Referee Comments (RC2):

This paper addresses the challenges associated with current groundwater exploration and evaluates the advantages and disadvantages of various methods for measuring hydraulic parameters. The author highlights the application of a novel approach, by using Controlled Source Audio-Frequency Magnetotellurics (CSAMT) method, which is employed to estimate 2D and 3D permeability at depths exceeding 1 km in highly heterogeneous rock environments. The study presents its methods and findings in a well-structured manner, offering insights into deep groundwater exploration.

However, certain assertions appear overly generalized and could benefit from further substantiation. Additionally, more detailed descriptions of the methodologies and the study area would enhance the clarity, reproducibility, and robustness of the research.

Response:

We sincerely thank the anonymous reviewer for their insightful and constructive feedback, which has significantly contributed to enhancing the quality of our work. We have made every effort to revise the manuscript thoroughly in line with the reviewer's suggestions.

In the revised version, we have expanded the descriptions of both the study area and the methodologies to provide greater clarity and context. Additional explanations and supporting information have also been included to substantiate our findings and address the points raised.

As per the journal's submission guidelines, we are first submitting our detailed responses to the reviewer's comments. Following this, we will submit the revised manuscript reflecting all the suggested changes.

Specific comments:

Comment 1:

Line108-119: the author might consider adding a little more evidence of the reason that CSAMT is selected for this study. For example, the author stated that VES method is used to evaluate groundwater resources in a single dimension by a broad of previous studies, but did not illustrate the background about why they did not use other methods, like CSAMT or ERT. Additionally, the author states that there are three main methods, but there are very few examples or introductions about ERT in this paragraph.

Response 1:

The entire paragraph from Lines 88–119 has been revised for improved clarity and structure in the updated manuscript. Both the original and the revised versions of the paragraph are provided below for comparison.

ORIGINAL PARAGRAPH:

“A number of prior groundwater investigations have made use of geophysical techniques (Bentley and Gharibi, 2004; Yadav and Singh, 2007; Fu et al., 2013; Vouillamoz et al., 2014; Robinson et al., 2016; Lin et al., 2018; Kouadio et al., 2020; Abbas et al., 2022; Kouadio et al., 2023; Zhang et al., 2024). A number of studies have shown that geophysical procedures outperform drilling techniques in terms of speed, ease of use, cost, and lack of invasiveness (Hu et al., 2013; Lin et al., 2018; Di et al., 2020; Fusheng et al., 2022; Hasan et al., 2024).

Additionally, they are capable of conducting thorough geological evaluations in both the vertical and horizontal planes (Fu et al., 2013; Hasan et al., 2021). These methods are superior to others when it comes to collecting hydrogeological data from various subterranean habitats (Niwas and De Lima, 2003; Wynn et al., 2016; Kouadio et al., 2023). Groundwater studies nowadays often include resistivity surveys. Resistivity methods offer a broader resistivity range compared to other geophysical parameters, which is a major advantage (Bentley and Gharibi, 2004; Camporese et al., 2011; Robinson et al., 2016). The three main methods for measuring resistivity are the controlled source audio-frequency magnetotellurics (CSAMT), vertical electoral soundings (VES), and electrical resistivity tomography (ERT) (Soupios et al., 2007; Di et al., 2020; Zhang et al., 2024). Niwas and De Lima (2003), Soupios et al. (2007), Majumdar and Das (2011), Nwosu et al. (2013), Hasan et al. (2021), and Asfahani (2023) are among the previous groundwater-based geophysical studies that primarily utilized the VES method to evaluate groundwater resources in a single dimension. It is unusual to evaluate aquifer yield at great depths in hard rock terrains using two- and three-dimensional hydraulic properties. Recent studies have demonstrated that CSAMT, which aims to gather extensive subsurface data at very deep depths using 2D/3D evaluations, is the most cost-effective and appropriate geophysical method for researching hard rock (Smith and Booker, 1991; Simpson and Bahr, 2005; Bai et al., 2010; Fu et al., 2013; Hu et al., 2013; Wang et al., 2015; Wynn et al., 2016; Di et al., 2020; Zhang et al., 2021; Kouadio et al., 2023; Hasan et al., 2024). Advantages of CSAMT over other geophysical research methods include its lower cost, its responsiveness to low-resistance rocks, and its ease of usage in challenging topographic circumstances (An et al., 2016; Kouadio et al., 2020; Zhang et al., 2021). Compared to most geophysical technologies, including ERT, CSAMT's subsurface assessment capabilities are superior due to its depth capacity of up to one kilometer (Zonge and Hughes, 1988; Hasan et al., 2024). When combined with empirically based methodologies, CSAMT becomes an even more powerful tool for studying the incredibly diverse topographical features.”

