GROUNDWATER IN SOUTH OMO

Assessment of fresh groundwater sources in hydrogeologically complex region in the South Omo zone, Ethiopia

ABSTRACT

The issues regarding the supply of fresh water in Ethiopia are well-known. Many projects creating new groundwater extraction wells have therefore been carried out. Some areas are hydrogeologically complex and face groundwater quality issues, which requires more in-depth research before decisions can be made. South Omo is such an area, where more than 50% of the current wells are abandoned due to their salinity. During this research, several methodologies will be put to use to gain a better understanding of the hydrogeology and water quality of South Omo. These methodologies include a literature study, EC measurements in wells in the region, a geophysical survey, and radon measurements to identify interaction between surface water and groundwater. Afterwards, recommendations regarding possible future well locations in South Omo can be given.

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1. Introduction

1.1. Background

Access to clean water and sanitation in Ethiopia is among the lowest in the world. A selection of statistics presented by UNICEF Ethiopia can support this: roughly two-thirds of households have access to improved water sources, while only a tenth of that has access to improved sanitation. In addition, 60 to 80% of communicable diseases are related to limited access to safe water. Overall water shortage also occurs frequently, which significantly affects the livelihood of Ethiopians and can even lead to loss of life.

This water insecurity can be attributed to several causes, ranging from severe droughts to political problems. The extreme poverty in Ethiopia also plays an important role; based on the publicly available data of the IMF (International Monetary Fund), Ethiopia has a gross domestic product per capita of $853, which is the 20th lowest GDP PC worldwide. With around 112 million inhabitants in 2019, Ethiopia is also the 12th most populous country. Thus, it goes without saying that there is cause for major concern.

This has led to varying NGOs carrying out emergency support related to WASH (Water, Sanitation and Hygiene) in Ethiopia. While emergency support is essential, it is also vital to reduce the number of emergencies with projects that create long-term, sustainable solutions for the water insecurity.

Among others, UNICEF Ethiopia aims to do this with their project titled *Groundwater mapping for climate resilient WASH in arid and semi-arid areas of Ethiopia*. In short, this project aims to create 'suitability maps' for eight clusters in Ethiopia in which the water supply and sanitation is especially underdeveloped. These maps are created by performing overlay analyses in GIS, implementing several factors which influence the occurrence of groundwater (e.g. lithology, land use, recharge etc.). The final products of such overlay analyses supposedly yield the most promising locations for groundwater extraction, which theoretically could greatly improve decision making.

While these suitability maps can give a decent impression of the most promising drilling locations in an area, they do not show the entire picture. The quality of the groundwater is not taken into account, which is a major problem in some regions. In addition, the maps are quite simplified, and thus do not necessarily represent the more hydrogeologically complex areas well.

The cluster located in the South Omo zone is an area which both has a complex hydrogeology and frequent water quality issues (mainly related to salinity). Therefore, a more in-depth hydrogeologic analysis of this area is not out of place. That is the inspiration and reason to conduct this research. A description of the research area follows in the next section (1.2).

1.2. Study area

1.2.1. Background

South Omo is a zone located in southern Ethiopia, bordering Kenya and South Sudan. It is part of the Southern Nations, Nationalities and Peoples' (SNNP) region. At a two-day drive from the capital Addis Ababa, it is one of the more remote and sparsely populated parts of the country. It covers an area of around 22,000 km². The study area only comprises roughly the southern half of South Omo, however. It includes the Nyangatom, Dasenech and Hamer woredas. In Figure 1, the South Omo zone is shown in green, and the actual study area in red.

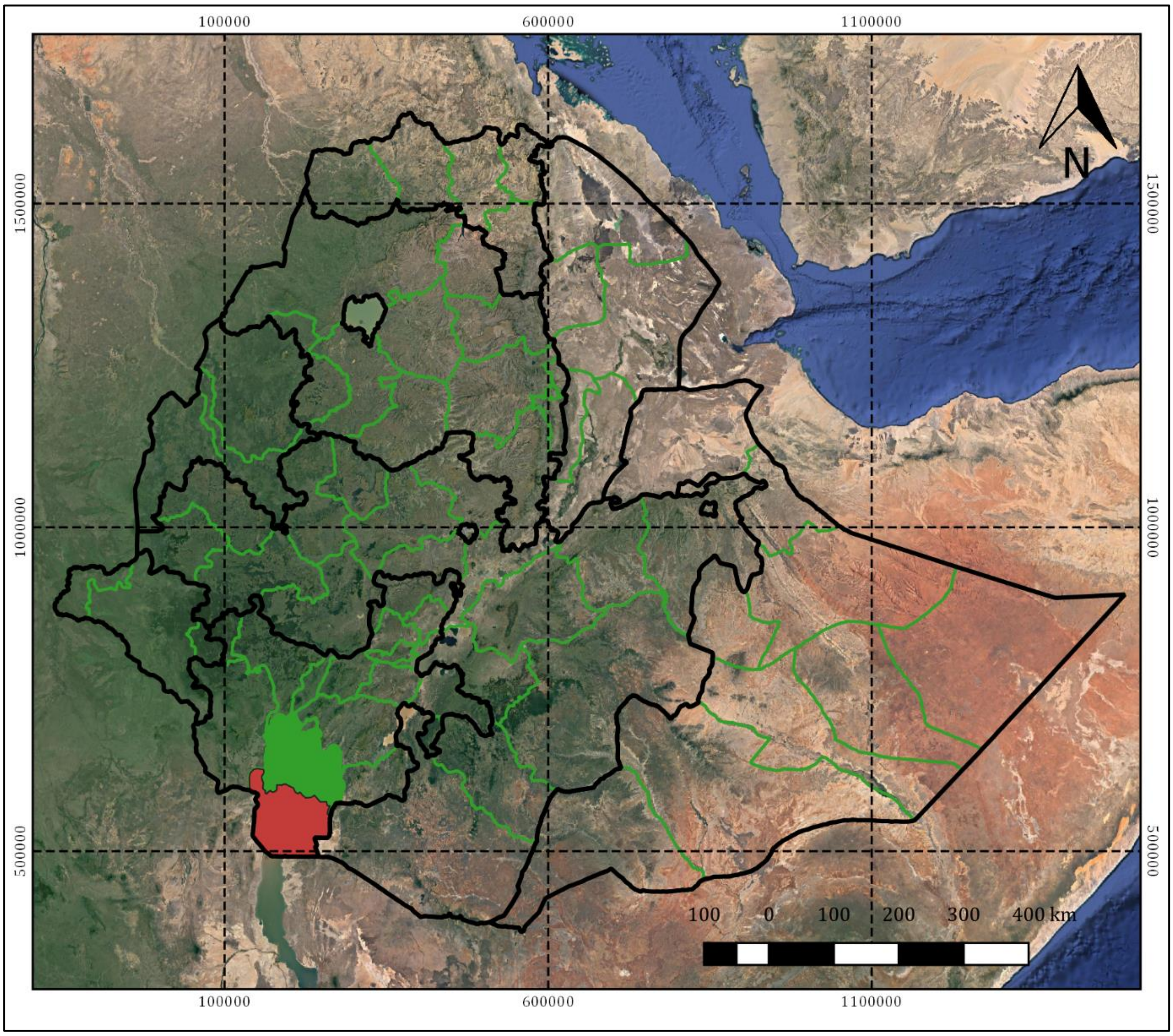

Figure 1. Map of Ethiopia. South Omo zone indicated in green. The actual study area is shown in red. The coordinate system is Adindan 37N, which will be used throughout this research.

These three woredas together have an estimated population of 177,500. This corresponds to a population density of 17 inhabitants per km², compared to a national average of around 100. The population estimate was obtained from the census 2007 data, corrected for the average annual population growth of Ethiopia of 2.46% *(UN – world population prospects, consulted April 2019)* to represent the 2019 population. This population is extremely diverse, with varied ethnic groups which mostly lead isolated lifestyles and speak their own languages. Only around 7.5% of the population lives in 'urban environments' (which is, according to my own experience, a relative term) *(CSA Ethiopia, 2007)*.

Figure 2. Lacking infrastructure.

Because of the significant social diversity and isolation, together with the typical historical neglect of marginal regions, it is unsurprising that the infrastructure of South Omo can be described as 'weak and for the most part non-existent' *(A.Y. Farah, 1996)*. This lack of decent infrastructure (Figure 2) has largely contributed to the overall underdevelopment of the area. Logically, it also has a substantial impact on the water, sanitation and hygiene (collectively known as WASH). The current water supply situation of the study area will be elaborated on in more detail in 1.2.3, after a brief geographical description.

1.2.2. Geography and climate

To get a general idea of the geographical features of the study area, the digital elevation model is shown in Figure 4. The blue line represents the Omo River (after which the South Omo zone is named), by far the most prominent river of the region. This river originates slightly west of Addis Ababa, through the convergence of the Gibe River and the Wabe River. From there it flows south to and through the South Omo zone to finally empty in Lake Turkana near the Kenyan border.

Figure 3. Sharp interface between highland and Chew Bahr rift.

The height model shows that the area consists of two flat valleys in the west and east (the Omo River valley and the Chew Bahr rift, respectively). These valleys lie at elevations between 350 and 550 m above sea level. In between, a highland is located, which reaches up to the considerably greater height of around 2100 m.

A terrain profile from the points A to B of the elevation model is shown in Figure 5. As can be seen, the transition between the western Omo Valley into the highland is gradual. On the eastern side of the highland however, the transition into the Chew Bahr rift is very abrupt, featuring steep cliffs. This is also shown in Figure 3.

Overall, the climate can be considered hot, with high maximum temperatures (30 – 40 °C) throughout the year. At higher elevations it can be considerably cooler, however. Precipitation seems quite scarce, but varies greatly in time. Most rain falls during two wet seasons.

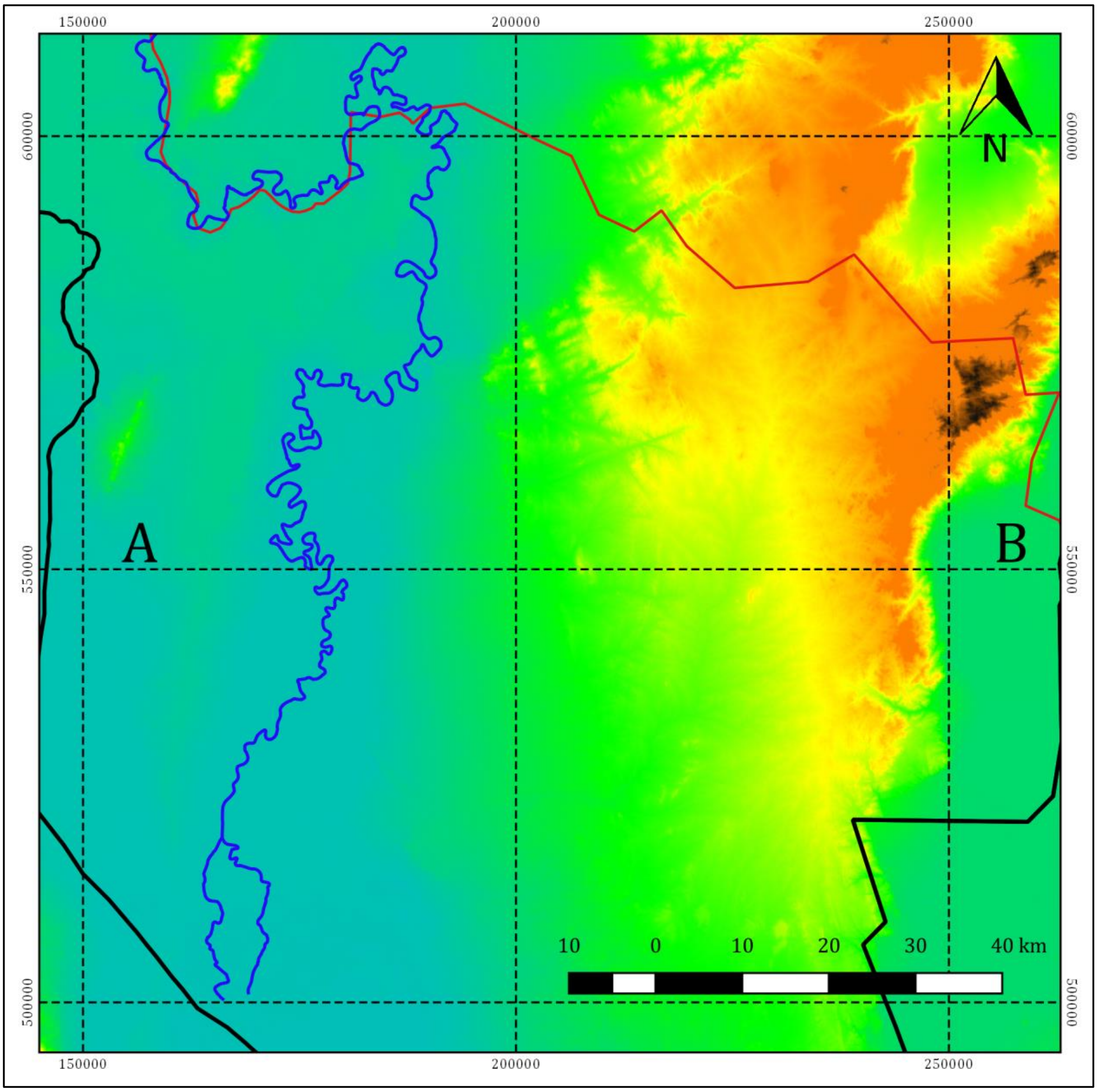

Figure 4. Digital Elevation Model (SRTM) of the study area.

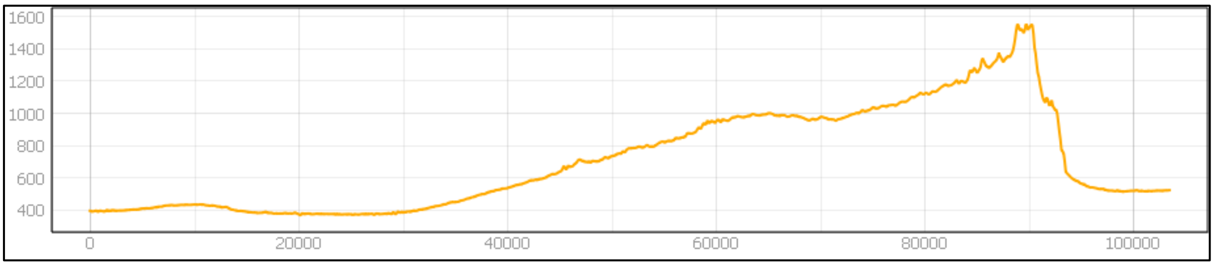

Figure 5. Terrain profile along the AB line as shown in Figure 4.

More detailed climate data is not readily available. While information about the Ethiopian climate does exist, climate data focusing on this specific region is not abundant. Given the large variety in climate conditions throughout Ethiopia, large-scale data is far from ideal to use. Satellite data was used useful to gain a somewhat better understanding of the climate of the study area.

1.2.3. Current water supply situation

Owing to its remoteness, thin population and lacking infrastructure, modern water facilities in South Omo are uncommon. The Omo River is thus considered to be a crucial source of fresh water (Figure 6).

Figure 6. Omo River.

The annual flood of the Omo River is of the utmost importance for the inhabitants of the lower Omo Valley; none of the groups living there could survive without the 'flood-retreat' agriculture facilitated by this annual event *(D. Turton, 2010)*. So, while the Omo River is undoubtedly an enormous source of fresh water for the region, the relatively recent construction of hydroelectric dams upstream of South Omo has led to some major concerns.

