Aquifer, Classification and Characterization

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Additional information is available at the end of the chapter

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Abstract

Aquifers in geological terms are referred to as bodies of saturated rocks or geological formations through which volumes of water find their way (permeability) into wells and springs. Classification of these is a function of water table location within the subsurface, its structure and hydraulic conductivities into two namely; Confined Aquifers and Unconfined Aquifers and then characterized these aquifers. The characterization of aquifers could be done using certain geophysical techniques like Electrical Resistivity, Electromagnetic Induction, Ground Penetrating Radar (GPR) and Seismic Techniques. Aquifer Characterization is dependent on the petro-physical properties (porosity, permeability, seismic velocities etc.) of the subsurface. Results of this Aquifer Characterization could be observed and analyzed using varying geophysical software (WinRESIST, RADpro etc.) to better image the subsurface.

Keywords: aquifers, unconfined aquifer, confined aquifer, aquifer characterization, electrical resistivity, electromagnetic induction, ground penetrating radar, seismic techniques

1. Introduction

To explore the term "Aquifer", it is paramount to understand a bit about the natural occurring resource groundwater depended on by vast majority of people and how it relates to Aquifers.

Groundwater is defined as fresh water (from rain, melting of ice and snow) that soaks into the soil and is stored between pore-spaces, fractures and joints found in within rocks and other geological formations. Groundwater occurs in various geological formations, the ability of geological formations to store water is a function of its textural arrangement. The source of groundwater most times could be linked to surface run-off and infiltration of rainwater into the subsurface and streams from which it leads to the establishment of the water table and serve as a primary supplier of streams, springs lakes, bays and oceans. The textural arrangement (uniformly or tightly arranged texture, loosely arranged texture) found within most geological formations and rocks have a strong role to play in *water retention* and *storative* capacity of any rock or geological formation. Rocks/Geological formation with uniformly or tightly arranged texture have high water retaining ability (porosity) but less transmitting or mobility ability (permeability) while those with higher porosity and higher permeability have sufficiently enough to yield significant quantities of groundwater to wells and springs as such any geological formation with such characteristic is been referred to as an Aquifer. Let us now consider other definitions for aquifers and look at the different types that exist based on its classification and what influences these classifications.

An **aquifer** according to word web dictionary refers to any underground layer of water-bearing rock or geological formation that yields sufficiently groundwater for wells and springs. According to geological terms an Aquifer could be referred to as a body of saturated rock or geological formation through which water can easily move (permeability) into wells and streams (**Figure 1**). The top of the water level in an aquifer is called the water table. An aquifer fills with water from rain or melted snow that drains into the ground. In certain areas, water could pass through the soil of the aquifer while in other areas it enters through joints and cracks in rocks where it moves downwards until it encounters rocks that are less permeable. Aquifers generally are known to serve as reservoirs and could dry up when people drain them faster than they are been refilled by nature.

Aquifers must not only be permeable but must also be porous and are found to include rock types such as sandstones, conglomerates, fractured limestone and unconsolidated sand, gravels and fractured volcanic rocks (columnar basalts). While some aquifers have high porosity and low permeability others have high porosity and high productivity. Those with high porosity and low permeability are referred to as poor aquifers and include rocks or geological formation such as granites and schist while those with high porosity and high permeability are regarded as excellent aquifers and include rocks like fractured volcanic rocks.

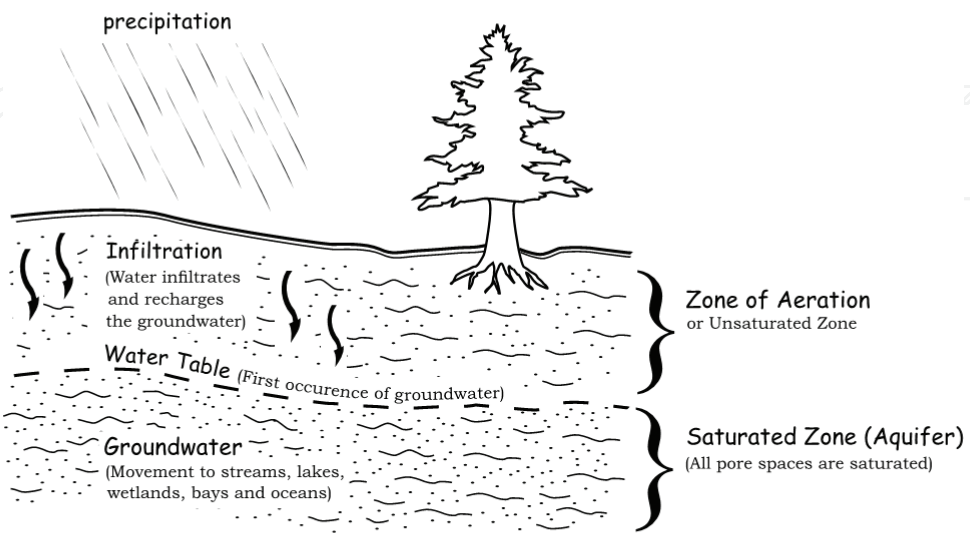

Figure 1. Aquifer formation (as adapted from http://water.usgs.gov/ogw).

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2. Classification of aquifers

Aquifers are generally been classed into two main categories namely confined aquifer and unconfined aquifers.

2.1. Confined aquifers

Confined Aquifers are those bodies of water found accumulating in a permeable rock and are been enclosed by two impermeable rock layers or rock bodies. Confined Aquifers are aquifers that are found to be overlain by a confining rock layer or rock bodies, often made up of clay which might offer some form of protection from surface contamination. The geological barriers which are non-permeable and found exist between the aquifer causes the water within it to be under pressure which is comparatively more than the atmospheric pressure. The presence of fractures, or cracks in bedrocks is also capable of bearing water in large openings within bedrocks dissolving some of the rock and accounts for high yields of well in karst terrain counties like Augusta, Bath within Virginia. Groundwater flow through aquifers is either vertically or horizontally at rates often influenced by gravity and geological formations in these areas.

Confined aquifers could also be referred to as "Artesian aquifers" which could be found most above the base of confined rock layers. Punctured wells deriving their sources from artesian aquifers have fluctuation in their water levels due more to pressure change than quantity of stored water. The punctured well serve more as conduits for water transmission from replenishing areas to natural or artificial final points. In terms of storativity, confined aquifers (**Figure 2**) have very low storativity values of 0.01 to 0.0001.

