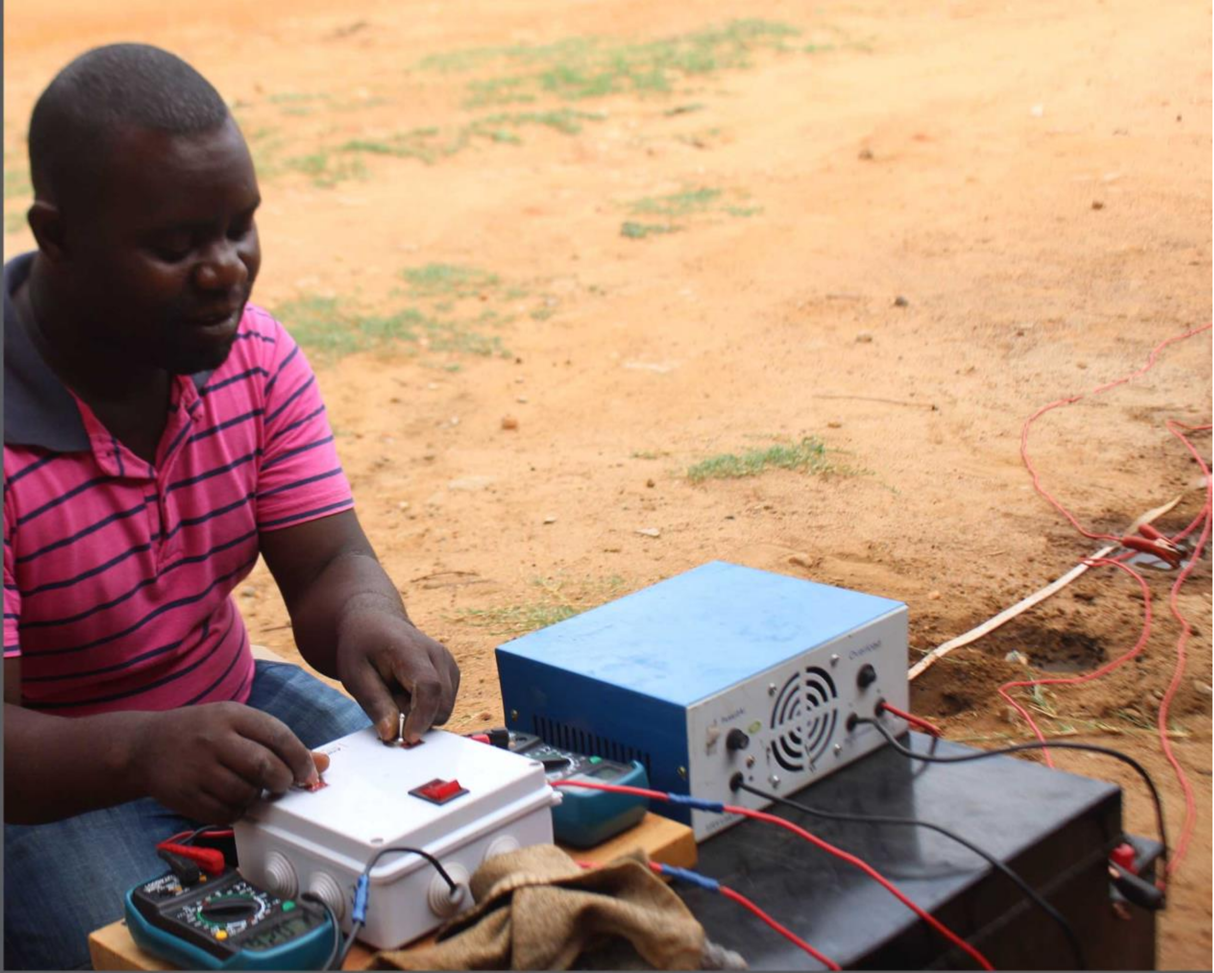
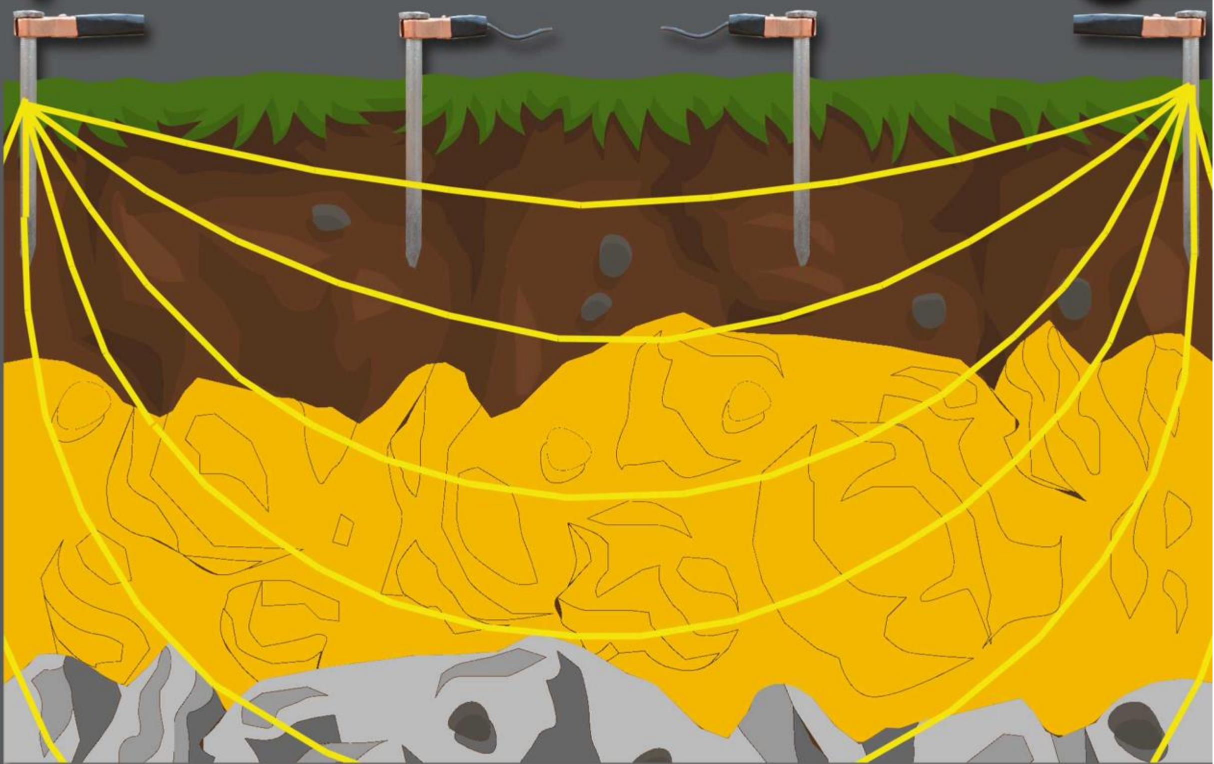
SMART Centres



Borehole siting



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The **SMART** Centre Group

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This manual uses the following symbols:

= the process to follow in 6 steps

= the use of “the Drilling Toolbox” Android app.

1 Copyright and disclaimer

It is highly recommended to use this manual in combination with practical hands-on training that can be provided by a SMART Centre. Please feel free to contact us via www.smartcentregroup.com

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2 Introduction

The construction of a borehole is a complicated process. Before drilling starts, a good drilling site has to be selected where there will be an adequate quantity and a good quality of ground water.

During any type of drilling process there are a lot of different aspects which require attention to make sure nothing goes wrong. Besides the practical drilling skills which are executed at ground level, attention has to be paid to important processes which are happening below ground level during drilling. Water used in drilling could flow away or worse; the borehole could collapse resulting in buried drilling equipment.

In many countries drilling teams experience problems with site selection, loss of working water, soil determination, well installation, well development, water quality and flow rate of the well. These problems may occur when the correct site-, well- and pump selection are not completely understood and important steps are missed.

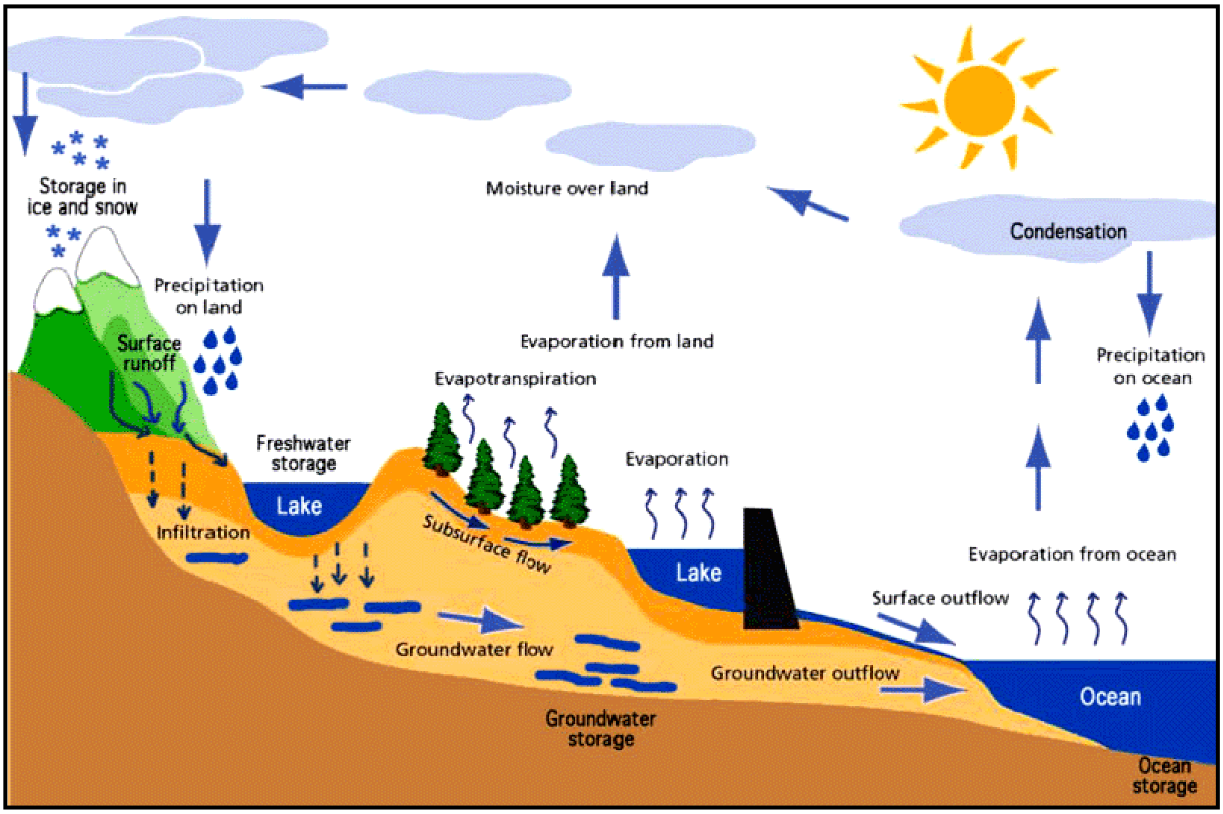
This manual will help you to understand the drilling process at ground level and also far below ground level and can therefore be used as a preparation before the actual drilling or digging.
This manual describes important issues to consider before you can start drilling or digging for water:

- What is the best place for having a borehole or well?
- What is the best method to obtain water: drilling or digging?

