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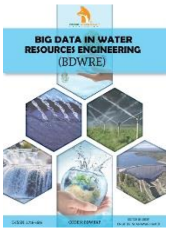

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REVIEW ARTICLE

PARAMETERS FOR ASSESSING THE SUBSURFACE WATER BEARING STRATA

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ABSTRACT

Assessing the subsurface water-bearing strata is a critical task for ensuring efficient water resources management because the worth of underground water cannot be overemphasized. A clear knowledge of its occurrence and characteristics is imperative for resourceful exploitations of natural resources (groundwater). The features of the rocks hosting the underground water in the subsurface, i.e. Aquifer, were treated. Water-bearing layers are classified into aquifer, aquitard, aquiclude and aquifuge. An aquifer is categorized into unconfined, confined, leaky aquifer, perched aquifer and idealized. In addition to the recharge mode, physical parameters that determine the ability of an aquifer to retain and transmit water such as Porosity, Permeability, Transmissivity and Storativity were also discussed. This review also focuses on various techniques used for evaluating the subsurface water-bearing strata. Geophysical methods including the Schlumberger technique of Vertical Electrical Sounding in electrical resistivity and seismic refraction technique were considered as means of assessing the aquifer which provide relative information about the subsurface such as rock type and aquifer zone. Natural and artificial contaminants were finally discussed. This review aims to provide an overview of the various techniques that are suitable for assessing the subsurface water-bearing strata.

KEYWORDS

Host-rock, Groundwater, Subsurface, Exploitation, Aquifer, Recharge, Geophysical Methods.

1. INTRODUCTION

Groundwater is the subsurface water that occurs in the saturated zone of inconstant thickness and depth penetration, in the earth's strata. It can also be regarded as water located beneath the ground surface in soil pore spaces and in the fractures of lithological formations. It is usually formed by rainwater or snow meltwater that seeps down through the soil and into the underlying rocks. An aquifer is an unconsolidated accumulation or a component of rock that can produce a serviceable quantity of water for domestic, industrial, agricultural and economic use. The water table is the depth at which soil pore spaces or fractures and voids in rock become fully water-logged with water (Baird and Low, 2022).

This note aims to discuss the characteristics of subsurface water-bearing strata, by looking at the geology needed to be studied to determine the composition of the rock formations that host groundwater. Methodologies involving seismic survey and electrical resistivity methods can be used to detect changes in the subsurface conditions that indicate the presence of water-bearing strata and evaluate the parametric characteristics of the strata and subsurface water contamination sources.

Subsurface water typically travels through aquifers (permeable strata) at a slow rate ranging from 1 s-m/year to 100 s-m/day from places of recharge to areas of discharge (Ghosh, 2021). The subsurface occurrence of groundwater is divided into two zones; zone of saturation (phreatic) and zone of aeration (vadose). All water-filled pores inside the zone of saturation are typically referred to as phreatic water. As a result, the top of this zone is referred to as the phreatic surface, although the term "groundwater table" is more frequently used (figure 1). The zone of aeration, where air and water both occupy the pores, is located above the zone of saturation. Three zones make up the zone, the capillary, intermediate and soil water zones (figure 1) (Sharan et al., 2021).

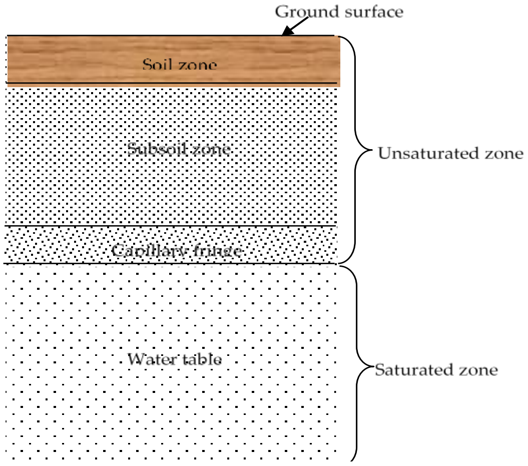

Figure 1: Schematic cross-section showing the distribution of subsurface waters.