2.2. Unconfined aquifer

Unconfined Aquifer unlike confined aquifers are generally found located near the land surface and have no layers of clay (or other impermeable geologic material) above the water table although they are found lying relatively above impermeable clay rock layers. The uppermost

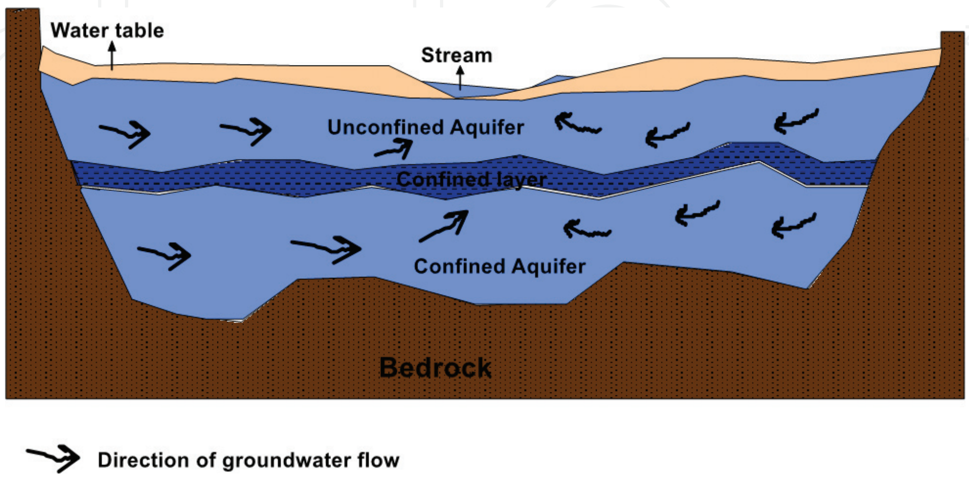

Figure 2. Schematic cross-section of aquifer types (source: http://en.m.wikipedia.org>wiki>Aquifer).

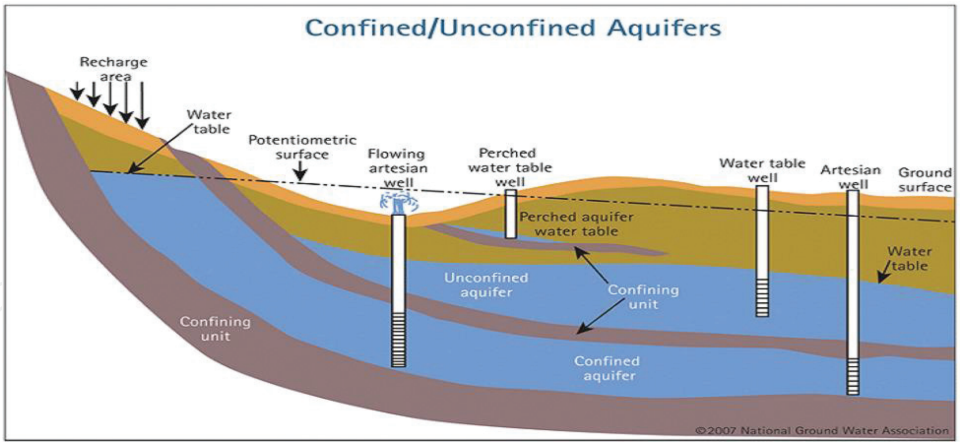

Figure 3. Schematic cross-section of aquifer types (source: coloradogeologicalsurvey.org>wateratlas).

boundary of groundwater within the unconfined aquifer is the water table, the groundwater in an unconfined aquifer is more vulnerable to contamination from surface pollution as compared to that in confined aquifers this been so due to easy groundwater infiltration by land pollutants. Fluctuation in the level of groundwater varies and depends on the stored up groundwater in the space of the aquifer which in turn affects the rise or fall of water levels in wells that derive their source from aquifers. Unconfined aquifers have a storative value greater than 0.01. "Perched aquifers" (**Figure 3**) are special cases of unconfined aquifers occurring in situation where groundwater bodies are separated from their main groundwater source by relatively impermeable rock layers of small areal extents and zones of aeration above the main body of groundwater The quantity of water found available in this type of aquifer is usually minute and available for short periods of time.

3. Petro-physical properties of aquifers

Petro-physical properties of aquifers are properties that help in the defining and characterizing aquifers. Some of the properties considered are:

3.1. Hydraulic conductivity

Hydraulic Conductivity could be described as the relative ease with which a fluids (groundwater) flows through a medium (in this case a geological formation or rock) which is quite different from intrinsic permeability in that though it describes the water-transmitting property of the medium it is however not influenced by the temperature, pressure or the fluid passing through the geological formation. Hydraulic conductivity of a soil or rock or geological formation depends on a variety of physical factors amongst which includes porosity, particle size and distribution, arrangement of particles and other factors.

Mathematically hydraulic conductivity could be defined by the formula below:

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$$K = k\frac{\rho g}{\mu} \tag{1}$$

where K is the hydraulic conductivity (cm/s or m/s), k is the intrinsic permeability, ρ is the density of fluid, μ is the dynamic viscosity of fluid.

Note: seconds (s) could be converted to days by time conversions.

Generally, for unconsolidated porous media, hydraulic conductivity varies with particle size as such clayey materials exhibits low values of hydraulic conductivity as compared to sands and gravels that exhibits high values of hydraulic conductivity (150 m/day for coarse gravels, 45 m/day for coarse sand and 0.08 m/day for clay). This is so because the small particle size arrangements (fine grained) in geological formations contained mainly of clayey materials though porous is not permeable enough to allow groundwater flow within it however in sands and gravels (medium to coarse grained) we have medium to coarse arrangement of particle sizes which results to a porous and permeable geological formations or rocks that allows a higher ease of groundwater flow. It is however essential to point out that we could have geological formations or rock that exhibit medium values of hydraulic conductivity, this is in the case where you have a geological formation made up of moderate amounts of clayey material and sandy materials. It should also be noted that variations in hydraulic conductivity values of geological formations or rocks is dependent on factors such as weathering, fracturing, solution channels and depth of burial.

3.2. Porosity

Porosity of a geological formation or rock or soil could be described as the measure of the contained voids or interstices expressed as a ratio of the volume of voids to the total volume. It could also be defined as the volume of pores within a rock or soil sample divided by the total volume of the rock matrix (pores and solid materials contained with the rock). When a rock is emplaced by either cooling from an igneous melt or induration from loose sediment or soil formation from weathering of rock materials, it possess an inherent porosity known as primary porosity which reduces with time by actions of cementation or compaction. However, when joints, fissures, fractures or solution cavities formed within rocks after the must have been emplaced it is referred to as secondary porosity. Therefore, total porosity is the sum of primary and secondary porosities.

If all the pores found contained in a rock are not connected, then only a certain fraction of the pores would allow for water movement. The fraction that allows for water movement is known as the effective porosity example of which includes pumice, glassy volcanic rock (solidified froth) probably would float in water because its total porosity is high and it contains much entrained gas.

Porosity of a rock is determined to a large extent by the packing arrangement of particle sizes and the uniformity of its grain-size distribution. As such a cubic packing (**Figure 4A**) would give a porosity of 47.65%, the greatest and most ideal a rock with uniform spherical grains can achieve as the centers of eight such grains from vertices of a cube. However, if the packing

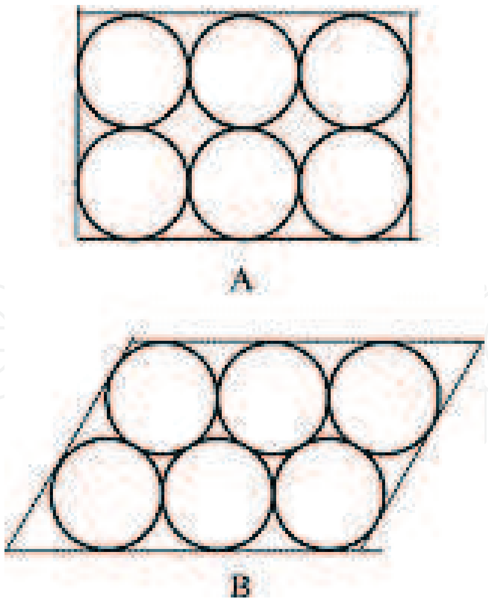

Figure 4. (A) Cubic packing (B) Rhombohedral packing.

arrangement of the rock where to change to be that of a rhombohedral (**Figure 4B**) then, its porosity would reduce to 25.85% as the centers of the eight adjacent spheres form the vertices of rhombus.