The development of these dams is certain to heavily influence the annual flood, as large amounts of Omo River inflow will be captured and held back. Likely consequences include **a)** the collapse of local livelihoods and widespread hunger among the peoples of the Lower Omo and Lake Turkana watershed; **b)** an increase in armed conflict over scarce resources; **c)** destruction of fragile downstream ecosystems *(C. Fong, 2014)*. The problem has also been raised that the poorest and most vulnerable members of the population are disproportionately affected by the dam. Those affected are likely to become even poorer as a result, which results in a downward spiral that is extraordinarily difficult to reverse *(D. Turton, 2010)*.

The influence of the upstream hydroelectric dams is however not the focus of this research, as this has already been studied quite extensively. Instead, the emphasis lies on groundwater resources in the region, and the interaction between the Omo River and these groundwaters. Still, the concerns regarding the dams are important to keep in mind when investigating the water supply of South Omo.

As stated, the water of Omo River is primarily important for agriculture. The water is turbid however, and unsuitable for direct consumption. Modern water purification technologies are practically non-existent in this region, so cleansing the river water is not a reliable option either. Yet, some people living close to the Omo River are known to use the root of a plant (*Maerua Subcordata,* locally known as 'Gluf') to purify the water; the root of this plant is known to be rich in polysaccharides, which is good as a coagulating agent *(S. Kebede, 2013)*.

Apart from this select group of people, inhabitants of the South Omo region are predominantly dependent on hand dug wells in sediments or along (usually dry) river beds (or excavations in the river beds themselves) for their drinking water and that of their livestock. Deeper boreholes are also encountered in the area, but are far less common than hand dug wells. In the lowlands, roof water collection is becoming an important source of potable water as well.

While functional wells are fairly prevalent throughout the region, water quality issues are common. Groundwater can often be of high salinity, which makes it unsuitable for both human and livestock consumption. The TDS (total dissolved solids) values of groundwaters in South Omo are known to vary between 500 and 50,000 mg/L. Unfortunately, the distribution of this variation in salinity is very complex, appearing to change with the geomorphology. Consequently, over 50% of wells in the Omo delta are abandoned as a result of their high salt content *(S. Kebede, 2013)*.

1.3. Research goal

As mentioned earlier in the introduction, the main aim of this research is to gain a better understanding of the hydrogeologic system of the South Omo zone, given its complex hydrogeology and water quality patterns. The following research questions will be assessed in order to reach this goal:

- What is the annual groundwater recharge and how is it distributed?
- How is the built-up of the sediment deposits in the valley and what are the major aquifers?
- What is the salinity and general water quality of the groundwater in the area?
- How can the salinity and water quality patterns be explained?
- What is the groundwater flow and recharge system in the valley?
- In what manner do surface water and groundwater interact with each other?

2. Methodology

2.1. Overview

In order to answer the aforementioned research questions, several methodologies will be put to use. In this paragraph, the overall approach will be described concisely. Thereafter, the methodologies that require some more elaboration will be explained in more detail.

As a basis, literature has been used whenever available. Literature on the specific study area is relatively scarce, however. Literature was of most use to gain background information, information regarding the geology of the area, and to verify the viability of the other methodologies.

As detailed climate data of South Omo is not readily available, satellite data for precipitation (CHIRPS, 2.2) and evaporation (MODIS, 2.3) was used to gain some basic insight in the area's climate, which was used to make an approximation of the annual recharge.

A geophysical survey has been performed by a geophysics team. This team has carried out a number of vertical electrical soundings (VES, 2.4) on the Omo valley sediments. I was not able to choose the specific locations in the study area that the geophysics team investigated. Still, their results can give an impression of the built-up of the deposits. Additionally, drilling records are available in a large, national database, which were used to identify major aquifers in the region.

In order to determine the groundwater quality (salinity) throughout the area and possibly find a pattern, several wells in the area were visited during a fieldwork. There, electric conductivity (EC), TDS and temperature measurements were conducted using a Hanna EC/TDS meter. Whenever possible, the water level in the wells was measured as well by use of a depth meter reaching up to 50 m. The coordinates for the wells were obtained from the borehole database, as well as from woreda water offices in Jinka, Dimeka and Omorate, which had hand-written well coordinates and data. The wells were located in the field using a Garmin eTrex 30x GPS. A Toyota Land Cruiser with an experienced driver was used for transport during the fieldworks (Figure 7).

Later, the field was visited again to take Radon-222 (^{222}Rn) measurements using RAD7 equipment (2.5). ^{222}Rn concentration values can offer an insight in the interaction between surface water and groundwater in the study area. Measurements were performed on river water to detect inflow of groundwater into Omo River. The measurements started at Omorate and ended roughly 30 km south of there, taking measurements at roughly equal intervals (if possible). In addition, ^{222}Rn values of water from wells close to Omo River was measured as well to distinguish inflow from River water into the groundwater. A few measurements were also taken at other locations.

In the end, QGIS was used to visualize, process and interpret the data gained from the aforementioned methodologies.

Figure 7. Toyota Land Cruiser (including driver).

2.2. CHIRPS

Climate Hazards group InfraRed Precipitation with Station data (CHIRPS) is a 30+ year rainfall data set. CHIRPS combines satellite imagery with in-situ station data to create a gridded rainfall timeseries with a spatial resolution of 0.05° and a temporal resolution of 1 day. It goes back to 1981.

A 2018 study validated the CHIRPS estimations over a topographically complex area in the Andes, Argentina. It was found that the CHIRPS data adequately reproduce several characteristics of the regional precipitation *(J.A. Rivera et al., 2018).* Because the 0.05° resolution is quite low, the data was interpolated bilinearly to a higher resolution of 250 m, creating a smoother image.

2.3. MODIS

Moderate resolution Imaging Spectrometer (MODIS) Evapotranspiration incorporates satellite remote sensing data to create a gridded timeseries of estimated evapotranspiration with an 8-day resolution. The spatial resolution is 1 km, and the timeseries started in 2000.

A validation study from 2011 showed that the MODIS Evapotranspiration data set can estimate actual evapotranspiration with reasonable accuracy under most conditions, with an underestimation occurring in some situations *(H. Woo Kim et al., 2011)*. As with the CHIRPS data, the MODIS data set was bilinearly interpolated to a 250 m resolution.

2.4. Vertical electrical soundings

VES is a common geophysical surveying method (Figure 8). During a VES, an electric current of known intensity is sent through the ground by two electrodes (commonly referred to as A and B) with a certain distance between each other. The electric potential difference is measured by two other electrodes (potential electrodes M and N), which are placed in the centre. In this manner, the bulk or apparent electrical resistivity of the soil is determined. The distance between electrodes A and B determines the penetration depth of the electric current. During this particular geophysical survey, the distance 1/2AB (i.e. the distance to either side from the centre) was increased step-by-step from a few metres up to 1 km. In a layered subsurface the apparent resistivities vary with the increasing 1/2AB and result in a VES sounding curve.

The obtained apparent resistivity values for different penetration depths (or 1/2AB's) can be converted into a layer model of true resistivities by inverse modelling. These layer resistivities can then be interpreted and linked to corresponding lithologies and water content (porosity) and the electrical resistivity of water. If in a certain case the latter is the most variable parameter, saline and fresh water can also be distinguished. After all, saline water has a low electric resistivity (high EC) compared to fresh water.

While a VES is undoubtedly a useful method to gain insight in the different lithological layers and water content of an area, the interpretation of the results remains highly subjective; a certain electrical resistivity value can often mean several things. Therefore, interpretation has to be carried out carefully and while taking other available geological and hydrogeological information into account.

Figure 8. Geophysics team at work.

2.5. Radon-222 as groundwater tracer

^{222}Rn is a natural radionuclide which is produced from the radioactive decay of ^{226}Ra in the decay chain of uranium-series isotopes (^{238}U). It is produced in rocks and minerals; after emanating from the surface of mineral grains through α-recoil, it accumulates in pore spaces *(H. Hofmann et al., 2011)*. ^{222}Rn is able to dissolve in water and has a half-life of approximately 3.8 days *(H. Hamada, 2000)*.

While radon is a noble gas and thus largely unreactive, it rapidly degasses to the atmosphere from surface water bodies *(H. Hofmann et al., 2011)*. Therefore, it is considered a good natural tracer of groundwater discharge, as it typically occurs in quantities 2 to 3 orders of magnitude higher in groundwater than in surface water *(W.C. Burnett et al., 2010)*.

RAD7 equipment (produced by *Durridge Company Inc.*) provides an opportunity to measure ^{222}Rn with relative ease in the field. At around 75 minutes per measurement, it is still very time-consuming to use, however.

Figure 9. RAD7 equipment being operated.

The RAD7 equipment is provided by the Addis Ababa University (Figure 9). The *Big Bottle System* is made available as well, which is an accessory to the RAD7 which enables the measurement of radon in water instead of in air. Followingly, a short description regarding the operation of the RAD7 will be given.

Before use, the RAD7 has to be purged and dried (by use of an attached drying unit), removing as much moisture and radon already present in the system as possible. This will decrease possible errors in measurements *(DURRIDGE Company Inc., 2019)*. The Big Bottle System extension allows one to attach a 2.5 L water sample to the RAD7. This sample has to meet two important criteria: **a)** the sample has to be representative of the water to be tested; **b)** the sample has to be collected without coming into contact with air (to minimize the effect of degassing to the atmosphere). After the purging and the collection of the sample, the test can be started *(DURRIDGE Company Inc., 2018)*. Once started, the sample is aerated (aerator stones blow air through the sample), which releases the radon from the sample into the (closed) air loop. The ^{222}Rn concentration in the air loop is then measured by the RAD7 in 15-minute cycles using a solid-state alpha detector which converts alpha radiation directly to an electrical signal. From this air concentration, the original radon concentration in the water sample is calculated using the equilibrium concentration ratio *(DURRIDGE Company Inc., 2018)*. As it can take up to 45 minutes to reach equilibrium between the water and the air in the system, the results of the first two cycles are usually discarded. The average of the third and fourth cycle is taken as the result. This is the reason the RAD7 measurements are so time-consuming.

3. Results

3.1. Climate and recharge

Detailed precipitation data of the area is scarce. Therefore, daily CHIRPS precipitation data was used to produce the map below (Figure 10). For more information regarding this data source, refer to the Methodology section (2.2). This map shows the average annual rainfall between 1981 and 2018 in mm/year. It displays great spatial variability, with mean precipitation varying from less than 300 mm/year to more than 1200 mm/year.

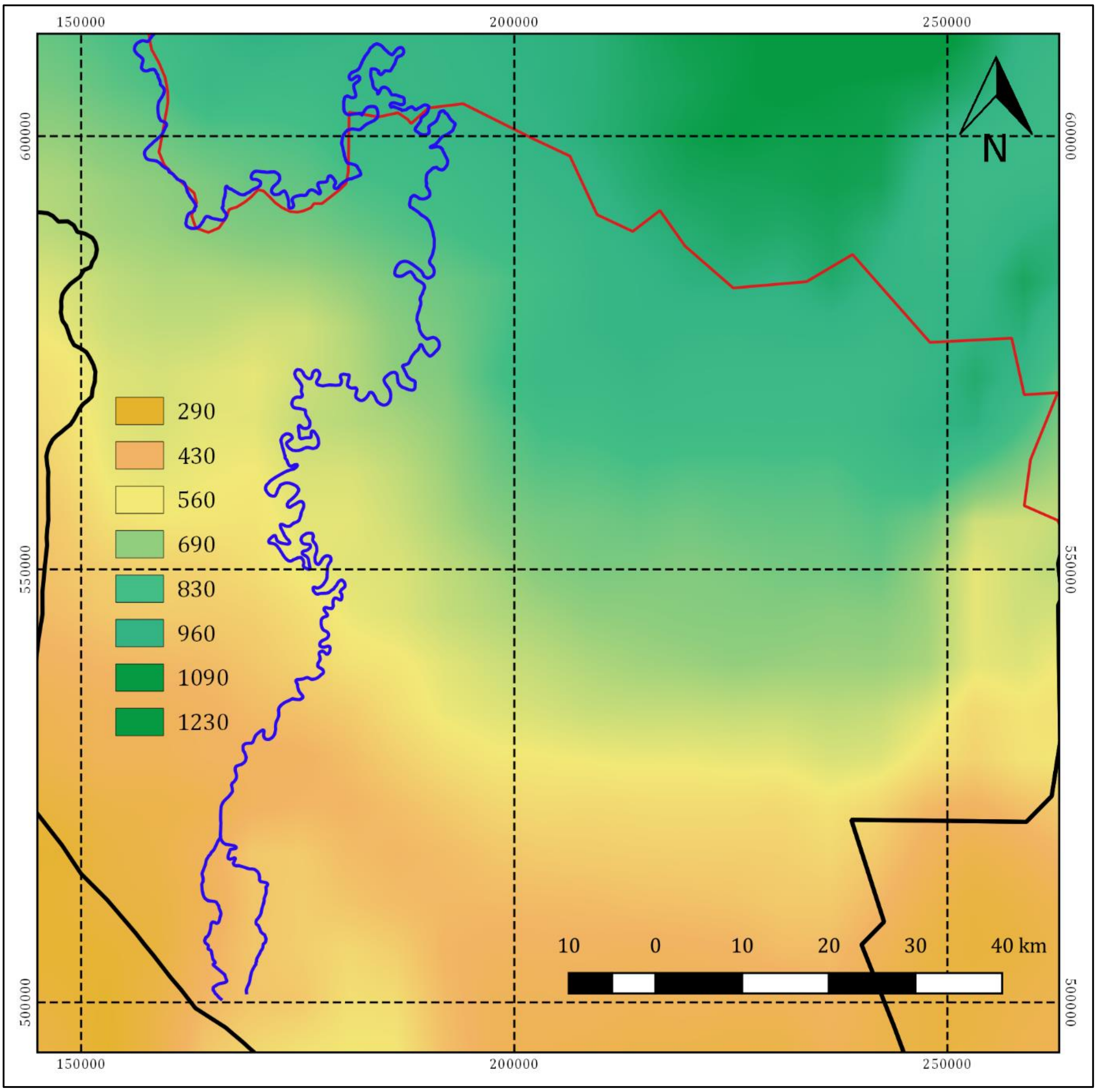

Figure 10. Mean annual precipitation in mm/year between 1981 and 2018.

The mean monthly precipitation between 1981 and 2018 was investigated as well. This time, the mean value of the entire mapped area was calculated for every month. This resulted in the graph displayed in Figure 11. This graph shows that there is not only great spatial variation, but also temporal variation throughout the year. From this graph, the average annual rainfall of the mapped area amounts to almost 700 mm in total.