3 Hydrology

Before discussing "Site selection" and "How does Vertical Electrical Sounding (VES) and Horizontal Electrical Profiling (HEP) works", we first must understand a bit about Hydrology and Geology.

Hydrology describes the complete cycle of water: water rises from the sea and the earth's surface because of evaporation. After evaporation, the water forms clouds that fall somewhere else to the earth as rain. Part of the water soaks into the ground and becomes part of the groundwater while another part flows through streams and rivers back into the sea. From here the whole cycle can start all over again.

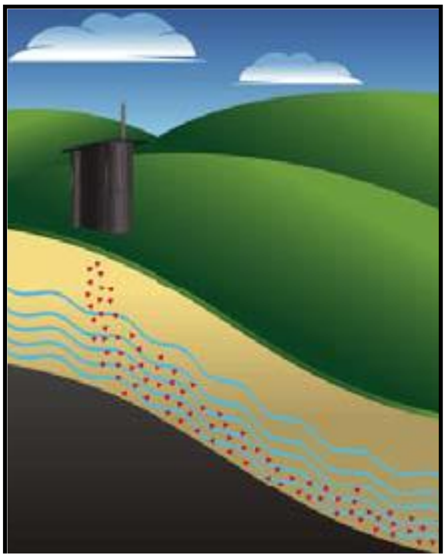


The water cycle

For drillers it is important to know the location and flow direction of groundwater and factors affecting the quality of groundwater.

3.1 Groundwater flow

Just as surface water moves in a river, also groundwater flows (although much slower) through the pores and cracks of the soil structure. It is difficult to determine the flow direction of groundwater but it could have great influence on the water quality of the well. Therefore it is necessary to know in which direction the groundwater is flowing and where the groundwater came from.



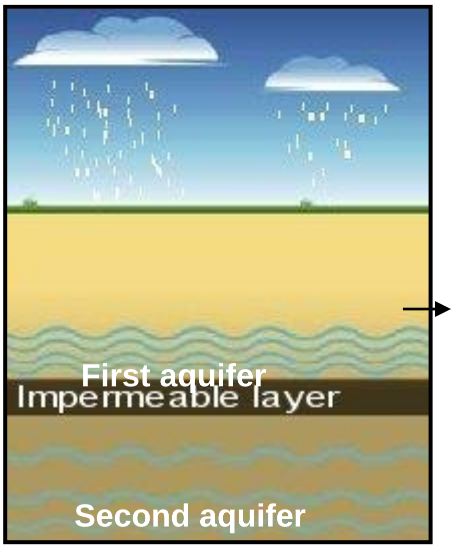
Pollution of groundwater by a latrine

Imagine a latrine close to a well which is used for drinking water. You don't want bacteria, viruses and parasites, originating from the latrine to flow together with the groundwater to your well.

When a latrine is located on the slope of a hill or a mountain, the groundwater is likely to flow in the same direction as the slope of the hill. In this case it would not be good to place the well 'downstream' of the latrine, but rather on the same level or above the latrine. When the area is less hilly, a good indicator can be the presence of a gully, stream or river. Rivers always flow through the lowest-lying parts of the area and groundwater in turn generally flows underground towards rivers. Be careful: this only counts for a natural river, not for manmade channels.

3.2 Aquifers

The word "aquifer" simply means "a water bearing layer" that can store water and allow water to flow through it. A good aquifer to extract water is a permeable layer below the groundwater table. A permeable layer is a layer that has an open soil structure allowing water to flow through it (for example sand). Impermeable layers don't allow water to pass through (for example clay). During drilling you may penetrate different aquifers at different depths, separated by impermeable layers (clay or loam).

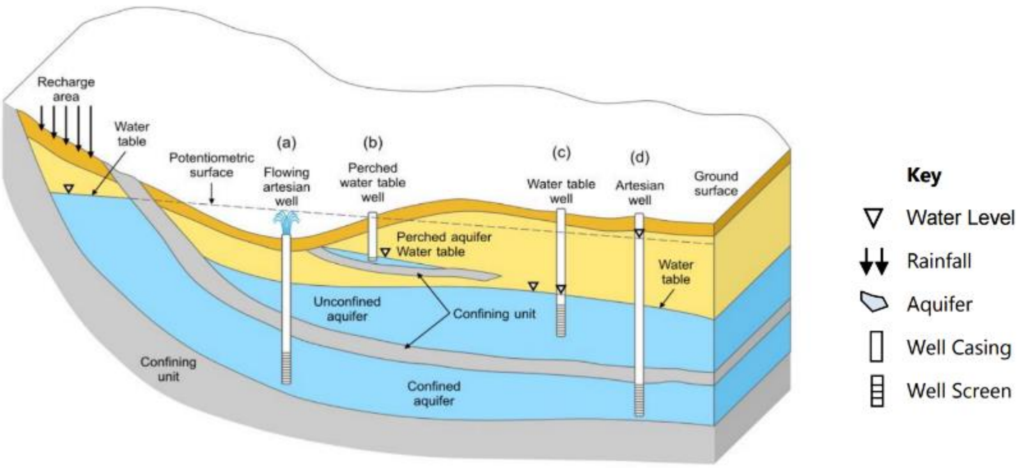


3.2.1 First aquifer

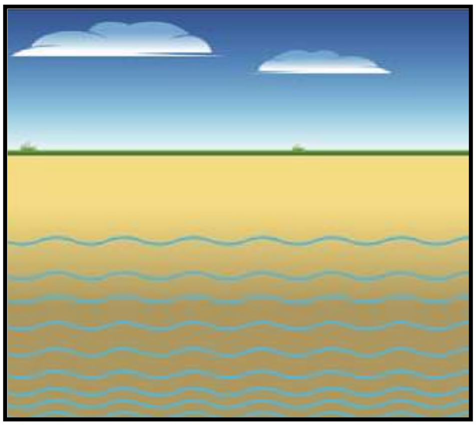
The upper aquifer is called the 'first' aquifer or unconfined aquifer. Rainwater directly infiltrates the soil. The rain water moves down and when it reaches the water level it is added to this aquifer. Rainwater can wash bacteria and pesticides down into the groundwater. Therefore a first aquifer can be polluted by activities taking place on surface.

Groundwater exists in a permeable layer above an impermeable layer. If this first layer is just a few meters thick, it may dry up at the end of the dry season.

3.2.2 Second aquifer



The next aquifer, covered by an impermeable layer on top (a clay or loam layer) is called the 'second' aquifer. (This is often a "confined aquifer"). This means that its water comes from areas with higher water levels, for instance mountains. After drilling into this aquifer, the water level will rise, sometimes even above the ground level because water pressure from the mountain pushed water up once you break the impermeable layer. We call this an "artesian well" or "flowing well". The impermeable layer above the second water bearing layer forms a barrier for bacteria and pollution preventing them from travelling down to the second aquifer. If there is a second aquifer present, it is generally best to extract water from this second aquifer and prevent water from the first aquifer to mix with the second by correct casing design and hygienic seal. Below the second aquifer there may be another impermeable layer and a third aquifer may be present.



3.2.3 One aquifer

Sometimes only one aquifer is present. In this case it is recommended to drill as deep as possible to prevent bacteria and pollution from entering the well. Every meter down, there are fewer pathogens will be present. It takes time for the pathogens to travel down and while they do they die off over time. Drilling deep also reduces the chance that wells will dry up because of seasonal fluctuations of the water table.

3.3 The quality of the water

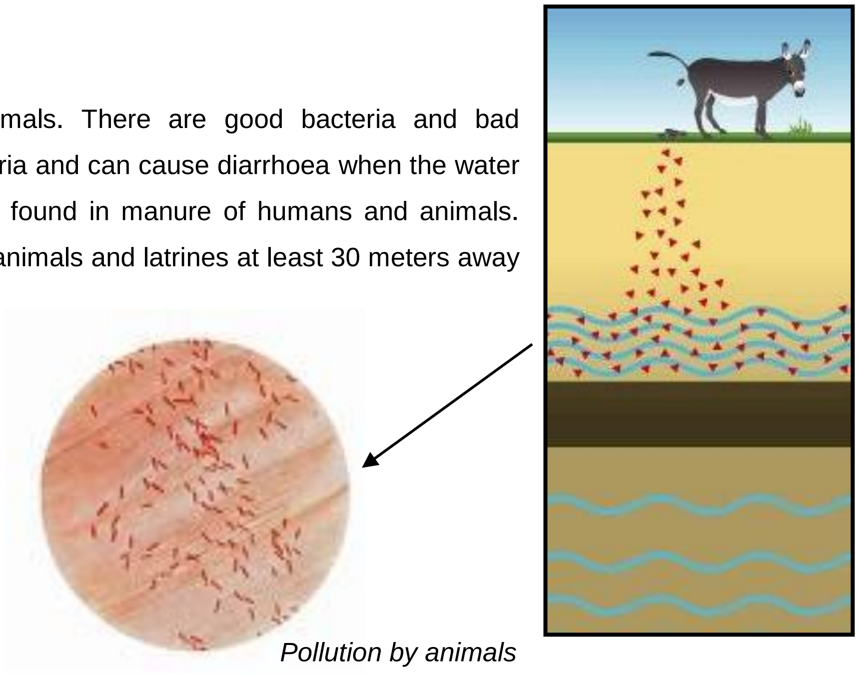
Each water source has a specific water quality. Sea water is salty, river water can be very turbid, etc. To determine if it is safe to drink the water, you have to determine the quality of the water. In this paragraph we will describe the three factors affecting water quality:

- Biological contamination (e.g. bacteria like E-coli, Cholera, viruses);
- Physical contamination (e.g. particles, turbidity, suspended solids);
- Chemical contamination (e.g. iron, calcium, salt, gasses, metals, pesticides).

Some examples:

3.3.1 E-coli

Bacteria are very small animals. There are good bacteria and bad bacteria. E-coli is a bad bacteria and can cause diarrhoea when the water is used for drinking. E-coli is found in manure of humans and animals. Therefore always try to keep animals and latrines at least 30 meters away from the borehole or well.



Pollution by animals

3.3.2 Plants

When, during drilling, remains of old plants are found, it is recommended not to install a well-screen in this layer. Plant remains, below the water table, decompose very slowly and create an acidic environment. A common example is peat. Groundwater extracted from a peat layer smells like decomposed plant material, is very acidic and looks brown.

3.3.3 Turbidity

Turbidity is a technical word for the cloudiness of water, caused by very small particles in the water (called suspended particles) like clay and silt-sized particles. If well water is extracted from a clay or silt layer, some of the fine particles in the formation may be transported by the flow and get mixed in the water. As a result the water will look turbid.

3.3.4 Calcium

If water from the well has a high content of the element calcium and magnesium (for example when drilling in limestone and chalk) and magnesium it is called ‘hard water’. Hard water is generally safe for drinking. However, it may cause some problems while washing your clothes. Soap gives foam easily in soft water but not in hard water. In other words, if the hardness of the water is high it may be difficult to use soap.

3.3.5 Gasses

Oxygen is a gas such as methane. Most of the bacteria need oxygen to survive. A second aquifer will almost contain no oxygen because it is separated from the first aquifer by an impermeable layer. If you have drilled through this impermeable layer, always close the layer again by installing a sanitary seal between the casing pipe and soil (see chapter 3.4 of this manual). Therefore boreholes are more hygienic than open wells.

