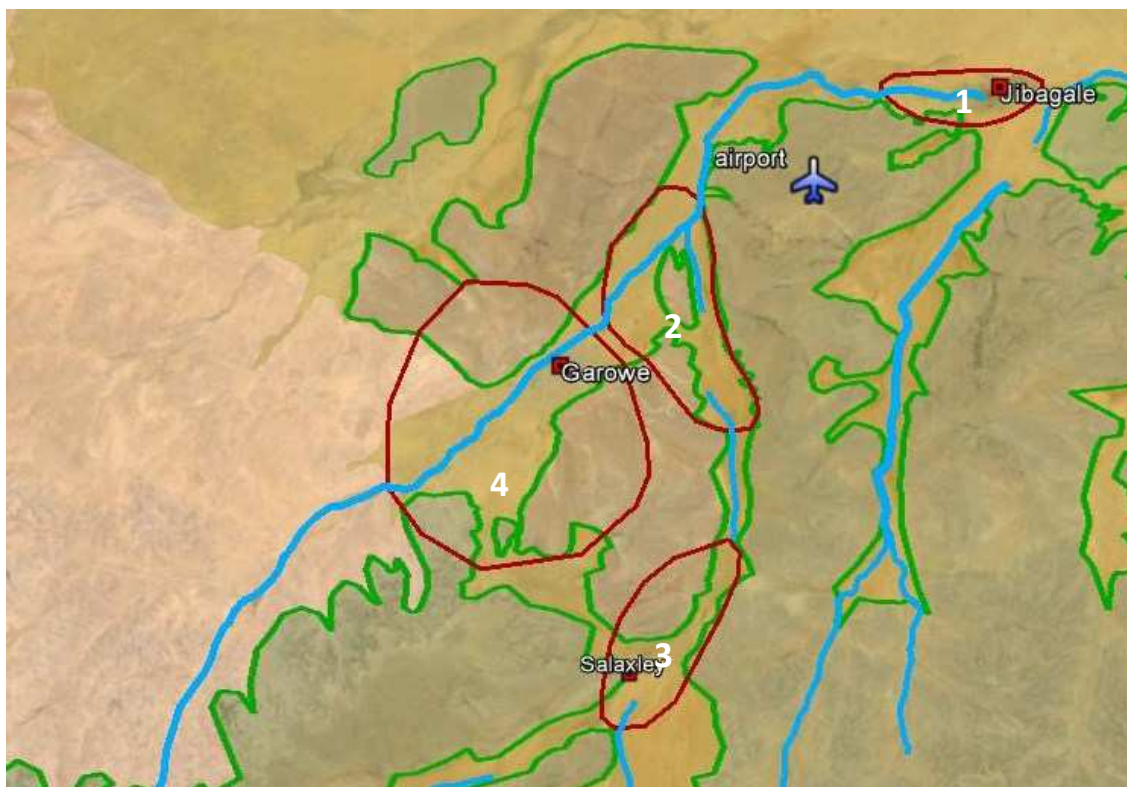


Figure 4 – target areas of the geophysical survey

The forth area was included not for hydrogeological considerations but on Nuwaco request. At the beginning the area was restricted to the proximities of the stream, in the town suburbs, but, after the first series of VES, the company asked for a wider scattered investigation, at the location of drilling tries decided by them.

The investigation in the area 3 was stopped because of open hostility of the population (or perhaps only of some community leaders), worried that the survey could be done only in the interest of the town of Garowe. TS suggested to Nuwaco to contact the Salaxley authorities to clarify and give insurance about the sharing of the water sources possibly found. It is not clear if such clarification occurred or not, but anyway it was suggested to our team not to continue the investigation.

5.2 SURVEY DIMENSIONS

Sixty (60) VES were carried out in the four areas. Their denomination has been changed more than once, because several VES were suppressed after the investigation failed for the presence of gypsum crusts on the ground, which made impossible an agreeable passage of current in the ground.

The denomination in areas 1, 2 and 4 are irregular because there were more investigation phases.

Where possible the VES have been interpreted then correlated in geo-electrical cross-sections to facilitate a more reliable interpretation. This procedure was not always possible in the area 4 because the locations are scattered on a very wide area and the correlation is unreliable when the distance between 2 adjacent VES is much larger of the distance between the current electrodes (A and B) of the single soundings.