REVISED PARAGRAPH:

“A number of prior groundwater investigations have made use of geophysical techniques (Bentley and Gharibi, 2004; Yadav and Singh, 2007; Fu et al., 2013; Vouillamoz et al., 2014; Robinson et al., 2016; Lin et al., 2018; Kouadio et al., 2020; Abbas et al., 2022; Kouadio et al., 2023; Zhang et al., 2024). A number of studies have shown that geophysical procedures outperform drilling techniques in terms of speed, ease of use, cost, and lack of invasiveness (Hu et al., 2013; Lin et al., 2018; Di et al., 2020; Fusheng et al., 2022; Hasan et al., 2024). Additionally, they are capable of conducting thorough geological evaluations in both the vertical and horizontal planes (Fu et al., 2013; Hasan et al., 2021). These methods are superior to others when it comes to collecting hydrogeological data from various subterranean habitats (Niwas and De Lima, 2003; Wynn et al., 2016; Kouadio et al., 2023). Groundwater studies nowadays often include resistivity surveys. Resistivity methods offer a broader resistivity range compared to other geophysical parameters, which is a major advantage (Bentley and Gharibi, 2004; Camporese et al., 2011; Robinson et al., 2016). The three main methods for measuring resistivity are the controlled source audio-frequency magnetotellurics (CSAMT), vertical electoral soundings (VES), and electrical resistivity tomography (ERT) (Soupios et al., 2007; Di et al., 2020; Zhang et al., 2024). Niwas and De Lima (2003), Soupios et al. (2007), Majumdar and Das (2011), Nwosu et al. (2013), Hasan et al. (2021), and Asfahani (2023) are among the previous groundwater-based geophysical studies that primarily utilized the VES method to evaluate groundwater resources in a single dimension. In recent decades, electrical resistivity tomography (ERT) has been widely used in hydrogeological studies for 2D and 3D assessment of groundwater resources (Bentley and Gharibi, 2004; Camporese et al., 2011; MLin et al., 2018; Abbas et al., 2022). However, it is unusual to evaluate aquifer yield at great depths in hard rock terrains using two and three dimensional hydraulic properties. Recent studies have demonstrated that CSAMT, which aims to gather extensive subsurface data at very deep depths using 2D/3D evaluations, is the most appropriate geophysical method for researching hard rock (Smith and Booker, 1991; Simpson and Bahr, 2005; Bai et al., 2010; Fu et al., 2013; Hu et al., 2013; Wang et al., 2015; Wynn et al., 2016; Zhang et al., 2021; Kouadio et al., 2023). The selection of resistivity methods in groundwater studies depends on several key factors, including survey objectives, depth of investigation, resolution, geological complexity, logistical constraints, cost and accessibility, electrical conductivity contrast, and field conditions, etc (Di et al., 2020; Hasan et al., 2024). VES is more suitable for shallow depths (< 200 m) for 1D resistivity imaging, has limited lateral resolution, is useful for layered aquifer characterization, works well in horizontally stratified formations, requires minimal equipment and is quick to deploy, is the most economical for small-scale studies, and may face limitations in highly resistive or conductive terrains (Soupios et al., 2007; Nwosu et al., 2013; Hasan et al., 2021). ERT offers better resolution for both shallow and intermediate depths (up to ~300 m) with 2D/3D imaging, provides high-resolution subsurface imaging, is ideal for detecting fractures/faults and heterogeneous aquifers, is better for complex geology (e.g., fractured zones, karst systems), is ideal for detailed aquifer geometry and contamination studies, needs more field effort and electrode spacing adjustments, and may face limitations in highly resistive or conductive terrains like VES (Camporese et al., 2011; MLin et al., 2018; Abbas et al., 2022). CSAMT is effective for deeper investigations (hundreds to thousands of meters) due to its low-frequency signal penetration, provides 2D/3D imaging over big area at large depths, has lower resolution than ERT but excels in deep structural mapping, is preferred for deep-seated structures like basement aquifers or geothermal systems, is used for regional groundwater exploration, demands specialized equipment and is more time-consuming compared with VES and ERT, is relatively more expensive than VES and ERT due to advanced instrumentation and processing, all resistivity methods rely on resistivity contrasts but CSAMT is more sensitive to deep conductive zones, and performs better in areas with cultural noise (e.g., urban settings) due to controlled signal sources (Zonge and Hughes, 1988; An et al., 2016; Kouadio et al., 2020; Zhang et al., 2021). When combined with empirically based methodologies, CSAMT becomes an even more powerful tool for studying the incredibly diverse topographical features at large depths (Hasan et al., 2024). So based on above factors, CSAMT was the most suitable method for this study."

Comment 2:

Line 120- 138: the author might consider reorganizing this paragraph to make the significance of the resistivity method stand out.

Response 2:

The paragraph previously located in Lines 120–138 has been reorganized for improved clarity in the revised manuscript. For reference, both the original and the revised versions of the paragraph are provided below.