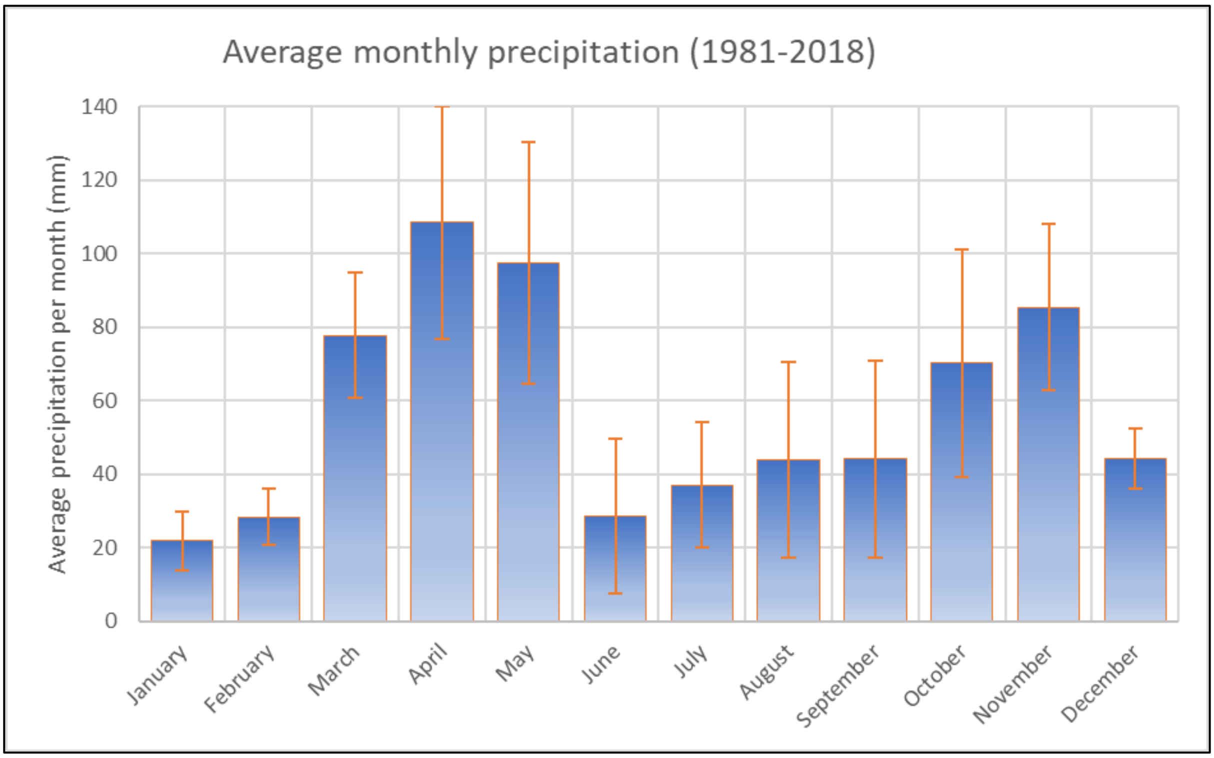

Figure 11. Mean monthly precipitation in mm/month of the mapped area between 1981 and 2018.

The net precipitation is visualized as well, in Figure 12. It was obtained by subtracting MODIS evaporation data (see Methodology, 2.3) from the precipitation data. Negative values coincide with Lake Turkana and the Omo River. Negative net precipitation is also encountered along edges of the highland. The mean net precipitation over the mapped area amounts to 240 mm, with a standard deviation of 133 mm.

Net precipitation on its own doesn't say much, however. Usually, rainfall doesn't stay in the same place and is, at least partly, transported as runoff. Therefore, a watershed delineation was performed to show the runoff system, yielding the image portrayed in Figure 13. Using the flow accumulation map for reference, the basins that are in contact with each other were combined into larger basins. Then, the mean net precipitation over each of these combined basins was calculated and multiplied by an infiltration factor of 0.2. This resulted in Figure 14, which shows the mean recharge for each combined basin. It varies between 20 and 70 mm/year.

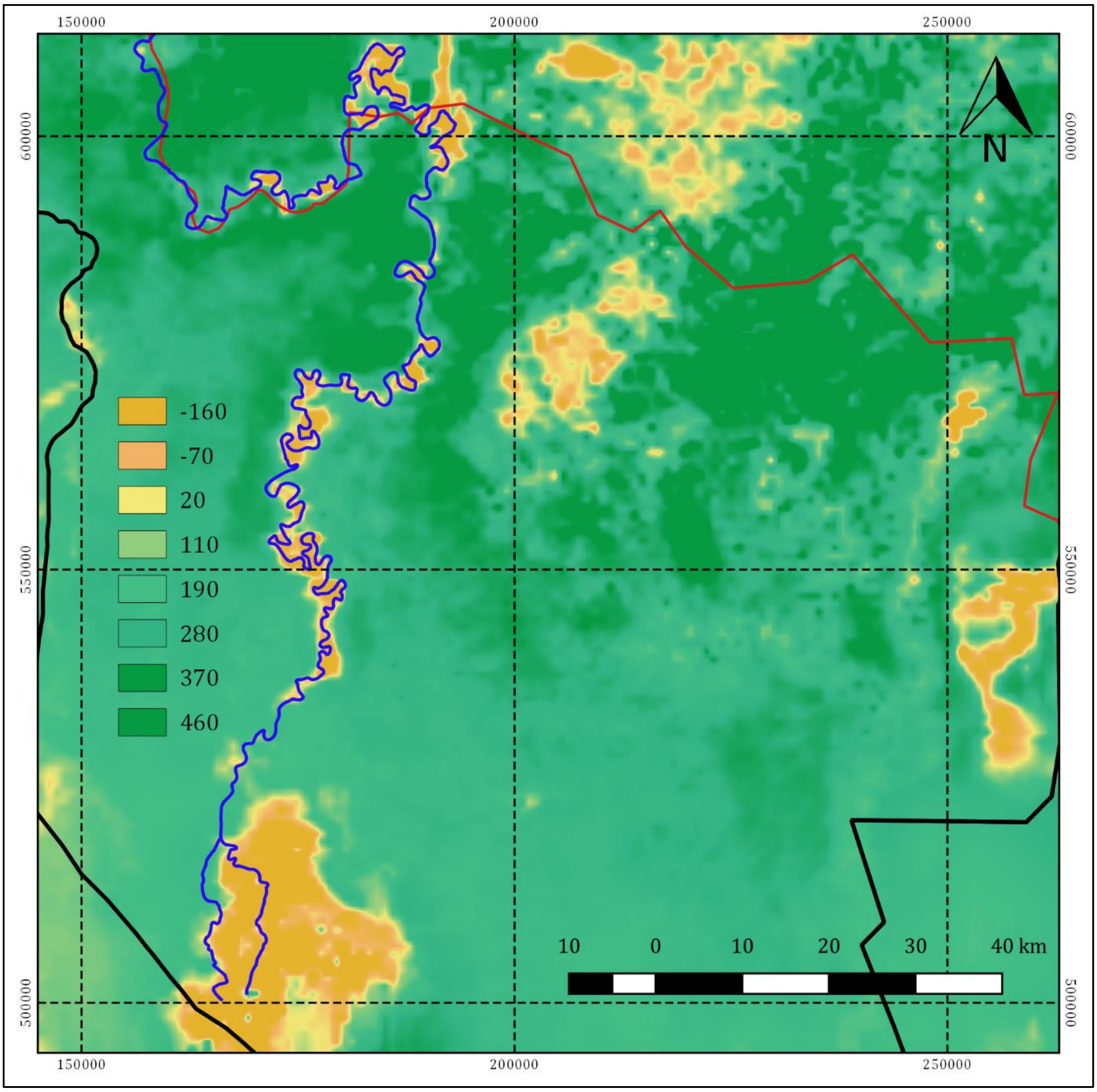

Figure 12. Mean net precipitation (P – ET) in mm/year.

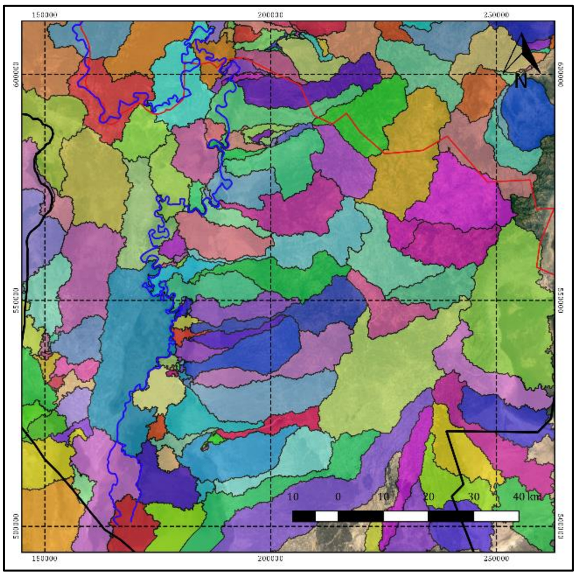

Figure 13. Watershed delineation.

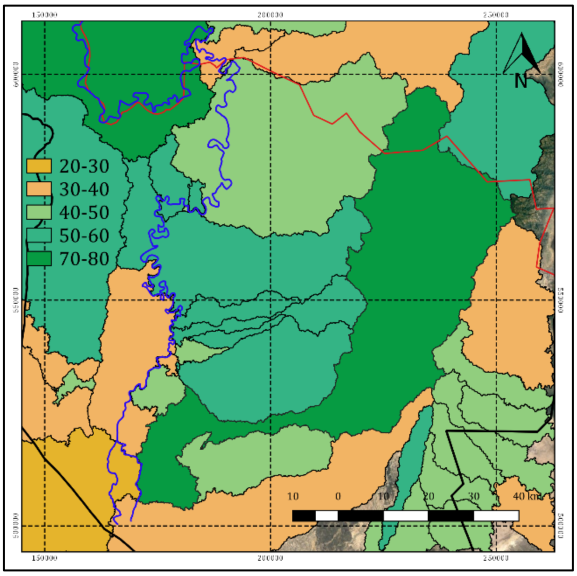

Figure 14. Annual recharge per combined basin in mm.

3.2. Geology

The geology the study area can be divided into three major zones. In the middle a highland is located in the form of the Hammer Koke block. This highland is bounded on both sides by tectonic depressions. The earlier subsidence that characterizes these areas made room for sediment infill (alluvial, fluvial and lacustrine) *(Feibel, 2011)*. The western part of the region is characterized by the Omo River valley, while the Chew Bahr rift is located east of the Hammer Koke highland.

A geological map of the study area is shown in Figure 15. For more convenient reference, geological units belonging to the same lithological group were given the same colour.

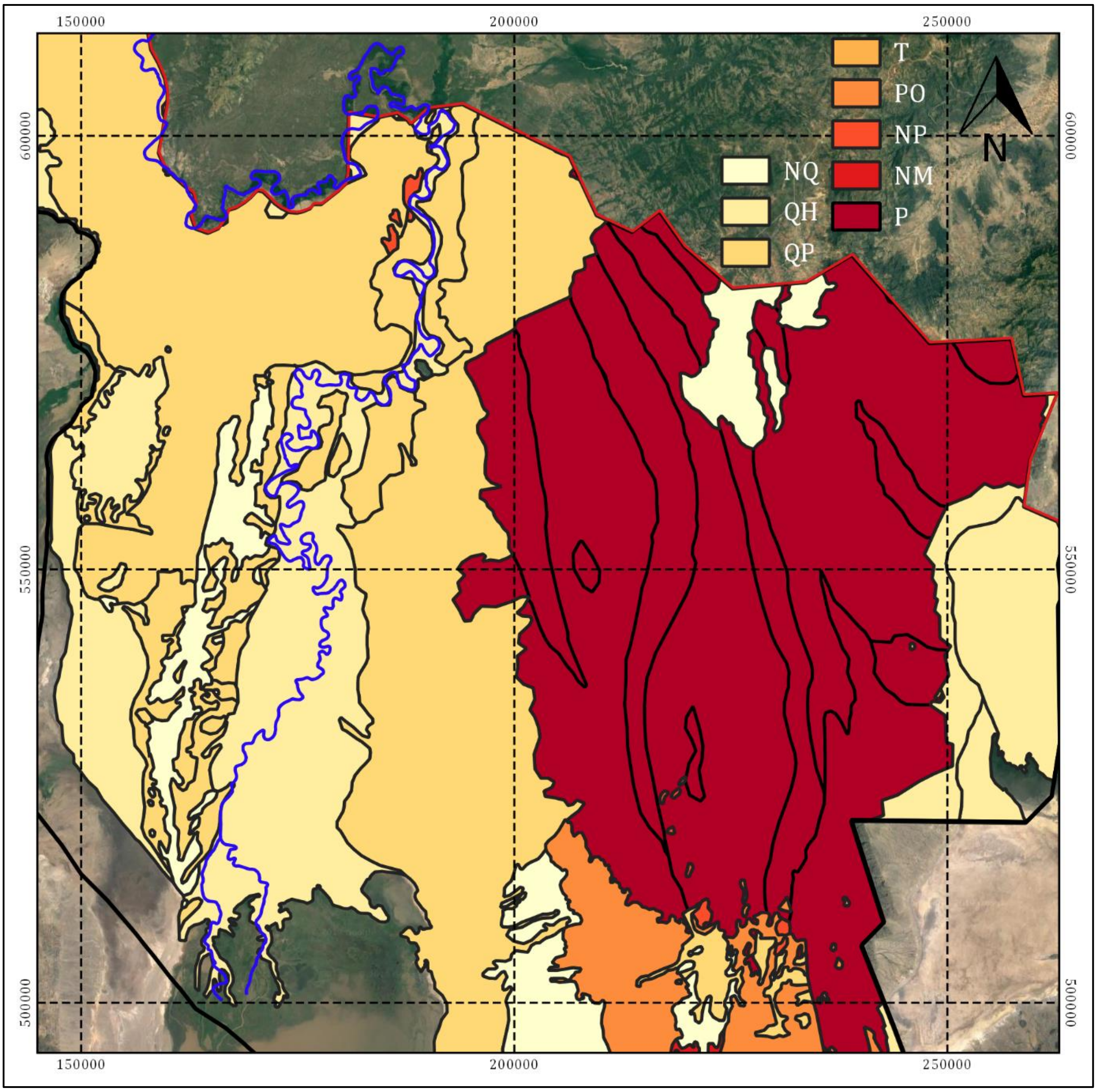

Figure 14. Geological map. NQ, QH, QP: various types of Neogene unconsolidated sediments. T: Basalts, rhyolites. PO: Fejej formation. NP: Harr Basalt. NM: Abate formation. P: various gneisses.

Please note that the described thickness of certain layers in the next sections should be considered an indication and not a precise value.

3.2.1. Omo River valley

The Omo River valley surrounds the Omo River and its junction with Lake Turkana near the Kenyan border to the south. The valley is underlain by a thick sequence of unconsolidated sediments of both fluvial and lacustrine origin *(S. Kebede, 2013)*. These sediments originate from the Pliocene, Pleistocene and Holocene; the majority of their ages lie between 4.2 and 0.75 Ma *(I. McDougall et al., 2008)*. Several layers of volcanic ash are also present in the sedimentary succession.

The Omo valley is characterized by the thick sediment coverage throughout (Figure 16), with said sediment being estimated to reach up to 3 – 4 km *(I. McDougall et al., 2008)*. Still, there are some notable variations across the area. In some parts, the built-up of layers can become quite complex. For example, west of the Omo River and north of the Lake Turkana delta lies the *Shungura* formation, which was dominated by fluvial depositional conditions. This formation has a thickness of roughly 750 m. It consists of a 300 m thick layer of basal lacustrine silts and clays and is overlain by unconsolidated, fluvial, fining-upward cycles of sandy channel deposits. These deposits in turn are overlain by finer siltstone deposits in the channel floodplain, which is covered by another layer of lacustrine silts and clays. A similar sequence is encountered north-east of the Lake Turkana delta, but with a smaller thickness of roughly 100 m *(A. Asrat, 2019)*.

The north-western part of the Omo valley is mainly represented by the *Kibish* formation. This is a succession of 50 m thick lacustrine silt and clay, and 100 m thick lacustrine and deltaic deposits.

The Kibish River and the Omo River flood plains are covered by 30 m thick fluvial sand and silt. On either side of the modern Omo River flood plain a 100 m thick layer of undifferentiated alluvial, fluviatile and lacustrine sediments is located.

Figure 15. Sediment coverage in Omo River valley.

3.2.2.Hammer Koke block

In the middle of the study area, to the east of Omo River valley, the Hammer Koke block is located. This highland is underlain by Precambrian, high-grade metamorphic basement rocks (Figure 17), highly deformed and metamorphosed (granulite facies) *(V. Foerster et al., 2012)*.

In particular, the Hammer Koke block is characterized by a succession of various types of Late Proterozoic high-grade gneisses. The gneisses are strongly foliated and folded along a N – S (NNW – SSE) axis. A large portion of these gneisses is heavily weathered and forms a regolith cover, apart from the highest elevations and steepest cliffs of the range *(A. Asrat, 2019)*. The thickness of the regolith cover generally does not exceed 3 m *(S. Kebede, 2013)*.