Groundwater occurs primarily in underground lakes or rivers is a commonly believed fact by many people. In treaty, lakes and rivers do exist, but most of the groundwater is found in the tiny openings called

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pores that exist between the grains in rocks, soil, and sediment. A large quantity of water can be contained in fractures which are rock formations. Fracture openings beneath the water table are mostly filled with water. In areas where the earth is dry, water-saturated material exists universally at some depth, usually from a few inches to a few hundred meters below the surface.

The top part of the earth's crust is composed of rocks heterogenic in nature. Some types of rocks can store and transmit water better than others. According to an online etymology dictionary, rock, sediment, and soil units that contain significant amounts of producible groundwater are called aquifers (from the Latin *aqua*, water, and *ferre*, to bring). In short subsurface water-bearing layers are called aquifers. The understanding of aquifers in detail follows.

2. TYPES OF WATER-BEARING LAYERS

Aquifers are generally categorized into two major classifications, confined and unconfined aquifers. Using the water-transmitting properties, water-bearing layers are further classified which are aquifers, aquitards, aquicludes, and aquifuge (Dzakiya et al., 2019).

2.1 Aquifer

A relatively porous substrate layer that contains and transmits groundwater is called an aquifer. It is also regarded as a geologic formation from which groundwater can be pumped for many purposes which include domestic, municipal, and agricultural use. An aquifer can also be regarded as a rock or soil mass that not only contains water, but it also has water that can be freely extracted in sufficient capacities. In most cases, aquifers are separated from one another by a formation that permits minute or not at all water to flow between them. This formation can be either less permeable than the aquifer or completely impermeable (Bersi and Saibi, 2020).

Unconsolidated materials that serve as good aquifers include gravel, sand, and sandstone, limestone with cavities formed from the action of acid water on marble with fissures and cracks, granite with slits and founts, weathered basement rocks such as gneiss and schist and basalts.

Geology, assembly of the substrate, and structure determine the characteristics of an aquifer where they occur. Generally, in sedimentary formations, aquifers are more productive than those obtained in basement complex terrain. In contrast, weathered and fractured crystalline rocks return relatively smaller amounts of groundwater in many settings (Lachassagne et al., 2021).

2.2 Aquiclude

This is a geologic formation that hardly transmits stored water in a significant amount into wells around e.g. clay, shale, etc. Such rocks act as boundaries to aquifers and may form confining strata.

2.3 Aquitard

Aquitard is a geologic formation that is characterized by a poorly permeable stratum but saturated which blocks the groundwater motion and does not supply water freely to wells but it may transmit appreciable water from the neighboring aquifer and may also act as groundwater storage where it exists sufficiently thick (Zhuang et al., 2019). Clay interbedded with sand and silts are usual cases (Clark et al., 2018).

2.4 Aquifuge

A geological formation characterized by neither porosity nor permeability is termed an aquifuge. It contains no interconnected openings and therefore cannot transmit water. They are not suitable for groundwater exploitation. Typical examples are found in massive granite and quartzite. Their porosity is less than 1% except where they are fractured or jointed. In Summary;

Aquifers - Rocks and soils having both *porosity* and *permeability*.

Aquicludes - Rocks and soils characterized by *porosity* but *no permeability*.

Aquitard - Rocks and soils characterized by *porosity* but *limited permeability*.

Aquifuge - Rocks and soils having *no porosity and permeability*.

Note: Permeability is the tolerant level of a membrane to allow passage of fluid; Porosity is the degree of empty spaces (voids) in a soil and is an element of the volume of voids over total capacity. These are the main distinguishing properties between aquifers, aquicludes, aquitards, and aquifuges.

3. TYPES OF AQUIFER

There are two major types of aquifers: unconfined and confined aquifers. Other types of aquifers include; leaky aquifers, perched aquifers and idealized aquifers.

3.1 Unconfined aquifer

An unconfined aquifer is a body of water that is partially saturated and limited below an impermeable layer and above a free water table (figure 2). In an unconfined aquifer, water flows in both horizontal and vertical directions (Khadka, 2021). This water table is at atmospheric pressure, and typically the level of water in a well that taps into this aquifer will not go higher than the water table unless there is vertical movement due to capillary action.