ORIGINAL PARAGRAPH:

“Several factors, such as the type of rock, fault, weathering degree, fluid content, permeability, pore-spacing, fracture, lithology, saturation, and joints, as well as the same structural heterogeneities, determine the geophysical and aquifer characteristics (Singh, 2005; Sinha et al., 2009; Hasan et al., 2021). Several prior studies utilized geophysical parameters in conjunction with hydraulic data or lithological logs to characterize underlying rock mass units hydrogeologically (De Lima and Niwas, 2000; Hubbard and Rubin, 2002; Niwas and De Lima, 2003; Singh, 2005; Soupios et al., 2007; Sinha et al., 2009; Majumdar and Das, 2011; Nwosu et al., 2013; Hasan et al., 2021; Asfahani, 2023). Resistivity methods provide an alternate option for aquifer parameter estimation by creating a beneficial relationship between electrical resistivity and the aquifer parameters (obtained from drilling tests). An innovative aspect of this work is its use of non-invasive geophysical techniques to create two- and three-dimensional k models in a diverse environment with a variety of rock types and significant depths. The planned study will necessitate the boring of a handful of boreholes at key spots all around the project site. A more trustworthy CSAMT study will allow us to evaluate the extensive research area. Then, by directly connecting geophysical and borehole data, k can be established for the entire researched site, even without drilling tests. Two- and three-dimensional k models are generated by applying the resulting equations to the full study area. This approach would reduce the need for costly boreholes to obtain a thorough and complete evaluation of subsurface hydrogeological conditions.”

REVISED PARAGRAPH:

“Resistivity methods are highly significant in groundwater studies due to their ability to characterize subsurface formations and identify potential aquifers. These techniques measure the electrical resistivity of subsurface materials, which varies depending on lithology, rock type, porosity, fluid content, weathering degree, faults, fractures, joints, saturation, and salinity (Singh, 2005; Sinha et al., 2009; Hasan et al., 2021). By integrating resistivity data with geological and hydrogeological information, researchers have been able to optimize the placement of wells, accurately assess groundwater potential, and support the effective and sustainable management of water resources (De Lima and Niwas, 2000; Hubbard and Rubin, 2002; Niwas and De Lima, 2003; Singh, 2005; Soupios et al., 2007; Sinha et al., 2009; Majumdar and Das, 2011; Nwosu et al., 2013; Hasan et al., 2021; Asfahani, 2023). By establishing a useful correlation between electrical resistivity and the limited borehole-based hydraulic parameters, resistivity methods offer the best alternative of the expensive drilling tests for estimating aquifer parameters over large area from shallow to large depths. In this study, we present a novel application of the Controlled Source Audio-Frequency Magnetotelluric (CSAMT) method to develop high-resolution 2D and 3D permeability (k) models at significant depths (up to 1300 meters) within a geologically complex and heterogeneous setting composed of sandstone, granite, and hornstone. Initially, a limited number of boreholes were drilled at strategically selected key locations across the study area. Subsequently, multiple CSAMT survey profiles were conducted, covering the entire region, including the borehole sites. By correlating the resistivity data obtained from the CSAMT surveys with permeability values derived from the borehole data, we established a reliable empirical relationship between resistivity and permeability. This correlation was then applied across the full CSAMT dataset, enabling the generation of 2D and 3D permeability models even in areas lacking direct borehole information. This approach allows for a more comprehensive and cost-effective assessment of deep groundwater resources, significantly reducing the need for extensive and expensive drilling campaigns.”

Comment 3:

Line 139- 140: the statement is too arbitrary; the language can be modified or more evidence is provided.

Response 3:

ORIGINAL STATEMENT:

“No one had ever tried to estimate K using direct or indirect methods in such a heterogeneous context before this work, where a broad diversity of rock types are present at a depth of 1 kilometer”.

REVISED STATEMENT:

“Prior to this study, no attempts had been made to estimate permeability (K) using either direct methods, such as borehole testing, or indirect geophysical approaches in such a geologically heterogeneous setting, characterized by a diverse mixture of sandstone, granite, and hornstone, extending to depths of up to one kilometer.”

Comment 4:

Line 161: in section 2.1 Study area, the author might consider adding more details about the rocks and geology of the study area.

Response 4:

Additional details about the rocks and geological characteristics of the study area have been added, as shown below.

ORIGINAL:

“Intruding rocks from the Indosinian, Caledonian, and Yanshanian eras are among the many geological formations and periods represented in the study region. Other layers from the Paleogene period are also present. The most common types of rock that have been discovered are sandstone, granite, and hornstone. The complex Kaiping concave fault and fold systems were the dominant geological features in the project region, which were developed as a result of magmatic processes and various structures (Qin, 2017). Emergence of joint fissured features symbolizes the various tectono-geological periods, with the local tectonic line corresponding with the faults strike, especially in the northeast orientation (Yang et al., 2021)”.