Methane is a gas that is extracted from natural plants that exist in the ground layers. If you are digging an open well, always use the a ventilator to remove harmful gasses. Most of the gas will leave the water if the water is aerated (mixed with air).

3.3.6 Iron

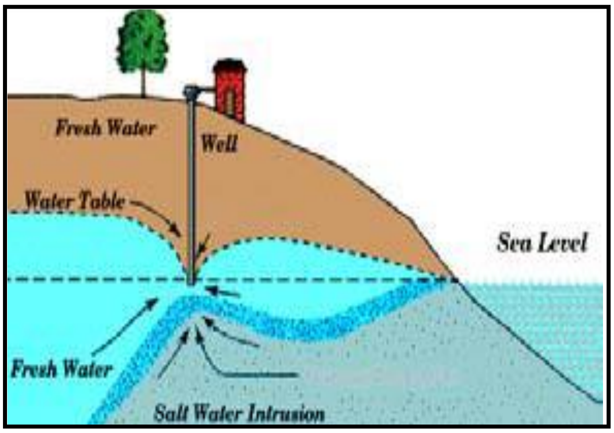
Sometimes water has a bad metallic taste and the colour of the water turns brown when it is left in a bucket or boiled. The water may create rusty looking spots on clothes and cooking material. This indicates the presence of high iron concentrations. Iron is a very common element of groundwater.

3.3.7 pH

The pH is a measure of the acidity of water. Water with a pH lower than 6.5 is considered an acid water. In areas of acidic groundwater this may cause corrosion to the steel and cast iron components of a hand pump and casing. In such cases, a pump and casing made of plastic (e.g. PVC or stainless steel) components should be considered.

3.3.8 Salt

Water can taste bad or be damaging to health due to natural salts in the aquifer. These salts have been present since the formation of the different geological layers and are now dissolved in the groundwater. Some well-known examples of natural chemicals in groundwater are calcium, chloride, arsenic, fluoride and iron. Salt concentrations that rise above a certain level may damage health and therefore a sample of the groundwater has to be analyzed in a laboratory to find out if these chemicals are present. Arsenic and fluoride are especially toxic above a certain level. Luckily in most places concentrations of these elements are so low that the water is safe for drinking.



In coastal areas, a deep aquifer could contain salty sea water. Salt water is heavier than fresh water. This means fresh water tends to float on top of the salt water layer. When a well is drilled in a coastal area where saltwater intrusion exists, the salty water may rise, due to the suction of the well. Therefore in coastal areas, drilling deeper is not always the best option.

3.4 Water treatment, rainwater storage

In cases where water may be contaminated with bacteria it is recommended to treat the water before drinking by boiling, adding chlorine or by using a water filter.

Where there is physical or chemical contamination it is advised to catch rainwater and treat it before drinking as mentioned above. The volume of the tank depends on the frequency and length of rain periods but should always be enough to cover the maximum dry periods. A typical volume for a family of 5 persons for 8 months would be 3 cubic meters.

4 Geology

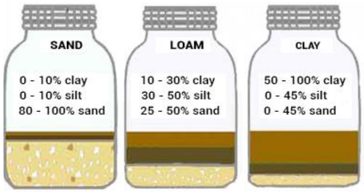
Now that you know about the basics of hydrology, we will continue with geology. Geology is the study of the earth. It describes the origins and formation of the soil under the surface of the earth.

4.1 Types of soil

There are many different types of soil, each with its own features:

Type of Soil	Particle size	Permeability
Clay	< 0.004 mm	Impermeable
Silt	0.004 – 0.06 mm	Impermeable
Sand	0.06 – 2 mm	Permeable
Gravel	2 – 6 mm	Permeable
Stones	> 6mm	Permeable

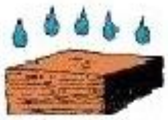
The most common soils and their sizes



For the construction of a good quality well it is essential to know the characteristics of different soils and their influence on the water yield, water quality and performance of the well.

(A mixture of) sand and gravel is a *permeable soil*. It is an excellent soil for the aquifer since the water can flow into the borehole or well easily. Water will flow easily through these layers.

A mixture of sand, silt and clay is *semi permeable*. Always drill boreholes in this type of soil as deep as possible and make a long filter-screen to ensure you will get enough water. Water will flow slowly through this soil layer.



Clay and loam soils (a mixture of clay and silt) are *impermeable*. These are not good soils for a borehole or well because no water will enter the well. Water will stay on top of this impermeable layer.

How do you determine the features of the soil?

Take a sample of the soil and squeeze it into a ball shape. Drop the ball from a height of 1 m.

- If the ball totally falls apart the material is ***permeable***.
- If the ball falls apart only partially or shows cracks. The formation will have a ***low permeability***.
- If the ball only deforms and does not show cracks, it is composed of clay and is ***not permeable***.

Bottle test

Another option to determine the soil features is collecting water - soil mixture in a transparent bottle. Shake it and leave it. After sometime the different materials in the water will settle. The heavy parts such as sand or gravel settles first, the light parts such as clay the last. From the thickness of the layers the % of grain sizes in the soil can be determined.

5 Site selection

Before drilling or digging of a new well, a site has to be found.

5.1 Procedure step 1: Customer preference

In most cases the customer who wants water will point out a few locations which are suitable for him or her as user.

But often this is not the best location! As a professional, you will have the responsibility to inform your clients about three important aspects:

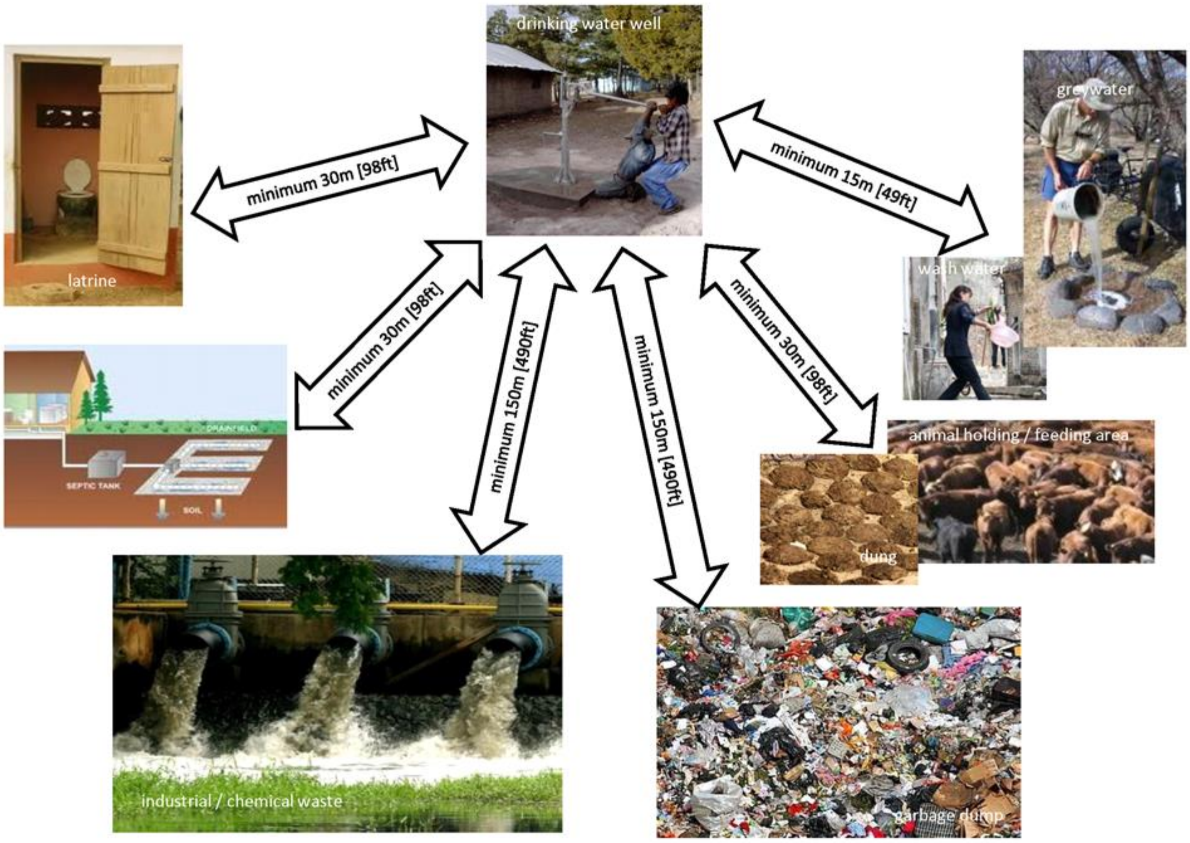
1. The best hygienic position of the well;
2. The availability of water;
3. The possibilities for (manual) drilling or digging due to soil structures.

Have a look around and ask questions before you start unpacking any dquipment!

5.2 The best hygienic position of the well

5.2.1 Distance to sources of pollution

Water pollution moves downwards through permeable layers and so can locally contaminate the groundwater. Although bacteria will not survive long outside the human body if they don't have oxygen, it will take a while before they die. Therefore groundwater close to latrines can contain bacteria. For a proper site selection, it is recommended to place the borehole or well up-stream or up-hill from a latrine. If you are not sure about the direction of groundwater flow, construct the well at least 30 meters away from the latrine. The picture below shows the required distance to different sources of pollution.



5.2.2 Hand pumps on sunny or shady places

While drillers may prefer to drill in the shade, it is not the best location for a well or hand pump. Many people will visit the well to fetch water, unaware that harmful pathogens are travelling on the soles of their feet. For example the bacteria can be picked from a latrine if someone has just been to the toilet. These contaminants will be washed off the feet in the well surrounding, which is often wet, and are therefore a threat to the quality of the drinking water. When a well is placed in the shade, bacteria and algae will flourish. If the well surroundings can dry up daily, the UV rays in the sunlight will disinfect the well surroundings by killing the pathogens.

5.3 Procedure step 2: Exclude pollution

Now that you have identified the possible sources of pollution, you must explain to your customer why some of the preferred points are not suitable. There might even be national laws about this subject so make sure you know them.

In this example 3 of the points that the customer preferred are within the contamination zone.

5.4 Procedure step 3: Collect visible and oral area info

The next few paragraphs explain how to collect useful information about the area which you can use to pre-select some good potential locations for the borehole or well.

5.5 The availability of water

Drilling will be much more successful if you are sure that there is water and when you know how deep the water is. For example: drilling a 40 meter borehole takes much more time and energy than drilling up to 10 meters. In practice it is difficult to know where and how deep the water is, although it is very helpful when planning. Chapter 2 and 3 of this manual gave more information about the flow directions of the water, water bearing layers and a good soil structure for water transmission. The information described in those chapters will help you to find the right location.

Important: Electrical tools like VES will indicate ground layers that may have water but will **NOT** tell you where water is.

5.5.1 Experience of people living in the area

Talk to several people in the area and not only from the customer.

Ask several people (not only your customer) in the area the following questions:

- Where do they get their water now?
- Can you show me existing wells and boreholes?
  Do they dry up? If it dries then ask why they did not dig deeper.
  Measure water level and depth.
  Look at the soil that came out (possibly, it is still next to the well).
- Did other (machine) drillers try to drill in this area and what did they experience?
- Do they know special vegetation that is green the entire year and that extracts much water?
- Ask about other indicators of water.