Mathematically porosity (*n*) is given by the formula below:

$$Porosity\ (n) = \frac{Vp}{Vt} \tag{2}$$

where *Vp* is the pores of rock or soil sample, *Vt* is the total volume of pores and solid material.

3.3. Transmissivity

Transmissivity (T) more simply could be defined as the property of aquifer to transmit water. It could also be defined as the amount of water that can be transmitted horizontally through an aquifer unit by full saturated thickness of the aquifer under a hydraulic gradient of 1 or as the rate at which water of prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit gradient.

It could be mathematically defined as:

$$T = Kb\ \left(m^2/day\right) \tag{3}$$

where *T* is the transmissivity, *K* is the hydraulic conductivity, *b* is the saturated thickness of the aquifer.

Aquifers are characterized by petro-physical properties such as *hydraulic conductivity* (alternatively called *permeability*), *transmissivity* (product of hydraulic conductivity and aquifer thickness) and *diffusivity* (ratio of transmissivity and storage coefficient). These properties could be examined using geophysical techniques such as Electrical Resistivity, Seismic techniques.

4. Aquifer characterization – electrical techniques

In geophysical investigations using electrical techniques, two primary properties of interest been considered are electrical conductivity or dielectric constant.

Electrical techniques make involves *profiling* and *sounding* mode of data collection which both involves the use of direct currents or low frequency altering currents passing through the subsurface. While profiling use of the terms profiling involves the inferring of subsurface measurements based on lateral changes in electrical properties over constant subsurface, Sounding infers subsurface measurements of single location as a function of changes in petro-physical properties as function of depth (**Figure 5**). The use of either of the two modes for data collection is function of the purpose of the investigation.

4.1. Electrical resistivity

Electrical resistivity (ER) is more frequently been used as compared to other electrical techniques in groundwater investigations of which includes the characterization of aquifers. Electrical Resistivity (ER) involves the introduction of time – varying direct current (DC) or very low frequency (<1 Hz) current into the ground between two current electrodes to generate potential differences as measured at the surface with units of Ohm-meters (Ω-m). A deviation from the norm in the pattern of potential differences expected from homogeneous proffer the necessary information on the form and electrical properties of subsurface inhomogeneities.

A typical Electrical Resistivity (ER) investigation made up of a 2 – electrode system would include 2 – current electrodes and 2 – potential electrodes. As current is been injected into the ground, corresponding potential differences (ΔV) is measured. This measurement coupled with known current (I) and a geometric factor (K) that is a function of the particular electrode configuration, can be used to calculate resistivity (ρ) following Ohm's law:

$$\rho = \frac{\Delta V}{I} K \tag{4}$$

The expression in Eq. (4) for a homogeneous ground is also the same applied for heterogeneous ground; however the general term "apparent resistivity (ρa)" is substituted for resistivity (ρ) in

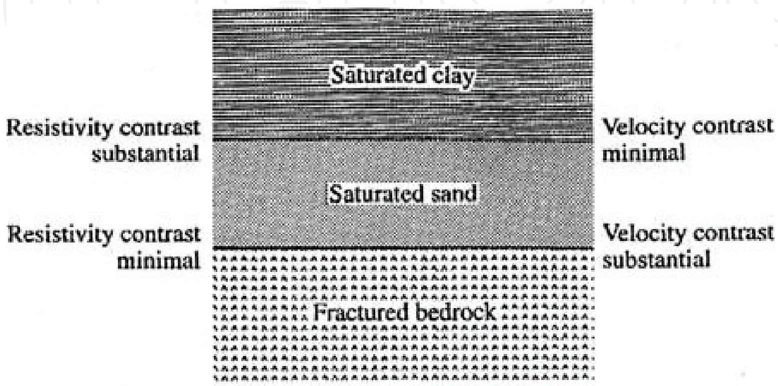

Figure 5. Schematic geological section and associated resistivity and velocity contrasts at interfaces (from Burger [2]. With permission.

Eq. (4). Apparent resistivity (ρa) is used here rather than the actual resistivity of the subsurface due to the non-homogeneity nature of the subsurface.

A four – electrode configurations is been used most commonly when it comes to measuring apparent resistivity of the subsurface. The simplest of these configurations is the Wenner configuration (**Figure 6a**) where the outer two current electrodes C_1 and C_2, apply a constant current, and the inner two potential electrodes, labeled P_1 and P_2, measures voltage difference created by this current. The electrode spacing has a fixed value a, and the apparent resistivity of the subsurface sampled by this array could be computed using the equation:

$$\rho a = \frac{\Delta V}{I} 2\pi a \tag{5}$$

Asides the Wenner array mode of electrode configuration, another commonly used electrode configuration is the Schlumberger array (**Figure 6b**), where the spacing (MN) between the potential electrodes (P_1, P_2) is much smaller as compared to the spacing (2 L) between the current electrodes (C_1, C_2).

The electrode configuration in (**Figure 6**) represents that of a dipole – dipole array where the potential electrode pair and current electrode is closely spaced, however there exist significant distances between the two sets of electrodes (**Figure 6c**) Unlike the cases of the Wenner and Schlumberger arrays, where data collected through either profiling or sounding mode depends a lot on the electrode array geometry.