Figure 16. Metamorphic basement rock of the Hammer Koke range.

3.2.3. Chew Bahr rift

The tectonically bounded Chew Bahr baoe sin represented to the east of the Hammer Koke block is seen as a transition zone between the southern sector of the Main Ethiopian Rift to the north-east, and the Omo-Turkana basin to the west.

The sediments of the Chew Bahr basin are formed by a thick succession of lacustrine silt and clay intercalated with fluvial silt and sand, and alluvium. These sediments have been accumulating in the basin since the Quaternary, as the basin was formed during an earlier phase of rifting. Based on airborne gravity and seismic reflection data, the total sediment infill is estimated to be 5 km thick *(A. Asrat et al., 2009)*.

Currently, the basin's main sources of sediment deposits are overflows of the Weyto River, as well as the extensive alluvial fans off the escarpment flanks: the Hammer Koke block to the west, the Teltele Plateau to the east (Figure 18). These influxes of sediment are highly episodic, given their close ties to rainfall; section 3.1 showed the strong seasonality of precipitation in the area *(V. Foerster et al., 2014)*.

The sediments are partly underlain by undivided gneisses from the Hammer Koke block in the west. In the eastern margins of the basin, basalt flows with subordinate rhyolite, trachyte, tuffs and ignimbrites are most common *(V. Foerster et al., 2012)*.

Figure 17. Foothills of the Hammer Koke block with the flat Chew Bahr rift behind them. In the far distance, the Teltele Plateau is visible.

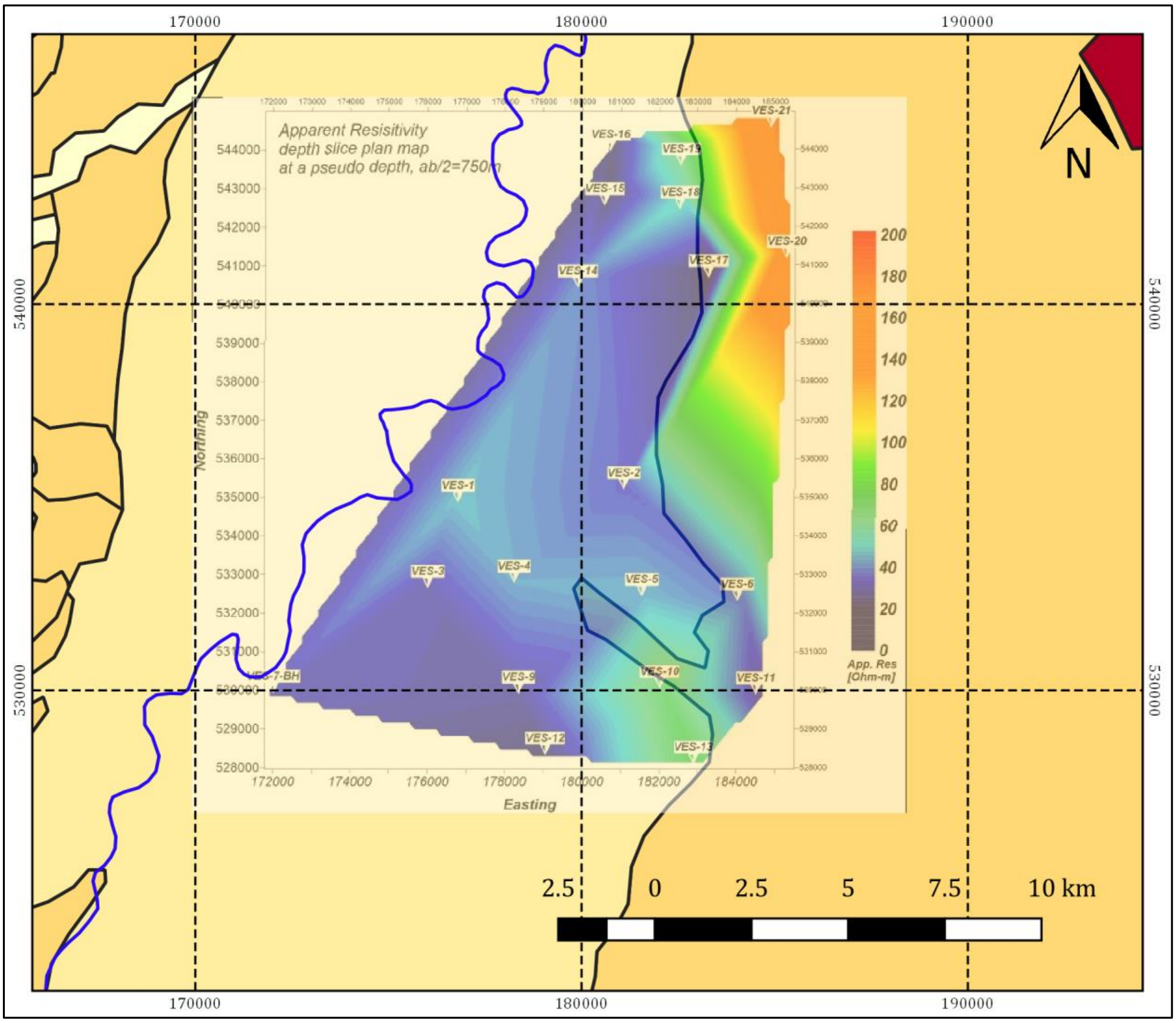

Figure 19. Apparent resitivity at pseudo depth AB/2=750 m underlain by geological map.

3.2.4.VES results

Unfortunately, the vertical electrical soundings carried out by the geophysics team are limited to a relatively small area (which was of most interest for the overarching project). The VES were performed along the west bank of the Omo River, just north of Omorate. The area covered by the VES is roughly 130 km². Because of their size, the VES results are presented in Annex 1, and will be further discussed in the Discussion (4.2). An example of the results is shown in Figure 19. Here, the result of 1/2AB = 750 m is underlain by the geological map, which shows that the geology mainly defines the variation in this case.

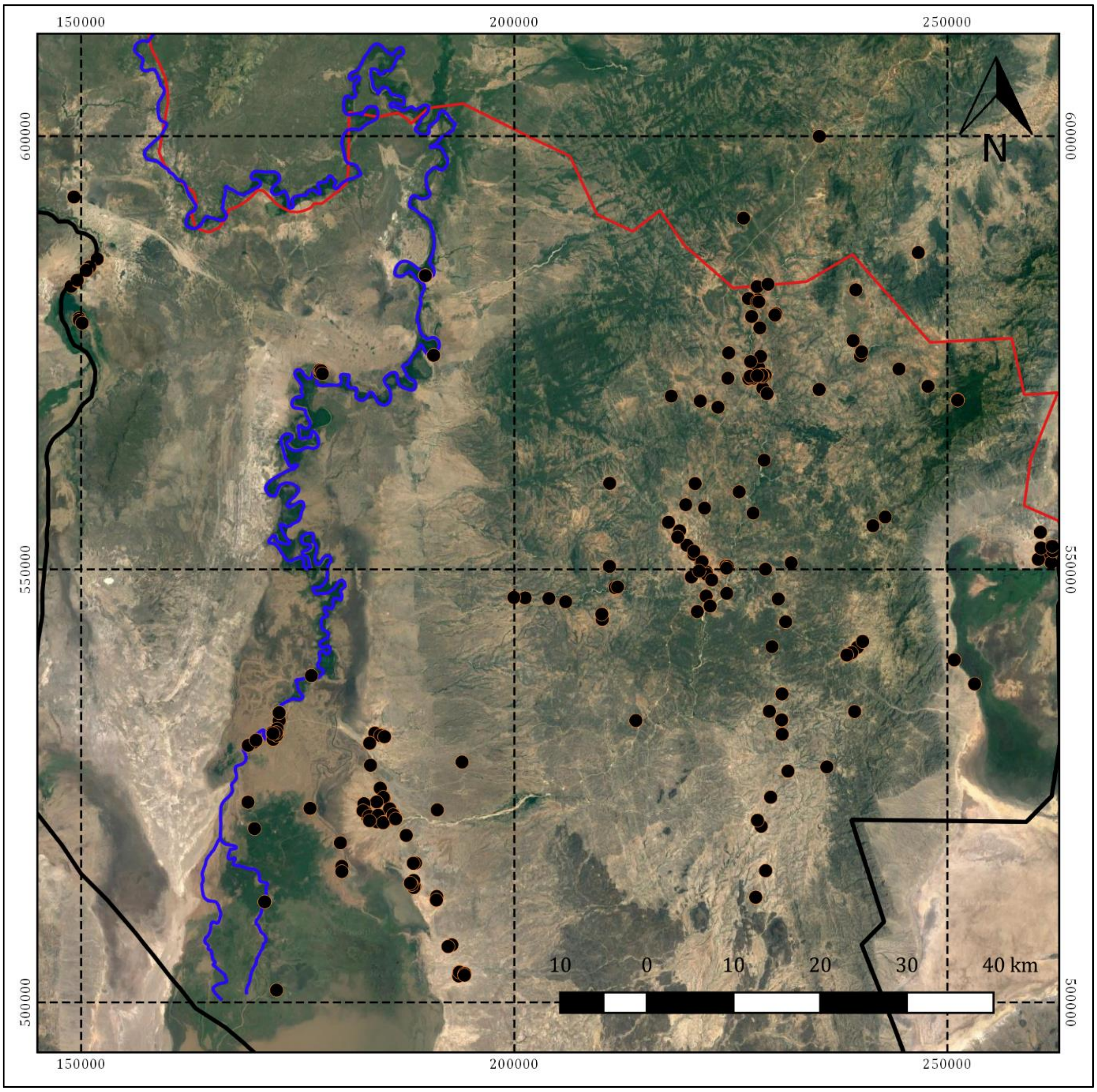

Figure 18. All (known) water points in the area.

3.2.5. Existing water points

A good number of well coordinates were obtained from the national borehole database, other studies and projects in the study area, and from the woreda water offices of Omorate (Dasenech) and Dimeka (Hammer). All well coordinates from these sources are shown in Figure 20.

Two major clusters with a high density of water points seem to exist in the area. In the south-western quarter of the area, many water points are present in the sediments within roughly 30 km of Lake Turkana. In the north-west, a high density of water points can be found on the Precambrian hard rock of the Hammer Koke highland. East of the highland, in the sediments of the Chew Bahr rift and close to Erbore, some wells are located as well. Along the Omo River, several river bank filtration wells are visible too.

3.3. Water quality inventory

In order to gain insight in the distribution of the water quality across the study area, a number of wells were visited during a fieldwork (Figure 21). The EC, TDS and temperature values were measured at each location. In addition, the depth of the groundwater level was measured wherever possible. This was usually not the case however, because of the presence of fixed hand pumps on top of the wells. Sometimes, the depth of wells could be obtained from available data at the water offices. In total, 43 wells were visited, 37 of which were functional at the time of visiting. The results of this well water quality inventory are presented in Table 1.

Note that all EC values of 3,999 μS/cm and TDS values of 2,000 mg/L represent the upper limit of the Hanna EC meter that was used, which unfortunately turned out to be considerably lower than the higher values encountered in Omo valley. Still, the most important goal is to find the groundwater of good quality, and anything above these values is unsuitable for consumption anyway.

Figure 19. Water quality inventory.

#	X	Y	TDS	EC	Temp	Depth	Comments
1	172604	531129	80	170	30		Tap. Not good for drinking purpose (water too long in pipeline).
2	172168	530378	401	805	30.6		Used for drinking. Slightly saline.
3	172451	530833					NF. 4 years dry.
4	172193	531150	2000	3999			Too saline for drinking. Used for cattle. Locals use water from Omo River treated with Gluf root.
5	172156	531036					NF. Mechanical problem. Used to be even more saline than other well close by.
6	172543	531574	542	1083	30.1		Not drinking quality. Used for washing clothes. The colour of the clothes appears to fade.
7	185021	530668	1111	2215	37.2		Used for drinking. Quality seems decent (even though TDS/EC values are high).
8	184740	530852					NF. Mechanical problem.
9	184544	530858	1475	2950	34.4		Quite saline. Other functional well close by much better quality.
10	183912	531080	1692	3386	36.5		No locals present to ask about quality/uses. Generally not a good sign.
11	183310	529923					NF. Mechanical problem.
12	185526	522152	360	721	36.1		Excellent drinking quality.
13	186018	521659	413	823	35.2		Good quality.
14	186320	521185	851	1701	34.6		Slightly saline. Used for drinking, but mainly good for cattle.
15	261987	550766	1262	2522	31.7	102	Tap. Saline, but used for drinking.
16	262022	552119	1114	2231	36.1	40	Drinkable, but not very good quality.
17	261726	551821	1239	2477	36.3	35	Drinkable, but not very good quality.
18	261966	552636					NF, even though recently maintained.
19	260745	554278	1125	2250	32.5	102	High discharge borehole. Used for everything. Used to supply entire area surrounding Erbore where no wells are located (transport by trucks).
20	238466	540097	960	915	29.7	56	Decent drinking quality. Constructed 6 months ago (as of April 2019).
21	238394	540104	2000	3999	29.7	82	Very saline. Was used for drinking before construction of the other well close by. Now only used for livestock.

22	239602	540995	2000	3999	29.5	54	Saline. Mainly used for livestock. Sometimes used for drinking during the dry season when other (shallower) wells can run dry.
23	238945	540380	638	1278	29.4	35	Decent drinking quality. Can become dry during dry season.
24	231332	543939	546	1093	30	32	Decent drinking quality.
25	227293	573972	425	853	26.6	28	Excellent drinking quality. Locals walk up to 10 km to this well because of good quality.
26	228045	573289	247	496	26.6	17	Excellent drinking quality.
27	228204	573292	381	762	27.4	10	Mainly used for irrigation. Also used for drinking when other well close by is dry. This one is so close to the River it never runs dry.
28	228154	572783	425	850	26.5	46	Pump depth 21 m. Never runs dry.
29	228474	572396	381	762	27.1	14	Good quality.
30	228625	572396	153	306	26.1	12	High discharge due to proximity to River. A 100 m3/h borehole with a depth of 90 m is close but under maintenance. This is used to distribute across the entire town.
31	228676	572255	173	346	26.1	9	Excellent drinking quality.
32	227500	572033				10	NF. Dry.
33	222197	549433	408	817	29.8		Decent drinking quality.
34	222254	549351	625	1252	29		Not suitable for drinking. Only used for washing.
35	221624	550963	269	540	29.6		Good quality.
36	221554	550840	458	915	29.4		Quality less than well on other side of the River. Preferably used for washing and cattle.
37	222170	549673	410	824	29.8	30	Used for drinking.
38	222133	549700	306	612	30.1		Used for drinking, not always open.
39	222083	549740	222	449	28		Dug hole in dry riverbed.
40	195842	493032	2000	3999			No drinking quality.
41	193679	503488	2000	3999			No drinking quality.
42	169270	529678	530	1058	31.3		Decent quality.
43	170014	530061	563	1124	30.9		Decent quality.

Table 1. Raw results of water quality inventory.

The distribution of EC values is visualized on the map in Figure 22. The water from wells in the vicinity of Omorate (close to the east bank of Omo River) can be considered of intermediate quality. EC values range from ~800 to ~1,150 here. The notable exception is the well outside of Omorate on the west side of the river, which yielded an EC of 3,999 (i.e. above the upper limit). A non-functional well was close by as well, and locals said it used to be even more saline than the currently functional one. Water from these wells is not drinkable, and locals therefore use water from Omo River treated with the *Gluf* root. Water from a (private) tap in Omorate was tested as well, which had a very low EC value of 170. However, despite the low EC, the water is not suitable for drinking purpose, as it was said that it remains in the pipeline for too long.

Around 12 km east of Omorate, four wells (of which one was non-functional) were encountered at a few kilometres from the road. The EC values obtained from these wells were quite high, between ~2,200 and ~3,400. Still, the well with the lowest salinity of these wells is used for both human and livestock consumption. This probably has to do with a lack of alternatives. The highest salinity well seemed mostly abandoned.

