



# Numerical modeling of vadose zone electrical resistivity to evaluate its hydraulic parameters

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## Abstract

Studying and determining the physical properties and hydraulic parameters of vadose zone sediments is an important key to evaluate the infiltration rate into them and assessing the extent to which aquifer sediments benefit from rainwater harvesting in arid and semi-arid areas. Due to the lack of sufficient data on the characteristics of this zone depths, a numerical modeling was used to simulate the electrical resistivity of these sediments by applying the electrical resistivity method, because it is the most affected by the physical properties of dry and wet sediments. This study was applied as a proposal for application in northwestern KSA to calculate the vertical hydraulic conductivity and transmissivity for the vadose zone. This was implemented by assuming a three-layer model using COMSOL Multiphysics model with different electrical resistivity values depending on some in situ electrical resistivity measurements for shallow depths. Hence, the infiltration rate of sediments in this area can be predicted with depth and its effect on aquifer recharge. The focus was on calculating the vertical hydraulic parameters of the most widespread surface sediments with depth and comparing the results of calculating these parameters for some sediments laboratory-wise to ensure their accuracy. Then, their infiltration rate was inferred separately with depth, predicting their ability to aquifer recharge and make the most of rainwater harvesting. Finally, this study can be considered as a preliminary study to determine the expected forward model of electrical resistivity and hydraulic parameters values for the vadose zone sediments with depth along the area and in any other areas, and then apply them accurately in situ to estimate the extent of its usefulness in rainwater harvesting, especially aquifer recharge.

**Keywords** Vadose zone soil textures · COMSOL Multiphysics model · Electric potential and resistivity · Hydraulic conductivity and transmissivity · Infiltration rate and aquifer recharge

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## Introduction

Generally, the vadose zone or the unsaturated zone is the zone of soil texture that covers the saturated zone or the groundwater aquifer. The sediment type of the soil texture of this zone is considered an interesting factor in groundwater recharge and pollution attenuation depending on their infiltrating rate. This rate depends upon the effective porosity and effective permeability or hydraulic conductivity of the sediments, as well as their thickness. The hydraulic conductivity is in general influenced by different factors such as soil texture, grain size distribution, roughness, tortuosity, shape, and degree of interconnection of water-conducting pores. The coarser textured soils would typically have higher hydraulic conductivities than fine-textured soils. The typical total and effective porosity values of the unconsolidated deposits were measured practically via different scientific

organizations. The logic and famous ranges values of porosities of different sediments are concluded in Table 1.

(Bouwer 2002) and (Healy and Scanlon 2010) state that the recharge rates to the groundwater aquifer from surface depending on the thickness of the vadose/unsaturated zone. If the unsaturated zone is thick, means that the rate of recharging to the groundwater is low while the small thickness of the unsaturated zone means that the recharging rate is high and fast. The impact of vadose zone has been evaluated through different analysis such as comparative analysis of material favoring to water percolation downwards using harmonic mean approach (Hussain et al. 2006). Most of the previous carried studies on the vadose zone were focused on the physical and hydraulic properties of the shallow or the thin thickness of the soil texture of this zone without focusing on the sediments beneath this thickness.

Depending on the flow of electrons of electric current through the same paths (pores) in which ions of water molecules move, as the flow of water is through pores that are connected or that have a high permeability, this numerical model will be applied to calculate the value of the electric potential for this current that passes through these pores, as well as the value of its electrical resistivity is also calculated. The used method to achieve this target is the resistivity method. Based on all this, it is possible to deduce the values of the hydraulic parameters of sediments of different grain sizes, which the larger their size, the greater the values of their electrical resistivity, and vice versa in the cases of dry and moisture, and then it is possible to calculate and predict their hydraulic parameters, especially the hydraulic conductivity and transmissivity. These two last parameters have a main role in predicting the infiltration rate and the ability to groundwater recharge.

Accordingly, this study will focus on the physical and hydraulic properties of the shallow sediments (dry sediments) and deep sediments (moisture sediments) of the soil texture of the vadose zone depending on their electrical characteristics using numerical modeling. This model will use to simulate the electrical resistivity of these sediments by computing the electrical potential of the electric current during passing through them. In general, this interesting electric

property (resistivity) depends upon different factors such as type of sediments, sizes of grains, porosity, permeability, and water saturation percentages of the pores among the grains of sediments as well as the water quality into the pores..., etc. In this study, the resistivity values of the shallow and deep sediments will be calculated from the computed electrical potential. These values will then be used to predict the type of sediment, its effective porosity, and its vertical hydraulic conductivity, as there are no surface tools to calculate these interesting parameters to predict the infiltration rate with depth, which is considered a high influence factor on groundwater recharge in this area and other areas at the arid and semi-arid regions. Also, using traditional methods to calculate the vertical hydraulic parameters with depth is considered difficult and requires accuracy, in addition to being high in cost and requiring a long time to implement. Therefore, to avoid the previous difficulties, in this study the electrical potential of subsurface sediments will be calculated to calculate their resistivity values with depth, which depend on several factors such as permeability, moisture content, water saturation rates, etc., using numerical modeling. So, along the selected area of study, as shown in Fig. 1, and according to the recorded types of sediments of the soil texture of the vadose zone, as shown in Fig. 3E, it will be simulating the electrical resistivity of these sediments for expecting and classifying the areas of high, medium and low vertical hydraulic conductivity and transmissivity and therefore the areas and zones with depth of high infiltrating rate and groundwater recharge potentials.

## Application area description

The selected area, as shown in Fig. 1, locates between latitudes 24° N and 32° N and longitudes 36° E and 45° E, especially north-west of the KSA. There are three main big towns within this area called Al-Jouf, Tabuk and Al-Qassim. The climate conditions of this area are generally arid with little annual rainfall. The ranges of rainfall are <30 mm/y (low)—170 mm/y (high) to the west and south east parts of the study area. These rates of precipitation are interesting

**Table 1** Approximate ranges of total porosity, effective porosity and hydraulic conductivity values and their averages of the different types of variable sediments (Freeze and Cherry 1979)

Types of sediments	Total porosity %	Average total porosity %	Effective porosity %	Average effective porosity %	Hydraulic conductivity in m/s
Gravel	25–44	34.5	13–44	28.5	$10^{-3}$ -1
Coarse sand	31–46	38.5	18–43	30.5	$10^{-5}$ - $10^{-2}$
Medium to fine sand	25–53	39	1/16–46	23.5–31	
Silt, loess	35–50	42.5	1–39	20	$10^{-9}$ - $10^{-5}$
Clay	40–70	55	1–18	9.5	$10^{-12}$ - $10^{-8}$

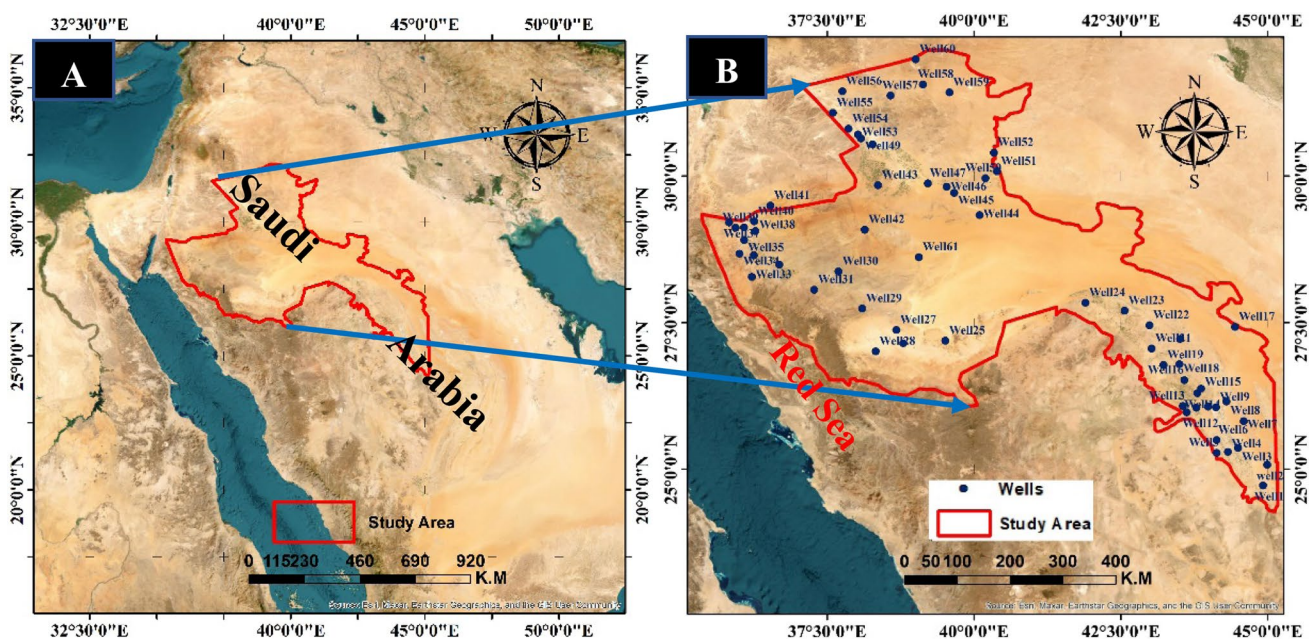


Fig. 1 General location map of the study area (A) and the groundwater wells distribution map (B)

in groundwater recharging especially in the areas of high infiltration sediments. Most the rainfall rates occur in two months October to April but in an irregular short-time. The rate of evaporation is in general high along the area. In summer, the ranges of temperature are about 43–48 °C and 32–36 °C during day time and night time, respectively, while it may reduce to 0 °C in winter.

Topographically, the western part has the highest elevations > 1800 m because of the presence of mountains. Along the western parts, the terrains are bounded by

valleys with an elevation of ~800 m and these are flat. In general, around 85% of this area is flat and it's dipping is generally toward the east direction. The general elevation, as shown in Fig. 2C, ranges from 900 m (W) to 400 m (E). This dipping is interesting in describing the surface morphology and in controlling all the surface operations, such as runoff and capacity of rainfall water infiltration (Daher et al. 2011). Where the areas of <5 in slope are considered more suitable for subsurface recharging (Zaidi et al. 2015).

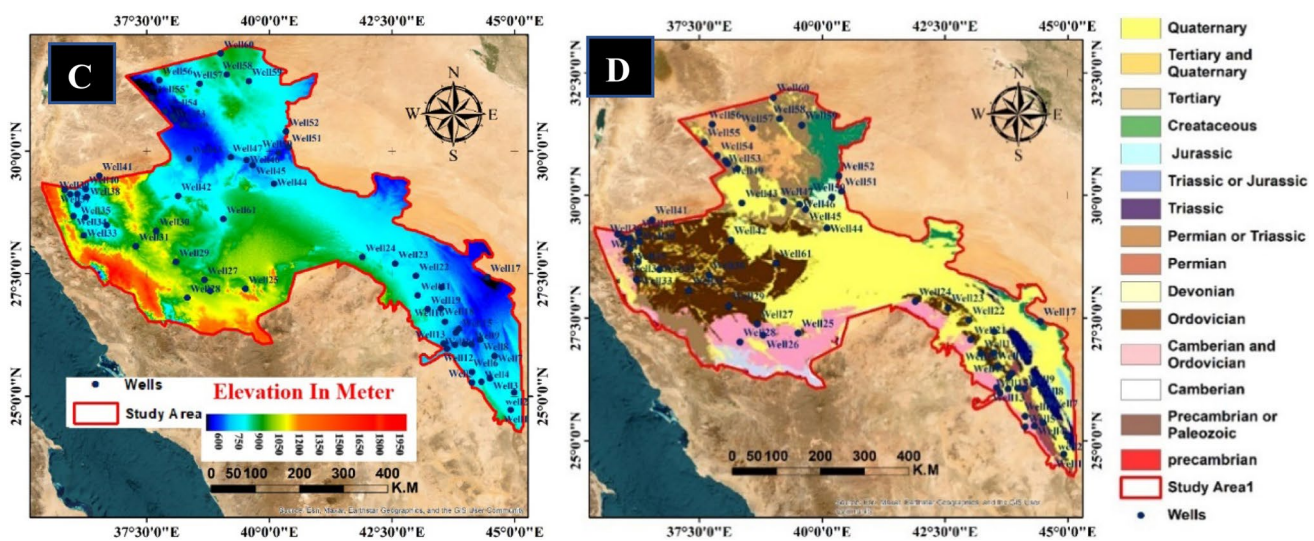


Fig. 2 Elevation map in m (C) and Surface geological map (D) of the study area (modified after Zaidi et al. 2015)

## Geology of the application area

Generally, along the Arabian Peninsula, there are two geological units one is the basement rocks (Arabian Shield to the west) and the other is the Phanerozoic sedimentary rocks (Arabian Platform to the east). This last sedimentary unit is thickening gradually from W to E (Rodgers et al. 1999). The Cambro-Ordovician Saq Sandstone was over the basement rocks and it is outcropped to the west where the Arabian Shield and made up of medium to coarse sandstone. The thickness of this formation ranges from 400 to 925 m and it is considered the major aquifer system in KSA, especially to the north (Alsharhan et al. 2001). According to (Laboun 2013) and (Al-Dabbagh 2013), the stratigraphic succession of this area consists of Cenozoic, Mesozoic, and Paleozoic periods. The Cenozoic sediments are made up of Quaternary Eolian deposits, which are made up of sand, silt and clay, as well as basaltic lava flows and carbonate rocks with thickness ranges from 135 to 230 m. The Mesozoic sediments made up of large amounts of limestone, shale intercalation and sandstone with thickness ranges from 2324 to 2462 m, as well as shale thickness ~ 116 m separates these sediments from the sediments of Paleozoic. These last sediments are made up of, from upper to lower, fractured limestone with shale (Kuff formation, 170 m thickness), sandstone (Unayzah formation, 80–85 m thickness), siltstone (190 to 270 m thickness), sandstone (Jubah formation, 300–410 m thickness), limestone with shale and sandstone intercalation (Jouf formation, 270–280 m thickness), sandstone (Tawil formation, 230–250 m thickness), shale, sandstone and siltstone (Qalibah formation, 450 m thickness), sandstone, shale, and siltstone (Tabuk formation, 140–160 m thickness), sandstone and shale (Qassim formation, 260 m thickness) then sandstone (Saq formation, 400–930 m thickness). From the previous sediments of the Paleozoic, the main sediments of this age are sandstone with minor shale, limestone, and siltstone and its total thickness ranges from 2490 to 3265 m. Accordingly, the total thickness of the previous stratigraphic succession ranges from ~ 4949 to 5957 m along the study area and it may reach greater than 8000 m at the areas of major sedimentary basins. Figure 2D represents the surface geological map which shows some of the previous sediments and their distribution on the surface along the study area.