- Area 1: in the Jibagale area 21 VES have been carried out (from 1 to 10 and from 41 to 51) in two different phases and correlated in 5 cross-sections named from jiba-1 to 5.
- Area 2: along the lower course of the stream Gar-2 (Togga Salaxley) and in the confluence area with T. Gar-1 (T. Garowe) 14 VES (from 11 to 24) have been done and correlated in 5 cross-sections.
- Area 3: in the upper course of T. Salaxley (Gar-3), not far from the village that gives the name to the course, 6 VES (from 31 to 37) have been done and correlated in 3 cross-sections. As told above, in this area the survey has been stopped because of difficult relationships with local village leaders.
- Area 4: 19 VES (from 25 to 30, from 37 to 40 and from 52 to 60) have been carried out in three different phases. The VES have been correlated in 4 cross-sections, but several of them are not correlated because far from the others or not interpretable.

In the figure 4 are shown the four target areas, while the location of the VES in the single areas are shown in the Annex C (figures 7.1 to 7.4). The field data, curves and interpretation of the VES are listed in Annex A, while the cross-sections are shown in Annex B.

5.3 GEO-ELECTRICAL UNITS

The resistivity values found by the VES interpretation can be grouped in 3 main units, described below.

- **Top Resistive:** the top layer is mostly characterized by resistive values ($20 < \rho \leq 1000 \Omega\text{m}$) and limited thickness ($h < 10 \text{ m}$). Normally the presence of the layer is to the drying effect of a hot dry climate or to the presence of sandy alluvial deposits, in the wadi courses, above the piezometric surface. In some cases the top resistive is covered by a thin conductive layer and normally in these cases the thickness of the resistive increases (to more than 10 m) as well as the ρ (resistivity) values. In such cases the **Top Resistive** can be constituted not simply by the top layer dried by the hot weather but from a different geological unit such as limestones or breccias (as it happens at Jibagale). In other cases, the **Top Resistive** is constituted by two thin layers with slightly increasing resistivity at depth.
- **Intermediate Unit:** this unit is mostly characterized by conductive values, which indicate the predominance of clay and marly deposits, with ρ values ranging between 2 and 30 Ωm . The

thickness varies from few meters to more than 200 m. The resistivity range is very wide but the unit is well defined from the presence of a resistive to the top and a deeper resistive to the bottom. Actually the ρ variation indicates a wide variation of the lithology where it is possible to find clay, sand, marls, marly limestones and, where ρ raises above 40 Ωm , also of almost pure limestones. All these lithologies are typical of the Karkar formation and the lower ρ values probably characterize the lower section of the unit, close to the Taleex Formation.

- **Bottom Resistive:** it is the deepest unit detected. Also in this case the resistivity range is very wide ($20 < \rho \leq 300 \Omega\text{m}$) but the variation could be only apparent and depending on the depth of the unit. Actually where the depth is more than 150-200 m the final raising of the curves is not very long and often it is not enough to evaluate the true resistivity of the layer. In some cases the final raising is not visible and the depth has been roughly calculated only verifying at which depth it is not present. This unit is constituted by the Taleex Formation, mainly constituted by gypsum, anhydrite and marls. The lower ρ values could depend also by a more abundant marly fraction. In the eastern section of the Jibagale area, in a several VES this unit has not been detected up to a depth of more than 250 m.