Moving southwards from the previous location, three more wells were tested. Two of these were of very good quality with EC values of ~700 to ~800. The most southern well of these three has an EC of ~1,700 however. This well is thus only used for cattle.

Even further to the south from here, close to Lake Turkana and the border of Kenya, high salinity was measured in two more wells. Drinking from these wells would be unadvisable, but they were both in use. Alternatives are likely scarce, as this area is hard to reach and remote; the road is only usable when rain has been absent for a considerable time.

Around Turmi, six wells were visited. They were all located either in or close to the dry wadi running through Turmi. At least four of these are of pretty good quality, with EC values ranging from ~400 to ~800. These are used by the entire town as a main source of drinking water. One of the wells is considered of insufficient quality by the locals (EC of ~1,200), and is only used for washing. Another well (EC ~900) is of better quality, but still seems to be mainly used for washing clothes (likely because another well yielding water of better quality is close). People also dig shallow holes in the wadi bed to extract water. This water generally has a low electric conductivity (~400), but it is very turbid and does not look suitable for direct consumption nor washing. It was therefore surprising that water from these hand dug holes was gathered in large quantities with the help of donkeys. Upon inquiry, it was said that this water is used for the creation of a local drink.

Around 25 km north of Turmi lies the town of Dimeka. Seven functional wells were found in and around this town, and generally the water was of really good quality. The EC values fall between roughly ~300 and ~800. It was stated that local people walk up to 10 km to the wells of Dimeka because of the excellent water quality.

Erbore village is located on the other side of the highland. Three functional wells are located in this village, and the quality of all of these is poor with EC values of ~2,200 to ~2,600. The salty taste of the water is obvious, but still the wells are used for consumption (again, owing to a lack of alternatives). A deeper borehole (102 m) is also present north of Erbore, and its EC value falls into the aforementioned range as well. This borehole was originally made in relation to planned oil exploration in the area. Because of its very high discharge, it is used to supply the entire region surrounding Erbore with water (outside of town water facilities are practically non-existent).

Along the road between Turmi and Erbore, a wadi with four sequential wells close together was encountered. The great variation in EC values found here is of some note. While the clusters of wells described above mostly had similar attributes, the EC of these four wells ranges from ~900 to >3999. The deeper wells appear to yield higher EC values.

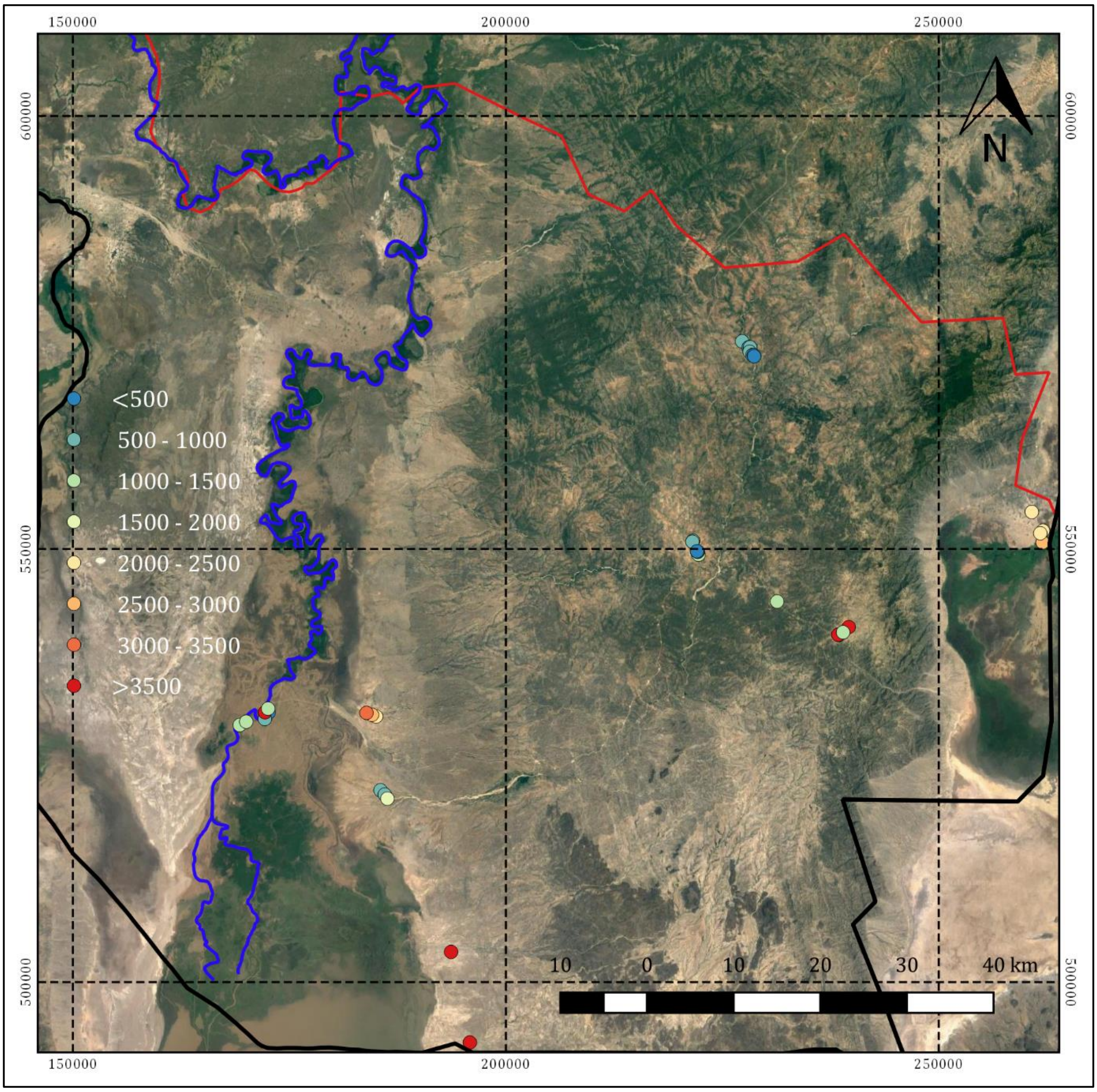

Figure 20. Visited water points with their respective EC values.

3.4. ^{222}Rn measurements

The results of the radon measurements performed with the RAD7 are presented in Table 2 (groundwater) and Table 3 (surface water). It is clear that the groundwater measurements yield much higher radon concentrations than the surface water, which is expected as described in the Methodology (2.5). For a more convenient overview, the results are also mapped in Figure 24 & 26.

Wells in and around Omorate, all within 200 m from Omo River, all have a relatively high ^{222}Rn concentration. It ranges from ~5,000 to ~20,000 Bq/m^3 (when the average of the 3rd and 4th cycle is taken as a representative result, see Methodology (2.5)). Further to the south, groundwater from two wells within a few kilometres from Lake Turkana was also tested, which yielded lower results in the order of 1,500 to 3,000 Bq/m^3. Furthermore, three measurements around Turmi were carried out as well. Two wells close to the wadi in Turmi yielded extremely different values of ~700 and ~20,000 Bq/m^3. Water from a hand dug hole in the wadi bed returned a radon concentration of ~1,100 Bq/m^3.

Surface water from the Omo River was tested, starting from Omorate and working southwards along the river over a distance of roughly 30 km. In addition to the map of Figure 24, the radon concentration sequence is also visualized in a graph in Figure 25. The distance on the x-axis represents the distance as measured along the river.

The concentration starts out at ~230 Bq/m^3 just north of Omorate. Between the distance of 0.9 km and 6.4 km from the first measurement, the radon concentration quickly rises from ~230 Bq/m^3 to ~450 (4 km) to ~560 Bq/m^3. Thereafter, the situation seems to turn around: within 1.1 km, the concentration drops to ~160 Bq/m^3. This drop in concentration continues until the low point of ~60 Bq/m^3 is reached (13.7 km). Followingly, the radon concentration stays quite low, fluctuating between ~90 and ~120 Bq/m^3. Only at the last point (34.3 km), at a junction in the river (Figure 23), a significant rise in concentration is encountered again. Here, a value of ~190 Bq/m^3 was found, the highest yielding measurement since the ~560 Bq/m^3 at 6.4 km.

Measurements 113 and 114 (at 32.1 km) were performed at the same location on both sides of the river, and yield very similar results. Surface water from Lake Turkana was tested as well, showing a comparably low concentration of ~100 Bq/m^3.

Figure 21. Junction in Omo River.

Code	X	Y	H	RAD7 (1st)	RAD7 (2nd)	RAD7 (3rd)	RAD7 (4th)	Comment
101	222133	549700	914	112	393	619	755	HDW near Turmi town
102	222083	549740	908	270	848	1200	1090	From dug hole in dry riverbed
103	222198	549431	909	6010	16200	19200	21300	Not sure if correct
116	172543	531574	385	3540	7010	7930	8730	Well in Omorate. Depth: 18m
117	195842	493032	399	1070	2260	2990	2810	Well at Bubua kebele. Depth: 80m. SWL: 33.8m. Q: 3.5 l/s.
119	193679	503488	399	807	1700	1900	1940	Well at Ochiloch kebele
120	169270	529678	347	1790	4260	5080	5710	HDW. Depth: 16 m.
121	170014	530061	372					
122	172168	530375	375	4110	13300	15800	17100	Depth: ~45-50m.
123	172193	531150		5640	13900	14500	14800	

Table 2. Raw results of 222Rn measurements in groundwater.

Code	X	Y	H	RAD7 (1st)	RAD7 (2nd)	RAD7 (3rd)	RAD7 (4th)	Comment
104	172493	532479	372	90	251	251	213	River sample
105	170983	531615	374	348	392	392	504	River sample
106	168541	529321	368	56	101	196	123	River sample
107	167297	525165	363	22.4	78.3	89.5	105	River sample
108	167317	524214	365	44.8	78.3	78.3	44.8	River sample
109	166014	521788	367	11.2	55.9	134	67	River sample
110	165476	518024	364	22.4	168	157	101	River sample
111	163923	514770	367	89.1	123	67	112	River sample
112	163978	512708	367	67.2	67.1	134	100	River sample
113	164947	508870	368	44.8	67.1	109	101	River sample
114	165025	508866		56.1	89.7	112	101	River sample
115	164227	506897	369	62.2	123	157	213	River sample, near river branch
	172516	531572		158	157	236	225	River sample near HDW (116)
	169427	529828		362	610	553	564	River sample near HDW (120)
118	190283	492644	366	78.7	89.2	11.2	101	Lake Turkana sample

Table 3. Raw results of 222Rn measurements in surface water.

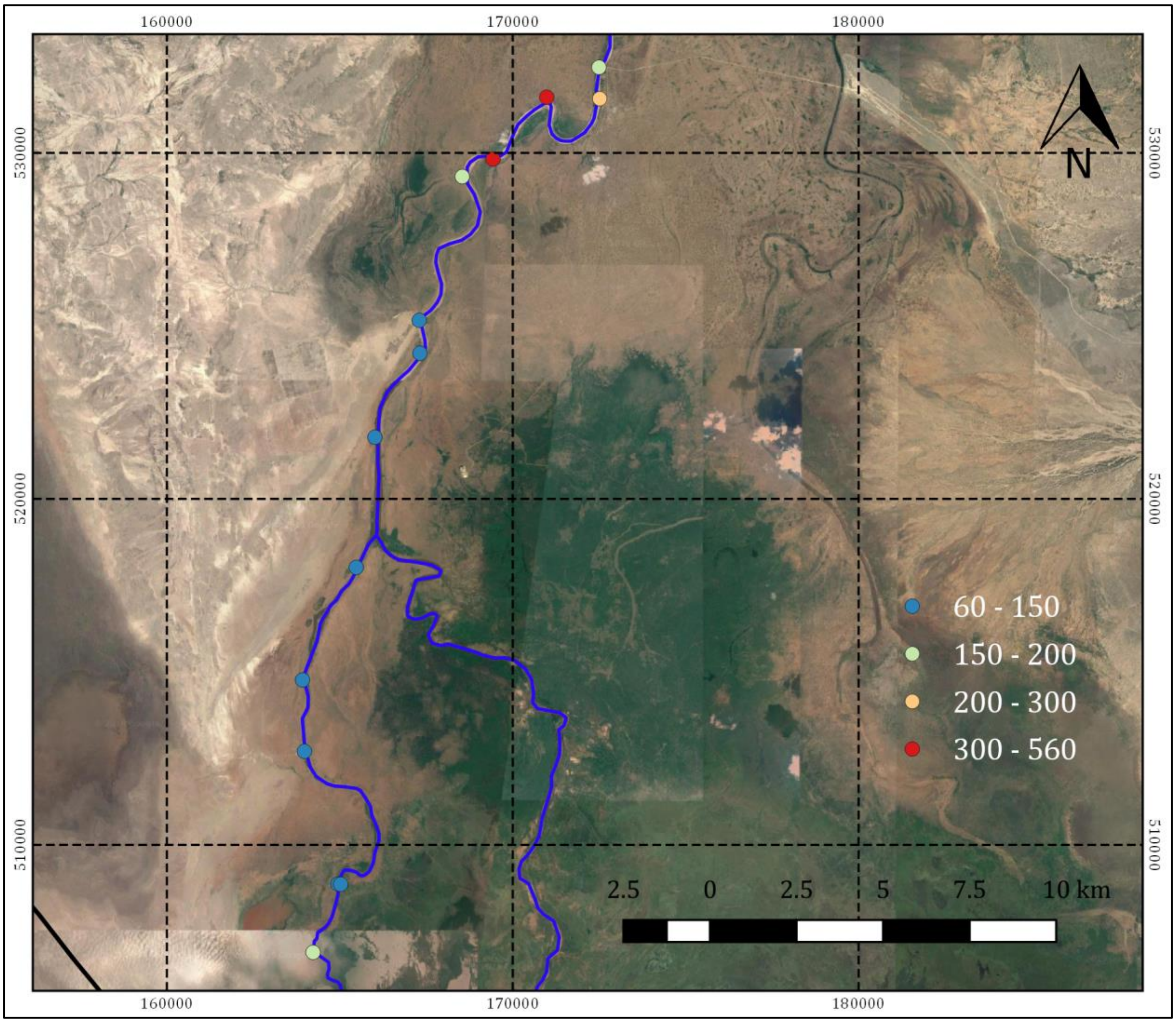

Figure 22. Surface water radon results mapped out.

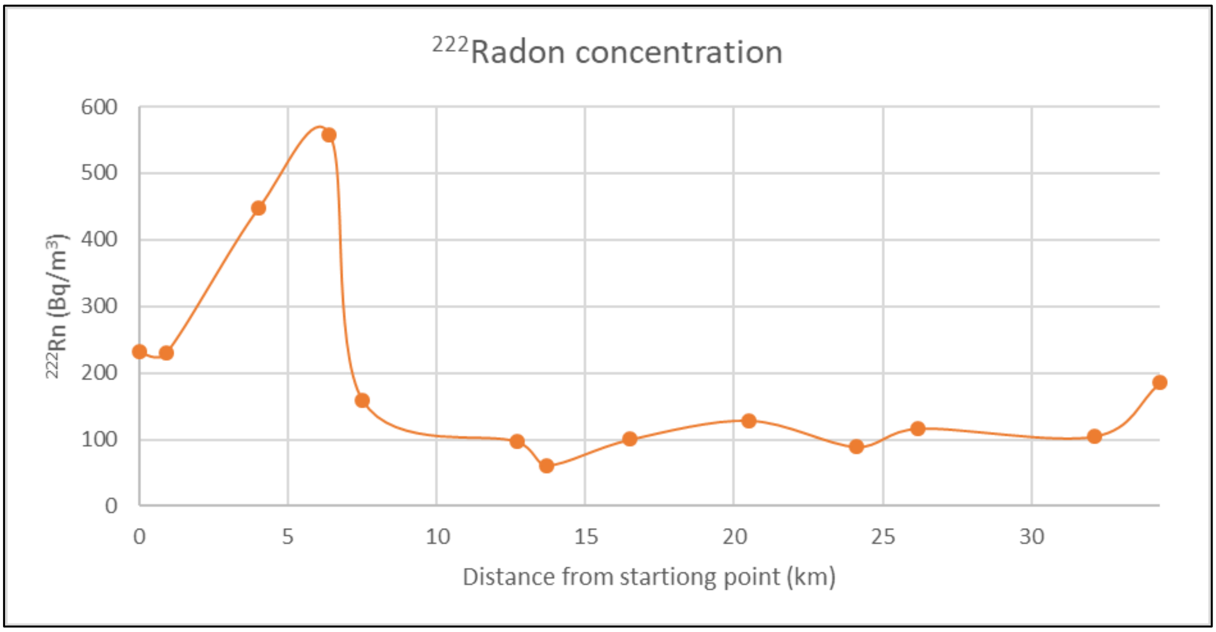

Figure 23. Surface water radon measurements visualized in graph.