REVISED:

“The study area exhibits a complex and diverse geological history, characterized by well-defined geometrical relationships among various lithologies. These formations and structural features are the result of multiple tectono-magmatic events spanning several geological periods. Intrusive rocks from the Indosinian (Late Triassic), Caledonian (Silurian–Devonian), and Yanshanian (Jurassic–Cretaceous) orogenies are well-represented, indicating a long sequence of crustal deformation and magmatic activity. These intrusions are primarily composed of granitic bodies, which suggest deep-seated magmatic processes associated with continental collision and subduction zones. In addition to these intrusive phases, sedimentary strata from the Paleogene period are also present, reflecting a later stage of basin development with fluvial and lacustrine depositional environments. Among the most prevalent rock types encountered in the region are sandstone, granite, and hornstone. Sandstone reflects high-energy sedimentary deposition. Granite indicates deep magmatic intrusions likely associated with Yanshanian tectonics. Hornstone (hornfels) results from contact metamorphism caused by magma intruding sedimentary rocks. The structural framework of the region is dominated by the Kaiping concave fault and fold system, a geologically significant and highly deformed zone that reflects multiple deformation episodes (Qin, 2017). These structures were primarily shaped by magmatic intrusions, crustal movements, and regional stress regimes. The presence of extensive jointed and fissured zones throughout the rock mass further supports a history of dynamic tectonic activity. These joints often serve as secondary permeability pathways and are critical in controlling groundwater flow in the fractured rock environment. Importantly, the orientation of these structural features, including faults and joints, is often aligned with northeast-trending tectonic lines, which are consistent with broader regional stress directions (Yang et al., 2021). This relationship among lithologies and structural features plays a critical role in controlling groundwater flow and permeability distribution."

Comment 5:

Line 204: what does "5-20%" represent for? More specific content is preferred for this sentence.

Response 5:

“The vertical resolution of 5–20% can be assessed by CSAMT when exploring depths ranging from 20 to 1000 meters” explained as in the revised version:

“In CSAMT, the vertical resolution, which refers to the ability to distinguish between adjacent subsurface layers, can typically range between 5% and 20% of the investigation depth from approximately 20 to 1000 meters. At shallower depths (e.g., 20–100 m), vertical resolution is higher (closer to 5%), enabling better differentiation between thin layers. At greater depths (up to 1000 m), resolution may degrade toward the 20% mark due to signal attenuation and broader averaging of resistivity data. This makes CSAMT a valuable tool for identifying significant lithological contrasts, fault zones, and resistivity anomalies related to geological structures”.

Comment 6:

Line 217: in section 2.2.2, why were 6 profiles selected? How did the author determine the locations of the profiles? The author might consider providing more evidence of the site location and data collection in the supporting material.

Response 6:

Further details regarding the selection criteria and rationale for the survey profiles have been provided in the revised manuscript.

ORIGINAL:

“The CSAMT data was acquired using six profiles (1–6) with a 50 meter interval between each station”.

REVISED:

“CSAMT data were acquired along six profiles (profiles 1–6), with a station spacing of 50 meters between each measurement point. The location of 6 CSAMT profiles was chosen based on several factors, including geological targets and objectives, surface geology and mapping data, topography and terrain accessibility, orientation relative to structures, spacing and coverage requirements, resistivity contrast expectations, integration with other data (boreholes), environmental and regulatory constraints, and source-receiver geometry requirements, etc. Carefully selected survey profiles enhanced the ability to resolve critical subsurface features and minimized ambiguities in the geophysical interpretation”.

Additional details are provided in the revised manuscript.

Comment 7:

Line 250-154: The author might consider providing more details of the static correction and the Hanning window spatial filtering method.

Response 7:

Additional details on static correction and Hanning window spatial filtering have been included in the revised manuscript to enhance clarity and support the interpretation of CSAMT data.

ORIGINAL:

“The static corrections were made using a Hanning window spatial filtering method, which involved geological information and curve analysis.”

REVISED:

“Static correction and spatial filtering using a Hanning window are essential preprocessing steps in CSAMT data analysis, aimed at improving data quality and enhancing the reliability of subsurface resistivity models. Static correction addresses the effects of near-surface resistivity inhomogeneities, which can distort electric field measurements and introduce static shifts, vertical displacements in apparent resistivity curves that misrepresent deeper subsurface conditions. This correction typically involves adjusting the measured electric fields by referencing them to a stable or averaged field, effectively removing shallow-layer influences and isolating true subsurface signals. Spatial filtering, on the other hand, is used to mitigate noise introduced by environmental and instrumental sources. Among various filters, the Hanning **(**Hann**)** window is commonly applied due to its effectiveness in reducing spectral leakage and smoothing data. When used in spatial filtering, the Hanning window averages measurements across adjacent stations in a weighted manner, preserving spatial trends while suppressing high-frequency noise. This improves the coherence of the dataset and ensures more stable and interpretable inversion results”.

Comment 8:

Figure 1: typos in (b), “uncertainty”; also the words are too small to read.

Response 8:

Figure 1, along with all other figures, has been redrawn and improved for better clarity and presentation. The updated figs are included at the end of the response/comments section in the attached file.