5.4 SURVEY RESULTS

1. In the Jibagale area (area 1) the geophysical survey detected an important variation from the western section to the eastern. In the latter area (VES 6-7-8-45-50-51) the **Bottom Resistive** (Taleex Formation) deepens to more than 250 m. In the same area the resistivity of the **Intermediate Unit** is always above 20 Ωm which means more chances to find limestones (or marly limestones or sands) with regard to the western area where clay and marls seem to prevail. On the top of the **Intermediate Unit**, always in the eastern section, there is a very resistive layer which seems made by almost pure limestone. Actually the bottom of one the deepest shallow wells visited was excavated in a kind of limestone conglomerate. These facts constitute agreeable conditions for groundwater research.
2. In the area 2 (lower course of T. Salaxley, confluence with T.Garowe) the conditions of the subsoil seem rather homogeneous with the **Intermediate Unit** mostly constituted by marls and clay. Some slightly higher ρ values have been detected in the more southern section (VES 19-20-24) up to a depth of 150 m. The area 2 does not seem very agreeable for groundwater research.
3. In the area 3 (near Salaxley village) the **Intermediate Unit** is characterized by ρ values very low (between 3 and 6 Ωm) so that mostly marls and clay are expected. The only exception is the VES 33, where a sharp ρ variation occurs raising to 35 Ωm . The layer extends up to about 100 m bgl. Limestones, marly limestones or sand are expected. The investigation should be extended SW-ward but it had to be stopped because of difficult relationship with the Salaxley authorities.
4. The area 4 has been explored in a rather scattered way because of the Nuwaco requests. In the SW suburbs of the town (cross-section Garowe-1) the survey found ρ values growing SW-ward (from 11 to 19 Ωm) in the **Intermediate Unit**. In this area at the NE edge of the cross section there is a borehole with the lower WEC of the town (3800 $\mu\text{S}/\text{cm}$). Along cross-section 2, on the hills NW of the town, the **Intermediate Unit** presents rather low ρ values (7-9 Ωm) with the exception of the VES 54 (35-11 Ωm). Unfortunately a drilling try up to 120 m of depth found very little water even if the presence of limestones and marly limestones was ascertained. Similar conditions were found at the VES 59 carried out at the NE suburbs. There a layer with $\rho = 30 \Omega\text{m}$ was detected up to the depth of 90 m. All the other VES scattered around the town gave not agreeable results for the presence of clay deposits and sometimes for the presence of the Taleex formation at very shallow depth.

CONCLUSIONS AND SUGGESTIONS

It is to underline that the geophysical survey cannot give certainty of the groundwater presence since even when it gives agreeable results for groundwater research, such as when limestones are found, the groundwater circulation is tied to the presence of fractured areas which cannot be directly detected.

The method is reliable on a statistic base, but cannot be considered as a way to see water in the subsoil.

For this reason in this area is very important to direct the investigation, carried out with geophysics and drilling tries, in the areas that are more agreeable because of the geological and hydrological conditions.

On the base of these factors three areas were selected because of the extension of the hydraulic basins (see figure 2), of the geology of the basin (the outcropping Karkar Formation is considered more agreeable for a lower water salinity) and for the presence of run-off and infiltration areas along the courses.

The area immediately surrounding the town was discarded then taken in consideration under the direct request of Nuwaco company, even because the target of a lower water quality is not for the moment a priority of the town which suffers for a continuous water shortage.

The target of the geophysical survey has been the geo-electrical unit, named **Intermediate Unit**, which is well identified by the VES methodology. This unit is probably constituted by the lower section of the Karkar Formation, and it is characterized by variable lithology and is considered the best aquifer of the area. Anyway as the recent drilling (on the hill NW of the town) demonstrated also where the **Intermediate Unit** is found with an agreeable lithology (limestones), the results can be negative.

In the following paragraph a description of the sites selected for drilling, area by area, is given.

- Area 1 (Jibagale): is the more promising area both for the geological-hydrological conditions (area of infiltration, presence of shallow and deep aquifers) and for the results of the geophysical survey that found a sharp thickening of the **Intermediate Unit** which bottom drops beyond the investigation depth (250 m). This feature is attributed to the presence of a possible tectonic line (see figure 5). In the area have been outlined two zones: *zone 1-1* (yellow polygon) where the **Intermediate Unit** extends up to 200-250 m of depth and the resistivity is above 20 Ω m, and the *zone 1-2*, in which the resistivity values are similar, but the unit bottom does not exceed 100 m. Possible future drilling should respect the depth here indicated. The area 1 is the only one where agreeable conditions are so widespread.