5.5.2 Water maps

In some countries and districts, water maps ("hydrologic maps") are available. Always counter check the e.g. Water District Department for any information about the area.

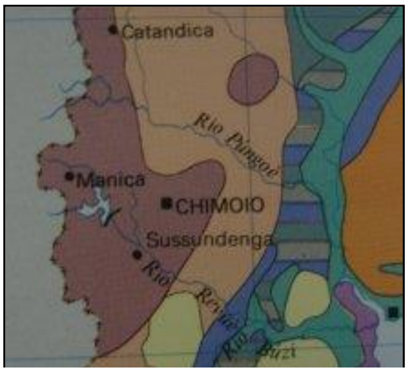
5.5.3 Divining

With divining people use different types of tools for instance copper, steel or a branch of a tree to find water. There is hardly any scientific proof of how divining works. It is likely that the diviner concentrates well and uses his or her intuition. If this intuition indicates a water source, the hands will move which will move the diviner's tool. Divining knowledge is ancient and used in many countries and it does provide often good results. To learn divining one needs to practice and have a feeling for it.

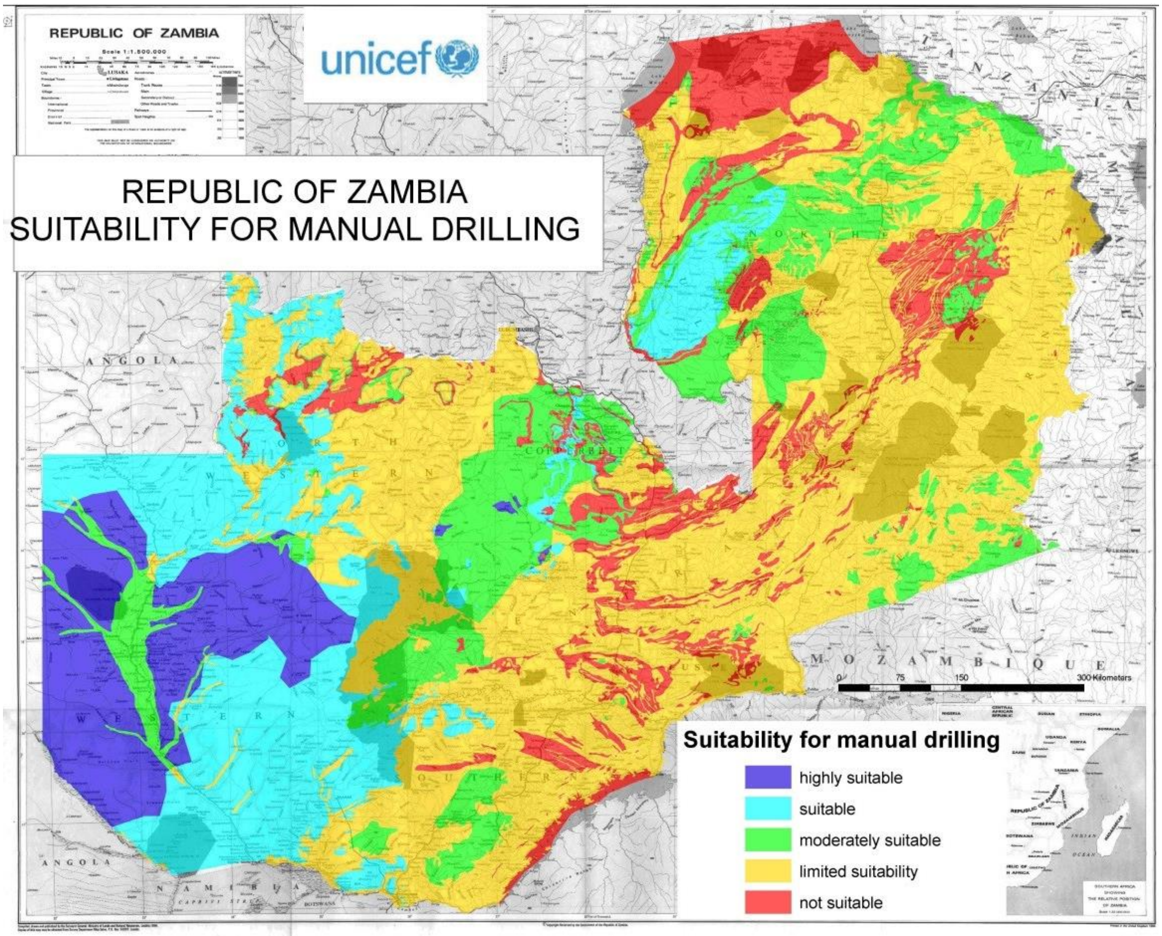
5.6 The possibility for manual drilling due to soil structures

Ask the (local) government and (local) organizations if they have information such as geology maps. And always ask people from the area what their experience is with the soil structure. This can be done by asking about and visiting existing boreholes and hand dug wells.

Soil structure of a hand dug well



Information about soil structures

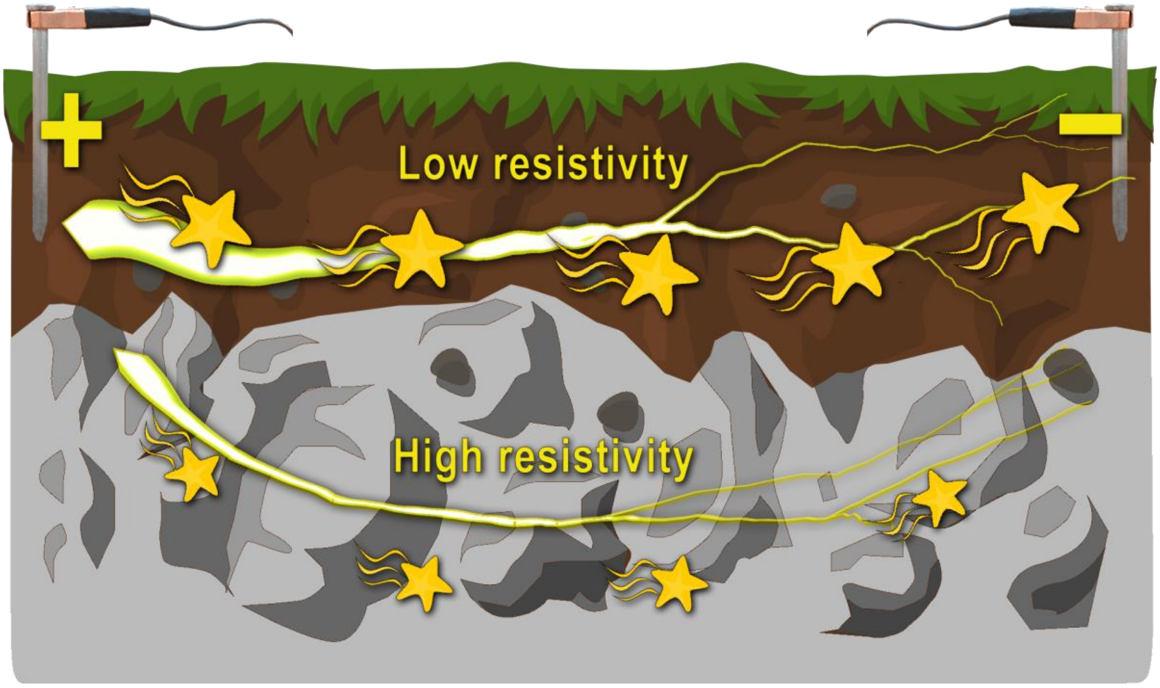


6 Electrical soil survey

6.1 Theory

Electricity travels easy through some soil types while it encounters more "resistance" in other soil types. For example wet sandy soil allows electricity to flow easily (low resistivity) while massive rock makes it difficult for electricity to pass through (high resistivity). By measuring the "resistivity(*)" of soil layers, we can say something about the type of soil. In general hard soils have high resistivity and soft soil types have low resistivity.

But how can we determine deep soil layers without drilling? We can only apply electricity at the ground surface by sticking probes in the ground and connect them to a power source. Luckily electricity flows in curves (see illustration). The farther apart we put the probes, the deeper these curves will reach.

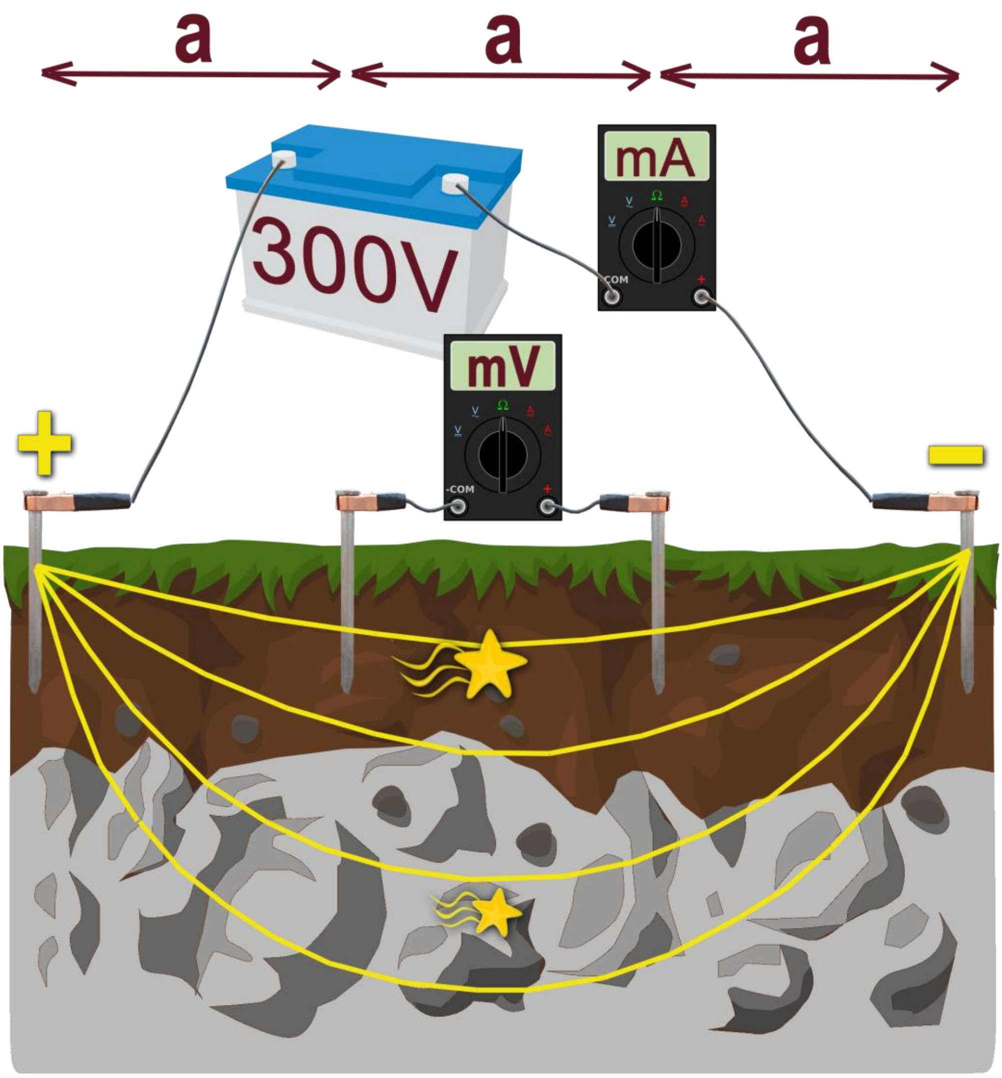


To measure resistance (in Ohms or Ω), we use a formula similar to Ohm = Volts / Amps. So we need to know how much current (Amps) is flowing through the soil and we need to know the difference in Voltage between two points in the soil.