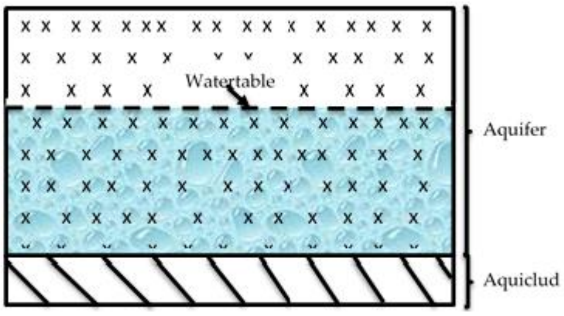

Figure 2: Unconfined aquifer.

3.2 Confined aquifer

A confined aquifer is a type of aquifer that is completely saturated and enclosed by aquicludes above and below (figure 3). The water pressure in a confined aquifer is generally greater than atmospheric pressure, resulting in the water in a well drilled into the aquifer rising the well tube to a level above the aquifer itself.

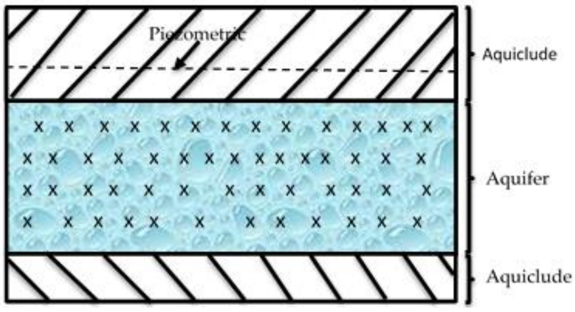

Figure 3: Confined aquifer.

3.3 Leaky aquifer

A leaky aquifer is a type of aquifer that is sandwiched between an aquitard and an aquiclude, which act as partially permeable boundaries that impede the flow of water through them (Figure 4). In cases where the aquitard extends to the surface, it may be partially saturated. However, when it is situated beneath an unconfined aquifer that's bounded by a water table, it will be completely saturated. This type of aquifer is called a semi-confined aquifer (Atangana, 2018).

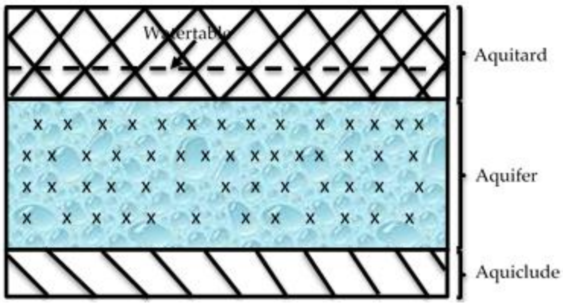

Figure 4: Leaky (Type a).

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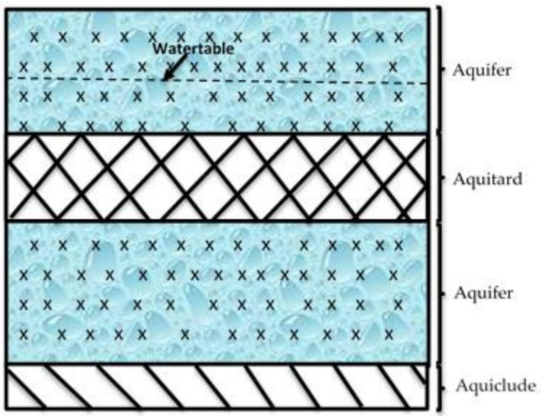

Figure 5: Leaky aquifer (Type b).

3.4 Perched aquifer

This current unconfined aquifer is a special event commonly found in arid and semi-arid regions (O'Reilly et al., 2020). It happens when the major groundwater body is isolated from another groundwater body by a thin, relatively impermeable layer, and some surface water is trapped above the impermeable bed or layer due to the zone of aeration above the main groundwater body. As a result, a separate water table known as the perched water table that is distinct from the local water table is created. The impermeable layer's surface correlates to a water table that is perched (Figure 6)

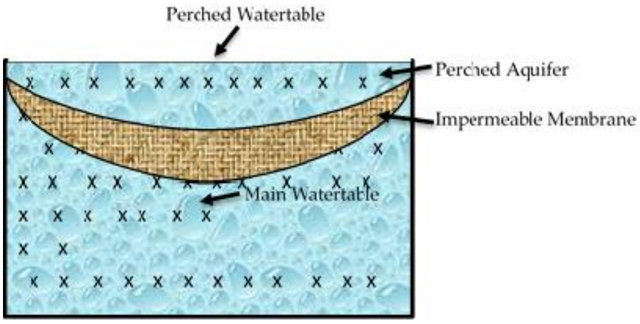

Figure 6: Perched aquifer.