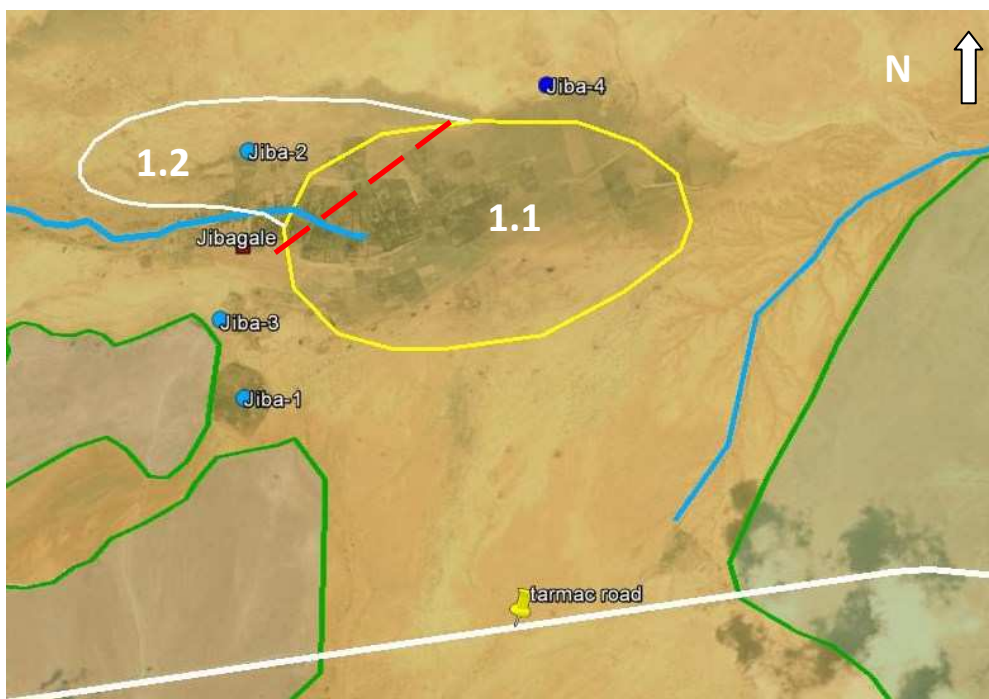


Figure 5 - area 1 drilling zones- *zone 1.1* (yellow) max depth 250 m; *zone 1.2* (white line) depth 100 m

- Area 2: in this area the agreeable geo-hydrological conditions (presence of infiltration areas, hydrological basin only on Karkar limestones) have not been matched by the geophysical parameters. Even if the presence of a top layer (10-20 m) of coarse deposits has been found, the resistivity values of the **Intermediate Unit** are rather low, while the depth can reach up to 150-160 m. Nevertheless two possible drilling zones have been outlined: *zone 2-1*, southward, in which the resistivity values range between 11 and 15 Ωm ; *zone 2-2*, northward at the confluence between T. Garowe and T. Salaxley courses, where the Ωm . The chances of successful drilling, with regard to area 1 is estimated less than 50%.