Comment 9:

Figure 7 and Figure 8: a little confused about the legend of the north direction in both figures

Response 9:

The north direction in these figures is correctly oriented, though slightly tilted, to provide a clearer and more informative view of the 3D permeability (k) models. The revised figures are included at the end of the response/comments section in the attached file.

Revised Figures

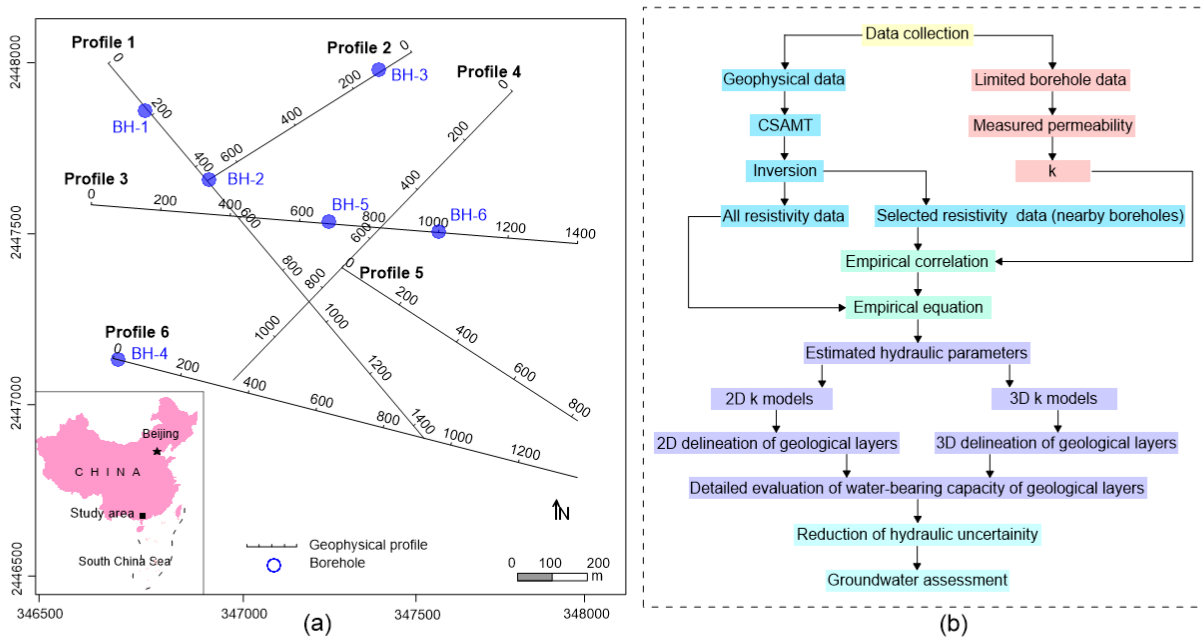

Fig. 1. (a) The location of the project site, with six boreholes BH1–BH6 (blue circles) and six CSAMT profiles 1-6 (black lines), (b) Flow diagram outlining the planned method for getting 2D and 3D k models for better, more thorough assessments of groundwater resources over large regions

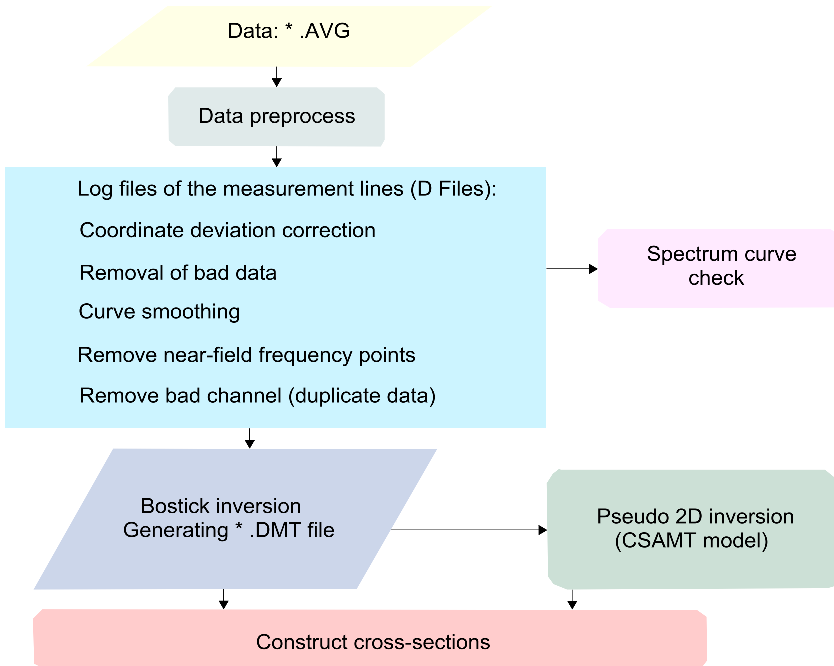

Fig. 2. Displaying the procedure of 2D inversion of CSAMT data by the use of Bostick inversion