3.5 Idealized aquifer

Aquifers are usually believed to be homogeneous for modelling purposes. A homogeneous aquifer has hydrologic characteristics that are uniform throughout; in this case, we use the ideals of the isotropic aquifer, whose characteristics are direction-independent. Such an aquifer doesn't exist.

4. AQUIFER PARAMETERS

These are the parameters that determine the ability to retain and transmit water. The two most crucial elements influencing the accumulation, movement and distribution of groundwater are Porosity and permeability. These two elements change within rocks in the course of geologic evolutions.

4.1 Porosity

Porosity $\boldsymbol{n}$ in this sense can be defined as the percentage of pore space relative to the host rock's bulk volume **(**Badawy and Ganat, 2022). It is written as;

$$n = \frac{V_v}{V_T} = \frac{V_v}{V_s + V_v} X\ 100\% \qquad (1)$$

Where: V_v = volume of void, V_T = total volume of the material concerned, V_s = volume of the solid.

Particle size, salting, grain size, fabric, or the organization of grains in a rock, degree of compaction and concentration, solution effect, and mineralogical composition of particles when there is clay present are a few of the variables determining a rock's porosity. When every grain is the same size, the maximum porosity is frequently reached. Table 1 shows a representative range for rock formations.

Table 1: Porosity Range for Sample Formations.

Rock types	Porosity (%)
Clay	45 – 55
Silts	40 – 50
Medium coarse sand	35 – 40
Uniform sand	30 – 30
Sand	30 – 35
Gravel	30 – 40
Sandstone	10 – 20
Shale	1 – 10
Limestone	1 – 10

4.2 Permeability

The rate at which water flows is determined by permeability. A liquid can move through or flow inside an aquifer without compromising the aquifer's structure. It can also refer to a rock's capacity to permit fluid to flow into or through it without endangering the stability of the structure. Permeability is crucial in figuring out variables like hydraulic conductivity and the flow characteristics of groundwater in aquifers.

In Darcy's law, which is the basic equation governing the flow of groundwater and physical properties of a fluid like viscosity, internal friction, and a pressure gradient useful to porous media, permeability is a proportionality constant. For a linear flow (Atangana, 2018).

$$v = \frac{K}{\mu}\frac{\Delta P}{\Delta x} \qquad (2)$$

Hence;

$$K = \frac{v\mu\Delta x}{\Delta P} \qquad (3)$$

Where: v is the superficial fluid flow velocity through the medium in ms^{-1}, K is the permeability of a medium in m^2, ΔP is the applied pressure difference in Pa, μ is the dynamic viscosity of the fluid in Pas, Δx is the thickness of the bed of the porous medium in m.

The following factors thus affect the permeability of an aquifer.

- The grain size distribution
- Porosity
- Shape and arrangement of pores
- Properties of the pore fluid
- Entrapped air or gas.

4.3 Transmissivity

Transmissivity is the rate of flow through a cross-section of a certain width over the whole saturated thickness of an aquifer at a given hydraulic gradient (Fetter, 2001). The ratio at which water of fundamental density and viscosity is discharged through a unit width of an aquifer under a unit hydraulic gradient is also known as transmissivity. Thus, it depends on the characteristics of the liquid, as well as the porous medium's thickness (Batu, 1998). Transmissivity is the result of the product of saturated thickness b and the aquifer hydraulic conductivity or permeability K of the aquifer (Olaniyan et al., 2020; Oli et al., 2022). It is expressed in m^2d^{-1}.

$$T = bK \qquad (4)$$

For a multilayer aquifer, the total transmissivity is the sum of the transmissivity of each layer.

$$T = \sum_{i=1}^{R} T_i \qquad (5)$$

4.4 Storativity or specific yield

The amount of water released from storage per unit surface area of the confined aquifer (or aquitard) per unit drop in the hydraulic head is known as storativity, also known as the coefficient of storage (Olaniyan et al., 2020). The storativity S in a confined aquifer (also known as aquitard) can range from $5\,X\,10^{-5}$ m^{-1} to $5\,X\,10^{-3} m^{-1}$ depending on the kind of thickness (Batu, 1998; Kuang et al., 2020). In a confined aquifer (or aquitard), storativity S is obtained from (Tu et al., 2020);

$$S = S_s b \tag{6}$$

Where: S_s is specific storage and b is aquifer (or aquitard) thickness.