## Hydrogeology of the application area

According to the previous studies, there are several layers represent the groundwater aquifer system along the area over the Precambrian Arabian Shield. In general, the aquifer systems along the study area include: Paleozoic sandstone of Saq, Al-Wajid and Tabuk formations, fractured limestone of Khuff formation; Mesozoic sandstone of Dhurma, Al-Biyadh and Al-Wasia formations; fractured limestone of

Um-Radmah and Al-Dammam formations; then Cenozoic alluvial deposits (calcareous, silty sandstone, sandy limestone and chert) (Alsharhan & Nairn 2003). So, the Saq formation is not considered the unique source of groundwater along the area but there are other sources of it. These groundwater sources include from bottom to top with depth to water level and hydraulic conductivity or the rate of groundwater movement through the saturated sediments ((MoWE 2008); (Ahmed et al. 2015)) are:

- Moderately cemented and medium to coarse-grained sandstone of Saq formation with depth to water level varies from 65 to 297 m, and low hydraulic conductivity is ~ 4.36 m/d;
- Sandstone with shale, Qassim formation, with depth to water level varies from 30 to 250 m and medium hydraulic conductivity is ~ 9.5 m/d;
- Sandstone and shale of Qassim formation to Sarah sandstones of Tabuk formation with depth to water level varies from 85 to 240 m and very low hydraulic conductivity is ~ 0.864 m/d;
- Shale, sandstone and siltstone of Qalibah formation and Tawil sandstones with depth to water level is 120 m and very high hydraulic conductivity is ~ 21.64 m/d;
- Sandstone of Jubah formation with depth to water level varies from 120 to 150 m and very low hydraulic conductivity is ~ 0.56 m/d;
- Fractured shaly limestone of Khuff formation with depth to water level varies from 192 to 250 m and low hydraulic conductivity is ~ 4.36 m/d; then
- The secondary Mesozoic, Tertiary and Quaternary sandstone and limestone (STQ) with depth to water level varies from 15 to 290 m, and very high hydraulic conductivity is ~ 17.49 m/d.

The last aquifer is characterized by limestone and more content of shale with small thickness of sandstone and it was separated from the previous six aquifers with shale of Sudair formation with thickness ~ 116 m. This means that the previous aquifer groups are under confined conditions. Also, there are two aquitards layers made up of limestone, shale, and sandstone of Jouf formation with depth to water level varies from 130 to 250 m, and very low hydraulic conductivity is ~ 0.68 m/d ((MoWE 2008); (Ahmed et al. 2015)) and sandstone and siltstone of Unayzah and Berwath formation with thicknesses varies from 170 to 280 m, 80 to 85 m, and 190 to 270 m, respectively. These two aquitard layers include units considered as aquifer ((Laboun 2013) and (Al-Dabbagh 2013)). All the previous aquifer groups are recharged from precipitation and the high recharge process occurred during the past wet climatic periods ((Scanlon et al. 2002); (Sultan et al. 2008); (Zaidi et al. 2015)). Therefore, the recharging of these groups of aquifers from rainwater

harvesting is expected to be difficult and depend on the parts of huge thickness of vadose zone and the ways of hydraulic connections like the major faults and location of the high transmissivity between these aquifer groups and location of high infiltration rates into the vadose zone.

### Vadose zone and groundwater level of application area

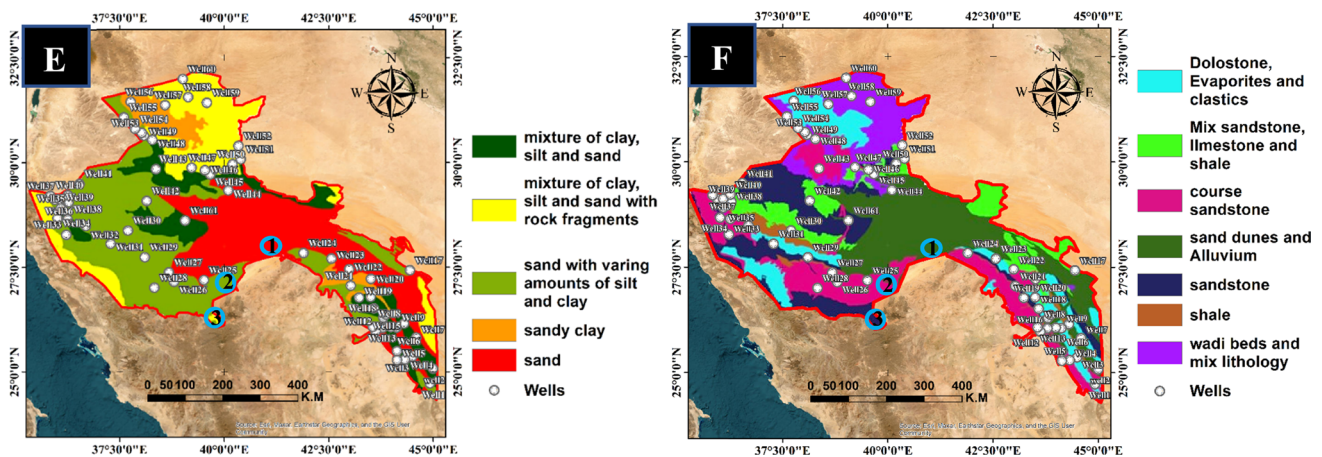
Generally, the vadose or unsaturated zone along the study area is composed of different soil textures, as shown in Fig. 3E. These textures are sand and gravel soil texture, sand with varying amounts of silt and clay soil texture, a mixture of clay, silt and sand soil texture, as well as clay and sandy clay soil texture. (Nazzal et al. 2014), stated that more than 50% of soil texture along the study area consists of silt and clay with mixture of sand while ~0.1% of sand with mixture of silt and clay. So, ~64% of the area is considered useless for rainwater harvesting because it is covered with sandy clay and silt which did not confine water long enough and was lost to infiltration. ~15.6% of the cover sediments are more confinement for rainwater harvesting due to its high capacity in water holding.

### Vadose or unsaturated zone characteristics

The hydraulic conductivity of the surface sediments as well as water confinement capacity are considered as main and interesting parameters and factors in subsurface recharging or for polluting the aquifers. These parameters are basically

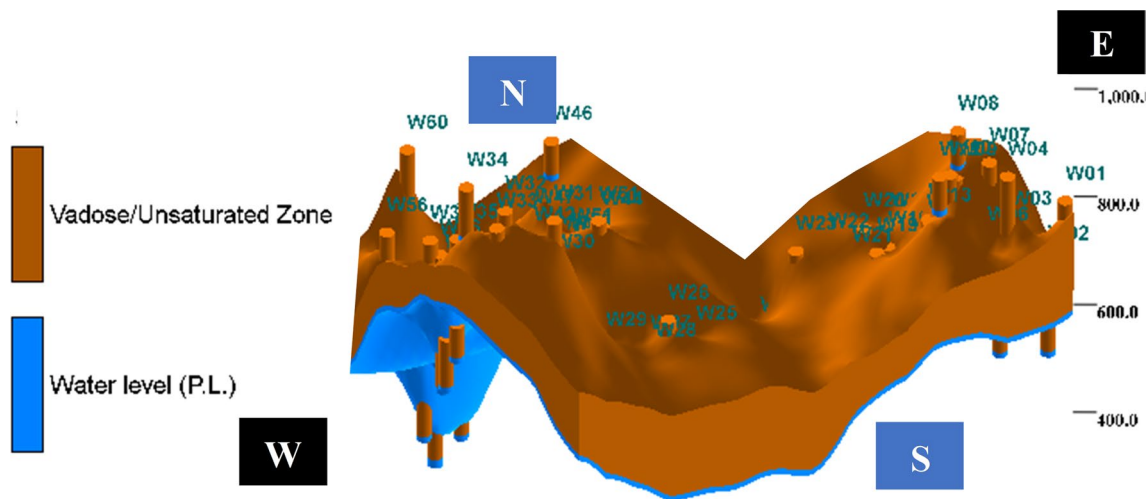
controlled by the mineral composition and texture of the sediments as well as the cover of land and area slope (Jang et al. 2013). According to the distribution of surface sediments along the study area (Fig. 3E), there is a mixture of clay, rocky (rock fragments) clay, sandy clay and silt, sand with clay and silt then sand. The areas of the high mixture of clay, sand and silt are very low in effective porosity and, accordingly, in hydraulic conductivity and considered as areas useless for groundwater recharging or percolating the rainwater to the aquifer or for good drainage to infiltration. While, the areas rich with sediments of sand (coarse and medium) and gravel with minor content of silt and clay are good for drainage. This means that these areas are very appropriate for groundwater recharging (Water Atlas of KSA 1984), especially at the areas of sandstone, fractured limestone, and Quaternary aquifers, as distributed on the map of subsurface aquifer sediments (Fig. 3F).

The thickness of this zone along the area is ranged from 30 to 295 m, as shown on the 3D visualizing model (Fig. 4), and 3D fence diagram (Fig. 5), and its average is around 108 m. These thicknesses are considered the depths to the subsurface aquifer. The depths to groundwater were measured in 2015 and it was found that these depths ranged from less than 20 to ~357 m from the surface (Zaidi et al. 2015), and the average of these depths is around 188 m. The groundwater level along the study area, as shown in the 3D Fence diagram (Fig. 5) and 2D visualizing model (Fig. 6), is ranged from 857 to 404 m (+msl), and its average is 619 m (+msl). Therefore, these 3D models show a high variation in the thickness of the vadose zone and groundwater levels or depths and groundwater aquifers along the study area.

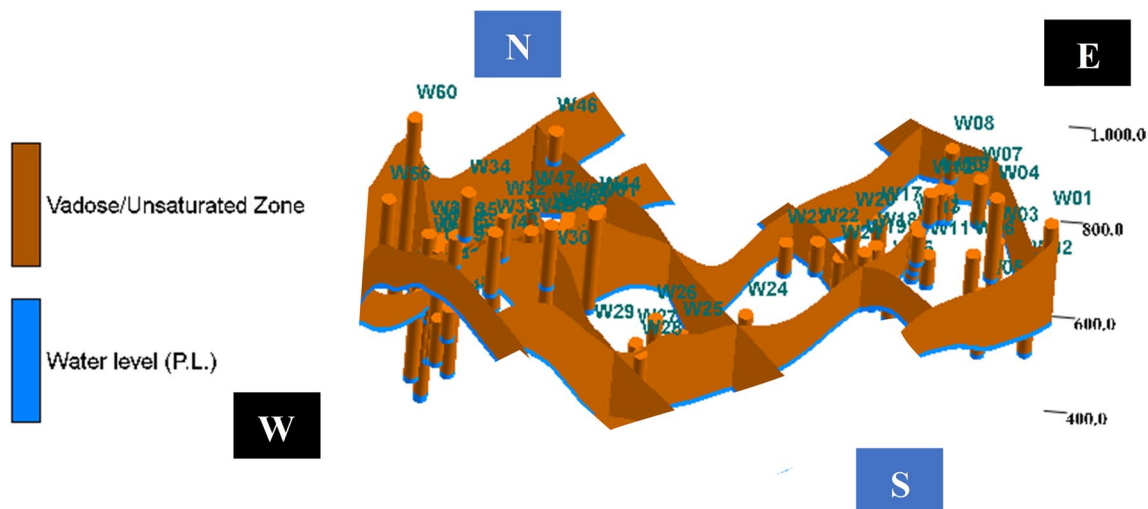


**Fig. 3** Surface soil textures distribution map (E) (modified after (Zaidi et al. 2015)) and Subsurface aquifer sediments distribution map (F) (modified after (Ahmed et al. 2015)) of the study area, as

well as the sites (1, 2, and 3, light blue circles) of the measured apparent resistivity data



**Fig. 4** 3D visualizing model for showing the vadose zone thickness and groundwater level fluctuation along the study area (designed by RockWorks16, new version of RockWare's integrated software package)



**Fig. 5** 3D Fens diagram for showing the vadose thickness and groundwater level fluctuation along the study area (designed by RockWorks16, new version of RockWare's integrated software package)

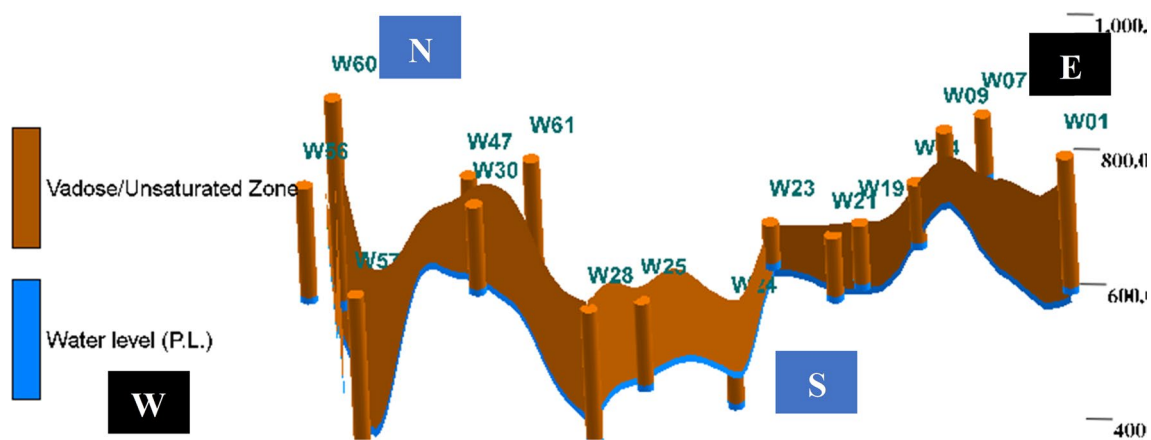
## Methodology

### Vadose zone electrical modeling

#### Inputs and assumptions of numerical model

COMSOL Finite Element Package, version 5.4, was used to simulate the electrical resistivity of the vadose zone/unsaturated zone which covers the saturated zone/groundwater aquifer for identifying and classifying the zones of high, medium and low infiltration rates and groundwater recharge potentials. In this study and according to the

classification of the soil texture along the area, as shown in Fig. 3E, the used model will compute the electrical potential values of the different sediments which represent the soil texture. Then these potential values will be used in calculating the resistivity of these sediments with depth, as forward model. These resistivity values will assist in reflecting the sediments types and their ability in infiltrating the rainwater and therefore expecting the recharging potential of the groundwater aquifer. For achieving this goal, we assumed parameters of the model for the recorded soil texture sediments along the area of study which include dry (shallow vadose zone) and moisture (deep vadose zone) sand and gravel soil texture, sand with



**Fig. 6** 2D visualizing model for showing the vadose zone thickness and groundwater level fluctuation along the study area (designed by Rock-Works16, new version of RockWare’s integrated software package)

varying amounts of clay and silt soil texture, mixture of the silt, clay and sand soil texture, then clay and sandy clay soil texture. The assumed parameters are including the classification of the shallow and deep geological media into three layers that are different in their resistivities/conductivities values and thickness. These layers are the dry shallow vadose zone, moisture vadose zone, and saturated zone (aquifer), as shown in Tables 2–5. These parameters have been assumed depending on the measured apparent resistivity data (forward model from the field measurements) at some soil textures in the study area, as shown in Fig. 3E, light blue circles (1, 2, and 3), especially for detecting and predicting the physical and geological properties of the shallow vadose zone sediments.