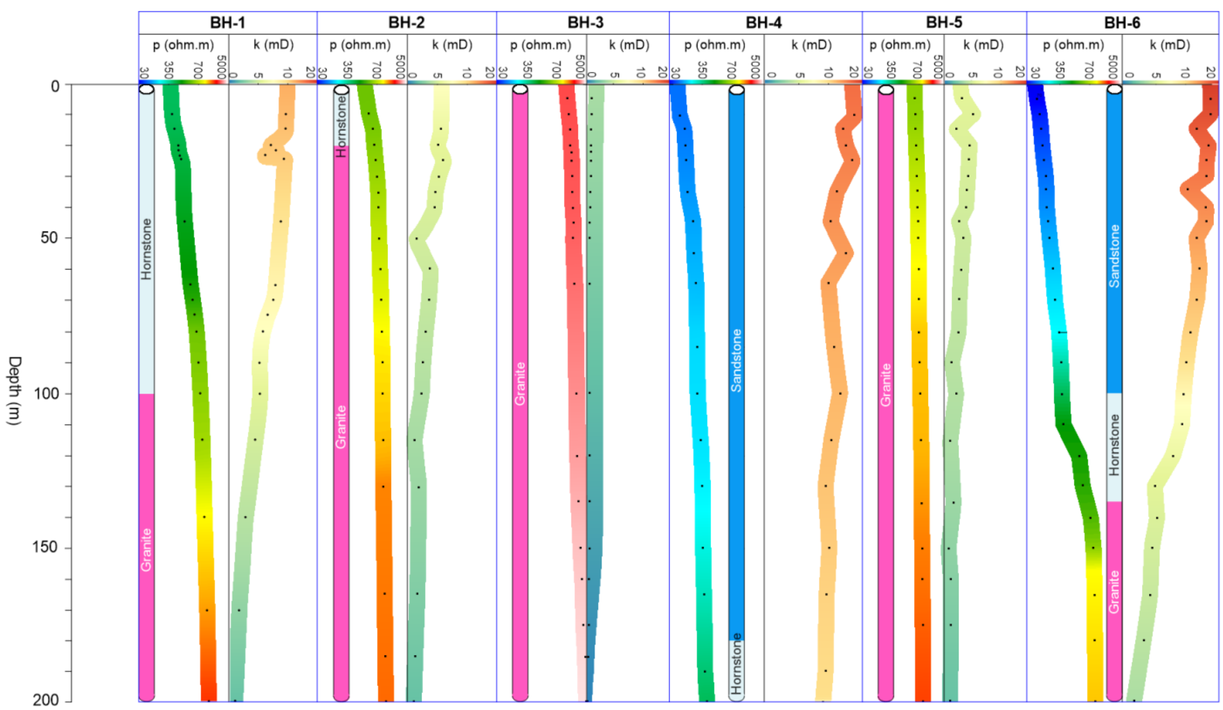

Fig 3. The evaluation of hornstone (HS), sandstone (SS), and granite (G) carried out by presenting 116 resistivity-k data points at depths ranging from 5 to 200 m using 6 drilled tests

(BH1–BH6) and associated resistivity (ρ) from CSAMT soundings. The small black dots show the data points

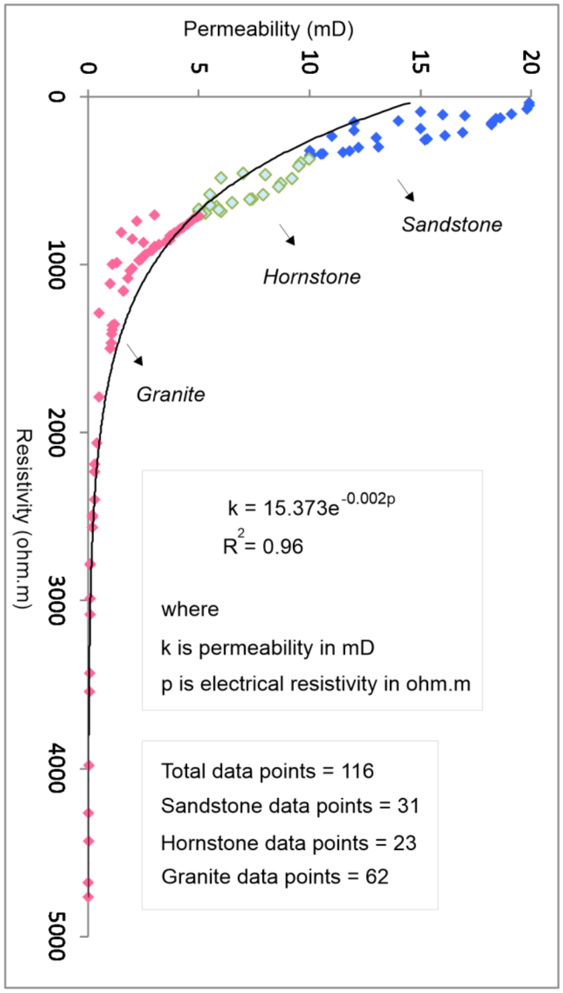

Fig 4. Using a total of 116 data points, the geophysical-borehole correlation for the predicted k