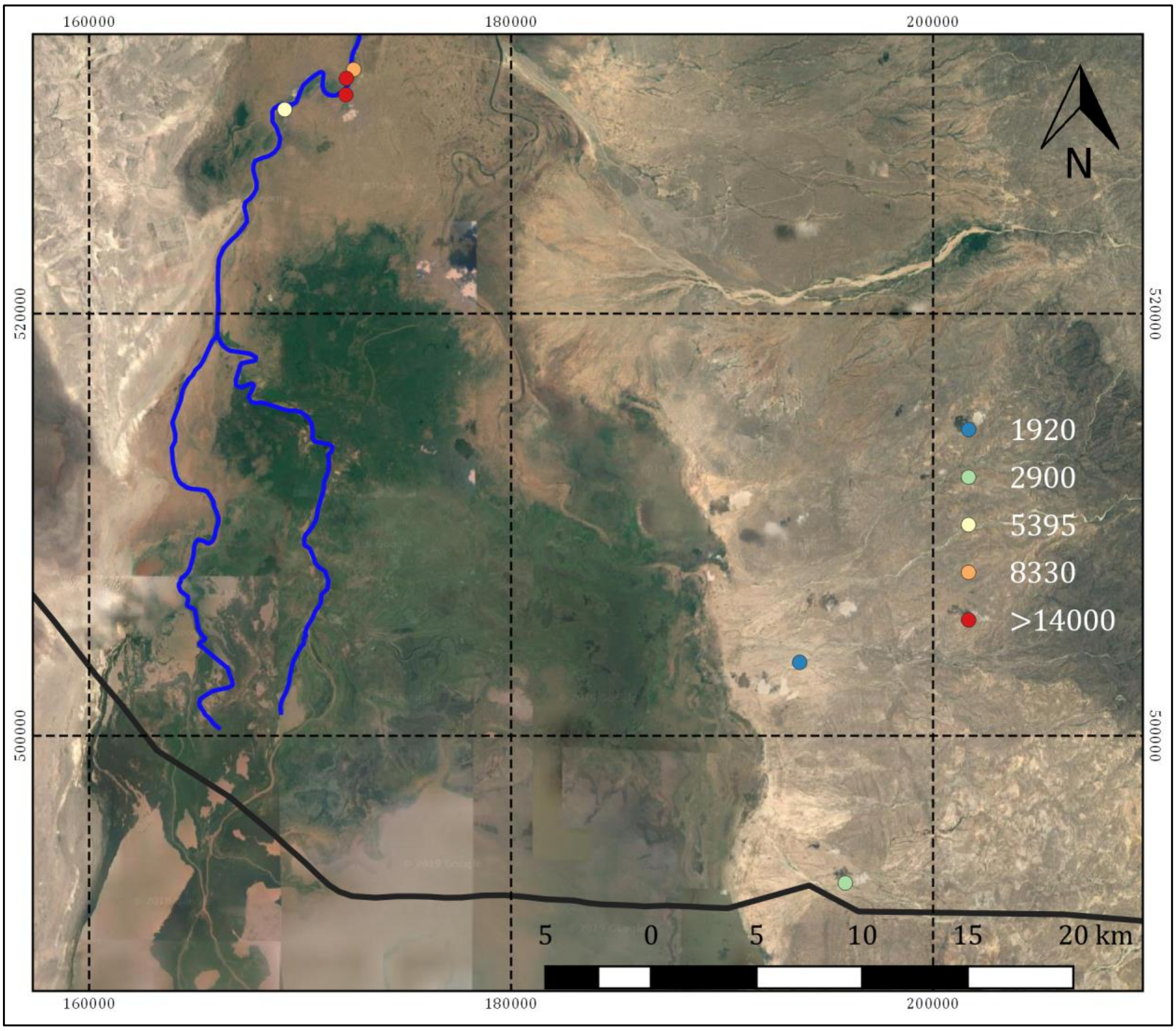

Figure 24. Groundwater radon measurements mapped out.

4. Discussion

In the following paragraphs, it will be discussed what the results presented in the previous section mean for the different aspects of the hydrogeology of South Omo (and, in specific, for the research questions stated in 1.3). Furthermore, possible inaccuracies, uncertainties and new questions encountered during the research will be mentioned.

4.1. Climate and recharge

The annual precipitation in the study area was shown to have great spatial variability. In the mapped area, which has an area of roughly 17,000 km^2, the mean annual precipitation varies between less than 300 and more than 1200 mm. Compare this to, for example, the Netherlands, which has an area 2,5 times as large, but hardly any spatial precipitation variation at all. When the mean precipitation map (Figure 10) is compared to the digital elevation model of the area (Figure 4), it becomes clear that the variation is mainly caused by the topography. Higher elevations receive significantly more rainfall than lower elevations.

Apart from this spatial variability, significant interannual variability in the precipitation was shown to exist as well. In the mean monthly precipitation graph (Figure 11), two rainy seasons are visible: March – May and October – November. The difference in mean precipitation between the driest month (January) and the wettest month (April) is a factor 5.

The average annual precipitation in the study area amounts to roughly 700 mm. This might seem like a decent amount of precipitation, but its variability (both spatial and temporal) make the value hard to interpret.

In order to gain insight in the recharge, the net precipitation was looked at as well. Negative values coinciding with Lake Turkana and Omo River is unsurprising, as the abundance of water there allows for a high amount of evaporation. Negative values were also found along parts of the edges of the highland, especially on the east side around Erbore. Precipitation probably flows down from the highland through wadis, creating an abundance of water in these areas.

The map which shows the average recharge over combined basins (Figure 14) clearly shows that locations in the lower valley which get runoff from large parts of the high-rainfall highland, are receiving significantly more recharge than locations in other basins. This could be of some importance for this study. On the other hand, it has to be noted that the aforementioned method of calculating recharge is obviously very simplified. It should be regarded as a general indication, and not as a precise result.

4.2. Geology and aquifers

In short, the geology of the study area was described as follows: in the east and west grabens filled with successions of sediment – of various origins and of a thickness of up to several kilometres – are located. In between these two grabens is the Hammer Koke highland, which consists of metamorphic basement rock, predominantly gneisses.

The sedimentary deposits are obviously more much more suitable for the occurrence of groundwater compared to the metamorphic rock of the highland. In addition, the regolith layer on top of the hard rock is at most 3 metres thick, which is insufficient for significant groundwater storage. Still, the borehole database indicated the presence of a great number of water points in the highland. This was quickly explained after the first field visit, however.

The only locations where wells can be found in the highland are the numerous wadis. These localized sediment deposits form the only way groundwater is stored in the highlands. Also, being wadi beds, they are expected to receive a decent amount of recharge from flash floods generated at higher elevations which receive a high amount of precipitation *(S. Kebede, 2013)*. Some of these wells were said to run dry during the drier seasons during which this recharge is limited to non-existent. This is unsurprising; the sediment deposits in the wadi beds are not likely to be anywhere near the thickness of the deposits in the lower lying valleys. Vertical electrical soundings were not performed in areas like this however, so the exact thickness of the sediment is unknown. On the other hand though, several wells that were visited in the highlands were said to never become dry. These were generally deeper.

Apart from the highland, wells can be encountered in various parts of the sediment-filled lowlands. A high concentration of wells is found in the form of river bank infiltration wells near Omo River. This is an excellent way to purify and make use of the enormous source of fresh water that the Omo River represents. Of course, the extent of the study area that can make use of this extraction method is limited.

Other wells are located throughout most parts of the Omo River valley, which is to be expected. The valley is quite evenly filled with sedimentary deposits, which are highly suitable for groundwater storage. In addition, the annual recharge from the highlands seems to be sufficient. Still, the study of the geology showed that the deposits across the valley are not homogeneous and can vary significantly. Therefore, some parts of the valley may be more suitable for groundwater extraction than others.

All available water point coordinates presented in Figure 20 indicate a preference for the southern half of the Omo river valley. It is questionable if conclusions should be drawn from this, however. Well locations are not solely dependent on the suitability of the local conditions, but also largely on the presence of villages. It was also found that not all water points are included in the database, as many unknown wells were found during the fieldworks. Finally, the north of the valley is less accessible than the south.

The VES results are limited. On the small area they cover, the variation seems to align with the boundary of the two geological units. This is demonstrated with the VES result of AB/2=750 m in Figure 19. The two geological units that are seen in this figure are 'fluviatile sand, silt' (west) and 'undifferentiated alluvial, fluviatile, and lacustrine sediments' (east). These geological units are very similar, so it is probable that the pattern is caused by the underlying hard rock.

Two of these soundings are interpreted in more detail, namely VES-7-BH (the most western one) and VES-20 (the most eastern one). The apparent resistivity is plotted in Figures 28 and 29, respectively. While the interpretation of these results is subjective, it was compared to the results presented in the report of a USAID project found at the water office in Omorate. These results regard vertical electrical soundings performed somewhat further to the south, but in the same lithological formations. An example of the USAID VES results is shown in Figure 27.

Based on these interpretations, Tables 4 and 5 were created. These tables indicate that variations can be significant even over short distances. Therefore, these results can't be used to draw conclusions for the entire Omo valley, while at the same time showing the importance of VES measurements. The results do however indicate that the saline groundwater is usually situated below the fresher groundwater. The specific depth at which fresh or saline groundwater occurs should be researched at the location of interest.

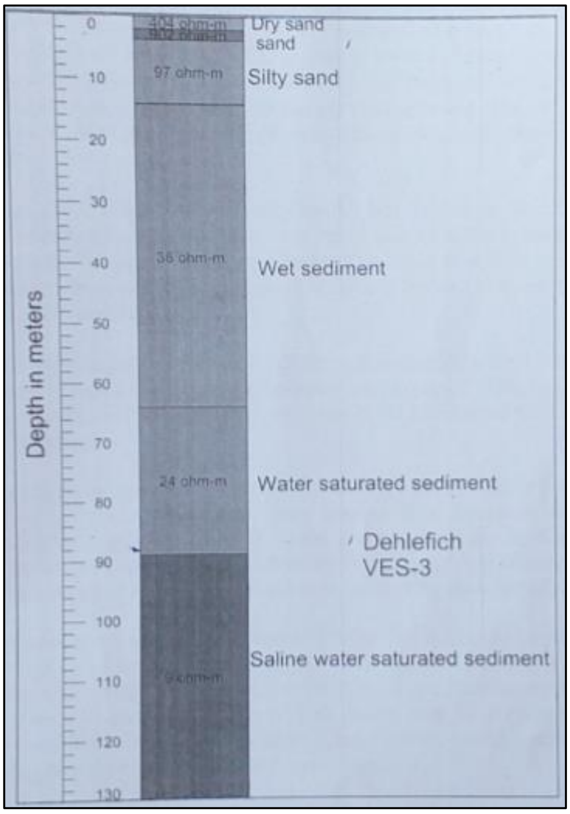

Figure 25. Example of VES interpretation used. Taken from the report of a USAID project.

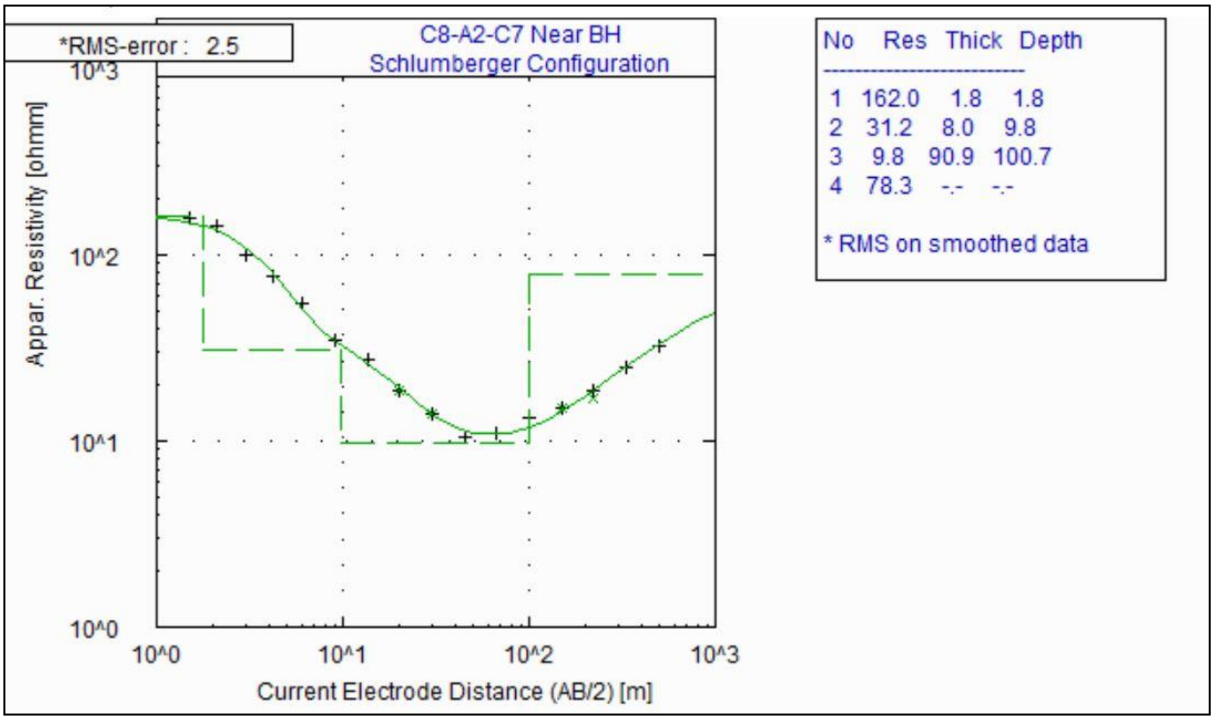

Figure 28. VES result VES-7-BH.