> You can compare electricity as a flow of electrons just like a flow of water molecules in a pipe.
> - The current (Amps) is like with the amount of water that is flowing through the pipe.
> - The Voltage is like the water pressure.
> - Resistance (Ohm or Ω) is like the friction that slows water flow down when passing through a narrow pipe. A narrow pipe would have higher friction (Ω) compared to a wider pipe.

(*) *Electrical resistance (in Ω) depends on the material and the distance electricity has to travel (long distances have higher resistance). Resistivity (in Ω.m) is electrical resistance of a specific material and does not depend on distance. It only depends on the type of material.*

Inventor Mr. Wenner discovered that the following setup combined with some calculations (software) gave good results: He put 2 probes far apart and connected them to a high voltage DC power supply and measured the current (Amps) flowing through it. He also used two other probes which are closer together and measured voltage between these probes. The distance (let us call it “a”) between the 4 probes must always be equal and that “a” is also the approximate depth that you are targeting. If you want to measure deeper, simply increase distance “a” and move all 4 probes farther apart.



Note: this is a theoretical sketch; in reality, we will use a normal 12V battery with an inverter and a rectifier to generate 300V DC.

6.2 📱 Using “the Drilling Toolbox” app

To improve accuracy and make analysing and reporting much easier, we suggest use of “the Drilling Toolbox” app for Android (download it from Google Play store). The application is free for the first few days. A full licence will require a once in a lifetime investment.

After installing, you will have to enter your “Profile” first.

Then make a new “Project” every time you go to another site or customer.

6.3 Horizontal Electric Profiling, how it is done?

With the knowledge you collected by asking questions and visiting wells, you can now wisely indicate a few (for example 4) locations which are far enough from sources of pollution and are likely to have water.

For safety of the drillers, make sure none of these points are close to power lines.

Horizontal Electrical Profiling (HEP) measures apparent resistivity (in Ohm – meter) at a specific depth over a range of places. It does not tell us what is above or under that depth, for that information we need to do a full Vertical Electrical Sounding (VES). But VES takes a lot of time and therefore HEP can help you to quickly get a rough idea about the how the soil changes laterally (horizontally) throughout the area.

1. Make sure there are no electrical cables above or under the measuring point.
2. Unpack your equipment at the place you want to measure.
3. Decide on what depth you want to measure by default we suggest an “a” = depth = 6m. But you are free to change that, if for example you experience challenges at another depth. .
4. Draw an imaginary line to roll out your cables.
   This line should not be parallel to power cables but can be at a 90˚ angle to a power line.
5. Roll out the current wires (big rolls) 1.5*a = 9 m to both sides of the measuring point.
   At both ends make a small hole in the ground, fill it with water, hammer the probe in the ground and connect the cable.
6. Roll out the voltage wire (small rolls) 0.5*a = 3 m to both sides of the measuring point.
   At both ends make small holes in the ground, fill it with water, hammer the probe in the ground and connect the cable.
7. Connect the cables to the measuring box, the box to the inverter and the inverter to the battery.
8. Initially put the Amp meter on “10 Amp” and the Volt meter on “20 Volt” to prevent instrument damage and prepare for fine tuning of the meters.
   Apply electrical current with the switch(s), read the meters and see if the Amp-meter and Volt-meter can be adjusted to a smaller more precise scale. **Especially pay attention to the Amp meter because if the set value is exceeded then the meter or fuse will be damaged!**
9. After fine-tuning the meters, you can do the measurement:
   a. Let current flow in one direction and record milli Amp and milli Volt (mA and mV).
   b. Then reverse the current by flipping both switches and record again mA and mV
   c. Return the current flow in the first position and measure again mA and mV
   d. Finally reverse the flow again and record once more mA and mV
10. Enter this data in the application (or Excel sheet) to find the apparent resistivity (in Ohm – meter).

Move your equipment to the next point you want to measure and repeat the steps until you measured all points you had in mind after the interviews.

You are now interested in the two points with the lowest apparent resistivity.

Measure a final new point in the middle of these two (but only if this point is not in a pollution risk area). From these 3 points, select the one with the lowest apparent resistivity and do the full VES measurement there.

6.3.1 Check measurement before moving equipment

NOTE: It is possible to have **negative voltage** values for measurements 1 and 3 or 2 and 4. Use these negatives and enter them as they are (do not try to "concert" them). But the average value of all 4 measurements should be positive.

As you learned above (in step 9), each point requires 4 measurements from these data you can do a quick for accuracy of your measurements:

- All mA values should be close together.
- mV values where current is flowing in the same direction should be close together. Meaning measurements 1 and 3 should have almost the same mV and also for measurements 2 and 4.

In the example measurement 1 and 3 seem Ok but the measurement 2 and 4 have a difference of 20 mV (almost 20%) and are not close to each other. So this measurement needs to be done again.

Point 7

Position: a = 6m

Measurements:

1	120 mV	67 mA
2	! ~~122 mV~~ !	67 mA
3	121 mV	66 mA
4	! ~~102 mV~~ !	67 mA

Check Measurement!

Point 7

Position: a = 6m

Measurements:

1	120 mV	67 mA
2	106 mV	67 mA
3	121 mV	66 mA
4	102 mV	67 mA

Ok

.

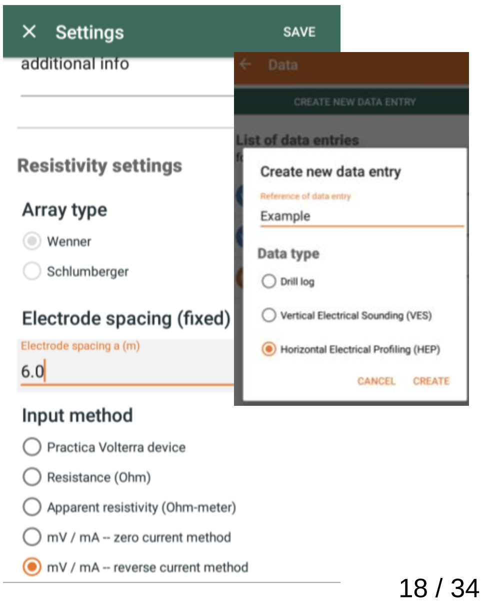
This example shows correct measurements:

- mA are almost the same
- mV of 1 and 3 are almost the same
- mV of 2 and 4 are also almost the same

6.3.2 Adding HEP data in the app

Make sure the correct project (customer or site) is activated and click on "Data".

- Click "Create new data entry"
- Give it a name
- Select "Horizontal Electrical Profiling (HEP)
- Click on the newly made item
- Click "Get geolocation" to get the GPS
- Enter your name at "Data entered by"



- Select Array type: “Wenner”
- Type the distance (or depth) “a” (6m) between probes that you will be using
- Select Input method: “mV / mA – reverse current method”
- Click Save (in upper right corner)

There are 3 point (physical location), where you can add data. Use “Create new point” to add points.

- Click on point 1 and the entry screen opens.
- Change the label and comment if you want.
- Get the exact GPS location for this measurement.
- Type the 4 mAmp and 4 mVolt values, the apparent resistivity will show immediately.
- Click Save (upper right).

Repeat these steps for all the points you wish to measure.

- The “Chart” option will show you all apparent resistivities for all points
- The “Map” shows you where these points are located. You might need to zoom in by touching/stretching the screen with two fingers.
- To get the full report click on the down arrow [v] in the list of data entries behind the required measurement name and select “submit report”. Now check your email and open the download links. You can do this at the office

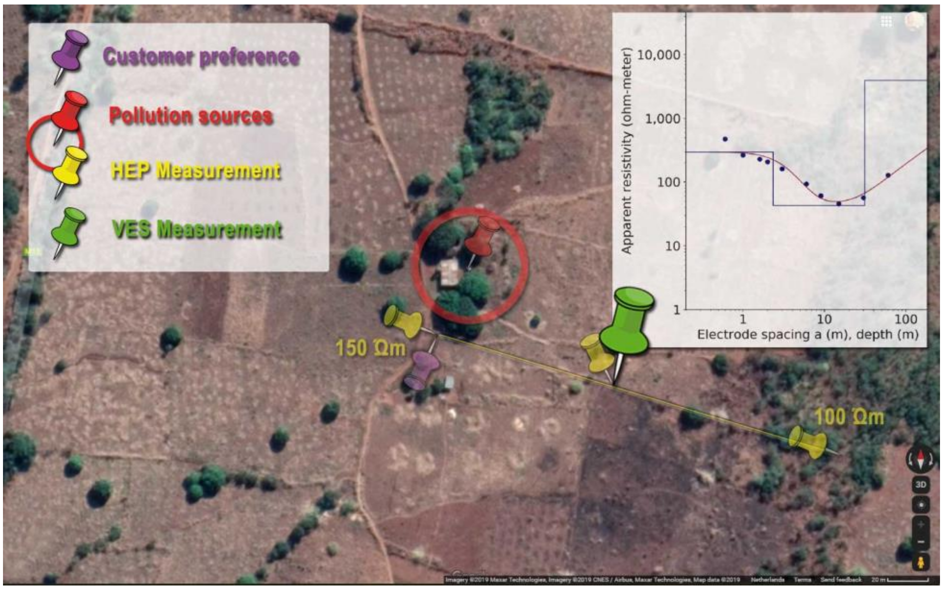
6.4 Procedure step 4: Horizontal Electric Profiling (HEP)

With the knowledge you collected by asking questions and visiting wells, you can now wisely indicate a few (for example 4) spots which are far enough from pollution and are likely to have water.
First you will make a “Horizontal Electrical Profile” of all these preferred places.
Draw an imaginary line between the two places with the lowest apparent resistivity [Ωm] and -if the middle of these two points is not too close to a pollution source then- do another HEP measurement at that middle point. Now you have 3 points on that line (example 150 Ωm, 50 Ωm and 100Ωm).

From these 3 points select the point with the lowest apparent resistivity [Ωm] and do the full Vertical Electrical Sounding measurement as describe in the next chapter.

6.5 Procedure step 5: Vertical Electric Sounding (VES)

Now you know the lowest resistivity at an apparent specific depth (for example a=6m) and it is time to find out what are the layers below that point. You can do that with a full VES measurement.



6.6 How VES work?

The HEP measurements (above) gave an indication of the best place to do the full in depth VES measurement.