The specific storage is the amount of water that an aquifer (or aquitard) releases from storage under a unit that falls in the head. The equation below is the relationship between specific storage and compressibility or the aquifer's ability to compress water (Rau et al., 2018).

$$S_s = \rho_w g(\alpha + n_e \beta) \tag{7}$$

where; ρ_w is the density of water (998 kgm^{-3}, g is the acceleration of free fall (g= 9.81 ms^{-2}), α is aquifer (or aquitard) compressibility, n_e is effective porosity, and β is the compressibility of water (= 4.4×10^{-10} ms^{2}kg^{-1} or Pa^{-1}).

The storativity of an unconfined aquifer includes its specific yield or drainable porosity and the storativity of a confined one as shown in equation 8:

$$S = S_y + S_s b \tag{8}$$

where S_y is specific yield

Table 2 shows a representative value of specific storage for various geologic rocks as reported by (Batu, 1998).

Table 2: Specific Storage of Some Rocks.

Material	S_s (ft^{-1})	S_s (m^{-1})
Rock, sound	$< 1\times10^{-6}$	To convert, divide S_s (ft^{-1}) by 0.3048
Rock, fissured	1×10^{-6} - 2.1×10^{-5}	
Dense sandy gravel	1.5×10^{-5} - 3.1×10^{-5}	
Dense sand	3.9×10^{-5} - 6.2×10^{-5}	
Loose sand	1.5×10^{-4} - 3.1×10^{-4}	
Medium hard clay	2.8×10^{-4} - 3.9×10^{-4}	
Stiff clay	3.9×10^{-4} - 7.8×10^{-4}	
Plastic clay	7.8×10^{-4} - 6.2×10^{-3}	

The volume of water released from storage by an unconfined aquifer per unit surface area of the aquifer per unit decrease of the water table is known as specific yield. It is the volume of water that can be drained by gravity from a mass of rock to the volume of that mass (Harter, 2004). According to (Beretta and Stevenazzi, 2018), specific yield and total porosity are related as follows;

$$n = S_y + S_r \tag{9}$$

Where: S_r is specific retention, which is also known as effective porosity, n is total porosity and S_y is specific yield.

5. AQUIFER RECHARGE

Aquifer recharge is the process of moving water from the ground surface or the unsaturated zone into the saturated zone (Basic Ground-Water Hydrology, 1983; Circular, 1998). That is recharge explains the procedure by which aquifers regain the water released at a given time. Aquifer recharge is crucial for comprehending the hydrologic cycle and applying it to water resources management. Volume is a frequent way to express recharge, and the unit is m^3. Recharge rate can be expressed as a flux into a specific area of the aquifer or as a flux density (volume per unit surface area) into an aquifer at a certain point.

Recharge processes can be divided into two categories: man-made recharge and natural recharge. Flooding, infiltration and percolation, precipitation, underflow from another aquifer, riverbed seepage, and other natural water inflows into the groundwater layers are all examples of natural recharge. The enrichment of natural groundwater resources through the use of infiltration basins, field flooding, infiltration galleries, roof water harvesting, field flooding, pits or injection wells is known as man-made aquifer recharge. Aquifer recharge is frequently carried out to enhance hub resources (i.e., increase storage) and is frequently included in a more comprehensive water resource strategy.

Infiltrating precipitation, permanent or ephemeral surface water, irrigation, and artificial recharge ponds are all sources of water for recharge. Recharge may come straight from segments of rivers, canals, or lakes, although it typically first passes through the unsaturated zone using a variety of methods (Olatunji and Musa, 2014). Concerning time and place, aquifer recharge varies greatly. For instance, seasonal or short-term fluctuations in precipitation and evapotranspiration exhibit temporal variation. In thin unsaturated zones, where recharging could happen soon after infiltration, this heterogeneity is particularly noticeable. Even though fluxes at shallow levels are unpredictable, in deep unsaturated zones, recharging may be homogenised over several years and occur with practically constant flux. Climate, terrain, soils, geology, and vegetation all cause variations in the environment.