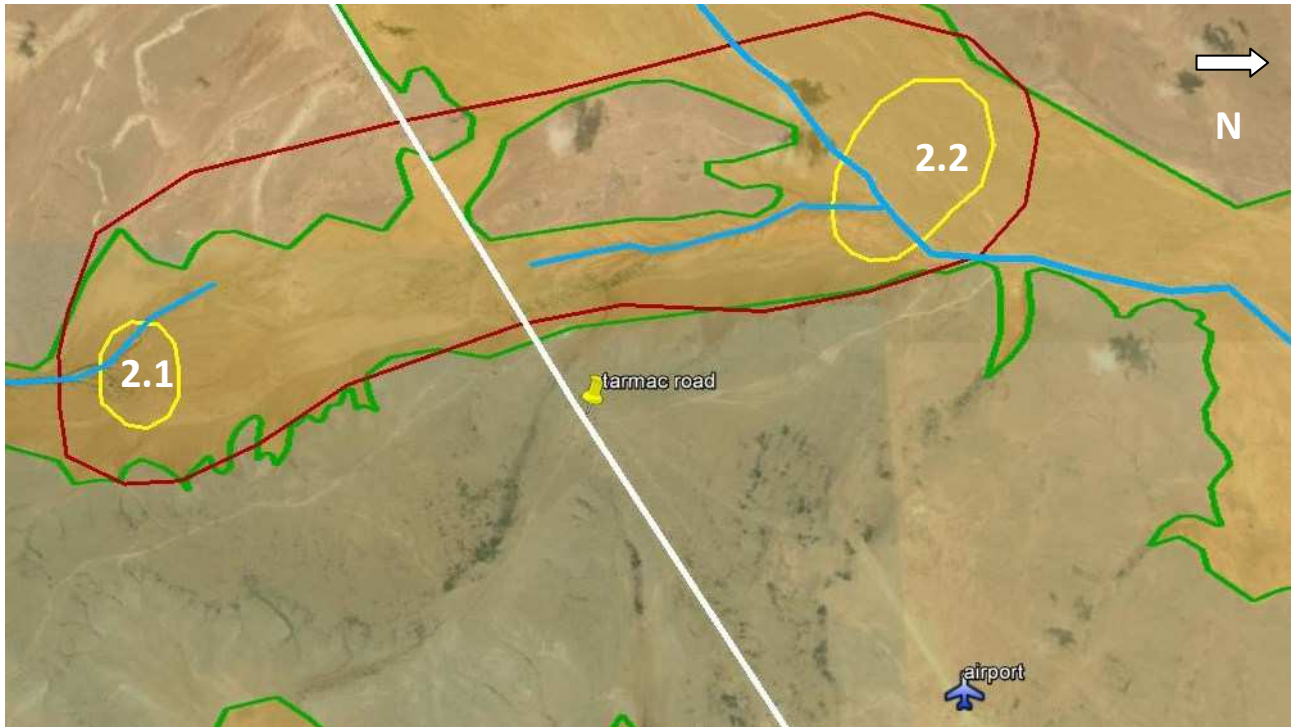


Figure 6 - area 2 drilling zones - *zone 2.1* $\rho = 11-15 \Omega\text{m}$; *zone 2.2* $\rho = 9-10 \Omega\text{m}$ – max depth 150 m

- Area 3: in this area the investigation has not been completed. Only 6 VES were done at the SW edge of the area (along the upper course of T. Salaxley, near the village) and it had been planned to extend the investigation toward SW. Of the VES done only on n. 33 there is an agreeable situation with a high value of resistivity ($\rho = 35 \Omega\text{m}$) up to 100 m of depth (see *zone 3.1* figure 7).
- Area 4: the investigation was scattered in several zones. In the *zone 4.1*, on the northern bank of T. Garowe, SW of the town, which includes borehole Nuwaco 2, 3 VES (37, 38 and 39) found resistivity values growing from 11 to 19 Ωm , proceeding from VES 37 to 39 (southwestward) and depths from 70 to 90 m. In the *zone 4.2* a layer with $\rho = 37 \Omega\text{m}$, up to 100 m, followed by a layer with $\rho = 11 \Omega\text{m}$ up to 220 m was detected by the VES 54. Unfortunately a drilling tried first up to 120 m then deepened (at unknown depth) found limestone and marly limestone, but with very little water. The other VES done in this area showed resistivity values below 10 Ωm . In the *zone 4.3*, on the southern bank of the course NE of the town, at VES 59, a layer with $\rho = 30 \Omega\text{m}$, up to 90 m of depth has been detected. More NE-ward at VES 60 the **Intermediate Unit** extends up to 180 m with a resistivity of 10 Ωm . The suggestion is to make a try first in the *zone 4.1*, between VES 38 and 39 (80-90 m), then in the *zone 4.3* at VES 59 (90 m) and, if negative, at VES 60 (180 m).