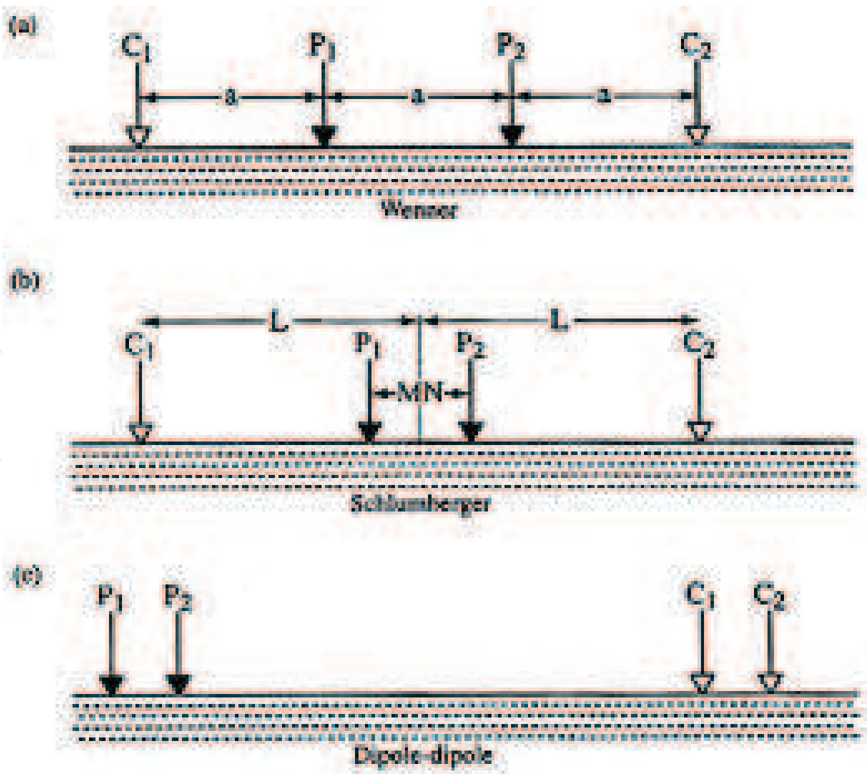

Figure 6. Common electrode configuration used to measure apparent resistivity of the subsurface C_1 and C_2 are the current electrodes and P_1 and P_2 are the potential electrodes. (a) Wenner Array (b) Schlumberger array (c) dipole – Dipole array. (from Burger [2]. With permission).

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To illustrate, we consider the Wenner array. Profiling involves the lateral movement of the entire array along the surface at fixed distances to obtain apparent resistivity measurements as a function of distance. The values of the measurements are assigned to the geometric center of the electrode array. Interpretation of measurements is usually with its data aimed at location of geological structures buried stream channels, aquifers or water bearing formations etc.

Sounding unlike profiling involves gradual and progressively expansion of expansion of the array about a fixed central point with current and potential electrodes being maintained at a relative spacing with depth been a function of electrode spacing and subsurface resistivity contrasts(**Figure 7a–c**). The dashed lines representing current flow lines in an homogeneous environment while bold lines represents actual current flow in single interface that separates units with different resistivities. Next we look how electrode spacing, current and its' influence on depth of penetration. In **Figure 7a**, when the electrode spacing is close, it is observed that the current only upper interface (i.e. the interface of lower resistivity). The scenario in **Figure 7b** is different; as electrode spacing has increased resulting in greater penetration depth and higher apparent resistivity values due to the influence of the lower (higher resistivity) layer. Lastly when the electrodes are farther apart, only substantial current amounts are found to flow through the resistivity layer (**Figure 7c**).

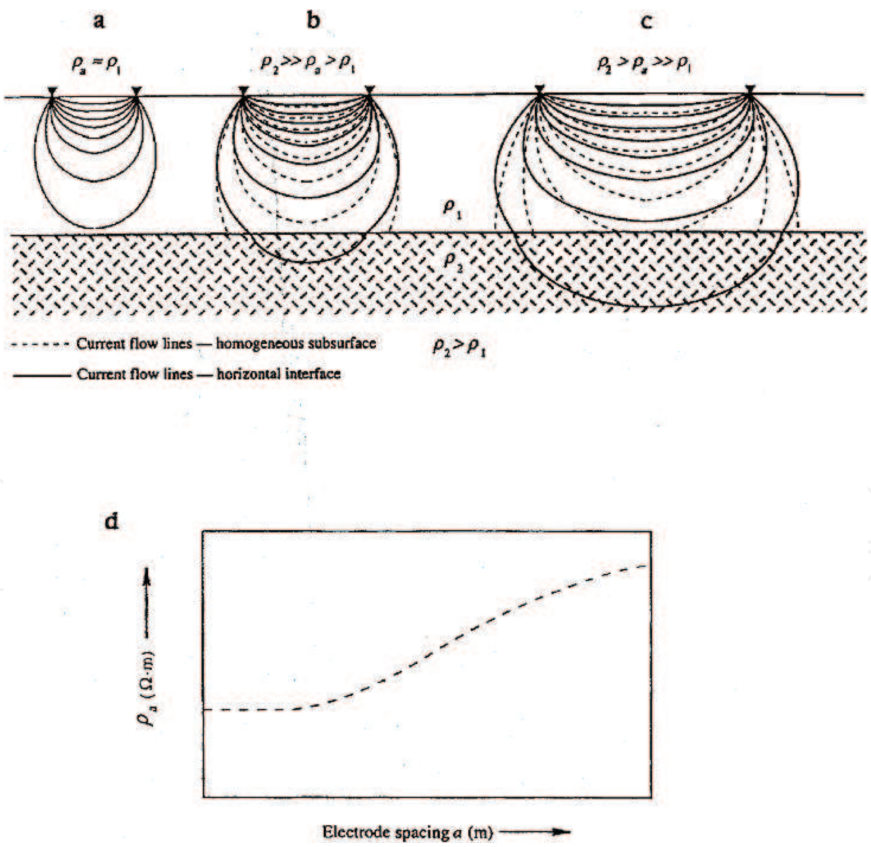

Figure 7. Effects of electrode spacing and presence of an interface on apparent resistivity measurements. The dashed lines represent current flow lines in the absence of the interface and the solid lines represent actual current flow lines (a–c) as the current electrode spacing is increased, the current lines penetrate deeper and the apparent resistivity measurements are influenced by the lower (more resistive) layer. (d) the qualitative variations in apparent resistivity as a function of electrode spacing are illustrated by the two-layer sounding curve (from Burger [2]. With permission).

The curve (**Figure 7d**) reveals qualitative variations in apparent resistivities which increases with electrode spacing, a, this curve is known as a sounding curve revealing geology of the subsurface with resistivity increasing with depth provided geology is homogeneous. However in the case where the geology is inhomogeneous it results in a complex sounding curve whose interpretation is non-unique. To interpret electrical resistivity sounding data, various curve-fitting or computer inversion schemes are used or measured and compared with model computations [1]. A classic example where both modes of data acquisition (profiling and sounding) is been used is in the location of a buried stream channel (**Figures 8a** and **6a**) using Wenner array. The contour map (**Figure 8a**) produced from resistivity measurements of several profiles collected near San Jose, CA, using an a-spacing (**Figure 6a**) of 6.1 [1, 2] reveals contours of equal apparent resistivity delineating an approximately east–west trending high apparent