1. Unpack your equipment at the spot you want to measure.
2. Draw an imaginary line to roll out your cables.
   This line should not be parallel to power cables but can at a 90˚ angle to a power line.
3. Roll out the current wires (big rolls) if you have the space 1.5 x 60 = 90 m to both sides of the point. If you don't have enough space go 1.5 x 50 = 75m.
   At both ends make a small hole in the ground, fill it with water, hammer the probe in the ground and connect the cable.
4. Roll out the voltage wire (small rolls) 0.5 x 60 = 30 m(or in case you did not have enough space (0.5 x 50 = 25m) to both sides of the point.
   At both ends make small holes in the ground, fill it with water, hammer the probe in the ground and connect the cable.
5. Connect the cables to the measuring box, the box to the inverter and the inverter to the battery.
6. Put the Amp meter on "10 Amp" and the Volt meter on "20 Volt" to prepare for fine tuning of the meters.
   Apply electrical current with the switch(s), read the meters and see if the Amp-meter and Volt-meter can be adjusted to a smaller more precise scale. **Specially pay attention to the Amp meter because when its range is too small then the meter or fuse will be damaged!**
7. After fine-tuning the meters, you can do the measurement.
   a. Let current flow in one direction and record milli Amp and milli Volt (mA and mV).
   b. Then reverse the current by flipping both switches and record again mA and mV
   c. Return the current flow in the first position and measure again mA and mV
   d. Finally reverse the flow again and record once more mA and mV

8. Enter this data in the application (or Excel sheet) to find the apparent resistivity (in Ohm – meter) and quick check your measurement (see paragraph below)

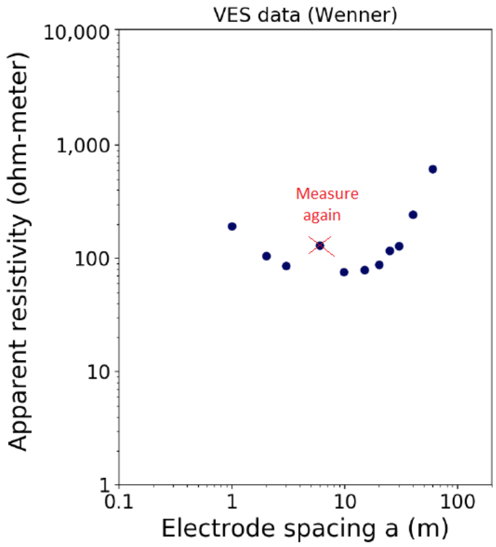
Now move the probes one step closer according to the table in the Appendix and measure again (starting from step 6 above).

Don't roll up the cable when changing the probe positions. Simply slightly pull the connector and leave the cable on the ground until you did all measurements. At the end of all measurements roll up the cable by turning the reel not by grabbing the cable and winding it around the reel. Otherwise the cable will be twisted and will damage much faster.

If the total analyses show that this spot is drillable and might have water, then your fieldwork is done. If you are in doubt, measure another spot or even repeat HEP at another more critical depth.

6.6.1 Check measurements before moving equipment

In The Drilling Toolbox app or Excel you can see a graph that plots your measuring points. If one single point jumps up or down from the rest of the curve then measure that point again. If it gives you the same result then do two extra measurements just before and just after it (adjust the "a" distance slightly).



As you learned above (in step 7), each point requires 4 measurements and with these data you can do a quick check for accuracy:

- All mA values should be close together.
- mV values where current is flowing in the same direction should be close together. Meaning measurements 1 and 3 should have almost the same mV and also for measurements 2 and 4.

6.6.2 Adding VES data in the app

Make sure you activate the correct project (customer or site) and click on "Data".

- Click "Create new data entry"
- Give it a name
- Select "Vertical Electrical Sounding (VES)
- Click on the newly made item
- Click "Get geolocation" to get the GPS
- Enter your name at "Data entered by"
- Select Array type: "Wenner"
- Select Input method: "mV / mA – reverse current method
- Click Save (in upper right corner)

Now you see 19 pre-set measuring points with different probe distances “a”, where you can add data.

- Click on a point with the correct distance “a” (or change that distance in the next screen) and the entry screen opens.
- Type the 4 mAmp and 4 mVolt values, the apparent resistivity will be show immediately.
- Click Save (upper right).

Repeat these steps for all the depths you wish to measure.

- The “Chart” option will show you all apparent resistivities for all points. Use it to check if none of the measurements jump out of the curve.
- To get the report click on the down arrow [v] in the list of data entries behind the required measurement name and select “submit report”. Check your email and open the download links when you are back in the office.

6.7 ➠Procedure step 6: Analysing electrical data

After collecting all field data, checking the measurements and knowing you found a suitable spot, you can now start analysing the data, interpreting it and combining it in a report for your customer (and the driller).

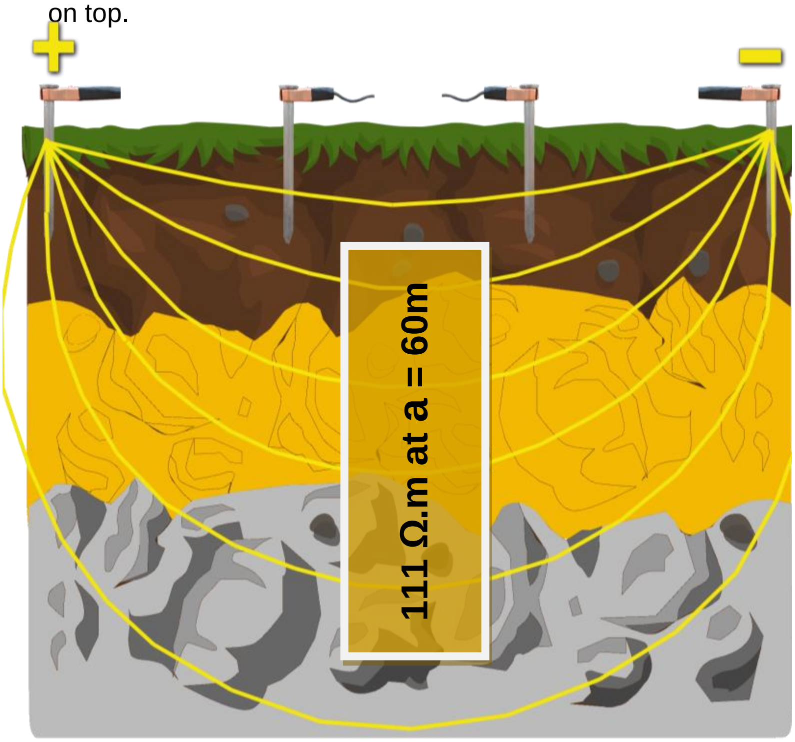
You collected the following electrical data:

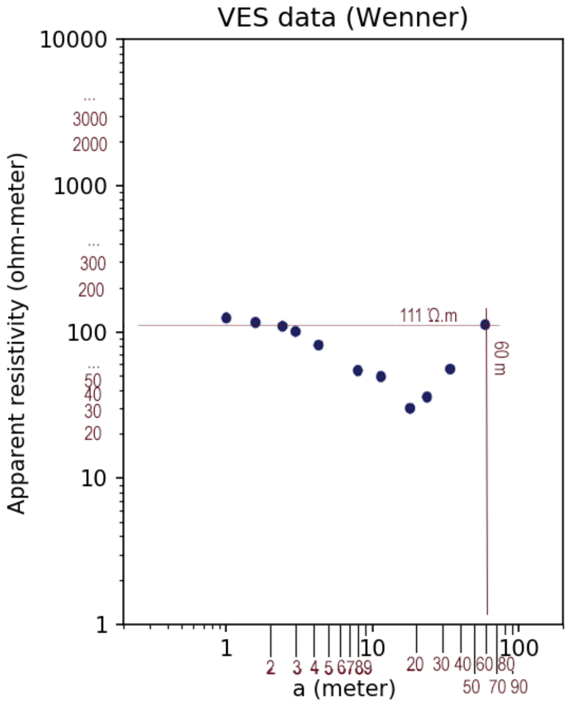
- a = distance between probes (in meters)
- I = current (in milli-Amps)
- U = potential (in milli-Volts)

The software calculates the "apparent resistivity" using this formula:

Apparent Resistivity = 2 x π x a x I / U (in Ω.m) (π = 3.1415927)

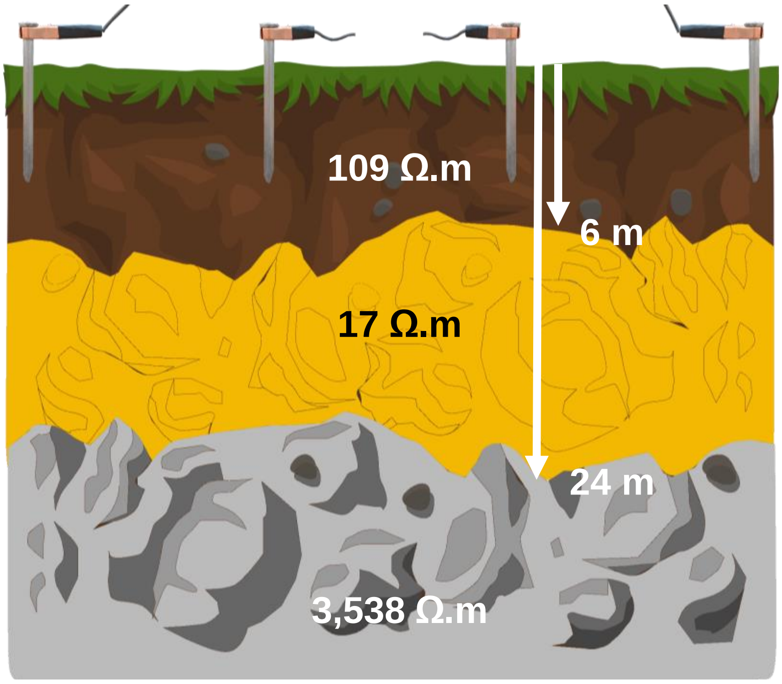
Each apparent resistivity represents all soil layers where electricity went through, including the layers on top.

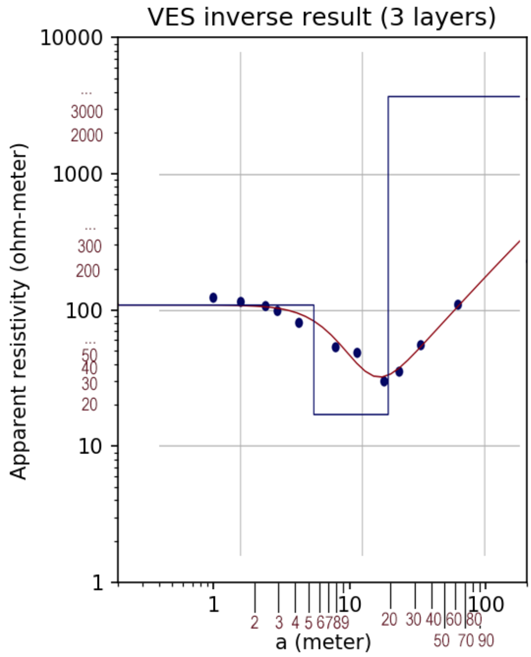




The apparent resistivity is normally represented in a double logarithmic scale. Meaning the big marks on the horizontal axis represent a = 1, next 10 and next 100m notice that the small marks between 1 and 10m are not equality spaced, they represent 1m, 2m, 3m, 4m until 10m. Same for the vertical Apparent resistivity axis (10, 20, 30, …100, 200,300,…1000 Ω.m). So be careful reading it.