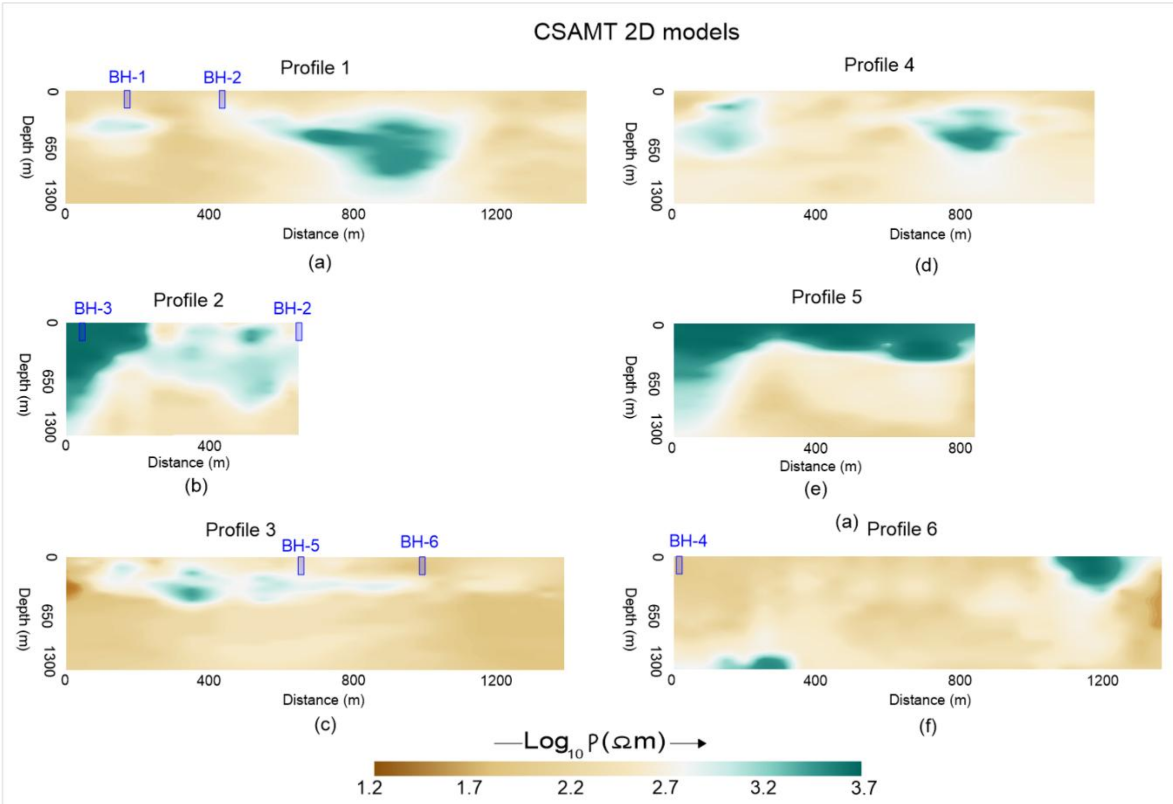

Fig. 5 2D CSAMT models along six geophysical profiles 1-6. Where resistivity increases from brown to green on a color bar.