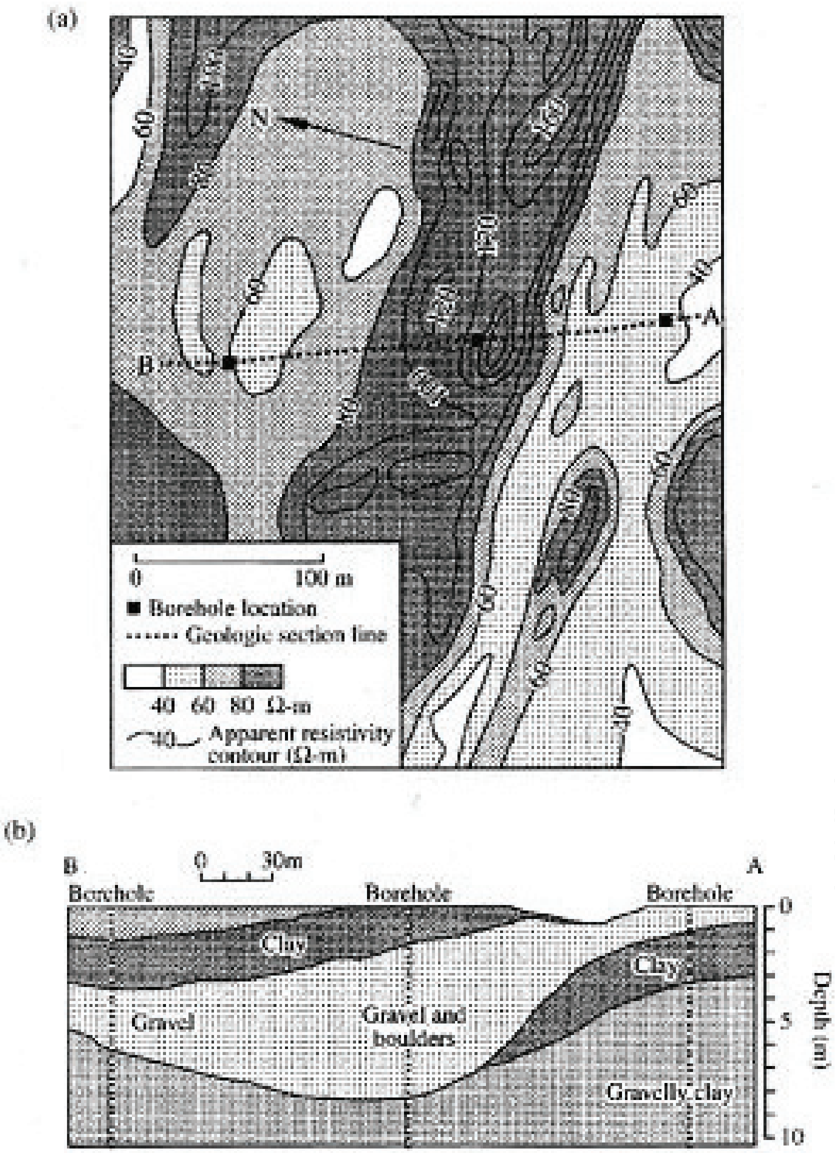

Figure 8. Resistivity survey used to delineate lateral and vertical variations in subsurface stratigraphy. (a) Contour map produced from resistivity measurements, (b) a geologic cross-section (BA) revealing high-resistivity trend in a zone of gravel and boulders that define the location of a buried stream channel (from Ref. [1] application of surface geophysics to groundwater investigations).

resistivity values. To understand the cause of high apparent resistivity values here, a geological cross-section (BA) was drawn across the map. The geological cross-section (BA) drawn is based on four expanding – spread traverses (soundings), apparent resistivity profile information and information from three boreholes whose locations are indicated on the cross-section. The critical observation of the cross-section shows that the area with high-resistivity as on the apparent resistivity map (**Figure 8b**) is a zone of gravels and boulders that defines the location of a buried stream channel (subsurface structure).

Aside the mapping of subsurface structure and stratigraphy, electrical resistivity measurements could be channeled towards the inferring lithological information and hydrogeological parameters needed for the mapping groundwater. For groundwater mapping, electrical conduction (inverse of electrical resistivity) is considered. Here the interest is the delineation of connected pore spaces, void spaces, interstices, fractures within rocks that are water filled which leads to a reduced resistivity values and high conductivity. However more information is still needed as high conductivity within rock formation or units could be due to a number of things asides water some of which includes presence of clay minerals, contamination plumes etc.

Common earth materials have wide range of electrical resistivity values revealed in **Table 1**, however some of these values are known to overlap for different earth materials. Values commonly vary over 12 orders of magnitude and have a maximum range of 24 orders of magnitude [3]. The following statements as regarding electrical resistivity holds;

- Resistivity is sensitive to moisture content; thus unsaturated sediments usually have higher resistivity values than saturated sediments.
- Sandy materials generally have higher resistivity values than clayey materials
- Granitic bedrock generally has a higher resistivity value than saturated sediments and frequently offers a large apparent resistivity contrast when overlain by these sediments.

Asides the use of sounding curves, empirical formulae have also been adapted in relating measurement of apparent resistivity with hydrological parameters of interest as this relates to aquifers. The empirical formula developed in the laboratory by Archie [4] relates these parameters:

$$\rho_r = a\varnothing^{-m}\, S^{-n}\, \rho_w \tag{6}$$

where ρ_r is the electrical resistivity of the rock, ρ_w is the pore water resistivity, $\varnothing$ is the fractional porosity, S is the fractional water saturation.

And n, a, and m are constants {$n \approx 2$, $0.6 \le a \le 1.0$, and $1.4 \le m \le 2.2$; Ward [5]}. Though Archie's law was formulated using lithified materials, Jackson et al. [6] posited its' accurate usability for unconsolidated materials also. The equation presented by Eq. (6) is used generally for well log interpretation however if ρ_r, ρ_w, and $\varnothing$ can be measured separately such that a and m are estimated reasonably then the fractional water saturation could also be inferred using electrical surveys [5]. This concept was utilized by Pfeifer and Anderson [7] to observe and monitor the migration of tracer-spiked water through the subsurface using resistivity array.

In conclusion, it could be said that the complexities that exist in the interpretation of sounding curves and the non-unique solution it gives, suggests the suitability of surface resistivity in

Material	Resistivity (ohm-m)	Dielectric Constant
Sand (dry)	10^3–10^7	3–6
Sand (saturated)	10^2–10^4	20–30
Silts	10^2–10^3	5–30
Shales	10–10^3	5–15
Clays	1–10^3	5–40
Humid soil	50–100	30
Cultivated soil	200	15
Rocky soil	1000	7
Sandy soil (dry)	7100	3
Sandy soil (saturated)	150	25
Loamy soil (dry)	9100	3
Loamy soil (saturated)	500	19
Clayey soil (dry)	3700	2
Clayey soil (saturated)	20	15
Sandstone (saturated)	25	6
Limestone (dry)	10^9	7
Limestone (saturated)	40	4–8
Basalt (saturated)	100	8
Granite	10^2–10^5	4–6
Coal	10^4	4–5
Fresh water	30–10^4	81
Permafrost	10^2–10^5	4–8
Dry snow	10^5–10^6	1
Ice	10^4–10^5	4–12

Table 1. Resistivity and dielectric constants for typical near-surface materials (data from Ref. [13]).

determined subsurface geology. Also due to its sensitivity to parameters like moisture content it's been termed a useful tool in hydrological investigations as reviewed by Ward [5], Van Nostrand and Cook [8].

4.2. Electromagnetic induction

Electromagnetic (EM) techniques as tool for geophysical exploration has dramatically increased in recent years served as a useful tool for groundwater and environmental site assessment. It involves the propagation of continuous-wave or transient electromagnetic fields in and over the earth through resulting in the generation of time-varying magnetic field. For any of such surveys to be carried out three components are essential; a transmitters, receivers, buried conductors or conductive subsurface. These three form a trio of electric-circuit coupled by an EM induction with currents been introduced into the ground directly or through inductive means by the transmitters.