For carrying out this simulation, we measured the apparent resistivity of the shallow section of the sediments at three stations using 1D vertical electrical sounding method, as distributed on the map in Fig. 3, (light blue circles), with focusing on the most widespread sediments along the study area, which are sand with gravel or wadi deposits, sand with varying amounts of silt and clay then the clay to sandy clay, as shown on Fig. 3E. The measured apparent resistivity data (soundings, VESs) by applying Schlumberger array geometry and using a Campus Omega ( $\Omega$ ) resistivity meter are represented in Fig. 7 for sand and gravel sediments (G), sand with varying amounts of clay and silt sediments (H) then

clay and sandy clay sediments (I). According to the interpretation of these curves, we assumed the required values of electrical resistivities and conductivities of the shallow depths of the vadose zone and the first depths of the deep zone of the vadose zone, as well as the assumed thickness of the vadose zone and the depth to groundwater aquifer depending, also, on good data. These data, as reported in Tables 2–5, were used as input data in the model for simulating the electrical resistivity of the shallow and deep depths of the vadose zone for predicting the flowing of rainwater harvesting vertically and the extent to which the aquifer is affected by it then to achieve the properties of the deep depths which were not recorded by the measured data.

In COMSOL Multiphysics model, the physics is electrical current and the solution is stationary. The electrical interface will be used to compute the electrical potential in the dry (resistive medium) and moisture (semi-conductive medium) vadose zone sediments. More details about this model were stated by (Ammar 2021) and (Ammar et al. 2023). The block geometry, the number of geologic layers (three-layer model) and their geologic and electrical (resistivity and conductivity) characteristics are shown in Fig. 8 and reported in Tables 2–5. The meshes type of these geological layers and surface cylinder are finer meshes and fine mesh (free tetrahedral mesh), respectively, as shown in Fig. 8. The resistivity of this cylinder has the same resistivity of the upper

**Table 2** Assumed parameters for a three-layer model of sand and gravel soil texture

Layers no.	Resistivity ( $\Omega$ .m)	Conductivity (S/m)	Thickness (km) equivalent to (m) in earth model	Geologic description of soil texture
L1	$\rho_1 = 1070$	$\sigma_1 = 0.00093$	$h_1 = 0.1$ km (100 m)	Dry sand and gravel (Vadose Soil)
L2	$\rho_2 = 190$	$\sigma_2 = 0.00526$	$h_2 = 0.3$ km (300 m)	Moisture sand and gravel (Vadose Soil)
L3	$\rho_3 = 50$	$\sigma_3 = 0.02$	$h_3 = 1.58$ km (1580 m)	Aquifer

(shallow) vadose zone, as recoded in Tables 2–5, and they are considered as one layer. The value of the applied direct current (DC) through the current ( $C_1$  and  $C_2$ ) electrodes is 0.05 A or 50 mA. Therefore, the 1D-Vertical Electrical Sounding (VES) by applying Schlumberger array will be used with different spacings between electrodes ( $C_1$  and  $C_2$ ) are 0.003, 0.008, 0.016, 0.03, 0.05, 0.08, 0.15, 0.3, 0.6, 1, 1.8, and 2 [km].

### Governing equations

Equation 1 is the assuming equation in case of electric current:

$$\nabla \cdot J = Q_{j,v} \quad (1)$$

where  $Q$  is a volumetric source of current inside the selected layers ( $A/m^3$ ) and  $J$  is the density of current (volume) ( $A/m^2$ ).

A discretization and dependent variable are the electrical potential  $V_2$ . The relation defines that; the current density is circulated by introducing a current. This current generated externally ( $J_e$ ). The resulting constitutive relations are shown as follow:

$$J = \sigma E \quad (2)$$

$$J = \sigma E + J_e \quad (3)$$

$$E = -\nabla v \quad (4)$$

where  $\sigma$  is the electrical conductivity (EC) (S/m),  $E$  is the electrical field,  $v$  is the electrical potential (V), and  $J_e$  is the external current density ( $A/m^2$ ).

### Outputs of numerical model

Generally, the computed electrical potential values and calculated apparent resistivity values are the main results of this model. Therefore, these results using this model will assist in understanding, identifying, and classifying the physical, geological and hydraulic properties of the vadose zone of different soil textures with depth.

### Calculating the values of electrical potential and apparent resistivity of the vadose zone soil textures

#### In case of sand and gravel soil texture

According to the assumed resistivity/conductivity values in Table 2 in case of the soil texture of the vadose zone is sand and gravel, the electrical potential due to flow the electric current through this texture will be computed. Figures 9,

10 in XY- view show the computed electric potential for this case, when the spacings between  $C_1$  and  $C_2$  are 30 m ( $C_1C_2/2 = 15$  m), in dry sand and gravel soil texture, and 150 m ( $C_1C_2/2 = 75$  m), in moisture sand and gravel soil texture. This short spacing between  $C_1$  and  $C_2$  is for computing the electrical potential values at shallow dry depths (L1); while, the long spacing is for computing the electrical potential values at deep moisture depths (L2) of the vadose zone. Accordingly, the electric potential values at the shallow dry depths are high, while these values reduce with depths at the moisture depths. This is due to the current density being very low in the shallow dry zone and low in the moisture zone. Figure 11 represents the electrical potential values in different spacings between  $C_1C_2$  in case of the vadose zone soil texture is sand and gravel.

According to the computed electrical potential values between different spacings of current electrodes  $C_1$  and  $C_2$ , as in Table 6, the apparent resistivity values for each spacing between  $C_1$  and  $C_2$  ( $C_1C_2/2$ ) were calculated using Eq. 5, as in Table 6. The resulting curves of electrical potential values and apparent resistivity values (VES) with different spacings between current electrodes of this case of vadose zone soil texture are represented in Fig. 12 (J and K), respectively.

$$\rho_a = \frac{2\pi}{\frac{1}{C_1P_1} - \frac{1}{C_2P_1} - \frac{1}{C_1P_2} + \frac{1}{C_2P_2}} \frac{\Delta V}{I} \quad (5)$$

Where  $\rho_a$  is the apparent resistivity ( $\Omega.m$ ),  $I$  is the current intensity (A),  $\Delta V$  is the potential difference between the potential electrodes (V),  $C_1$  and  $C_2$  are the current electrodes, and  $P_1$  and  $P_2$  are the potential electrodes.

In this case, the maximum and minimum electrical potential values are 1.518993845 V, computed when  $C_1C_2/2 = 1.5$  m at the first depths of the dry vadose zone, and 0.0383335 V, computed when  $C_1C_2/2 = 1000$  m at the last depths of the moisture vadose zone, respectively. The maximum and minimum apparent resistivity values were calculated at the same previous spacings of  $C_1C_2$  and they were 1139 ( $\Omega.m$ ) (very high value) and 267 ( $\Omega.m$ ) (high value), respectively (Table 6). The high value of the apparent resistivity at the deep depths are due to the effect of the moisture content of the zone over the groundwater water level. This moisture content is considered the main effect on reducing the resistivity of the sand and gravel soil texture at these depths.

#### In case of sand with varying amounts of silt and clay soil texture

Also, according to the assumed resistivity/conductivity values in Table 3 in case of the soil texture of the vadose zone is sand with varying amounts of silt and clay, the electrical potential of this texture was computed.



**Table 3** Assumed parameters for a three-layer model of sand with varying amounts of clay and silt soil texture

Layers no.	Resistivity ( $\Omega$ .m)	Conductivity (S/m)	Thickness (km) equivalent to (m) in earth model	Geologic description of soil texture
L1	$\rho_1 = 379$	$\sigma_1 = 0.00264$	$h_1 = 0.1$ km (100 m)	Dry sand with minor silt and clay (Vadose Soil)
L2	$\rho_2 = 156$	$\sigma_2 = 0.00641$	$h_2 = 0.3$ km (300 m)	Moisture sand with minor silt and clay (Vadose Soil)
L3	$\rho_{3-n} = 50$	$\sigma_3 = 0.02$	$h_3 = 1.58$ km (1580 m) Ave	Aquifer

**Table 4** Assumed parameters for a three-layer model of the mixture of silt, clay and sand soil texture

Layers no.	Resistivity ( $\Omega$ .m)	Conductivity (S/m)	Thickness (km) equivalent to (m) in earth model	Geologic description of soil texture
L1	$\rho_1 = 78$	$\sigma_1 = 0.01282$	$h_1 = 0.1$ km (100 m)	Dry mixture of silt, clay and sand (Vadose Soil)
L2	$\rho_2 = 35$	$\sigma_2 = 0.0286$	$h_2 = 0.3$ km (300 m)	Moisture mixture of silt, clay and sand (Vadose Soil)
L3	$\rho_{3-n} = 20$	$\sigma_3 = 0.05$	$h_3 = 1.58$ km (1580 m) Ave	Aquifer

**Table 5** Assumed parameters for a three-layer model of clay and sandy clay soil texture

Layers no.	Resistivity ( $\Omega$ .m)	Conductivity (S/m)	Thickness (km) equivalent to (m) in earth model	Geologic description of soil texture
L1	$\rho_1 = 7$	$\sigma_1 = 0.14286$	$h_1 = 0.1$ km (100 m)	Clay (Vadose Soil)
L2	$\rho_2 = 19$	$\sigma_2 = 0.05263$	$h_2 = 0.3$ km (300 m)	Moisture sandy clay (Vadose Soil)
L3	$\rho_{3-n} = 12$	$\sigma_3 = 0.0833$	$h_3 = 1.58$ km (1580 m) Ave	Aquifer

Figures 13, 14 in XY- view show the computed electric potential for this case, when the spacings between  $C_1$  and  $C_2$  are 30 m, in dry sand with varying amounts of silt and clay soil texture, and 150 m, in moisture sand with varying amounts of silt and clay soil texture. Accordingly, the electric potential values at the shallow dry depths are medium; while, these values are low at the moisture depths, due to the current density is medium at the shallow dry zone and medium at the moisture zone. The electrical potential values of this case are represented in Fig. 15. According to the computed electrical potential values (Table 7), the apparent resistivity values were calculated (Table 7). The resulting curves of electrical potential values and apparent resistivity values (VES) of this case of vadose zone soil texture are represented in Fig. 16 (L and M), respectively.

Also, the maximum and minimum electrical potential values were 0.535101632 V, computed when  $C_1C_2/2 = 1.5$  m, and 0.014846755 V, computed when  $C_1C_2/2 = 1000$  m, respectively. The maximum and minimum calculated apparent resistivity values were 401 ( $\Omega$ .m) and 146 ( $\Omega$ .m), respectively (Table 7). The previous high values are resulted due to the occurrence of minor amounts of clay and silt but the medium values due to the effect of the moisture content of the zone over the groundwater water level and medium amounts of clay and silt. In this case, the moisture content and the amounts of clay and silt

are considered the main effect of reducing the resistivity values.

**In case of a mixture of silt, clay and sand soil texture**

Also, according to the assumed resistivity/conductivity values in Table 4 in case of the soil texture of the vadose zone is a mixture of silt, clay and sand, the electrical potential was computed. Figures 17, 18 in XY- view show the computed electric potential for this case, when the spacings between  $C_1$  and  $C_2$  are 30 and 150 m, respectively. Therefore, the electric potential values at the shallow dry zone are low; while, these values are very low at the moisture zone, due to the current density is high at the dry zone and very high at the moisture zone. The electrical potential values of this case are represented in Fig. 19. According to the computed electrical potential values, as in Table 8, the apparent resistivity values were calculated, as in Table 8. The resulting curves of electrical potential values and apparent resistivity values of this case of soil texture are represented in Fig. 20 (N and O), respectively.