6. ASSESSING AQUIFER

Geophysical investigation of the subsurface can be made either on the land or in a drilled hole. Geophysical investigation can be surface geophysical techniques and boreholes. Surface geophysical techniques are the electrical resistivity method, Seismic refraction method, Magnetic method and Electromagnetic method. In this review, electrical and seismic methods have been explained.

6.1 Electrical resistivity method

This entails injecting current into the ground and quantifying the potential difference created by the presence of the current. It involves the application of Ohm's law to obtain resistance. Current sinks AB and potential electrodes MN are expanded gradually, following specific rules (not fully discussed here). A deeper probe is done by widening AB (figure 7).

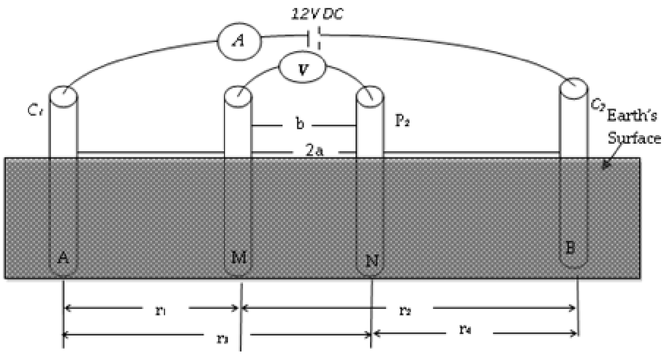

Figure 7: Vertical electrical sounding i Schlumberger Array Mode (After (Olatunji and Musa, 2014)).

$$R = \frac{V}{I} \text{ and } \rho_a = KR \tag{10}$$

$$R = \frac{\rho L}{A} \text{ and } V = \frac{I\rho L}{A} \tag{11}$$

At M and N, a potential gradient is measured when current I is driven into the ground through A and B. If A and B are two-point electrodes at the surface, the equipotential surface is semi-spherical downward the surface area will then be $2\pi l^2$ where l is the radius of the sphere. By deduction, potential (V_M) due to C_1 and C_2 is given by;

$$V_M = \frac{I\rho}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r_2}\right] \text{ and } V_N = \frac{I\rho}{2\pi}\left[\frac{1}{r_3} - \frac{1}{r_4}\right] \tag{12}$$

$$\text{The potential difference } \Delta V = V_M - V_N \tag{13}$$

For an inhomogeneous body, apparent resistivity is

$$\rho_a = K\frac{\Delta V}{I} \tag{14}$$

K is known as the geometric factor, given by

$$K = 2\pi\left[\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)\right]^{-1} \tag{15}$$

There are two basic instruments used to conduct electrical survey; resistivity meter where V and I are separately measured to obtain R and terrameter which directly gives R in Ohms. Other important materials needed for making a resistivity survey include a power source, electrodes, cables and reels. Data is presented as depth sounding curve on a log-log graph and interpretation follows.

6.2 Seismic refraction method

The seismic refraction method provides information to cover a few meters below the ground surface. The energy sources for this investigation include; vibroseis, weight drop, hammer blow, explosives (dynamite) and pimacord. Additionally, the exploration employing seismic refraction can provide the following knowledge: Aquifer thickness and depth, aquifer boundaries in a broad groundwater basin, and identification of clearly distinguishable water-bearing strata

The seismic refraction method (figure 8) involves creating elastic waves through artificial sources that travel at varying velocities depending on the subsurface formation. As these waves encounter different layers of varying acoustic impedance, they undergo reflection and refraction, causing changes in direction and returning to the earth's surface (Rastogi, 2006). This process is similar to the behaviour of light waves.

The production of shock waves can be achieved by detonating approximately 500 grams of dynamite in an excavated and backfilled hole of a depth of around one meter. Alternatively, a plate can be hammered over the ground surface. Once these waves travel through and are refracted from the subsurface boundary, they are detected by a device referred to as a geophone. Geophones are arranged in a line at specific intervals and transmit electric signals upon receiving elastic waves. These signals are typically weak, and therefore, amplified and recorded. By noting the time of shock wave origin and its initial arrival on the surface, whether as direct or refracted waves, seismic refraction can be deduced by referencing figure 8.