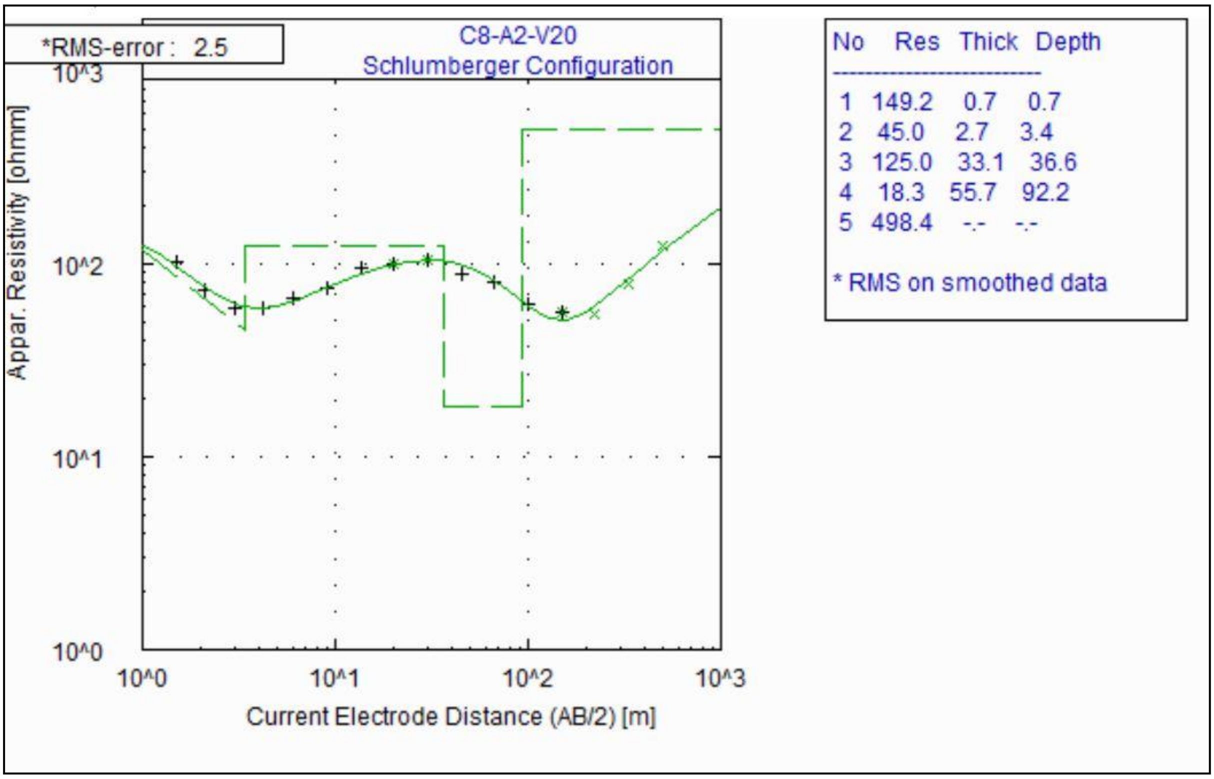

Figure 26. VES result VES-20.

VES-7-BH		
Depth	**Resistivity**	**Interpretation**
0-1.8	162	Silty sand/wet sediment
1.8-9.8	31.2	Water saturated sediment
9.8-100.7	9.8	Saline water saturated sediment
>100.7	78.3	Coarse sediment/highly weathered hardrock

Table 4. Interpretation of resistivity as measured at location of VES-7-BH.

VES-20		
Depth	**Resistivity**	**Interpretation**
0-0.7	149.2	Silty sand/wet sediment
0.7-3.4	45	Water saturated sediment
3.4-36.6	125	Silty sand
36.6-92.2	18.3	Saline/brackish water saturated sediment
>92.2	498.4	Hard rock

Table 5. Interpretation of resistivity as measured at location of VES-20.

4.3. Salinity pattern

The abundance of saline (or brackish) groundwater in the South Omo zone seems unexpected at first, as there is no sea or ocean in the vicinity which can cause saline water intrusion. The watersheds and flow accumulation map presented in 4.1 indicate that water flows from the highlands through wadis in the direction of the lowest elevation of the valley (i.e. Omo River). The distance between the highland and Omo River is quite long however (around 50 – 60 km on average). Given the high mean temperatures in the Omo valley, a considerable amount of evaporation can take place along the way. It is therefore likely that most water from the highlands either infiltrates or evaporates before it can reach Omo River. The high amount of evaporation results in a higher salinity (and thus higher EC value) in the remaining water that can infiltrate. Evaporation is also the reason that the water from Lake Turkana is considerably more saline than its source, the Omo River.

As stated in the previous section, the more saline groundwater appears to exist at greater depths (generally). This is coherent with the observations made during the water quality inventory (3.3) as well, where the deeper wells mostly yield higher EC values compared to shallower wells in their vicinity. Deeper groundwater is usually the older water, thus having been subject to more evaporation. A higher salt content in deeper groundwater is therefore not unexpected. Besides, saline water also has a higher density.

Apart from the variation in EC values with depth, it would also be useful to recognize a spatial pattern. An attempt to relate the EC to the geology was unsuccessful. A direct link to the annual precipitation pattern could not be distinguished either.

Assuming that the salinity of the groundwater is indeed caused by the major evaporation, one would expect the salinity to increase further away from the highland. After all, as the distance from the highland increases, so does the amount of evaporation that the water is subject to before infiltration. This only seems to be partly true.

Indeed, the water from wells located in wadis in the highlands (around both Dimeka and Turmi) generally has a good quality compared to the other visited wells. Exceptions are only found at greater depths (>50 m). While most wells are hand dug and do not exceed a depth of ~30 – 40 m, wells 21 and 22 in Table 1 have a depth of 82 and 54 m respectively. These are very saline compared to the surrounding, shallower wells.

Further down into the valley, the overall salinity increases (as expected). It doesn't increase evenly with distance from the highland, however, which can be seen in Figure 22 in the Results chapter (3.3). Thus, it was attempted to find an additional explanation.

Using the estimation of the average annual recharge per combined drainage basin produced in 4.1, a relation can be found. Water points located in drainage basins with a higher mean annual recharge yield lower electric conductivities, which is shown in Figure 30. It indeed sounds logical that a higher amount of yearly (fresh) water recharge leads to less salinization of the groundwater. On the other hand, it would give a false impression of certainty to specifically state that this relation exists, given the relatively small data collection and the extremely simplified way in which the recharge was determined. Still, the relation seems to fit remarkably well.

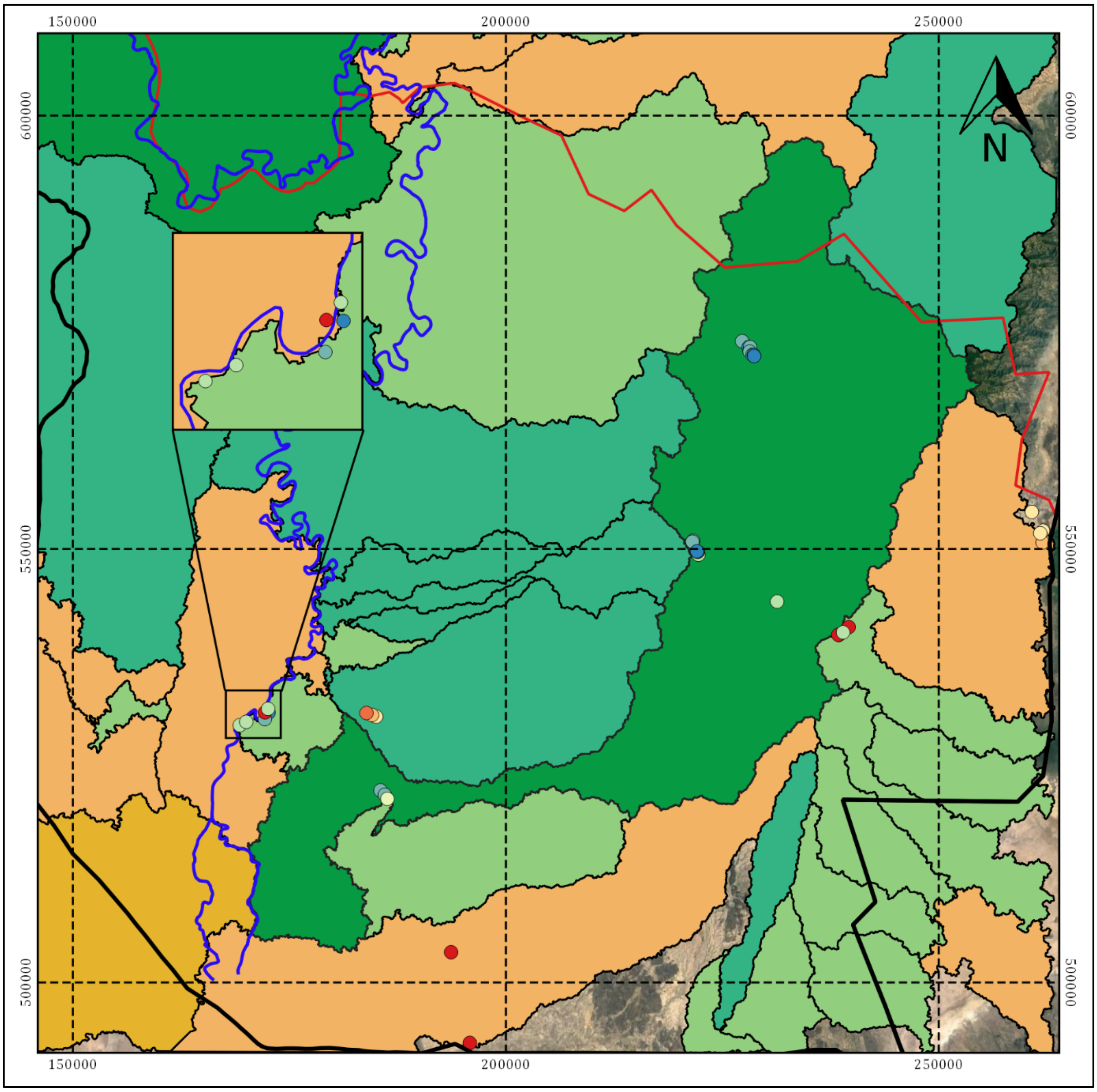

Figure 27. Measured EC values overlain on annual average recharge per basin.

4.4. Surface and groundwater interaction

It is known that surface water and groundwater aren't separate media and often interact with each other. In the study area, this is likely most prominent along the Omo River, as it is the only perennial river in the zone. As described in the results (3.4), a trajectory of around 30 km was investigated with 14 radon concentration measurements. This has shown to be a reliable method to trace groundwater inflow or surface water outflow of a river *(L. Ortega et al., 2015)*.

The sequence is shown in Figures 24 and 25 in the Results chapter (3.4). These results clearly show that there is a significant amount of interaction between surface water of Omo River and the groundwater.

The quick rise in ^{222}Rn concentration around the Omorate area suggests an influx of groundwater into the river. On the other hand, the radon decrease that quickly occurs thereafter, does not necessarily indicate an outflow of river water into the groundwater. After all, the ^{222}Rn concentration is expected to decrease over time in surface water through degassing, as was described in the Methodology (2.5).

After this rapid increase and decrease, the concentration remains relatively constant. While it is hard to say with certainty, it is expected that there is some inflow of groundwater into the river along this trajectory. Without any groundwater inflow, the concentration would normally decrease over this distance. The radon increase that occurs at the end of the sequence indicates a higher amount groundwater inflow at this location.

Wells close to Omo River in the Omorate area showed various ^{222}Rn concentrations, and a clear relation could not be found. This might have to do with the varying well depth. Additionally, the river concentration sequence showed that there is inflow of groundwater into the river in this area, and not the other way around. It is thus unsurprising that the radon concentrations in these wells are comparably high. It is also coherent with the fact that water from these wells is quite saline, even being this close to the river.

Two wells in the vicinity of Lake Turkana yielded significantly lower concentrations compared to those around Omorate. Combined with the low ^{222}Rn encountered in the Lake Turkana sample, this might indicate inflow of surface water from the lake into the surrounding groundwater. With a large body of stagnant water like Lake Turkana, this doesn't sound illogical.

So, it is clear that significant interaction between surface water and groundwater occurs along the Omo River (at least along the investigated trajectory) and around Lake Turkana. Along the river, groundwater predominantly flows in, while Lake Turkana water seems to enter the groundwater. Unfortunately, it is hard to quantify this interaction without knowledge of the background radon content of the river and its discharge at the time of measurement. Also, the amount of measurements is relatively limited, as the RAD7 is time-consuming to use in the field.

5. Conclusion

From this analysis on the hydrogeological system of the South Omo zone, several conclusions can be drawn regarding groundwater sources. The findings that are of interest regarding possible new well locations will be summed up in this paragraph.

- In the Hammer Koke highland, groundwater sources are limited. Apart from small alluvial deposits in the northern part of the highland, wadi beds are the only sensible option for groundwater extraction. Salinity appeared to increase with depth, a possible result of the deeper water having been subject to more evaporation as well as being denser. Therefore, shallow wells are a safer option. On the other hand, shallow wells were found to have a higher probability of running dry during the dry season. Therefore, the catchment size of the wadi should be investigated in order to get an approximation of its recharge.

- In the lowlands, which are filled with sediments, possible well locations are more numerous. Groundwater can be found in many places and wells rarely run dry, but salinity is often a problem here as well. Even on small scale, the variance can be great. Some general guidelines for a higher probability of fresh groundwater can be given, however. Groundwater with low EC values is often encountered closer to the highland. Further down into the valley the salinity increases, likely as a result of runoff never reaching the river and evaporating. A linear relation between distance and EC does not exist, however. The recharge did seem like it could play a role. Wells at locations receiving runoff from catchments with a higher annual recharge generally yielded lower EC values. Additionally, VES results showed that saline groundwater is usually encountered beneath fresh groundwater. The depth at which fresh and saline groundwater occur varies greatly across the entire area, though. More geophysical research at sites of interest is therefore necessary.

- The Omo River is an enormous source of fresh water, but its water is not readily drinkable. River bank filtration wells along the Omo River therefore seem an excellent option for reliable and sustainable groundwater extraction. Unsurprisingly, many wells are found along the river, but many of these still have a high salt content. Using Radon-222 as a tracer, it was shown that there is a significant amount of inflow of groundwater into Omo River. Especially around Omorate, where a high density of wells is located, radon concentrations increased greatly. This might explain why so many wells close to the river are saline; they probably receive no inflow of fresh water from the river.

  The reverse process, river water infiltrating the groundwater, is harder to trace. After all, radon concentrations are always expected to drop along a certain trajectory because of degassing. Measurements in wells along the river didn't yield any significant results either. Close to Lake Turkana however, there are indications for an influx of surface water into groundwater. Wells in the vicinity of the lake show much lower radon concentrations compared to those around Omorate. Furthermore, the water from Lake

Turkana has a relatively low radon content, indicating that at least there is no inflow of groundwater.

These results show that the use of ^{222}Rn as a tracer might be very beneficial when deciding on suitable locations for wells along the river. Locations where high radon concentrations are encountered in surface water might not be as suitable, as the groundwater is probably not recharged by the fresh river water there. Of course, if abstractions are high the outflow may be reversed and back infiltration can occur. Initially though, the groundwater outflow into the river will be intercepted, which is generally saline at this distance from the highland.