In this case, the computed maximum and minimum electrical potential values were 0.197416573 V, when  $C_1C_2/2 = 1.5$  m, and 0.003233713 V, when  $C_1C_2/2 = 1000$  m, respectively. Also, the maximum and minimum calculated apparent resistivity values were 88.9

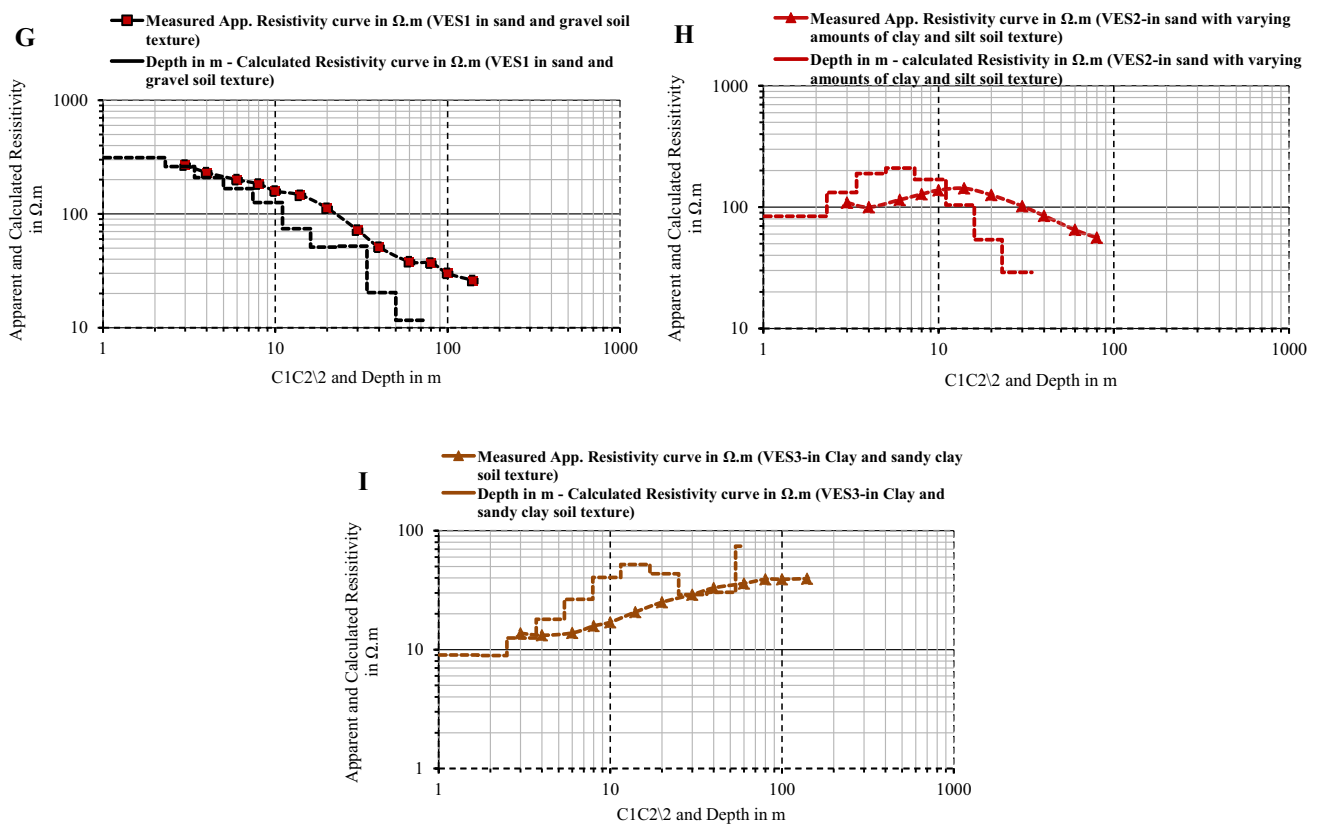


Fig. 7 Measured apparent resistivity data (VESs curves) in different vadose zone sediments along the study area

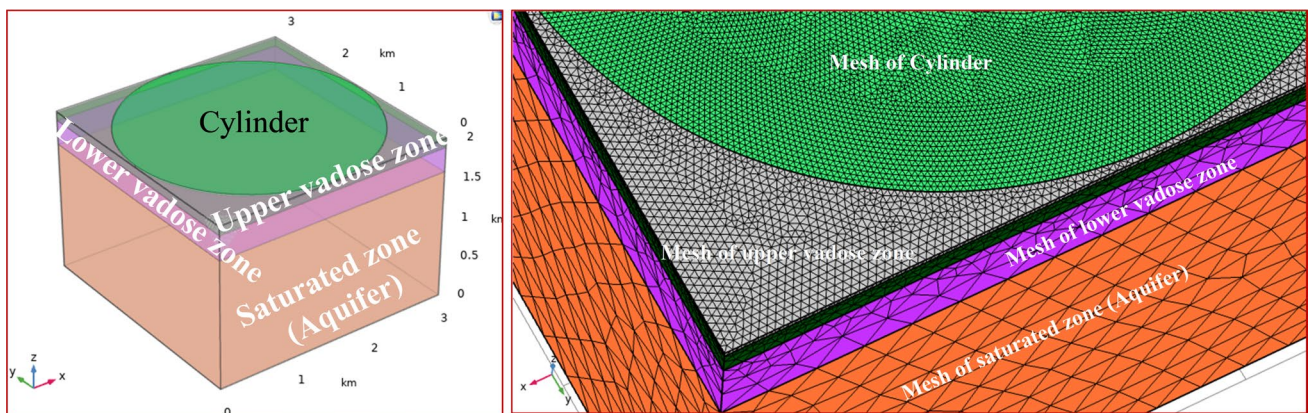


Fig. 8 3D view for showing the meshes types of the zones and surface cylinder

( $\Omega.m$ ) and 35 ( $\Omega.m$ ), respectively (Table 8). The previous medium values are resulted due to the occurrence of medium amounts of clay and silt but the low values due to the effect of the moisture content zone and medium amounts of clay and silt. In this case, the moisture content and the medium amounts of clay and silt are considered the main effect of reducing the resistivity values of this texture.

**In the case of clay and sandy clay soil texture**

According to the assumed resistivity/conductivity values in Table 4 in case of the soil texture of the vadose zone is clay and sandy clay, the electrical potential was computed. Figures 21, 22 in XY- view show the computed electric potential, when the spacings between  $C_1$  and  $C_2$  are 30 and 150 m, respectively. Therefore, the electric potential values at the

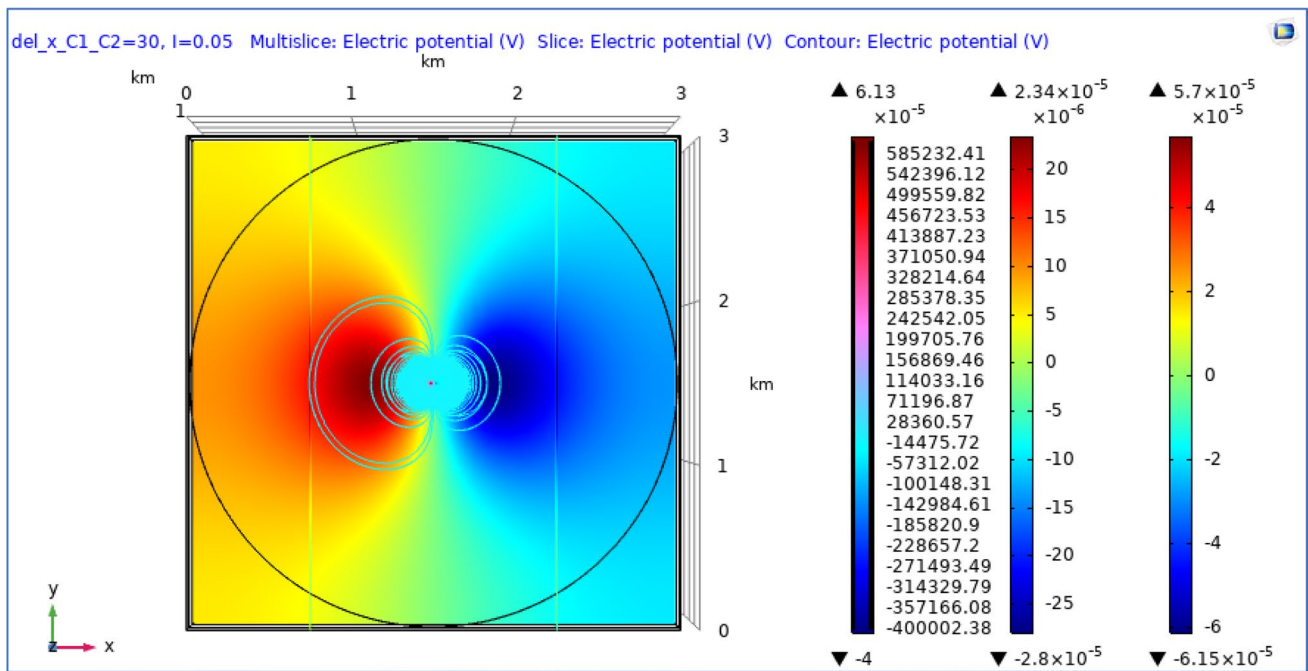


Fig. 9 XY plan view for showing the electrical potentials (V) distribution (contours and slices), as well as their values in the case of dry sand and gravel soil texture [C<sub>1</sub>-C<sub>2</sub>=30 m]

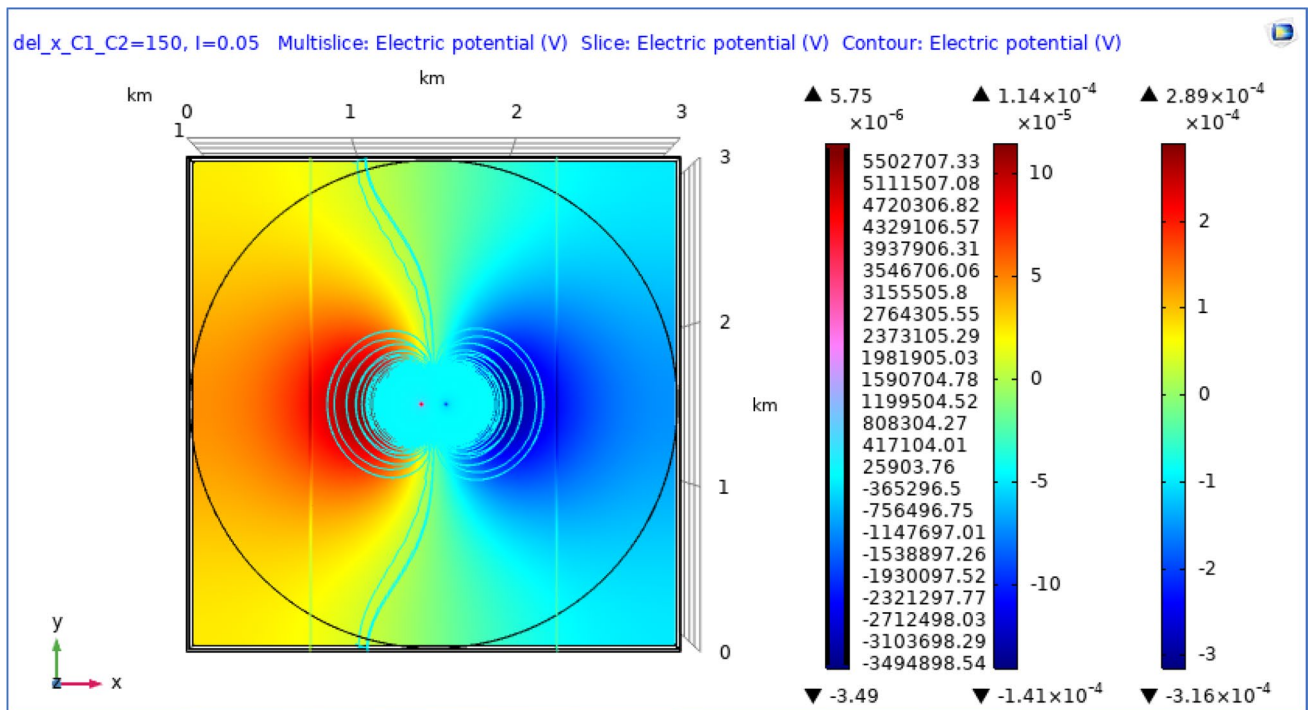
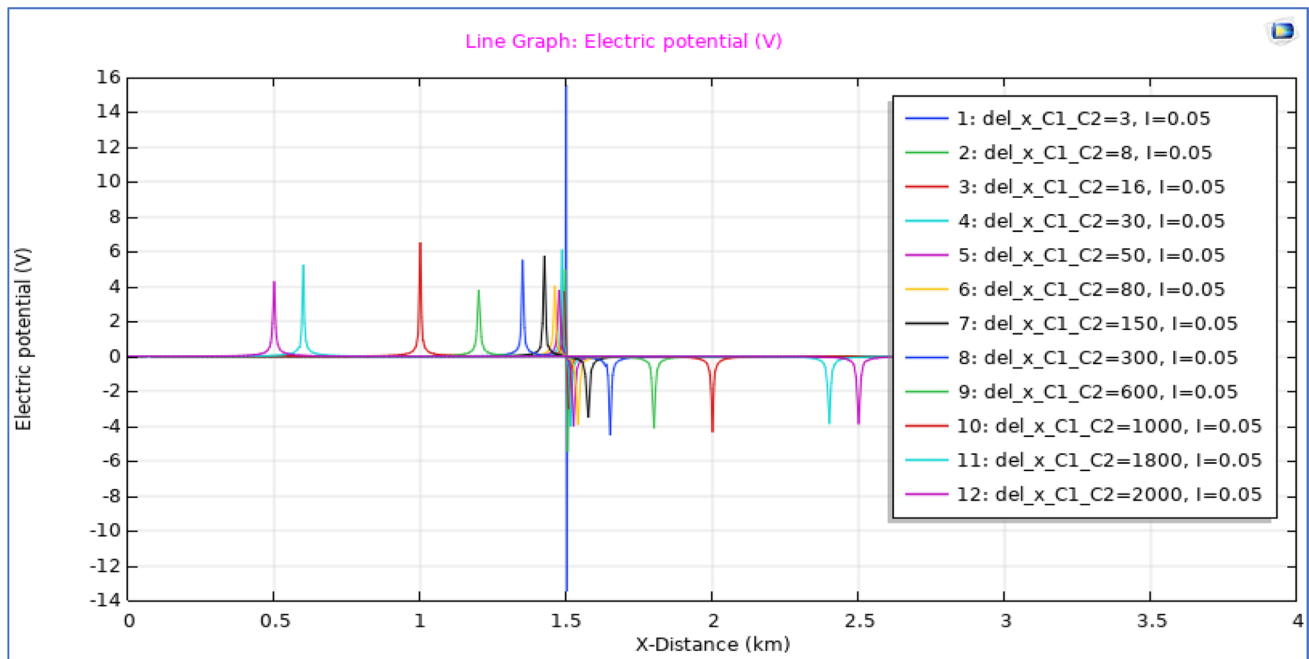


Fig. 10 XY plan view for showing the electrical potentials (V) distribution (contours and slices), as well as their values in the case of moisture sand and gravel soil texture [C<sub>1</sub>-C<sub>2</sub>=150 m]



**Fig. 11** Electrical potential values between the current electrodes  $C_1$  and  $C_2$  of the vadose zone in the case of soil texture made up of sand and gravel

**Table 6** Computed electrical potential values and the calculated apparent resistivity in the case of soil texture vadose zone made up of sand and gravel

$C_1C_2/2$ (m)	Computed electrical potential (V) of sand and gravel soil zone	Calculated apparent resistivity ( $\Omega$ .m) of sand and gravel soil zone
1.5	1.518993845	1139
4	0.506151957	1130
8	0.393450157	1116
15	0.492575722	1066
25	0.330447314	1097
40	0.357610601	1087
75	0.334168178	1062
150	0.179096532	952
300	0.082914196	668
500	0.080883702	466
900	0.051511891	281
1000	0.0383335	267

shallow wetted clay zone and deep moisture sandy clay zone are very low, due to the current density is very high at the two zones. The electrical potential values of this type of soil texture are represented in Fig. 23. The apparent resistivity values were calculated from the computed electrical potential values, as in Table 8. The resulting curves of these values are represented in Fig. 24 (P and Q), respectively.