Some software is required to calculate estimates for layer thickness and resistivity for each layer. The software needs the measurements of higher layers to include in the calculations for the resistivity of each subsequent lower layer. You could look at it as if it is pealing an onion. You must peel down each layer separately before reaching the centre.
In the example the software predicted the following estimates for 3 layers





Layer #	Start at	End at	Layer Resistivity
1	0 m	4 m	109 Ω.m
2	4 m	16.3 m	17 Ω.m
3	16.3 m	Infinity	3740 Ω.m

Notice that the layer information is not necessarily the same as the measured apparent resistivity.
In the example at “a”= 60 m the measurements showed apparent resistivity = 111 Ω.m while the layer information suggest at 60 m you are in a layer with Resistivity = 3740 Ω.m. That is quite a difference.
By now you understand that the HEP measurements (that only measure one point eq. “a” = 6m) are only very rough estimates and can’t say much about layers.

Important: In reality layers are hardly ever change quickly at an exact level.
So the layer thickness calculated by the software is only a guideline!

6.7.1 📱 Analysing using the app

Simply submit the report of a VES measurement and the app will send you an email with a link to a PDF file and a link to an Excel file. When you download the PDF file and open it, you will notice that the software calculated several models for 3, 4 and 5 layers and an “Accom VES inverse” (which will be discussed later chapter 6.8.2 Interpreting resistivity graphs page 27).

It is up to your experience to decide which model is closest to reality. The 3 layer model is most common. To see the if one of the 4 or 5 layers models is more reliable you might look at:

- If layer thickness is very thin it is probably not a layer and you better use a model with less layers.
- Also if neighbouring layers have almost the same resistivity, you can count them as one.

For example for the above example measurement the 5 layer model looks like this:

Layer #	Start at	End at	Layer Resistivity
1	0 m	1.2 m	128 Ω.m
2	1.2 m	6.1 m	73 Ω.m
3	6.1 m	11.7 m	9 Ω.m
4	11.7	17.4 m	74 Ω.m
5	17.4	Infinity	9307 Ω.m

So in this case it is better to use the 3 layer model.

6.8 Procedure step 7: Interpreting of the analyses

The software only makes calculations easy. It will provide you with different models. But it is up to your experience to make the correct conclusions and provide the correct advice.

6.8.1 Soil types

All types of soil in nature are a complex mixture of different minerals and grain sizes. That mixture is often different from place to place. Clay in Nairobi is of another mixture compared to clay in Lusaka. Both are clay but have slightly different resistivity. Therefore it is not possible to say that a specific resistivity exactly matches a specific soil type. It varies from place to place and it is going to be your (future) experience that will help to determine what resistivity is what soil type.

The following table can give an indication, but you will have to adjust it according to your experience and location.

Resistivity (Ω.m)		Estimates for soil types
Low	High	
0.2	0.2	Sea water
0.5	5	**Wet salty** sands and gravels
1	10	**Wet** clay
2	20	Clay
20	100	Marls, Volcanic ash and tuff
50	100	Spring **water**
50	300	Clayey sandstone
50	500	**Wet** sands and gravels
100	300	Clayey or weathered schists
100	1,000	Weathered gneiss or granite
300	3,000	Schists
300	10,000	Limestones, Sandstones and quartzites, Lavas
1,000	10,000	**Dry** sands and gravels, Gneiss and granite

Important: There is a danger in providing this information, only provide it if you are sure

For example using the above table for our example would theoretically result in:

Layer	Start	End	Resistivity	Possible material
1	0 m	4 m	109 Ω.m	[Clayey sandstone] ***OR*** [**Wet** sands and gravels] ***OR*** [Clayey or weathered schists] ***OR*** [Weathered gneiss or granite]
2	4 m	16 m	17 Ω.m	[Clay]
3	16 m	Infinity	3740 Ω.m	[Limestones, Sandstones and quartzites, Lavas] ***OR*** [Dry sands and gravels, Gneiss and granite]

If you would **only give this** "Possible material" information to your customer (which you should not do), they would think:

- Water can only be found in the upper 4 meters and only if the soil type is [**Wet** sands and gravels].
- Between 4 and 16 m is Clay and is impermeable, no water there.
- Below 16 m the layer is too hard for manual drilling and look dry as well.

Based only on the material estimates, you would probably advise not to drill here. But wait there is more in the next chapter.

Before we go to the next chapter, allow me to explain what drillers actually found: The drillers drilled two tube-wells (5m appart). In both cases:

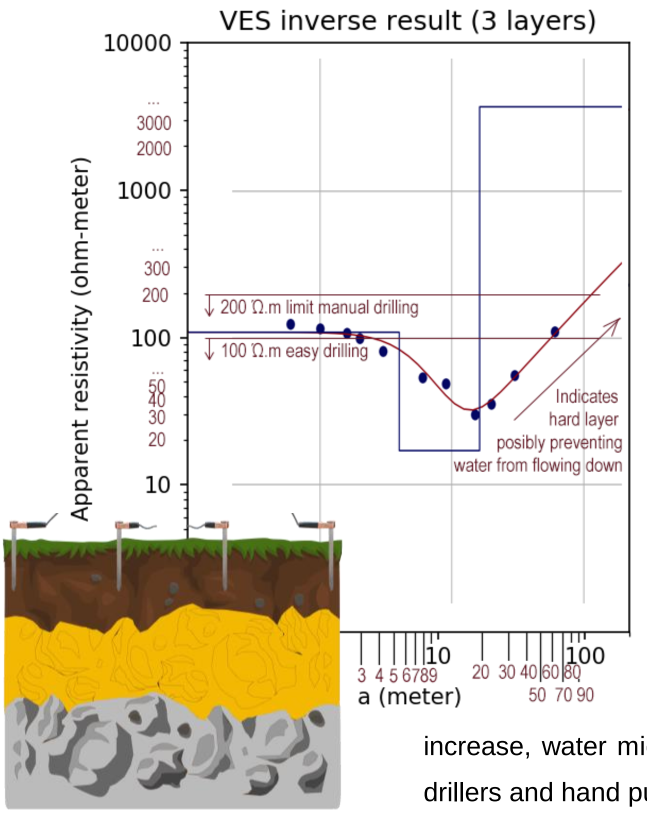
- There was little variation in soil type: clay with a bit of sand from 0 to 9 m.
- Water was found at 5 m.
- At 9 m they hit a rock (We will talk about this in Chapter 6.9 Limitations to HEP and VES page 28).

One of the tube-wells provided **more than enough water** even for a small garden (can't be pumped empty with a hand pump) the other provides a bit less water but still enough for a household.

This real information is very important for you for future sitings. So follow up after drilling. It will make your work better. We will talk about this more in chapter 7 Getting experience, drilling log page 30.

6.8.2 Interpreting resistivity graphs

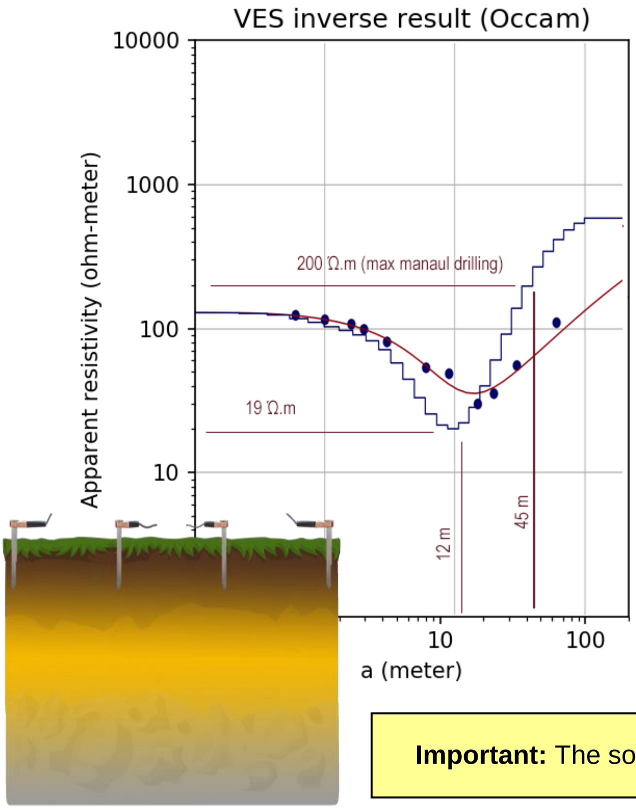
The shape of the resistivity graph can also give you some useful information. For example:



This example graph says: “Manual drilling is possible to 24m because deeper is too hard. This very hard layer could prevent water from flowing down. As a result water might be staying on top of that hard layer.”

Rule of thumb:

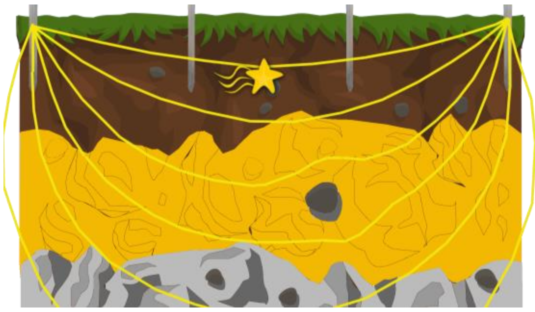
- Manual drillers and hand diggers can drill or dig easily through layers with resistivity of 100 Ω.m or less and it becomes hard, but still manageable up to 200 Ω.m.
- A 45˚ angle at the end of the graph indicates a hard layer that possibly will prevent water from leaking down to deeper layers.
- In situations where resistivity does not increase, water might flow too deep, beyond the depth where manual drillers and hand pumps can’t reach it (40 m or more).



The Occam inverse (also called a ’smooth’ inverse) is a model in which the resistivity of the layers vary smoothly. The model uses a large number of layers with a fixed thickness. During calculations, only the resistivity is allowed to change and sharp changes between layers are prevented. The Occam model often gives a good indication of the rough layering in resistivity in the subsoil. It should be kept in mind that even when there’s a sharp change in the resistivity actually occurs, the model will not show that. If in reality soil types changes smoothly then this model works fine. The example would say “Soil gets slightly softer until 12 m then gets harder.

Important: The software computer cannot tell you which model to follow

6.9 Limitations to HEP and VES



Electricity is like water: It will travel along the path of least resistance. As a result:

- The system will not see stones of limited size. Electricity will run past it. But it will detect full layers. In our example the drillers possibly hit limited sized stones at 9 m a third attempt could have missed the stone and gone deeper.
- If shallow levels have low resistivity, for example because it has just rained and the top layer is wet. Then part of the electricity will flow through that layer even if you are targeting deep layers. The system will not know this unless you measured these shallow levels and tell the software what you found. Only then, the software can compensate for this.
- Even if there is a hard contrast between a very soft layer and very hard layer, the measured resistivity will never jump and will always look smooth. Because the electricity will not go only through the depth that you are targeting. Before it reaches there, it will have to pass all layers on top of it and some electricity will never reach the level that you are targeting. But if you measured enough shallower points as well, then software can use that information to compensate for this effect and it can produce estimates for layers that sometimes seem harder or softer than your measurements show.
- VES assumes layers are horizontal layers. If the area has steep topographic variation then the survey will not provide the correct information.
- VES surveys are a limit to how far the detectable depth is by the available space to roll out the cables and the power of the DC power source.
- The locally made affordable VES equipment is labour-intensive. All four electrodes must be moved for every measurement. This exercise requires 2 to 4 people to consistently move electrodes simultaneously, or one person moving each electrode one-by-one throughout the survey. This is both time-consuming and makes human error rate high. There is more time efficient equipment on the market.