The Primary field travels from the transmitter coil to the receiver coil via paths above and below the surface. Where a homogenous subsurface is detected no difference is observed between the fields propagated above, below and within the surface other than a slight reduction in amplitude. However, the interaction of the *time-varying field* with a *conductive subsurface* induces eddy currents, which gives rise to a secondary magnetic field (**Figure 9**). The attributes

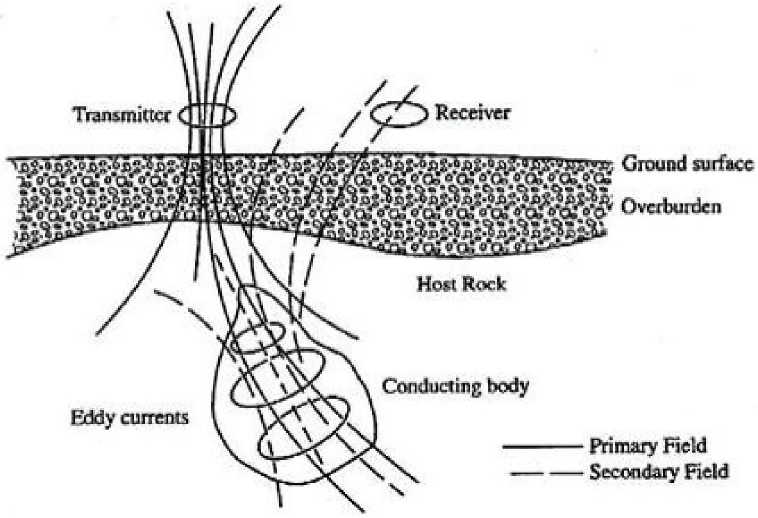

Figure 9. Electromagnetic induction technique (from Ref. [9]).

of the fields generated, such as amplitude, orientation and phase shift can be measured by the receiver coil and compared with those of the primary field as such information about the presence of subsurface conductors, or subsurface electrical conductivity distribution can be inferred.

It's paramount to recall that electrical conductivity is an inverse of electrical resistivity; as such electrical conductivity measurements made using electromagnetic methods is also dependent on subsurface texture, porosity, presence of clay minerals, moisture content and the electrical resistivity of the pore fluid presence. The acquisition of EM data requires less time, achieving greater depth of investigation than resistivity techniques. However, the equipment used are expensive and the methods used to qualitatively interpret data from EM surveys is complicated than those used in resistivity methods. This is because a conductive subsurface environment is essential to set up a secondary field measured with inductive EM methods (**Figure 9**). Electromagnetic methods as a tool for geophysical investigation and exploration is most suited for the detection of water—bearing formation (aquifers) and high – conductive subsurface target such as salt water saturated sediments.

Instrumentation could take in varying forms; but mainly consist of a source and receiver or receiver units. The source (transmitter) transmits time-varying magnetic fields with the receiver measuring components of the total (primary and secondary) field, magnetic field, sometimes the electric field and the necessary electronic circuitry to process, store and display signals [9, 10]. Data obtained from electromagnetic surveys, like their resistivity counterpart can be collected in profile and sounding mode with their information been presented as maps or pseudo-section to give a better picture of the subsurface. Acquisition, resolution and depth of investigation from this survey are been governed by mostly by conditions of the subsurface and domain of measurement.

EM surveys are divided into two domain system of measurement namely; frequency and time domain system. For frequency domain EM systems, we have the transmitter classed as either high or low frequency transmitters; high transmitter frequencies permits high- resolution investigation of subsurface conductors at near-surface or shallow depths while lower transmitter frequencies allows for deeper depth of investigation at the expense of resolution. This implies that high frequency EM surveys yield better result for near-surface due to high resolution, however if interested in deeper subsurface investigation (low frequency EM surveys) then we have need a way around the low resolution. In the case of time domain system, secondary magnetic field is measured as a function of time, with early – time measurement being suited best for near-surface information while late- time measurement yields results of the deeper subsurface. It is paramount to note that depth of penetration or investigation and resolution is also been governed by coil configuration; while measurements from coil separations are influenced by electrical properties thus the larger coil separation investigates greater depths while smaller coil separation investigates near-surface.

Because Electrical Conductivity is related inversely to Electrical Resistivity, as such discussions relating electrical resistivity to lithology or hydrological properties can be applied in an inverse manner to measurements involving electrical conductivity. Electrical conductivity for example is higher for *saturated sediments*, clayey materials than for *unsaturated sediments* and sandy materials respectively. Some examples of investigations involving EM surveys include Sheets and Hendricks [11], who used EM induction methods to estimate soil water content and McNeill [12] that discussed the relation between electrical conductivity and hydrogeological parameters of porosity and saturation.

5. Aquifer characterization – ground waves techniques

5.1. Ground penetrating radar

Ground Penetrating Radar (GPR) as a geophysical technique is relative new and becoming increasingly popular critically understanding the events of the near-surface or shallow subsurface. Davis and Annan [13] viewed the Ground Penetrating Radar (GPR) as a technique of imaging the subsurface at high resolution using electromagnetic waves transmitted at frequencies between 10 to 1000 MHz. GPR could also be viewed as a non-destructive geophysical technique due to its successful geological applications in urban and sensitive environments. Some of these applications include the subsurface mapping of water table soils and rocks structures (e.g. groundwater channels) at high resolutions. It is similar in principle to seismic reflection profiling in however, propagation of radar waves through the subsurface is controlled by electrical properties at high frequencies.

The GPR survey system is made up of three vital components; a *transmitter*, *a receiver* directly connected to the *antenna* and the control unit (**Figure 10**). The transmitter radiates EM waves into the subsurface that could be refracted, diffracted or primarily reflected depending on the dielectric permittivity and electrical conductivity nature of the subsurface interfaces encountered. Recorded *radar data* received after the survey is first been observed, analyzed and interpreted by the aid of inbuilt radar processing software like RADPro, Ekko depending on the system type and make. These data are presented in form of *radargrams* which could either be presented as 2D or 3D subsurface images depending on the combination of the different axes (x, y and z) involved. Interpreting of radargrams is performed by interface mapping which is quite similar to the technique used in interpreting of seismograms. Here each band within on a radargram is presumably classed and identified as a distinct geological horizon;

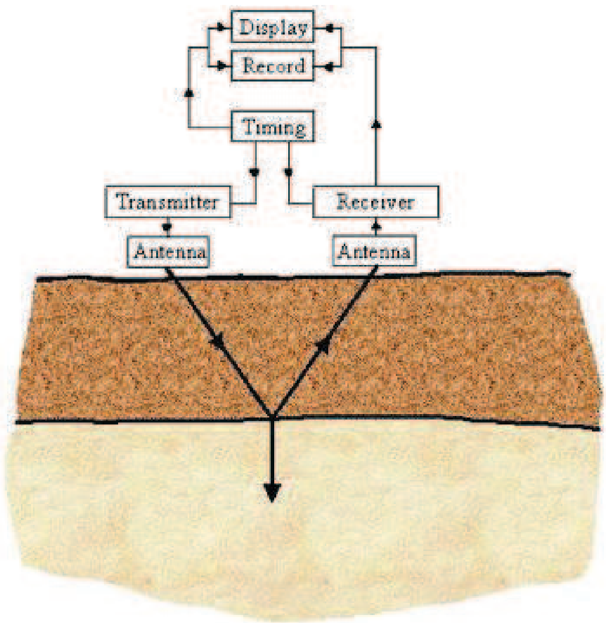

Figure 10. Flow chart for a typical GPR system (after [13]).

this would have been correct except for the effects of multiples, interference with previous reflections, noise etc. All this effects on the radargram need to be removed to correctly identify the different geological horizons and geological structures as present within the radargram as such radargram are subjected to varying radar processing operations depending on the aims, objective of the survey been undertaking through the help of inbuilt system radar processing software like RADpro, Pulse Ekko system software etc.