The computed maximum and minimum electrical potential values were 0.005202597 V, when  $C_1C_2/2 = 15$  m, and 0.00029792 V, when  $C_1C_2/2 = 1.5$  m, respectively. The maximum and minimum calculated apparent resistivity values were 11.6 and 6.74 ( $\Omega$ .m), respectively (Table 9). The previous very low values resulted due to the occurrence of pure and wetted clay and high amounts of clay in sandy clay, as well as high moisture content.

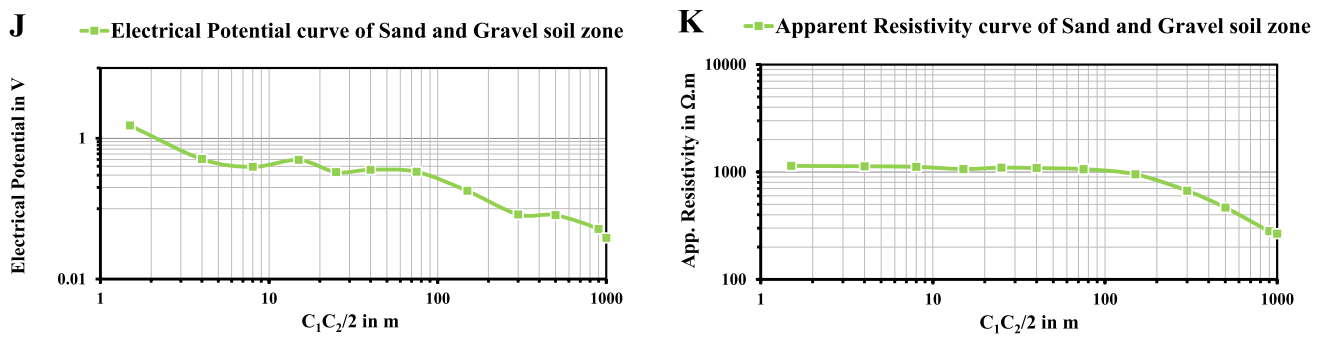


Fig. 12 Computed electrical potential curve (J) and the calculated apparent resistivity curve (K) in the case of soil texture in the vadose zone made up of sand and gravel

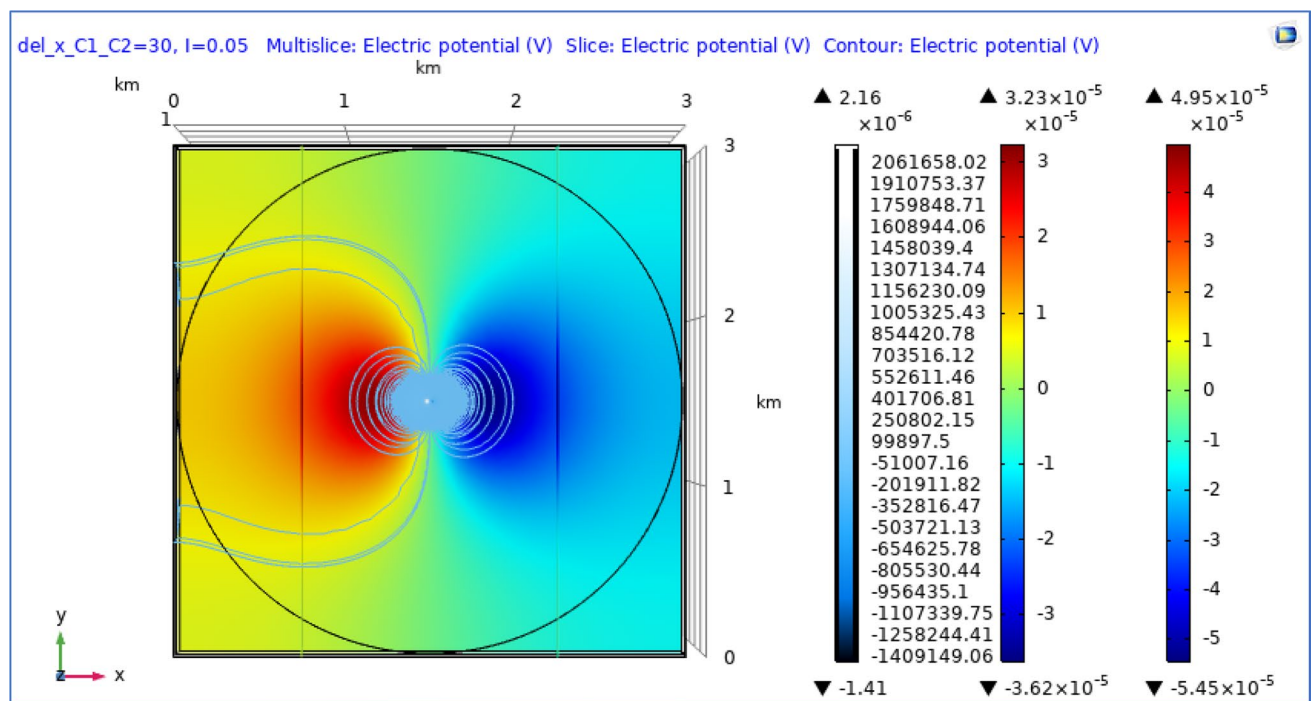


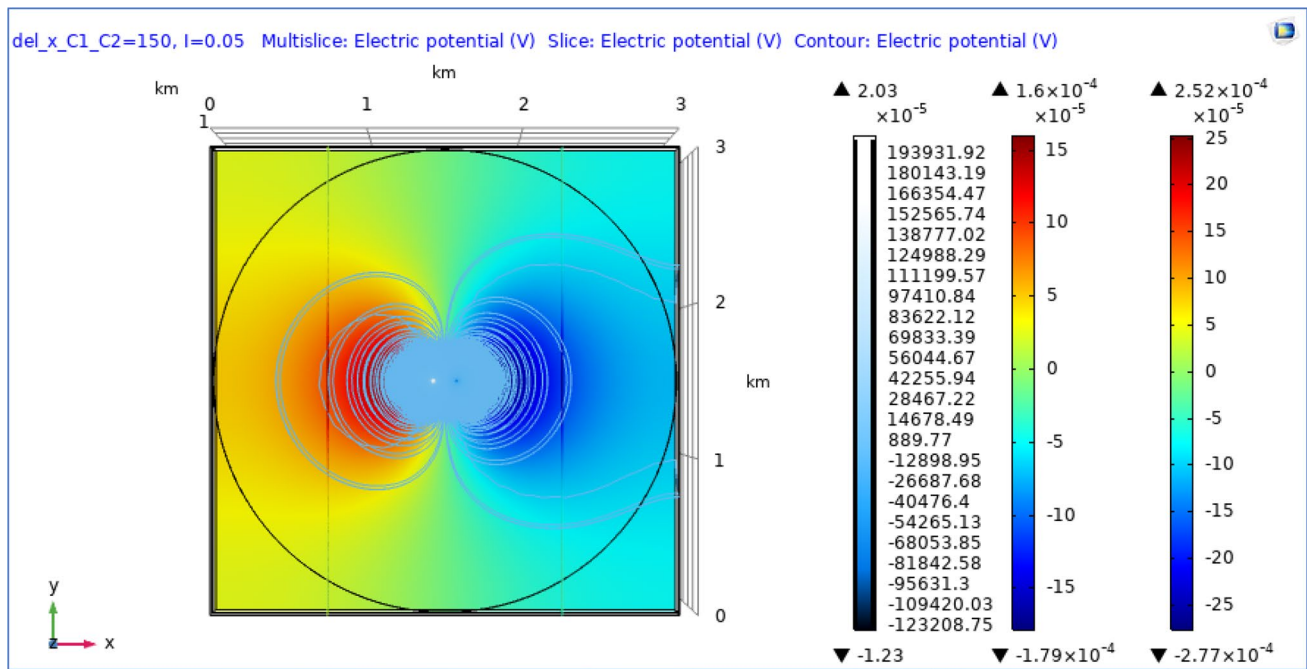
Fig. 13 XY plan view for showing the electrical potentials (V) distribution as well as their values in the case of dry sand with varying amounts of silt and clay soil texture [ $C_1-C_2=30$  m]

## Results and discussion

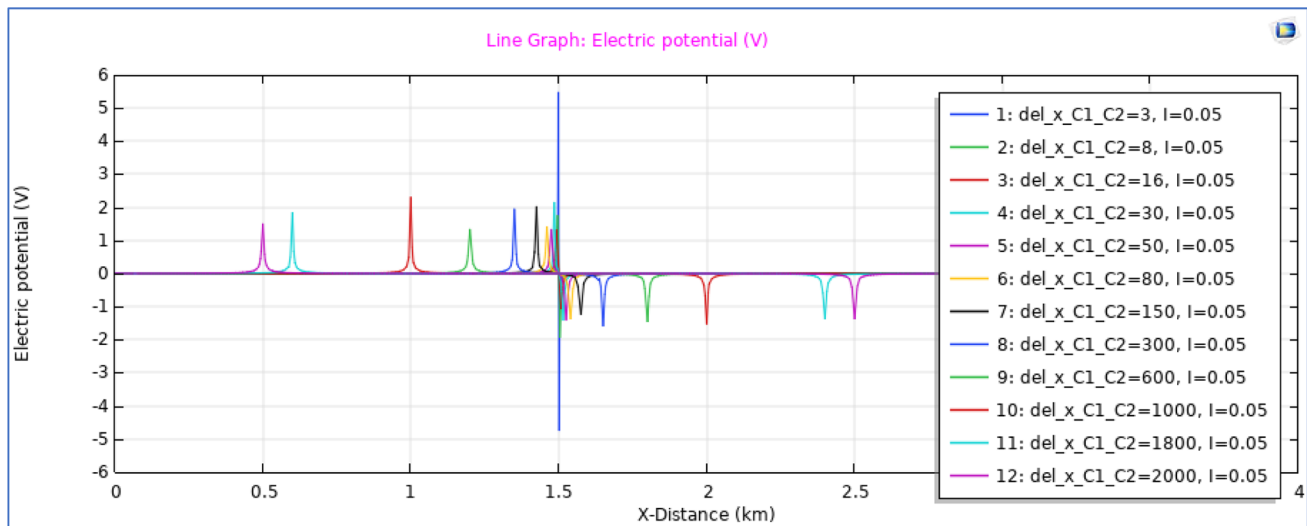
### Comparison between the values of electrical potential and apparent resistivity of the vadose zone soil textures

From the comparison between the electrical potential values (Table 10 and Fig. 25R), there is decreasing in values with changing the texture of the soil especially with increasing the amounts of clay and silt content. Accordingly, these values reduce from very high (sand and gravel

soil texture) to very low (clay soil texture). The maximum value was recorded in sand and gravel soil texture (1.518993845 V); while, the minimum value was recorded in clay soil texture (0.00029792 V). Also, the maximum value of the apparent resistivity was recorded in sand and gravel soil texture (1139  $\Omega.m$ ); while, the minimum value was recorded in clay soil texture (6.74  $\Omega.m$ ), as in Table 11 and Fig. 25S. This reduction in values of the electrical potential or the apparent resistivity of the vadose zone soil texture refers to the changing in grains sizes of sediments from big sizes, mixture sizes to small sizes. The sediments of big grains sizes have very high values of



**Fig. 14** XY plan view for showing the electrical potentials (V) distribution, as well as their values in the case of moisture sand with varying amounts of silt and clay soil texture [ $C_1-C_2=150$  m]



**Fig. 15** Electrical potential values between the current electrodes  $C_1$  and  $C_2$  of the vadose zone in the case of soil texture made up of sand with varying amounts of silt and clay

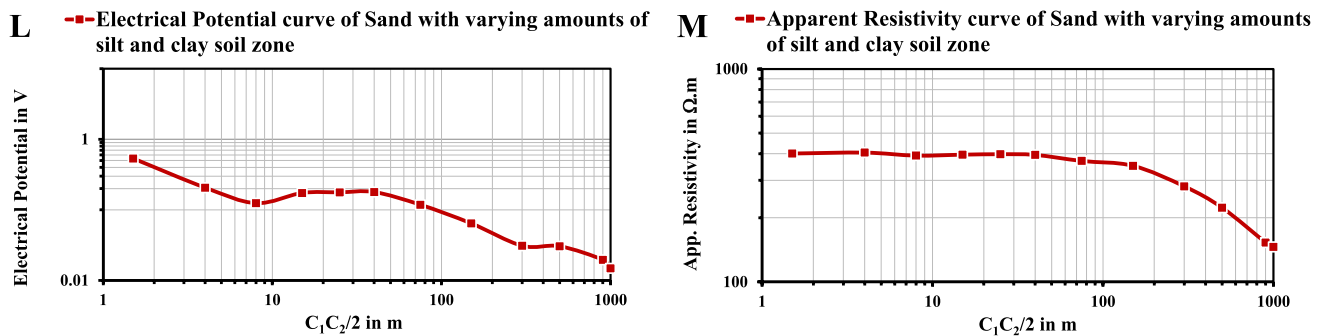
electrical potential and apparent resistivity and this reflects that these sediments have high hydraulic conductivity and transmissivity; and therefore, the infiltration rate is high. The sediments of small grains sizes have very low values of electrical potential and apparent resistivity. So, these types of sediments are characterized with low to very low hydraulic conductivity, transmissivity and infiltration rate.

While, the mixture sizes of grains are characterized with medium values in hydraulic conductivity and transmissivity and infiltration rate. The last type of sediments can be defined with medium values in apparent resistivity.