Suppose that there is a point A on the surface of the ground, and below it lies a seismic refractor at a depth H. The seismic wave travels from point A and reaches point B, which is located in a different medium. The time it takes for the seismic wave to travel from point A to point B through the low-velocity medium v_1 to higher-velocity medium v_2 is denoted by T (Sato et al., 2012).

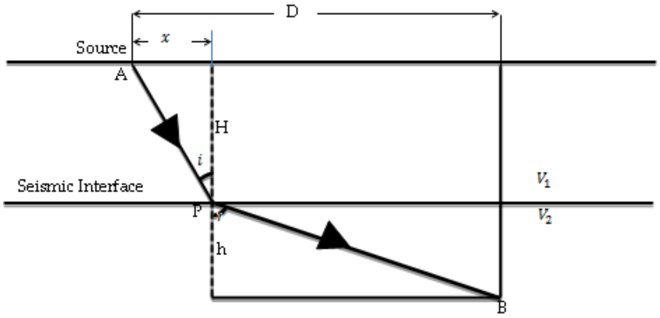

Figure 8. Seismic refraction method.

$$T = \frac{AP}{V_1} + \frac{PB}{V_2} = \frac{\sqrt{H^2+x^2}}{V_1} + \frac{\sqrt{h^2+(D-x)^2}}{V_2} \tag{16}$$

Differentiating (16) with respect to x and equating to zero i.e. $\frac{dT}{dx} = 0$, we have

$$\frac{x}{V_1\sqrt{H^2+x^2}} - \frac{D-x}{V_2\sqrt{h^2+(D-x)^2}} = 0 \tag{17}$$

$$\frac{\sin i}{V_1} = \frac{\sin r}{V_2} \text{ or } \frac{\sin i}{\sin r} = \frac{V_1}{V_2} \tag{18}$$

For the seismic refraction to take place along the interface boundary, $r = 90^0$, and if the corresponding angle of incidence is θ:

$$\sin\theta = \frac{V_1}{V_2} \tag{19}$$

To determine the depth of the aquifer, one can either use the intercept time method or the cross-over distance method.

6.2.1 *Intercept time method*

For direct waves,

$$T_D = \frac{x}{V_1} \tag{20}$$

For refracted waves,

$$T_R = T_{AB} + T_{BC} + T_{CD} = \frac{AB}{V_1} + \frac{BC}{V_2} + \frac{CD}{V_1} \tag{21}$$

$$T_R = \frac{2H}{V_1\cos\theta} + \frac{x-2H\tan\theta}{V_1} = \frac{x}{V_2} + \frac{2H}{V_1\cos\theta} - \frac{2H\tan\theta\sin\theta}{V_1} = \frac{x}{V_2} + \frac{2H}{V_1\cos\theta}[1-\sin^2\theta] \tag{22}$$

$$T_R = \frac{x}{V_2} + \frac{2H\cos\theta}{V_1} = \frac{x}{V_2} + \frac{2H\sqrt{{V_2}^2-{V_1}^2}}{V_1V_2} \tag{23}$$

The slope of this segment on the travel time curve is $\frac{1}{V_2}$ and the intercept on the time axis is

$$T_i = \frac{2H\sqrt{{V_2}^2-{V_1}^2}}{V_1V_2} \tag{24}$$

Therefore, the depth of the formation is given as:

$$H = \frac{V_1V_2T_i}{2\sqrt{{V_2}^2-{V_1}^2}} \tag{25}$$

6.2.2 *Cross-over distance method*

The cross-over distance method is an alternative method for determining **H**. Due to the absence of a precise linear relationship in the field data, it is recommended to verify the outcomes utilising different approaches such as the cross-over distance method. This technique takes into account that both direct and refracted waves reach the geophone simultaneously. The direct wave arrives first when the distance is less than this value, whereas the refracted waves arrive first when the distance is greater than the value (Hamid and Ezadin, 2020).

Hence, for $\mathbf{X} = \mathbf{X_D}$, $\mathbf{T_D} = \mathbf{T_R}$.

$$\frac{X_D}{V_1} = \frac{X_D}{V_2} + \frac{2H\sqrt{{V_2}^2-{V_1}^2}}{V_1V_2} \tag{26}$$

$$H = \frac{1}{2}\left[\sqrt{\frac{V_2-V_1}{V_2+V_1}}\right]X_D \tag{27}$$

To explore the thickness of the aquifer, we use the geometry in Figure 9.