Processing of the radargram could be simplified by processing operations such as dewowing (removal of low frequency components), Gain Control (strengthen weaker events), deconvolution (restores shape of downgoing wave train such that primary events could be recognized more easily), Migration (useful in removing diffraction hyperbolae and restoring dips). The resultant radargram when correlated with the subsurface geology shows varying interfaces, geological structures that might be present (**Figure 11a** and **b**). Though GPR has successfully been utilized in unsaturated (non-electrically conductive or highly resistive) and saturated (electrically conductive) environment [14], however performance is higher in unsaturated (non-conductive) than in saturated (conductive) such as non-expanding clay environment such as at Savannah River Site in South Carolina [15].

The depth of penetration or investigation of GPR survey is function of the frequency of the EM waves or radar waves and nature of the subsurface material been investigated as shown in **Figure 12** for varying subsurface materials at frequencies ranging between 1 and 500 MHz. If the nature of subsurface material is highly resistive and has low conductivity then we expect a higher depth of penetration however for subsurface materials that are less resistivity and very conductive we expect low depth of penetration. Depth of penetration asides from been dependent on nature of the subsurface material (i.e. resistivity or conductivity nature) is also a function of frequencies which in turn affects resolution of subsurface imagery or radargram. Thus at low frequencies, we expect a greater depth of penetration at the expense of resolution while at high frequencies, we achieve a lower depth of penetration at higher resolution.

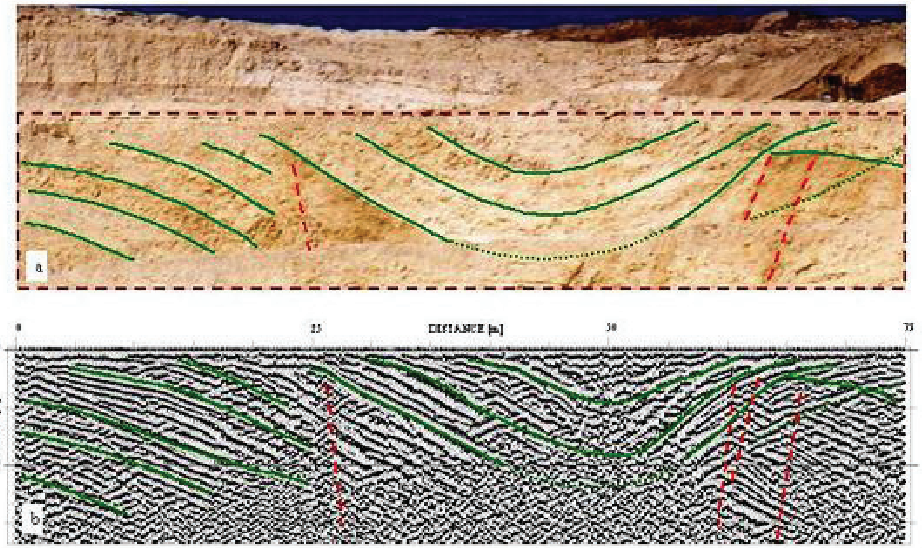

Figure 11. (A) Interpretation of a GPR profile image (B) interpretation of the prominent stratigraphic units, structures and faults.

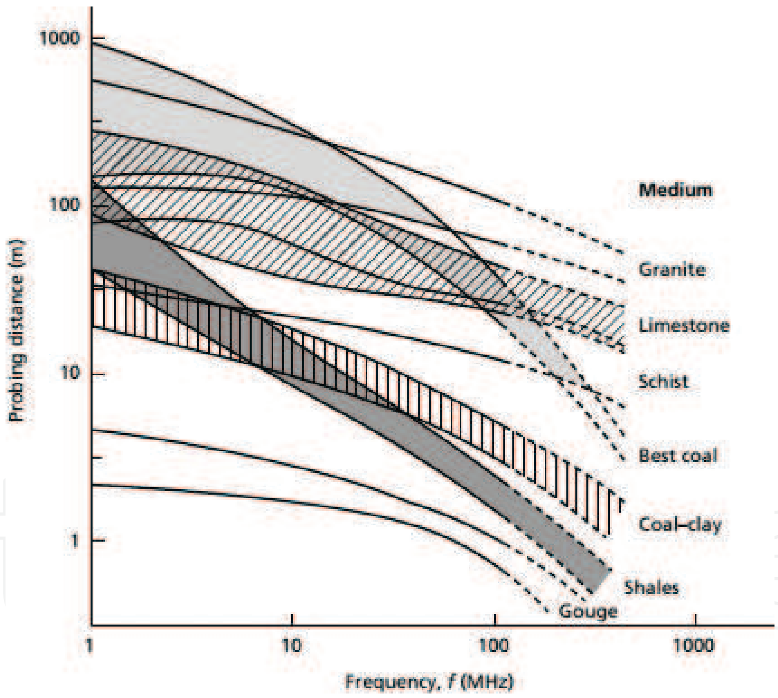

Figure 12. The relationship between probing distance and frequency for different materials (after Cook 1975).

Ground Penetrating Radar (GPR) data have been successful utilized in the hydrogeological investigations to locate the water table and to delineate shallow, unconsolidated aquifers [16].

5.2. Seismic techniques

The use of Seismic techniques in subsurface characterization is based on the propagation of elastic waves generated from a seismic controlled source, propagated through the subsurface, boreholes, received by receivers (geophones or hydrophones) and displayed on seismographs (as a combination of waves velocities and attenuation). From these, properties of the subsurface like porosity, hydraulic conductivity, elastic moduli and water saturation which could help us better understand the subsurface could be derived.

Subsurface investigation involving Seismic techniques are categorized into three; Seismic Refraction, Cross-hole transmission (tomography) and Seismic Reflection.