According to the distribution of the soil texture types along the study area (Fig. 3E) which most of them have amounts of clay and pure clay, the expected infiltration rate

**Table 7** Computed electrical potential values and the calculated apparent resistivity in the case of soil texture in the vadose zone made up of sand with varying amounts of silt and clay

C1C2/2 (m)	Electrical potential (V) of sand with varying amounts of silt and clay soil zone	Calculated apparent resistivity (Ω.m) of sand with varying amounts of silt and clay soil zone
1.5	0.535101632	401
4	0.20653072	405
8	0.124431795	392
15	0.173535894	396
25	0.176911942	398
40	0.178724165	395
75	0.118250586	370
150	0.064324078	351
300	0.030991856	281
500	0.030535547	223
900	0.019614573	153
1000	0.014846755	146



**Fig. 16** Computed electrical potential curve (L) and the calculated apparent resistivity curve (M) in the case of soil texture in the vadose zone made up of sand with varying amounts of silt and clay

of these sediments will be low to very low and this will become more effect on the groundwater aquifer recharge. This result confirms the stated results from Groundwater Development Consultants (1979) and Bureau de Recherches Geologiques et Minieres (BRGM) (1985) where they reported that the recharging rate of the subsurface sediments had estimated ~ 15% and ~ 7 mm of precipitation value. Also, (Nazzal et al. 2014), reported that ~ 64% of the area, covered with sandy clay and silt, is considered useless for rainwater harvesting and did not confinement water long enough and lost to infiltration while ~ 15.6% of the area are more confinement for rainwater harvesting.

**Calculating the hydraulic parameters of the soil textures with depth**

According to the resulting power regression (6) from the application of the DC resistivity in profiling surface soil texture by (Ammar 2012), it can be used this regression (6) for

estimating the hydraulic conductivity (K) from the resistivity (ρ) with expecting error (E) percentages ~ 5%:

$$K = 0.001\rho^{2.379} \tag{6}$$

$$(R^2 = 95\%)$$

Where K is the hydraulic conductivity in m/d and ρ is the resistivity values in Ω.m.

Generally, the two parameters hydraulic conductivity and infiltration rate are very interesting parameters to evaluate the vadose zone soil textures and groundwater recharge potential because both parameters are affected by each other. So, to calculate the hydraulic conductivity, it can expect the infiltration rate, which is denoted by the flux of rainwater moving through the transmission zone, to be about equal to the value of hydraulic conductivity especially at the water content of the transmission zone (Radcliffe and Simunek 2010). Also, it will determine the restricting depths of the soil texture that has the lowest hydraulic conductivity as

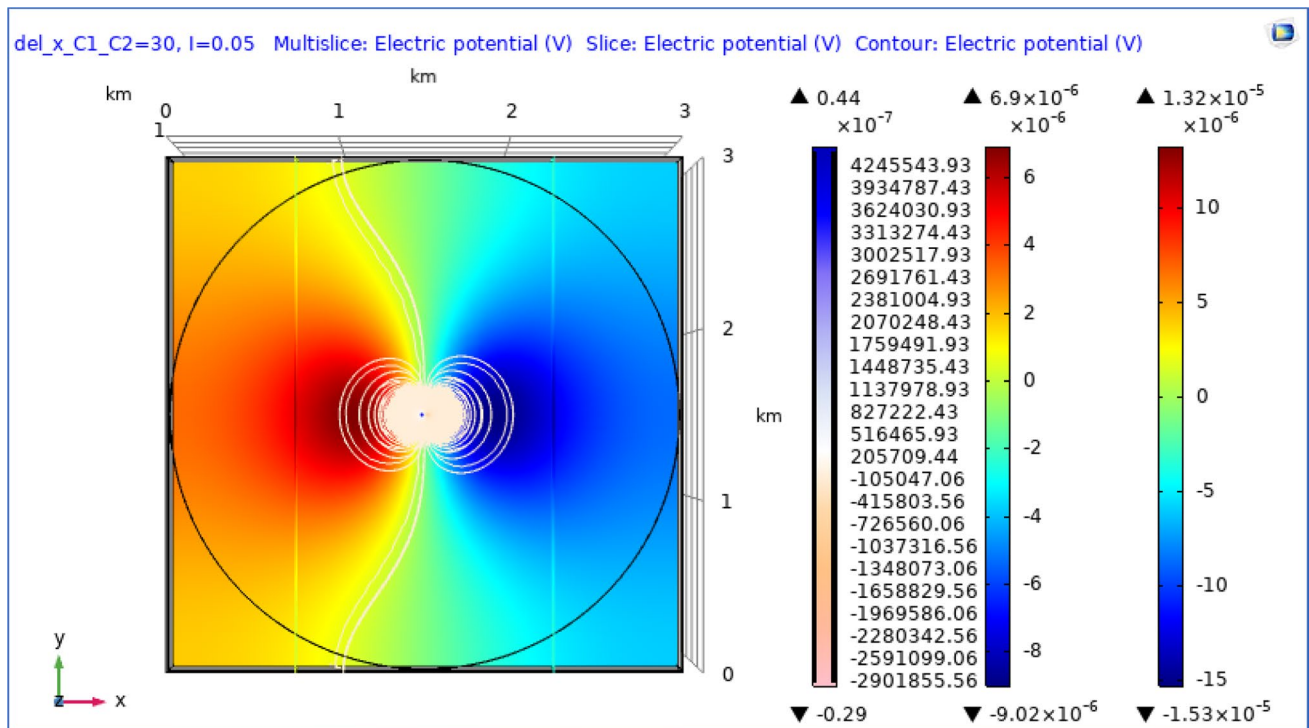


Fig. 17 XY plan view for showing the electrical potentials (V) distribution, as well as their values in the case of dry mixture of silt, clay and sand soil texture [ $C_1-C_2=30$  m]

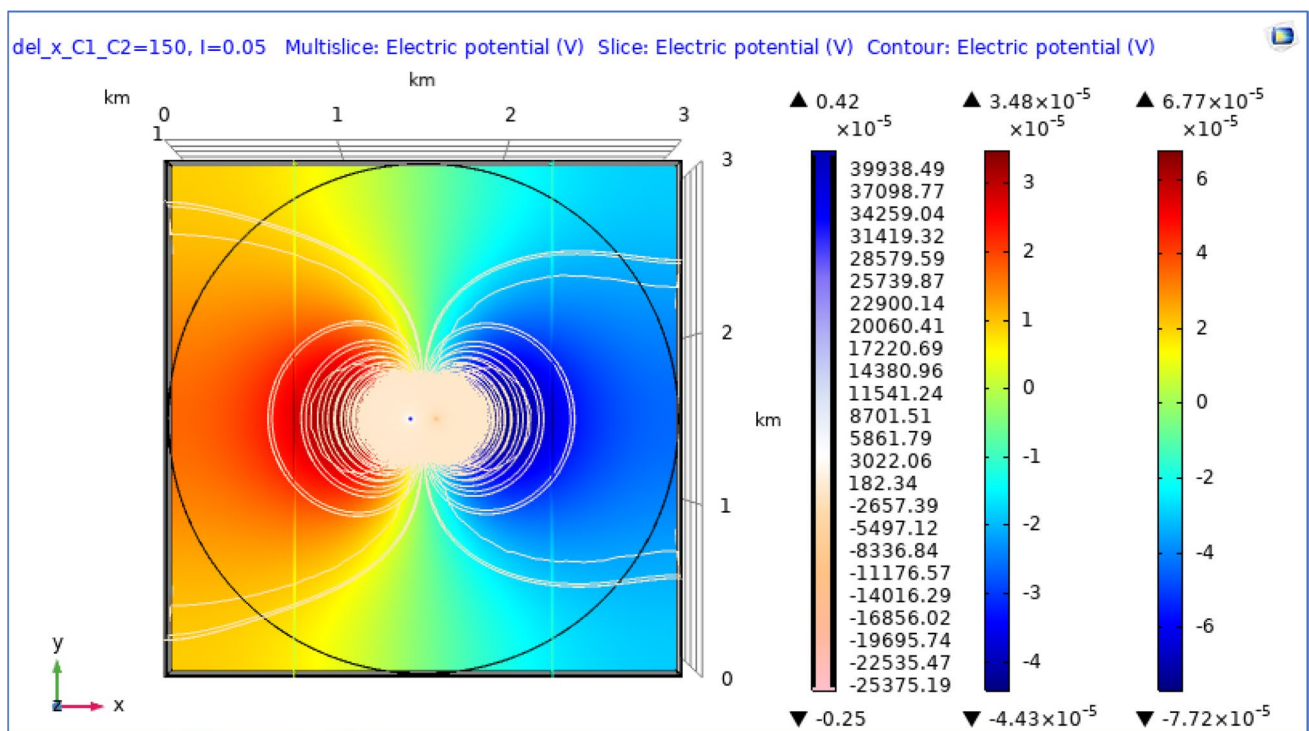
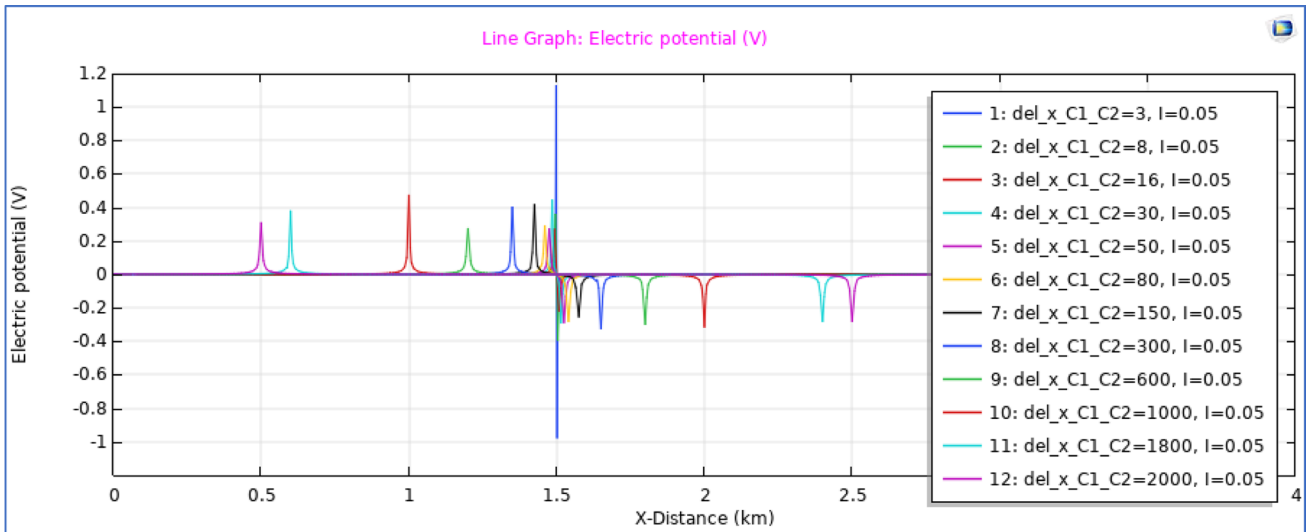


Fig. 18 XY plan view for showing the electrical potentials (V) distribution, as well as their values in the case of moisture mixture of silt, clay and sand soil texture [ $C_1-C_2=150$  m]

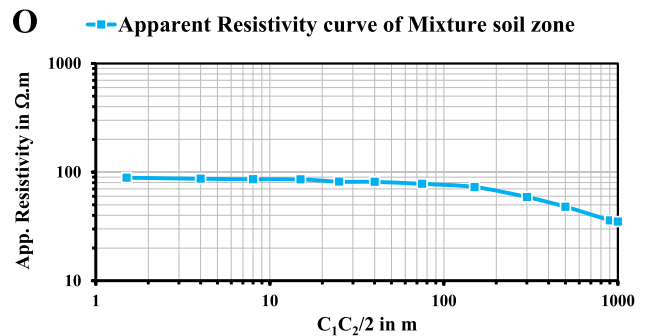
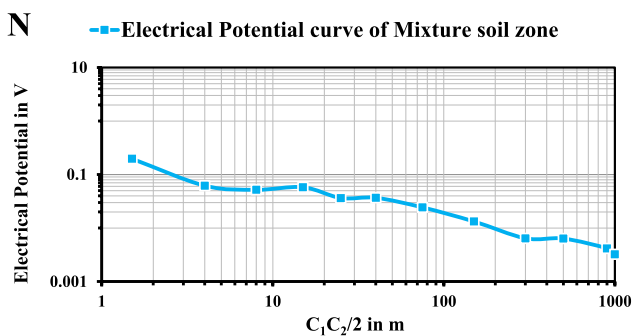




**Fig. 19** Electrical potential values between the current electrodes  $C_1$  and  $C_2$  of the vadose zone in the case of soil texture made up of mixture of silt, clay and sand

**Table 8** Computed electrical potential values and the calculated apparent resistivity in the case of soil texture in the vadose zone made up of mixture of silt, clay and sand

$C_1C_2/2$ (m)	Electrical potential (V) of mixture of silt, clay and sand soil zone	Calculated apparent resistivity ( $\Omega.m$ ) of mixture of silt, clay and sand soil zone
1.5	0.197416573	88.9
4	0.061964948	87
8	0.051969868	86
15	0.057964269	85.8
25	0.036432146	81.8
40	0.036807975	81.4
75	0.024365207	78
150	0.013282547	73
300	0.006444651	59
500	0.00637211	48
900	0.00417654	36
1000	0.003233713	35



**Fig. 20** Computed electrical potential curve (N) and the calculated apparent resistivity curve (O) in the case of soil texture in the vadose zone made up of mixture of silt, clay and sand