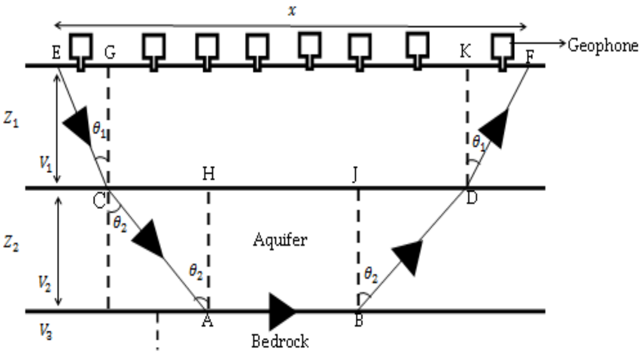

Figure 9: Exploration for aquifer thickness.

$$T_{RR} = T_{EC} + T_{CA} + T_{AB} + T_{BD} + T_{DF} \tag{28}$$

$$T_{RR} = \frac{EC}{V_1} + \frac{CA}{V_2} + \frac{AB}{V_3} + \frac{BD}{V_2} + \frac{DF}{V_1} \tag{29}$$

$$T_{RR} = \frac{2EC}{V_1} + \frac{2CA}{V_2} + \frac{AB}{V_3} \tag{30}$$

$$\frac{V_1}{V_2} = \frac{\sin\theta_1}{\sin\theta_2}\ ;\ \frac{V_2}{V_3} = \sin\theta_2 \tag{31}$$

$$\frac{V_1}{V_2} = \sin\theta_1\ ; EC = \frac{Z_1}{\cos\theta_1}; CA = \frac{Z_2}{\cos\theta_2} \tag{32}$$

$$T_{RR} = \frac{2Z_1}{V_1\cos\theta_1} + \frac{2Z_2}{V_2\cos\theta_2} + \frac{x-EG-CH-JD-KF}{V_3} \tag{33}$$

$$T_{RR} = \frac{x}{V_3} + \frac{2Z_1\cos\theta_1}{V_1} + \frac{2Z_2\cos\theta_2}{V_2} \tag{34}$$

7. AQUIFER CONTAMINATION

Many things can render aquifer water useless by making it unhealthy for consumption. The contaminants can be grouped into natural and artificial.

7.1 Natural contaminants

- The presence of radioactive elements in the host rock
- The presence of microbes in the pore water as a result of decayed organic matter

- Presence of substances such as heavy metals like lead, iron, manganese, arsenic, chlorides, fluorides and sulphates in the host rocks.

7.2 Sources of artificial contaminants

- Landfills and dumpsite
- Applications of pesticides and fertilizer
- Oil spills and other petroleum products
- Industrial waste disposal
- Aftermaths effects of war
- Burial site

8. CONCLUSION

Careful consideration and detailed explanation of the characteristics of the subsurface water-bearing strata in this review. Water-bearing layers have been classified according to their water-transmitting properties into aquifers, aquitards, aquicludes and aquifuge. The aquifer has further been classified as confined, unconfined, leaky, perched and idealized depending on their permeability and porosity characteristics.

Parameters that determine the ability to retain and transmit water such as porosity and permeability which are the two most important factors governing the accumulation, migration and distribution of groundwater have also been discussed in this note. Both parameters change within rocks in the course of geologic evolutions. Storativity and transmitivity were also discussed.

Surface geophysical techniques of the Electrical resistivity method and Seismic refraction method have been looked into as a way of assessing the subsurface water-bearing strata. The electrical resistivity method entails injecting current into the ground and quantifying the potential difference created by the presence of the current. The seismic refraction method involves the artificial generation of elastic waves using sources like vibroseis, weight drop, hammer blow, explosives (dynamite) and pimacord in the ground.

Recommendation is hereby given for subsequent review of this nature to include the determination of depth at which water is found in the subsurface, the chemical composition and suitability of water for its intended use, hydrogeological studies which could include the study of geological processes that affect the distribution and movement of subsurface water and the sustainable amount of water that can be drawn from an aquifer over a while without causing adverse impacts on the environment.

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