With Seismic Refraction, the incident ray is refracted along the target boundary before returning to the surface (**Figure 13**). The arrival times gotten from the refracted energy are displayed as function of distance from the source with their interpretation been made manually using simple software or forward modeling techniques. The relationship between arrival times and distances could be used to obtain velocity information directly. Seismic Refraction techniques are the most

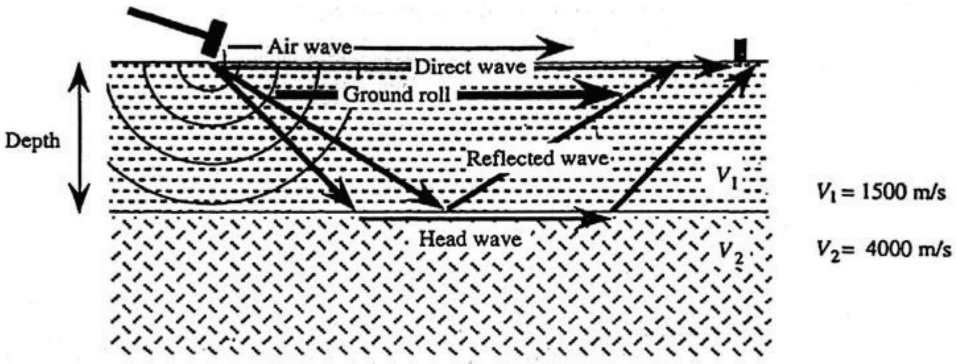

Figure 13. Major ray paths of P-wave energy (from Burger [2]).

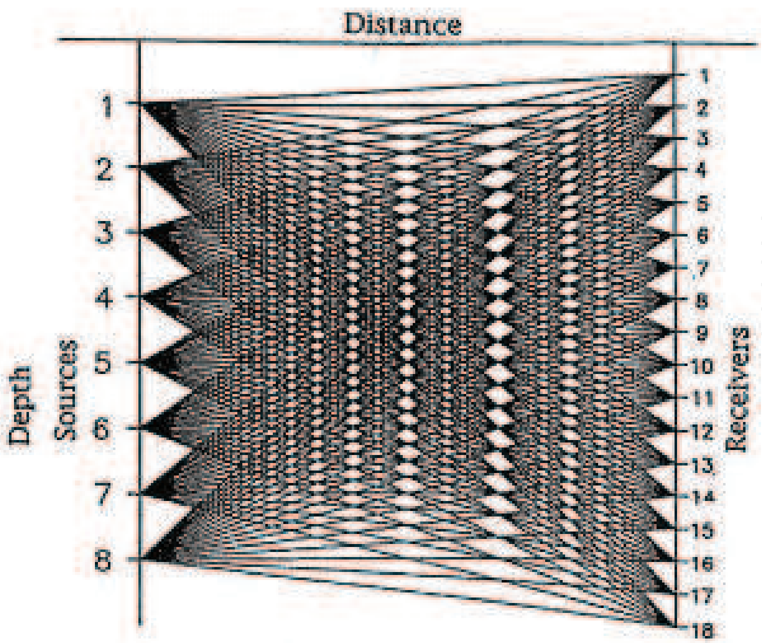

Figure 14. Cross-hole tomography geometry for seismic and radar methods. Sources and receivers are located in separated boreholes, and energy from each source is received by all geophones. Cross-holes acquisition geometries have also been used with electrical resistivity and EM methods.

appropriate for a few shallow (50 m) targets of interest, or where one is interested in identifying gross lateral velocity variations or changes in interface dip [17]. Though Seismic Refraction yields lower resolution than Seismic Reflection and Seismic Cross-hole tomographic, it is however chosen over Reflection as they are inexpensive and help to determining the depth to the water table (buried refractor) and to the top of bedrock, the gross velocity structure, or for locating significant faults. The buried refractor is usually saturated and has a greater velocity than the unsaturated equivalent soil unit and the bedrock surface [18].

Cross-hole transmission (tomography) data acquisition is possible using several techniques amongst which includes seismic techniques, electrical resistivity, electromagnetic, radar with seismic being the most common. Majority of cross – hole tomographic seismic data have been collected for research however the those collected over extremely high resolution of up to 0.5 m are better suited for site characterization. **Figure 14** shows a typical example of seismic cross-hole survey. The multiple sampling of the intra-wellbore area permits very detailed estimation of the velocity structure [19]. As seismic P-wave velocities can be related to lithological and hydrogeological parameters as discussed above, this extremely high resolution method is ideal for detailed stratigraphic and hydraulic characterization of interwell areas [20].

6. Conclusion

In conclusion, Aquifers could be classified into confined or unconfined aquifers on the basis of the presence or absence of the positioning of water table. Its characterization is a function of variations in subsurface petro-physical properties (porosity, hydraulic conductivities, and permeability) measured using geophysical techniques like electrical resistivity, electromagnetic induction, ground penetrating radar and Seismic techniques.

7. Recommendations

Having considered, what aquifers are and their characterization based on petro-physical properties of the aquifers. It is also essential to note that these properties help in selecting suitable techniques for aquifer exploration, characterization and its exploitation. However the most widely used and suitable of these techniques is the electrical methods particularly use of the electrical resistivity technique because of its speed, reliability and the fact that it is more economical in terms of use for exploration and exploitation.

Glossary

Aquifer: A permeable geological formation or body that will yield water in economical amounts.

Confined Aquifer: An aquifer overlain by an impermeable layer such that the piezometric head rises above the top of the aquifer.

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Cross-hole tomographic: involves the measurement of the travel times of seismic ray paths between two or more boreholes in order to derive an image of seismic velocity in the intervening ground.

Dielectric Constant: A measure of the separation (polarization) of opposite electrical charges within a material that has been subjected to an external electrical field.

Effective Conductivity: The coefficient multiplying the expected value of the head gradient to yield the expected value of the flux.

Electrical Profiling: An electrical survey made at several surface locations using a constant electrode separation distance. Electrical profiles, also called constant spread profiles or resistivity profiles, provide information about lateral changes in apparent resistivity.

Electrical Resistivity: A measure of the ability of electrical current to flow through materials, measured in Ohm-m. Electrical resistivity is an intrinsic property of a material and is the inverse of electrical conductivity.

Electrical Sounding: An electrical survey made at a single surface location by moving electrodes progressively farther apart. Electrical soundings, also called expanding spread profiles, provide information about apparent electrical resistivity as a function of depth.

Normal Moveout Correction (NMO): Adjusting seismic or radar velocity estimates to flatten the parabolic appearance of reflectors due to offset between sources and receivers.

Radargram: A picture of the subsurface profile (graph like) representing a profile length along x-axis and y-axis or A radar image of mineral deposits or a planetary surface.

Reflection: Energy that bounces back from a surface due to a change in physical properties, such as seismic impedance in the case of sound waves resolution.

Transmitter: A transmitter is an electronic device used to produce radio waves in order to transmit or send data with the aid of an antenna during a geophysical investigation.

Receiver: A receiver is a device used to receive signals and decode signals and transform them into information the computer understands during a geophysical investigation.

Seismograms: Is an instrument used for measuring earthquake (seismic) signals which could also be adapted to be used for other geophysical investigations. These are held in a very solid position either on the bedrock or on a concrete base.

Seismic Refraction: Is a geophysical principle governed by Snell's law. Used in the fields of engineering geology, geotechnical engineering and exploration geophysics, seismic refraction traverses are performed using a seismograph(s) or geophone(s) in an array and an energy source.

Seismic Reflection: Is a method of exploration geophysics that uses the principles of seismology to estimate the properties of the earth's surface from reflected seismic waves. It's the most common geophysical methodology used for oil and gas exploration which exhibits the highest degree of technical sophistication in terms of both data acquisition and signal processing capabilities.

Unconfined Aquifer: An aquifer that has no overlying confining impermeable layer.

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