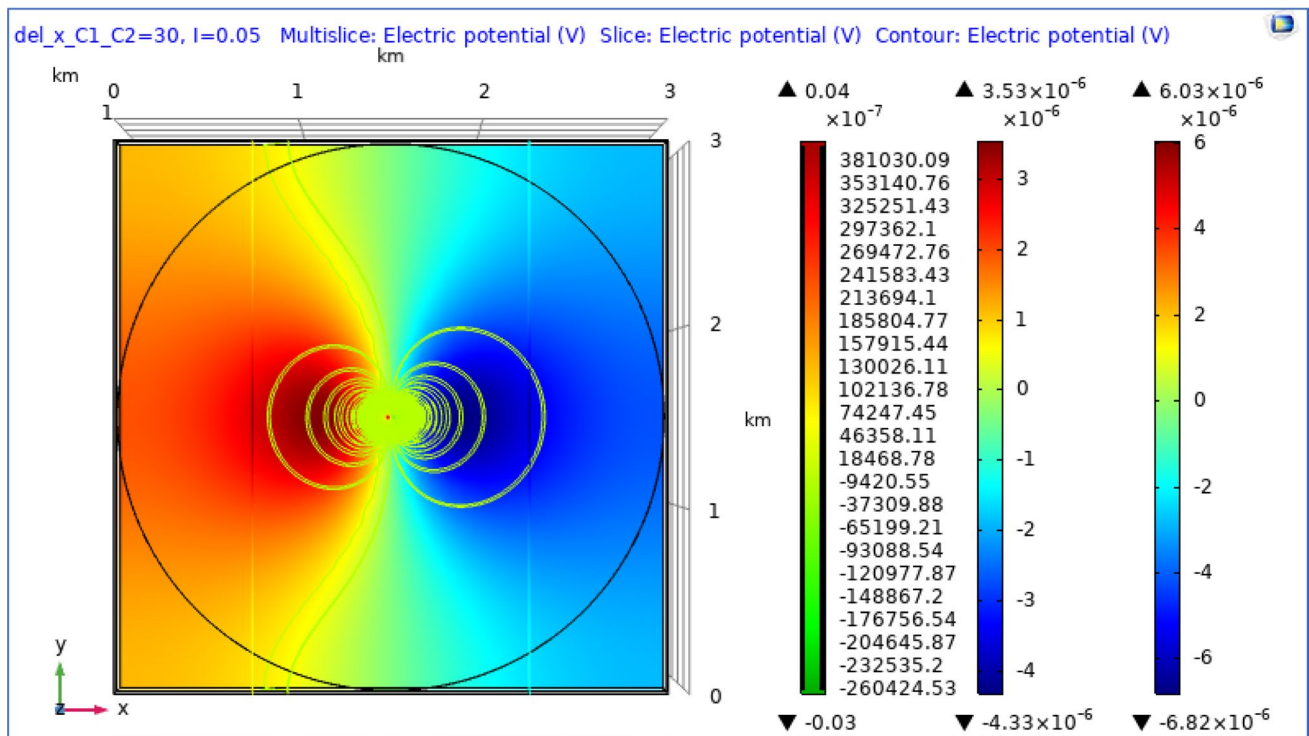


Fig. 21 XY plan view for showing the electrical potentials (V) distribution, as well as their values in the case of moisture clay soil texture [ $C_1-C_2=30$  m]

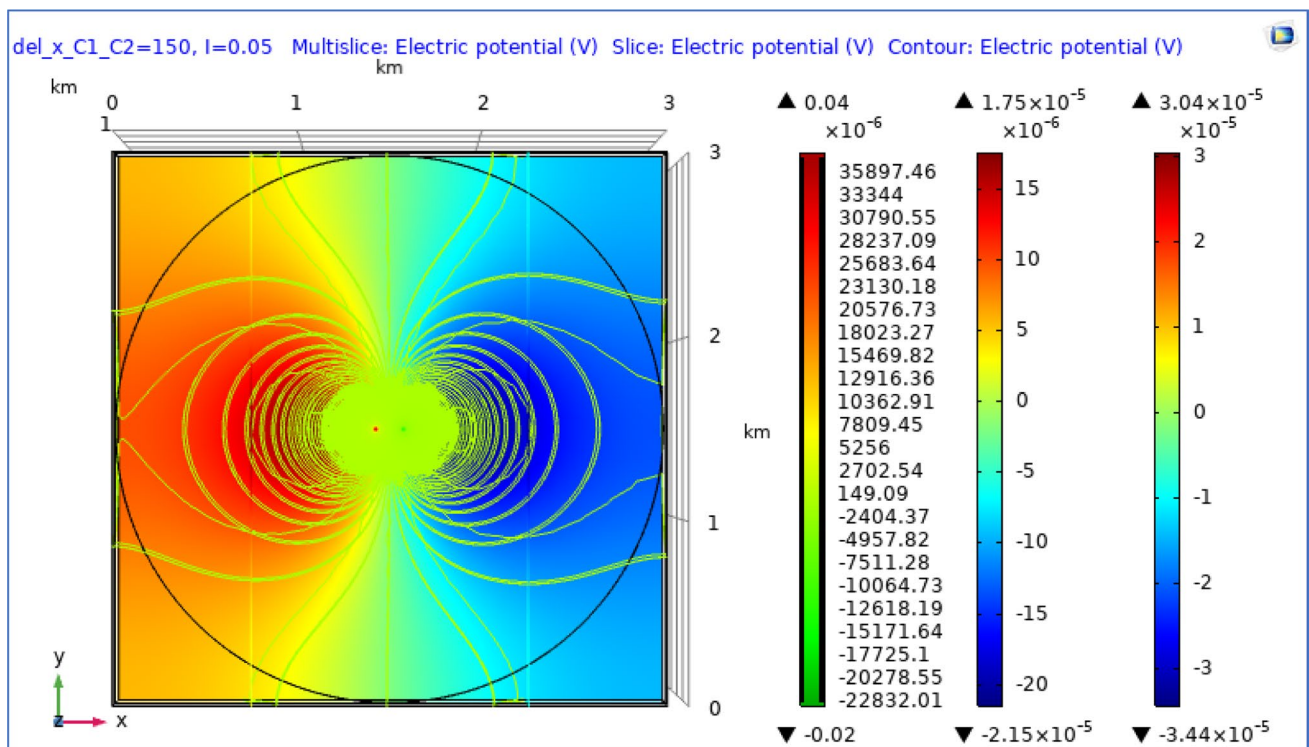
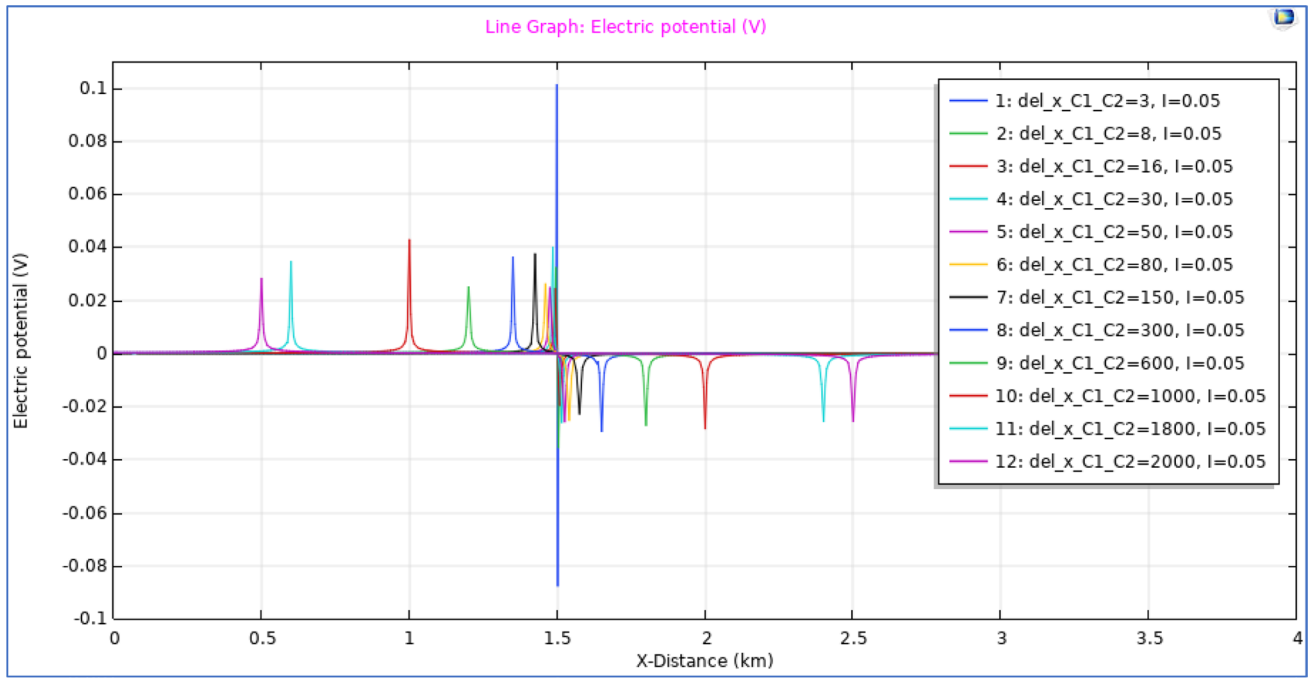
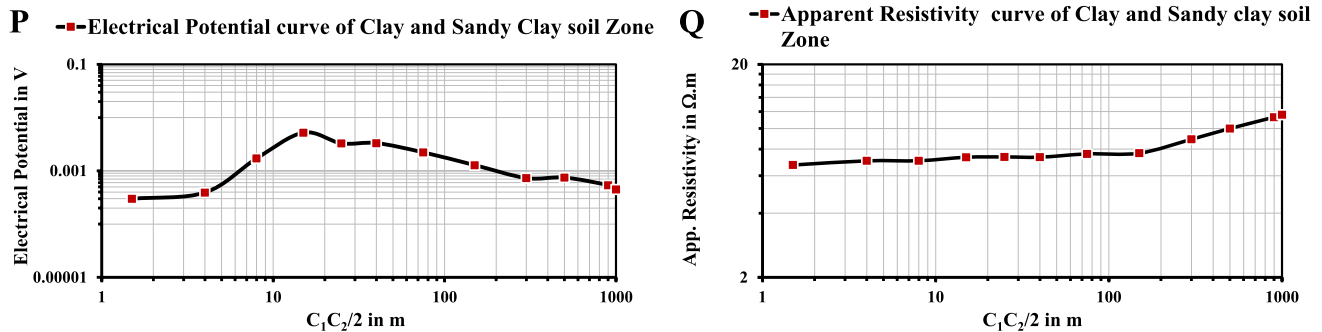


Fig. 22 XY plan view for showing the electrical potentials (V) distribution, as well as their values in the case of moisture sandy clay soil texture [ $C_1-C_2=150$  m]



**Fig. 23** Electrical potential values between the current electrodes  $C_1$  and  $C_2$  of the vadose zone in the case of soil texture made up of clay and sandy clay



**Fig. 24** Computed electrical potential curve (P) and the calculated apparent resistivity curve (Q) in the case of soil texture in the vadose zone made up of clay and sandy clay

reported in Tables 14, 15 in the case of mixture soil texture and clay to sandy clay soil texture, respectively. From the relationship between the infiltration rate and hydraulic conductivity, (Leiveci et al. 2016) stated that there is close correlation between the two parameters.

The transmissivity ( $T$ ) can be calculated from the hydraulic conductivity values by using the following Eq. (7):

$$T = h * K \tag{7}$$

where  $h$  is the estimated thickness in  $m$  of the soil texture under investigation from the spacing between the current electrodes ( $C_1$  and  $C_2$ ), which in general equal to  $1/3$  of the  $C_1C_2/2$ .

### Calculating the hydraulic conductivity and transmissivity of sand and gravel soil zone

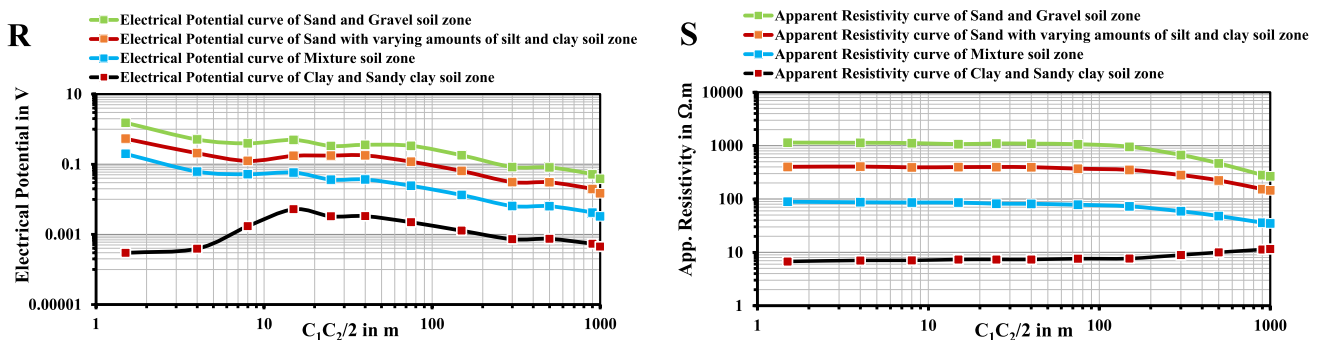
In general, the values of hydraulic conductivity and transmissivity for sand and gravel soils are expected to be very high, since their grain sizes are large and thus their effective porosity is expected to be very high, as well as the pores involved are related to each other. By applying power regression 2 and Eq. 3 (Table 12), the calculated hydraulic conductivity values of this type of soil ranged from 17,750 m/d—563 m/d in the dry vadose zone and the moisture vadose zone, respectively. The calculated maximum and minimum values of this parameter

**Table 9** Computed electrical potential values and the calculated apparent resistivity in the case of the soil texture in the vadose zone made up of mixture of clay and sandy clay

C1C2/2 (m)	Electrical potential (V) of clay and sandy clay soil zone	Calculated apparent resistivity ( $\Omega$ .m) of clay and sandy clay soil zone
1.5	0.00029792	6.74
4	0.000391	7.05
8	0.001706809	7.06
15	0.005202597	7.33
25	0.003272779	7.355
40	0.003313042	7.336
75	0.002220176	7.6
150	0.001275392	7.66
300	0.000728665	8.9
500	0.000745722	10
900	0.000536606	11.3
1000	0.000447988	11.6

**Table 10** Comparison between the computed electrical potential values of the different soil textures of the vadose zone