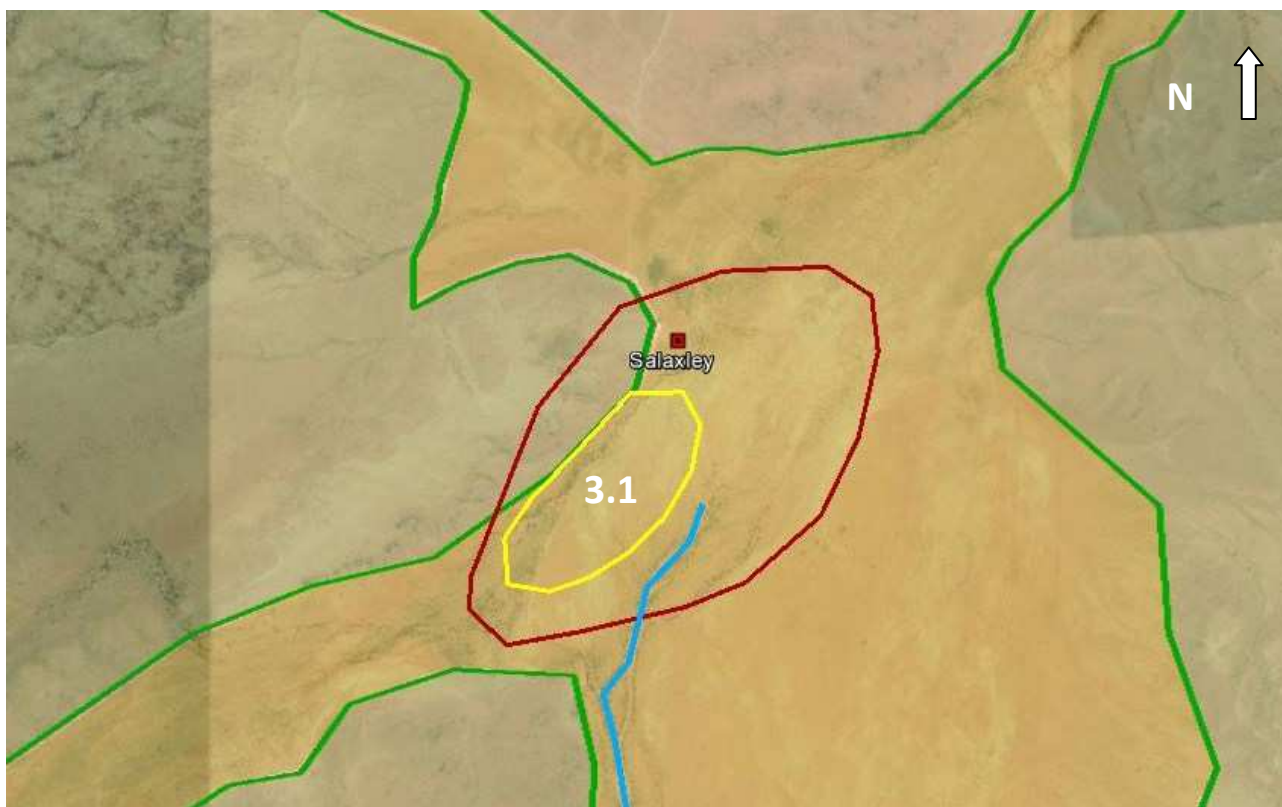


Figure 7 - area 3 drilling zone - zone 3.1 $\rho = 35 \Omega\text{m}$ – max depth 100 m



Figure 8 - area 4 drilling zones - zone 4.1 $\rho = 17-19 \Omega\text{m}$ – max depth 80-90 m – zone 4.2, already tested with negative results – zone 4.3 $\rho = 30-10 \Omega\text{m}$ – max depth 90-180 m

The survey could not include all the planned calibration VES because most of the boreholes are in built areas with limited chances to operate. For this reason it is not yet clear if the higher resistivity values really indicate more agreeable lithologies for the groundwater research. The results of the next drilling shall help in finding a more clear relationship between resistivity, aquifer potential and water EC. The conclusions of the present study could change after next try, but, for this reason, the execution of a test drilling at Jibagale (area 1) is very important.

Since the Taleex Formation, at the base of the **Intermediate Unit**, is considered negative for water quantity and quality, we strongly recommend not to deepen the drilling beyond the depth suggested in the table 3. Actually several deep boreholes, drilled also inside the Taleex, have dried up few years after drilling. The active borehole Nuwaco 3 (WEC > 5000 $\mu\text{S}/\text{cm}$) which dries after few hours of exploitation seems one of these.

In the table 3 are listed the suggested locations, area by area, with the coordinates of the future drilling tries and the maximum depth. In the 4th column is given an estimate of the chances for a successful drilling.

Area	Zone	VES	Chances	Latitude	Longitude	Drilling depth
1	1	6	H	8.49776	48.62841	250
		7		8.49235	48.63459	250
		50		8.49336	48.64127	250
		45		8.49782	48.64562	250
		46		8.50128	48.63824	200
	2	41	M	8.50050	48.61728	110
		43		8.50393	48.63162	130
2	1	24	M	8.39124	48.54375	150
	2	21	L	8.46103	48.52100	170
		23	L	8.45181	48.53163	160
3	1	33	M	8.29655	48.50589	100
4	1	39	M	8.38977	48.45705	90
		38	M	8.39185	48.46015	80
	2	54	MX	8.41375	48.45973	220
	3	59	M	8.41745	48.50589	90
		60	L	8.42323	48.51382	180

Table 3: location, drilling depth and chances estimate divided for areas
Chances column: H=high – M=medium – L=low – MX =medium but negative results