6.10 Procedure step 8: Reporting to your customer

By now you understand that borehole siting is not an exact science. There are many factors that are uncertain even after intensive investigation. This means you have to choose your advice carefully and make sure the uncertain factors in your report are well explained. You have investigated the site from several different angles using different techniques. Explain to your customer what you have done and what you learned in each step.

- Customer preferences

  What is the water going to be used for and how much per day is needed.

  What locations did the customer prefer.
- Possible sources of contamination

  Mention these sources and how far you need to keep away from them.
- Field observations

  What you learned from interviews and visits to wells.

  For existing wells: Mention water levels, total depth and if it runs dry in the dry season.

  How successful were other (machine) drillers in the area?
- Horizontal Electric Profiling

  use the pdf report and explain what this means
- Vertical Electric Sounding

  use the pdf report and add your interpretation of it
- Conclusion

  Formulate your conclusion (where to drill and if you know what technique is most suitable) as a suggestion and mention the things that you are not sure about and why.

  If your customer wants a submersible (solar) pump always advise waiting to buy the pump until the borehole is ready and you know how much water it can produce.

Don't forget to mention your (company) name and contact details. A good, detailed, informational, easily understood, honest and nice looking report will help you get more customers.

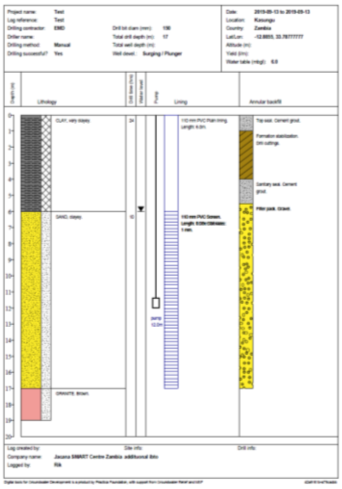
7 Getting experience, drilling log

As a borehole siting company you need to get as much experience in the area as you can. Visits to drilling sites and chatting with drilling teams about their drilling challenges is a good idea not only because these can be your future customers but also to learn. A good drilling company will keep records of the soil types they encountered.
See if you can match this real data to your theoretical VES interpretation to improve your Resistivity – Soil table (chapter 6.8.1 Soil types page 25).
The appendix has an empty form for drill log information.

Every meter a soil sample is collected

7.1 📱 Drill log in the app

In the future when you have gained a lot of experience and you have increased your knowledge about different types of drilling and pumps, you could become a borehole drilling supervisor and/or even advise customers on what pump to buy. At one point you might work as a consultant guiding your customer from start to completion of their water system. In that case you want to present a final or handover report to your customer after all work is completed and water is provided. That report should include a drill log. The Drilling Toolbox app provides a system to make a professional drill log.



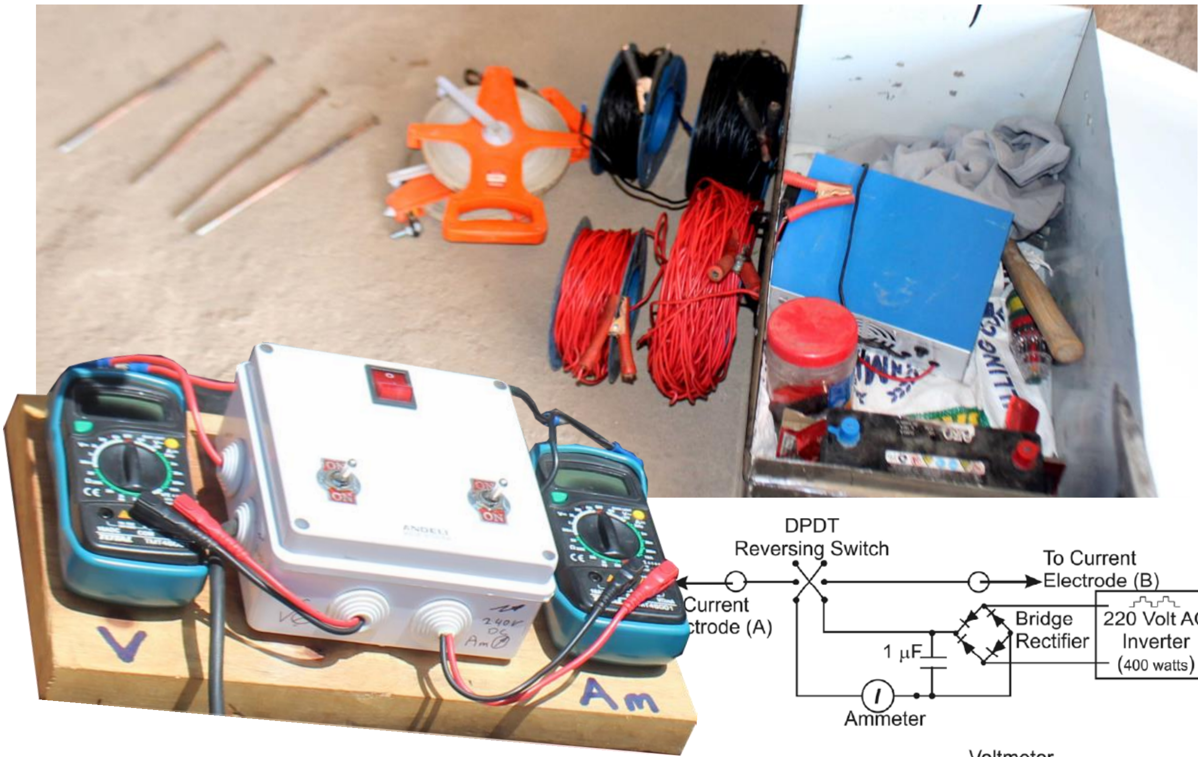
- Make sure to activate the correct Project (customer or site)
- Go to “Data”
- “Create new data entry”
- Type a name for the drill log
- Click on this new item in the list
- Enter the GPS coordinates (you can copy them from other documents if you are not in the area) and click “Save” (upper right)
- Now you see an empty drill log, starting with the Geology entry option
- Click (+) to add a layer and select type options that match reality and click “Save”. Continue to add layers using the (+) button
- Click the (▼) button (bottom right) to add the static water level
- Then click on “Lining” (upper right) to enter data about the casing
- Click (+) to all different parts of the casing Plain or Screen
- Click the (▮) button (bottom left) to add the position of the pump intake.
- Then click “Back” (upper right) to enter data for backfilling
- Use the (+) button to add all backfilling layers for example gravel pack, sanitary seal and formation stabilizer.

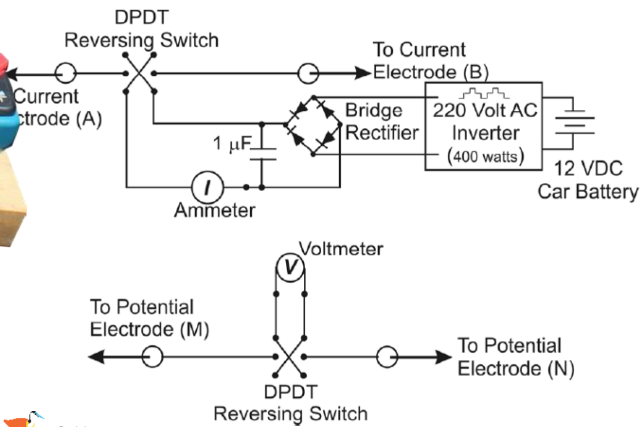
Finally go back one level and submit the report and you will get an email with a link to the pdf report.

8 Appendix

8.1 VES and HEP Equipment

This Simple Market based Affordable Repairable Technology (SMART) can be made with local available materials in most African countries.





8.2 VES forms

App Test point	Volt probe separation Depth a [m]	Amp probe location [m]	Volt probe location [m]
1	0.5	0.75	0.25
2	**1.0**	**1.5**	**0.5**
3	1.5	2.25	0.75
4	**2.0**	**3.0**	**1.0**
5	**3.0**	**4.5**	**1.5**
6	4.0	6.0	2.0
7	**6.0**	**9.0**	**3.0**
8	7.5	11.25	3.75
9	**10.0**	**15.0**	**5.0**
10	**15.0**	**22.5**	**7.5**
11	**20.0**	**30.0**	**10.0**
12	**25.0**	**37.5**	**12.5**
13	**30.0**	**45.0**	**15.0**
14	**40.0**	**60.0**	**20.0**
15	50.0	75.0	25.0
16	**60.0**	**90.0**	**30.0**

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You have to do some low points 2, 4 and 5, because if they have low resistivity then electricity will pass there even when you are measuring deep.

You have to measure a deep point 16 (or else 15), because if there is an impermeable layer, then water can be on top. If not then water might be too deep.

Spend most of your time on HEP. For VES at least measure the bold printer points, others are optional.

Location	
Description/Date	*For use with "the Drilling Toolbox" app*

App Test point	Volt probe separation Depth a [m]	Amp probe location [m]	Volt probe location [m]	Meas #	Current [mA]	Volt [mV]
2	**1**	**1.5**	**0.5**	1 →		
				2 ←		
				3 →		
				4 ←		
4	**2**	**3**	**1**	1 →		
				2 ←		
				3 →		
				4 ←		
5	**3**	**4.5**	**1.5**	1 →		
				2 ←		
				3 →		
				4 ←		
7	**6**	**9**	**3**	1 →		
				2 ←		
				3 →		
				4 ←		
9	**10**	**15**	**5**	1 →		
				2 ←		
				3 →		
				4 ←		
10	**15**	**22.5**	**7.5**	1 →		
				2 ←		
				3 →		
				4 ←		
11	**20**	**30**	**10**	1 →		
				2 ←		
				3 →		
				4 ←		
12	**25**	**37.5**	**12.5**	1 →		
				2 ←		
				3 →		
				4 ←		
13	**30**	**45**	**15**	1 →		
				2 ←		
				3 →		
				4 ←		
14	**40**	**60**	**20**	1 →		
				2 ←		
				3 →		
				4 ←		
(15) Or **16**	(50) Or **60**	(75) Or **90**	(25) Or **30**	1 →		
				2 ←		
				3 →		
If you don't have enough space for point 16 (90m) then do point 15				4 ←		
extra	JACANA SMART Centre Zambia			1 →		
				2 ←		
				3 →		
				4 ←		

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DRILLING LOG

Start date: ____________

Completion date: ____________

Static water level: ____________

Dynamic water level: ____________

Well ID No: ____________

GPS E. ____________

S. ____________

Name of client: ______________________

Village/District: ______________________

Drilling Company: ______________________

Name of drillers: ______________________

Drawing			Depth (meter)	Description of the soil	Observation of soil (texture/color)	Drilling speed (minutes)	Remarks
PVC pipe	Backfilling	Type of soil					

Legend

PVC
- Blind PVC
- Filter screen

Backfilling
- Gravel pack
- Sanitary seal
- Cutting/back filling

Type of soil
- Permeable
- Impermeable
- Semi-permeable

Description of soil
1- Clay (<0,002mm)
2- Silt (0,05 – 0,002mm)
3- Fine sand (0,25 – 0,05 mm)
4- Medium sand (0,5 – 0,25 mm)
5- Course Sand (1,0 – 0,5 mm)
6- Very Course Sand (2,0 – 1,0 mm)
7- Gravel (> 2,0mm)
8- Mixed

Observation of soil
1. Compact
2. Soft
3. Color