C1C2/2 (m)	Computed electrical potential (V) of sand and gravel soil zone	Computed electrical potential (V) of sand with varying amounts of silt and clay soil zone	Computed electrical potential (V) of mixture of silt, clay and sand soil zone	Computed electrical potential (V) of clay and sandy clay soil zone
1.5	1.518993845	0.535101632	0.197416573	0.00029792
4	0.506151957	0.20653072	0.061964948	0.000391
8	0.393450157	0.124431795	0.051969868	0.001706809
15	0.492575722	0.173535894	0.057964269	0.005202597
25	0.330447314	0.176911942	0.036432146	0.003272779
40	0.357610601	0.178724165	0.036807975	0.003313042
75	0.334168178	0.118250586	0.024365207	0.002220176
150	0.179096532	0.064324078	0.013282547	0.001275392
300	0.082914196	0.030991856	0.006444651	0.000728665
500	0.080883702	0.030535547	0.00637211	0.000745722
900	0.051511891	0.019614573	0.00417654	0.000536606
1000	0.0383335	0.014846755	0.003233713	0.000447988



**Fig. 25** Comparison between the computed electrical potential curves (R) and the calculated apparent resistivity curves (S) for the different soil textures of the vadose zone

**Table 11** Comparison between the calculated apparent resistivity values for the different soil textures of the vadose zone

C1C2/2 (m)	Calculated apparent resistivity (Ω.m) of sand and gravel soil zone	Calculated apparent resistivity (Ω.m) of sand with varying amounts of silt and clay soil zone	Calculated apparent resistivity (Ω.m) of mixture of silt, clay and sand soil zone	Calculated apparent resistivity (Ω.m) of clay and sandy clay soil zone
1.5	1139	401	88.9	6.74
4	1130	405	87	7.05
8	1116	392	86	7.06
15	1066	396	85.8	7.33
25	1097	398	81.8	7.355
40	1087	395	81.4	7.336
75	1062	370	78	7.6
150	952	351	73	7.66
300	668	281	59	8.9
500	466	223	48	10
900	281	153	36	11.3
1000	267	146	35	11.6

**Table 12** Calculating the expected values of hydraulic conductivity and transmissivity ( $E = \sim 5\%$ ) from the calculated apparent resistivity values for sand and gravel soil zone

C1C2/2 (m)	Calculated apparent resistivity (Ω.m) of sand and gravel soil zone	Calculated hydraulic conductivity (m/d) of sand and gravel soil zone ( $E = \sim 5\%$ )	h (m)	Transmissivity (m <sup>2</sup> /d) ( $E = \sim 5\%$ )	Vadose zones
1.5	1139	17,750	0.5	8875	Dry vadose zone
4	1130	17,418	1.3	23,224	
8	1116	16,909	2.7	45,091	
15	1066	15,162	5	75,810	
25	1097	16,232	8	135,268	
40	1087	15,882	13	211,764	
75	1062	15,027	25	375,676	
150	952	11,585	50	579,256	
300	668	4987	100	498,732	
500	466	2117	167	352,909	Moisture vadose zone
900	281	636	300	190,685	
1000	267	563	333	187,617	

in the dry vadose zone are 17,750 m/d and 2117 m/d, respectively. The calculated average value of this parameter is  $\sim 11,189$  m/d and its expected value/m with depth is  $\sim 34$  m/d. While, the calculated maximum and minimum values in the moisture vadose zone are 636 and 563 m/d, respectively. Also, the calculated maximum and minimum values of the transmissivity of this type of soil are 579,256 m<sup>2</sup>/d and 8875 m<sup>2</sup>/d, respectively. The calculated average value of transmissivity is  $\sim 223,742$  m<sup>2</sup>/d and its expected value/m with depth is  $\sim 671$  m<sup>2</sup>/d. Accordingly, it can be concluded that this type of soil is characterized by very high values of hydraulic parameters; and therefore, its infiltration rate will be fast and the ability to groundwater recharge also will be high.

**Calculating the hydraulic conductivity and transmissivity of sand with varying amounts of silt and clay soil zone.**

The hydraulic conductivity and transmissivity values for sand with varying amounts of silt and clay soil zone are expected to be high to medium, due to the presence of silt and clay, which have small particle sizes, and therefore its effective porosity is expected to be high to medium, as well as some pores that are not connected to each other. The calculated hydraulic conductivity values of this type of soil ranged, as in Table 13, from 1517 to 134 m/d in the dry vadose zone and the moisture vadose zone, respectively. The calculated maximum and minimum values of this parameter in the dry vadose zone are 1517 and 1079 m/d, respectively.

**Table 13** Calculating the expected values of hydraulic conductivity and transmissivity ( $E = \sim 5\%$ ) from the calculated apparent resistivity values for sand with varying amounts of silt and clay soil zone

C1C2/2 (m)	Calculated apparent resistivity ( $\Omega \cdot m$ ) of sand with varying amounts of silt and clay soil zone	Calculated hydraulic conductivity (m/d) of sand with varying amounts of silt and clay soil zone ( $E = \sim 5\%$ )	h (m)	Transmissivity ( $m^2/d$ ) ( $E = \sim 5\%$ )	Vadose zones
1.5	401	1481	0.5	741	Dry vadose zone
4	405	1517	1.3	2022	
8	392	1403	2.7	3742	
15	396	1438	5	7188	
25	398	1455	8	12,125	
40	395	1429	13	19,053	
75	370	1223	25	30,578	
150	351	1079	50	53,948	Moisture vadose zone
300	281	636	100	63,562	
500	223	367	167	61,121	
900	153	150	300	44,898	
1000	146	134	333	44,627	

While, the calculated maximum and minimum values in the moisture vadose zone are 636 and 134 m/d, respectively. The calculated average value of this parameter is  $\sim 1026$  m/d and its expected value/m with depth is  $\sim 3.08$  m/d. The calculated maximum and minimum values of transmissivity are 63,562 and 741  $m^2/d$ , respectively. The calculated average value of transmissivity is  $\sim 28,634$   $m^2/d$  and its expected value/m with depth is  $\sim 85.9$   $m^2/d$ . Therefore, it can be deduced that this soil type is distinguished by high to medium values of hydraulic parameters and so, its infiltration rate will be rather fast and the ability to groundwater recharge also will be high to medium.

From calculating the average values of the calculated hydraulic conductivity of the sand and gravel soil texture (11,189 m/d) and the average values of the calculated

hydraulic conductivity of the sand with varying amounts of silt and clay soil texture (1026 m/d). Also, from calculating the average values of this parameter/m with depth of the same soil textures,  $\sim 34$  and  $\sim 3.08$  m/d, respectively. It was found that the average value of hydraulic conductivity/m with depth, also, of the same two soil textures is  $\sim 18.5$  m/d (equal to  $\sim 17.575$  m/d with an error of 5%). Due to the little results and also there is little tests were carried out in the laboratory to determine the hydraulic parameters of the sediments of this area, the last calculated value of this parameter were compared with the available laboratory tests to verify the accuracy of the calculations and it was very close to the value of  $\sim 17.49$  m/d, as calculated by (MoWE 2008) and (Ahmed et al. 2015), and as reported in the hydrogeological section, especially

**Table 14** Calculating the expected values of hydraulic conductivity and transmissivity ( $E = \sim 5\%$ ) from the calculated apparent resistivity values for a mixture soil zone

C1C2/2 (m)	Calculated apparent resistivity ( $\Omega \cdot m$ ) of mixture soil zone	Calculated hydraulic conductivity (m/d) of mixture of silt, clay and sand soil zone ( $E = \sim 5\%$ )	h (m)	Transmissivity ( $m^2/d$ ) ( $E = \sim 5\%$ )	Vadose zones
1.5	88.9	41.1	0.5	21	Dry vadose zone
4	87	39.1	1.3	52	
8	86	38.0	2.7	101	
15	85.8	37.8	5	189	
25	81.8	33.7	8	281	
40	81.4	33.4	13	445	
75	78	30.1	25	753	
150	73	25.7	50	1287	Moisture vadose zone
300	59	15.5	100	1551	
500	48	9.5	167	1582	
900	36	4.8	300	1436	
1000	35	4.5	333.3	1493	

in the case of the shallow Tertiary and Quaternary sediments.

**Calculating the hydraulic conductivity and transmissivity of the mixture of silt, clay and sand soil zone.**

The values of hydraulic conductivity and transmissivity of the silt–clay mixture with the sandy soil zone are expected to be low and sometimes very low, because the main soil consists of silt and clay with little sand content, and therefore its effective porosity is expected to be generally low and sometimes very low. The calculated values of the hydraulic conductivity for this type of soil ranged, as in Table 14, from 41.1 to 4.5 m/d in the dry zone and the moisture zone, respectively. In the dry vadose zone, the maximum value is 41.1 m/d while the minimum value is 25.7 m/d. In the moisture vadose zone, the maximum value is 15.5 m/d; while, the minimum value is 4.5 m/d. The calculated average value of this parameter is ~ 26.1 m/d and its expected value/m with depth is ~ 0.078 m/d. The calculated maximum and minimum values of transmissivity are 1582 m<sup>2</sup>/d and 21 m<sup>2</sup>/d, respectively. The calculated average value of transmissivity is ~ 766 m<sup>2</sup>/d and its expected value/m with depth is ~ 2.3 m<sup>2</sup>/d. According to the previous calculated values of the hydraulic parameters, it can be concluded that this type of soil is characterized by low to very low values of the hydraulic parameters, therefore, its infiltration rate will be slow which will cause significant loss of rainwater harvesting amounts and the ability to recharge the aquifer becomes weak.

**Calculating the hydraulic conductivity and transmissivity of clay and sandy clay soil zone.**

In general, this type of soil is characterized by pure clay and minor content of sand and their expected values of hydraulic conductivity and transmissivity are very low, because the main soil composed of clay which has very low effective porosity. After calculating the hydraulic conductivity, it was observed that its values are very small as in Table 15 and range from 0.32 m/d, as a maximum value, –0.09 m/d, as a minimum value, in the moisture sandy clay zone and the pure clay zone, respectively. The calculated average value of this parameter is ~ 0.1567 m/d and its expected value/m with depth is ~ 0.0005 m/d. Also, the transmissivity values are observed to be very small and range from 108 m<sup>2</sup>/d, as a maximum value, and 0.04 m<sup>2</sup>/d, as a minimum value, in the moisture sandy clay zone and the pure clay zone, respectively. The calculated average value of transmissivity is ~ 22.2 m<sup>2</sup>/d and its expected value/m with depth is ~ 0.0666 m<sup>2</sup>/d. Accordingly, it can be deduced that this type of soil is distinguished by very low values of the hydraulic parameters; therefore, its infiltration rate will be very slow and nonexistent due to the pure clay content which will lead to a significant loss in rainwater harvesting amounts and thus becomes the ability to recharge the groundwater aquifer not available and impossible.

**Conclusion**

Determining and understanding the physical properties and hydraulic parameters of the soil texture of the vadose zone sediments seems to be a difficult task because it needs accurate and sufficient data. Its properties and parameters

**Table 15** Calculating the expected values of hydraulic conductivity and transmissivity ( $E = \sim 5\%$ ) from the calculated apparent resistivity values for clay and sandy clay soil zone

C1C2/2 (m)	Calculated apparent resistivity ( $\Omega.m$ ) of clay and sandy clay soil zone	Calculated hydraulic conductivity (m/d) of clay and sandy clay soil zone ( $E = \sim 5\%$ )	h (m)	Transmissivity (m <sup>2</sup> /d) ( $E = \sim 5\%$ )	Vadose zones
1.5	6.74	0.09	0.5	0.04	Dry vadose zone
4	7.05	0.10	1.3	0.13	
8	7.06	0.10	2.7	0.26	
15	7.33	0.11	5	0.54	
25	7.355	0.11	8	0.91	
40	7.336	0.11	13	1.45	
75	7.6	0.12	25	2.96	
150	7.66	0.12	50	6.03	Moisture vadose zone
300	8.9	0.17	100	17.23	
500	10	0.23	167	37.89	
900	11.3	0.30	300	91.23	
1000	11.6	0.32	333	107.88	

can be determined at shallow and very close depths to the surface, but it is difficult to determine them for deep depths. Therefore, this study was conducted for this area to determine its hydraulic parameters using numerical modeling by simulating its electrical resistivity. To do this, the electrical resistivity method using schlumberger array was applied. This study was applied at the northwestern of KSA to clarify the extent of the electric potential change by changing soil texture with depth and also its saturation and then to calculate its vertical hydraulic conductivity and transmissivity. The electrical resistivity values of a three-layer model for this zone have been assumed, whether the dry zone or the moisture zone of it, depending on some shallow field measurements in some locations. This is to determine the hydraulic properties, especially in the deep depths of this zone, and to predict its infiltration rate and the extent of its effect on aquifer recharging by rainwater harvested and the most suitable sediments for recharging in this area of arid to semi-arid areas.

Depending on the most prevalent surface sediments along the area, which are sand and gravel, sand with varying amounts of clay and silt, mixture of silt, clay and sand, then clay and sandy clay, a simulation of the electric potential was made for it using COMSOL Multiphysics model; and then, its electrical resistivity was calculated, from which its hydraulic conductivity and transmissivity were calculated. It was found that their maximum and minimum hydraulic conductivity values (m/d) are 17,750 and 563, 1517 and 134, 41.1 and 4.5, then 0.32 and 0.09, respectively. Also, their maximum and minimum transmissivity values (m<sup>2</sup>/d) are 579,256 and 8875, 63,562 and 741, 1582 and 21, then 108 and 0.04, respectively. The average value of hydraulic conductivity/m with depth is ~ 18.5 m/d (~ 17.575 m/d with an error of 5%); while, the average value of transmissivity/m is ~ 378 m<sup>2</sup>/d to the sand and gravel and sand with varying amounts of silt and clay soil textures. Accordingly, these types of soils are, respectively, characterized by high infiltration rate and aquifer recharge capacity, high to medium infiltration rate and aquifer recharge capacity, low infiltration rate and aquifer recharge capacity, then very low infiltration rate and aquifer recharge capacity. This study led to the identification of the interesting characteristics of the vadose zone through which the extent and locations of the maximum benefit from rainwater harvesting can be expected. It is also an important preliminary study to determine the hydraulic parameters of this zone in the areas of interesting to rainwater harvesting in case of lacking of lab tests. It can then be applied in the field for accurate positioning and estimation of its usefulness in rainwater harvesting.

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**Ethical approval** This paper has not been published or is being considered for publication elsewhere.

**Consent to Participate** The authors declare that they are aware and consent to their participation in this paper.

**Consent for Publication** The authors declare that they consent to the publication of this paper.

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