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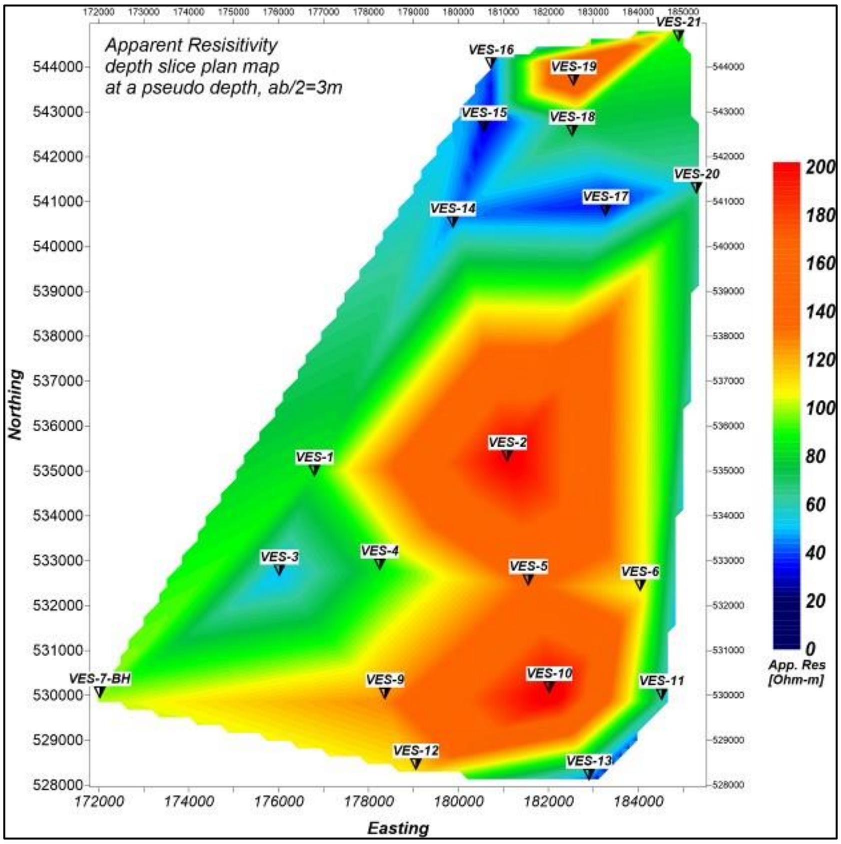
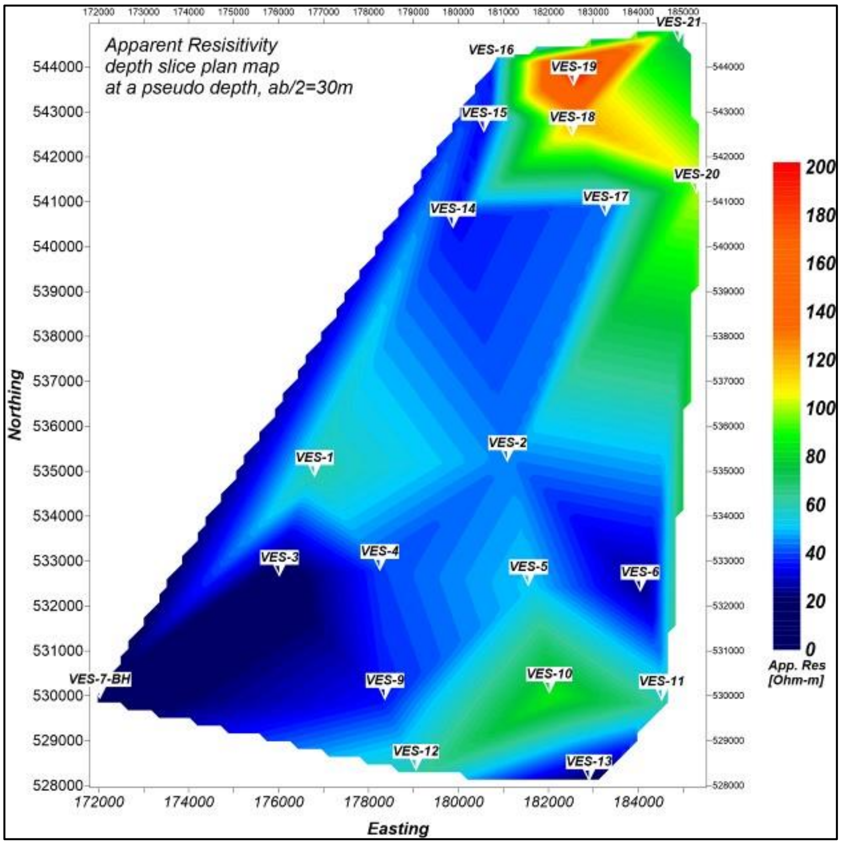
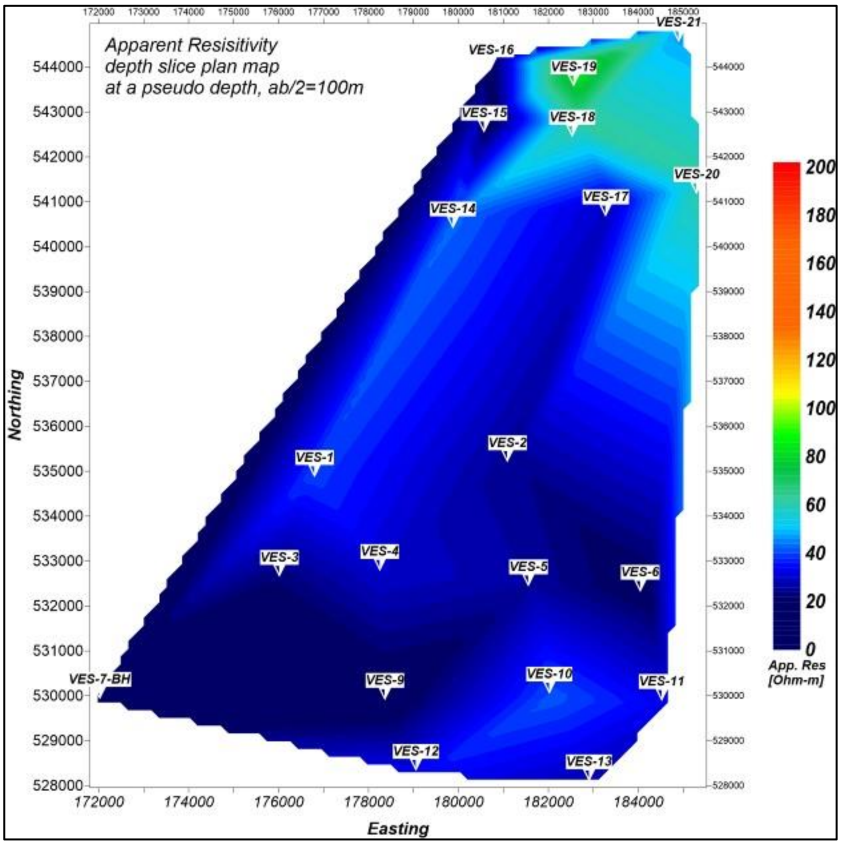
Annex 1: VES results






Apparent Resisitivity
depth slice plan map
at a pseudo depth, ab/2=100m
Northing
Easting
App. Res
[Ohm-m]
VES-1
VES-2
VES-3
VES-4
VES-5
VES-6
VES-7-BH
VES-9
VES-10
VES-11
VES-12
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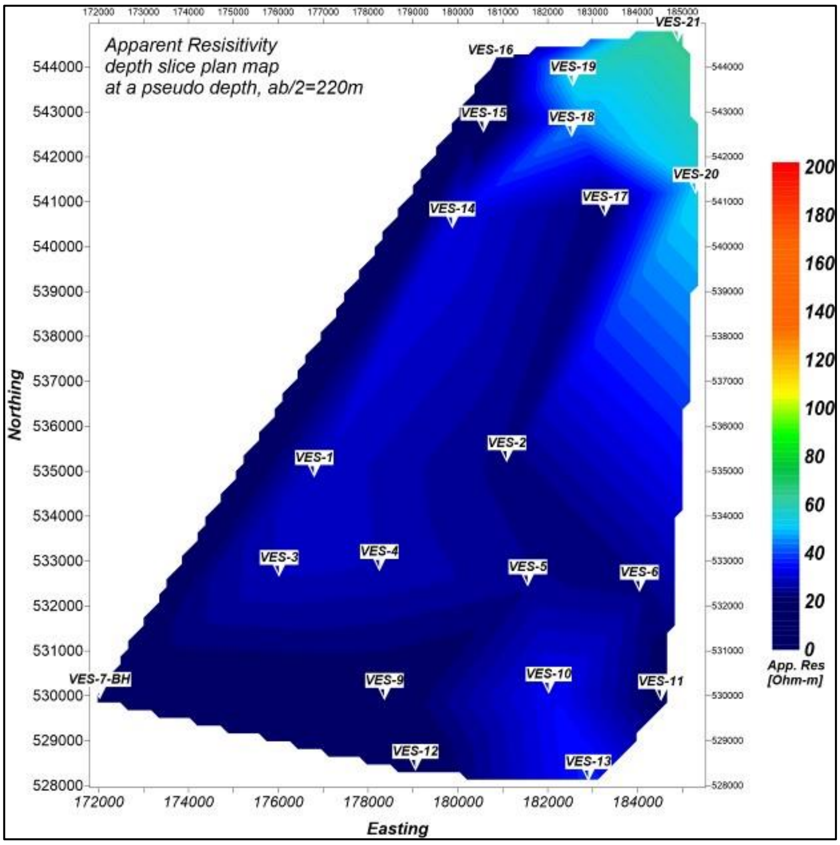
VES-19
VES-20
VES-21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depth slice plan map
at a pseudo depth, ab/2=220m
Northing
Easting
App. Res
[Ohm-m]
VES-1
VES-2
VES-3
VES-4
VES-5
VES-6
VES-7-BH
VES-9
VES-10
VES-11
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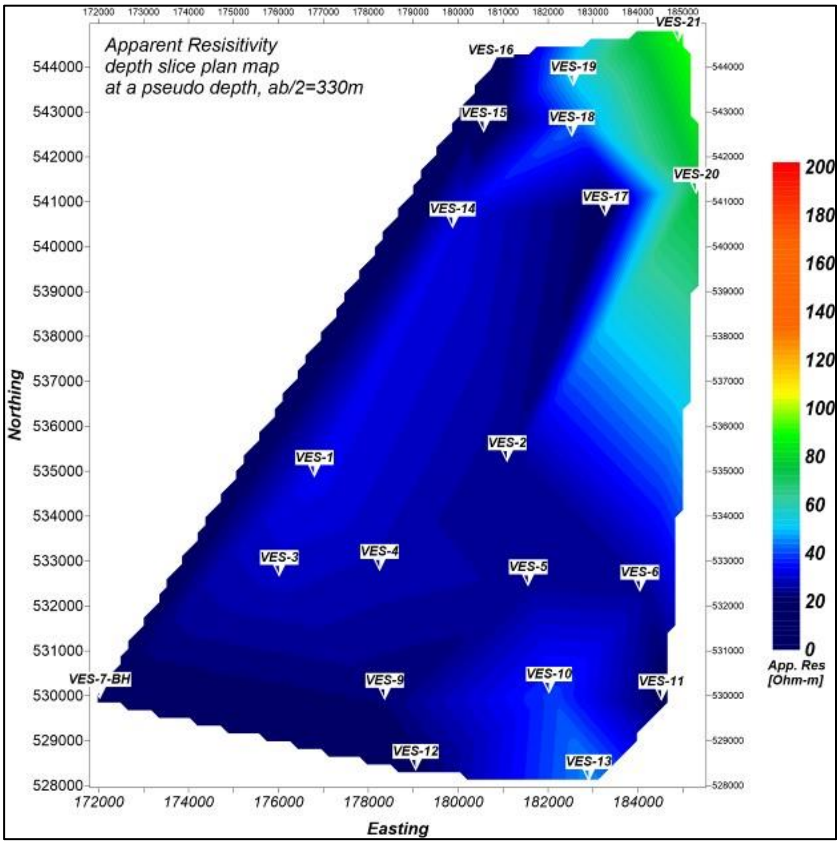
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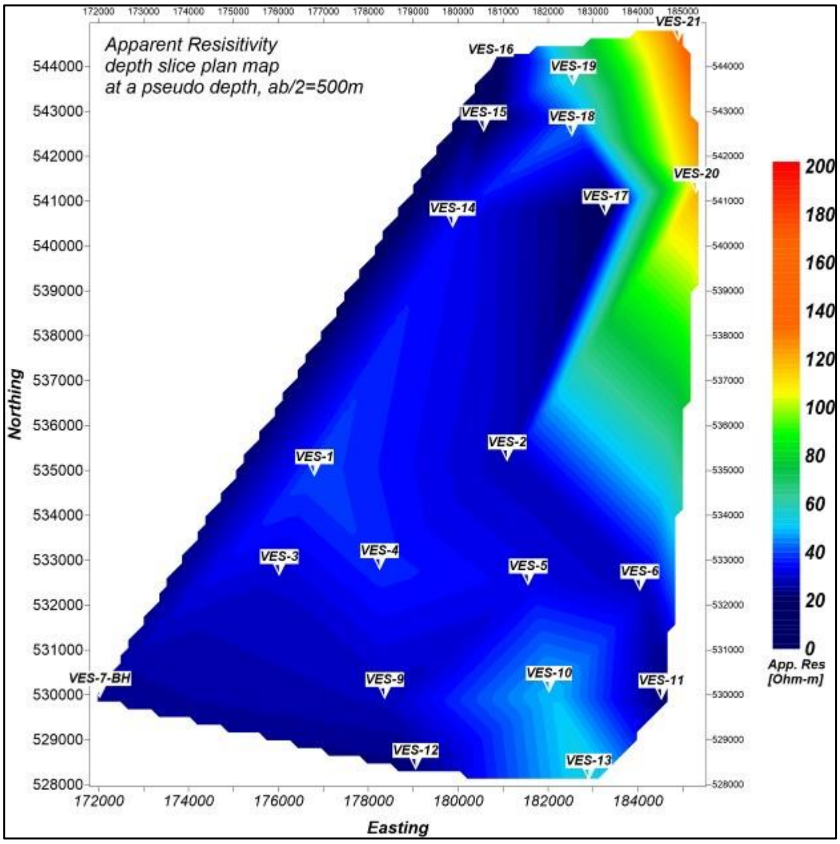
depth slice plan map
at a pseudo depth, ab/2=330m
Northing
Easting
App. Res
[Ohm-m]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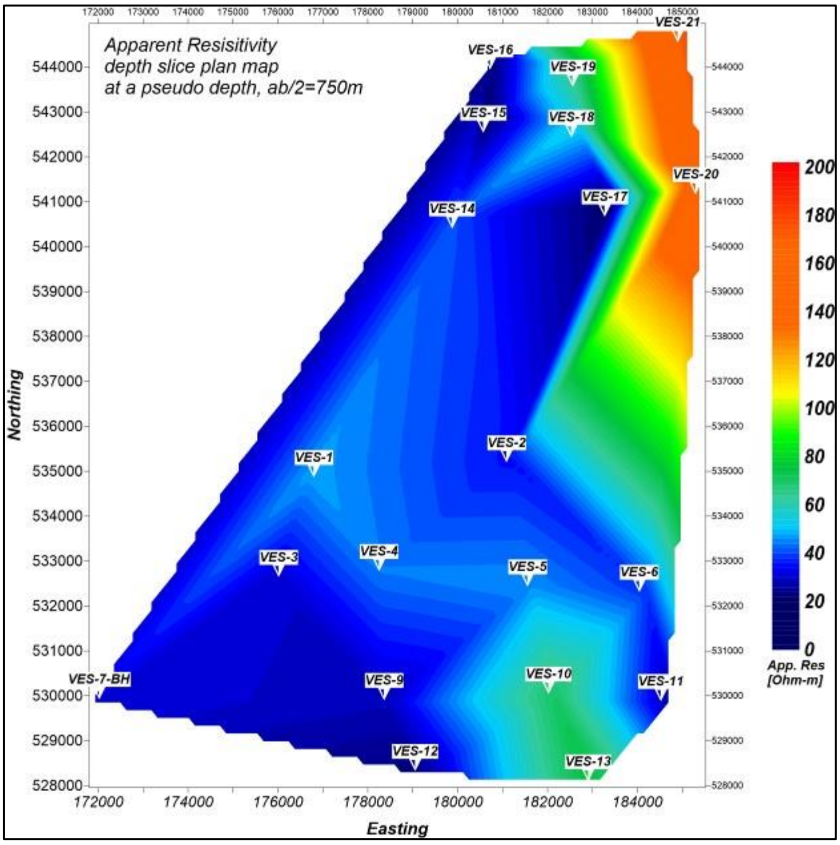
Northing
Easting
App. Res
[Ohm-m]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VES-16
VES-19
VES-21
VES-15
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VES-14
VES-17
VES-1
VES-2
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VES-4
VES-5
VES-6
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VES-13
Northing
Easting
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