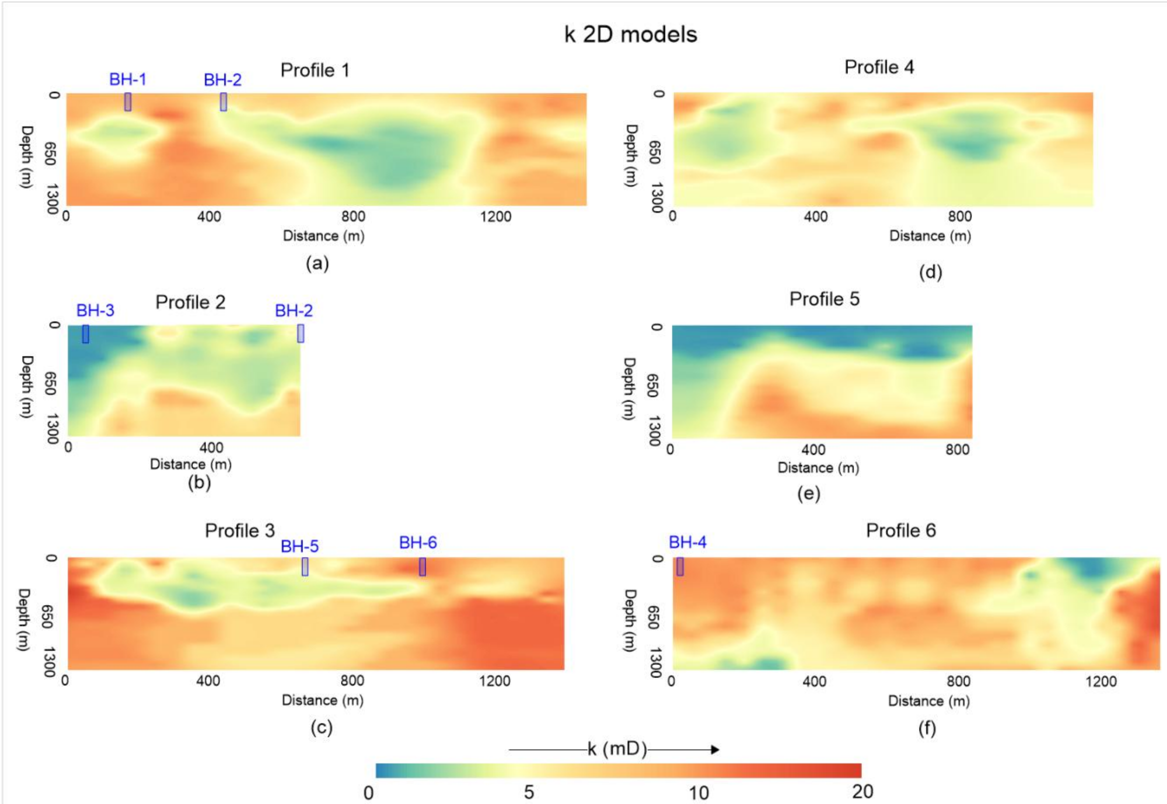

Fig. 6 The predicted 2D k models obtained from CSAMT data along six geophysical profiles 1-6. Where k increases from light green to red on a color scale

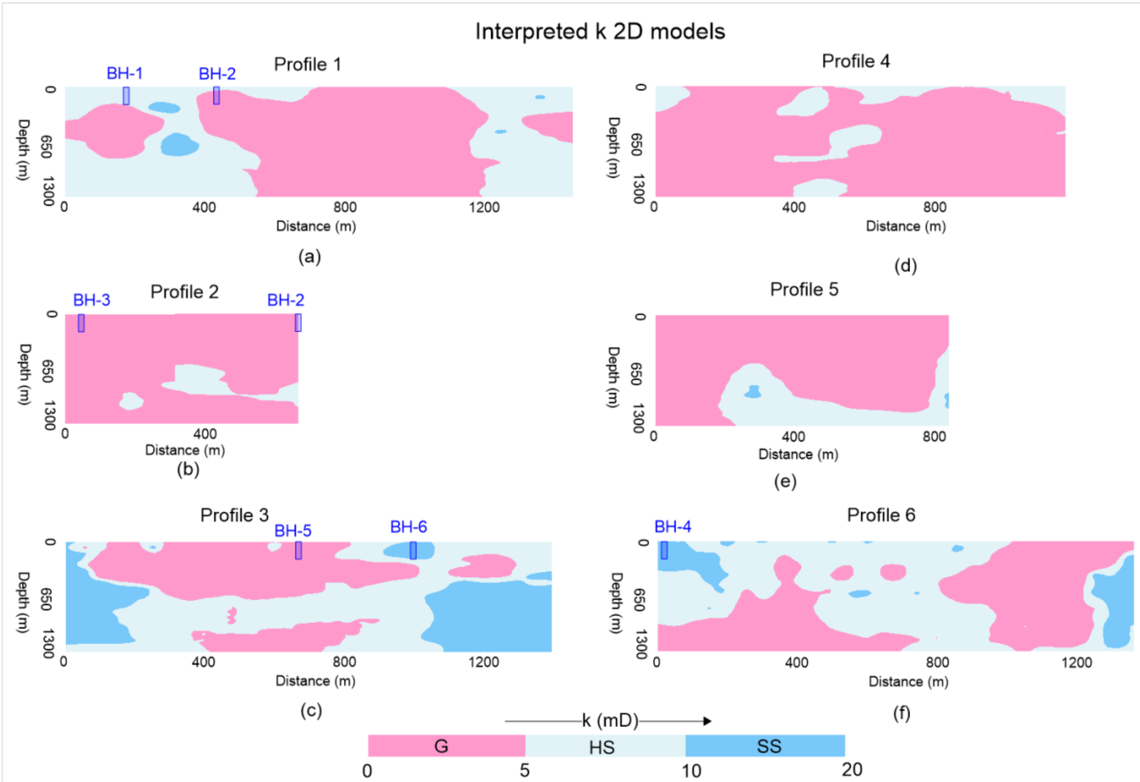

Fig.7 The interpreted (hydrogeological) 2D models along six geophysical profiles 1–6 obtained via geophysical-borehole correlation, facilitates groundwater assessment through high potential aquifer (HPA), medium potential aquifer (MPA), and low potential aquifer (LPA) associated with sandstone (SS), hornstone (HS), and granite (G), respectively

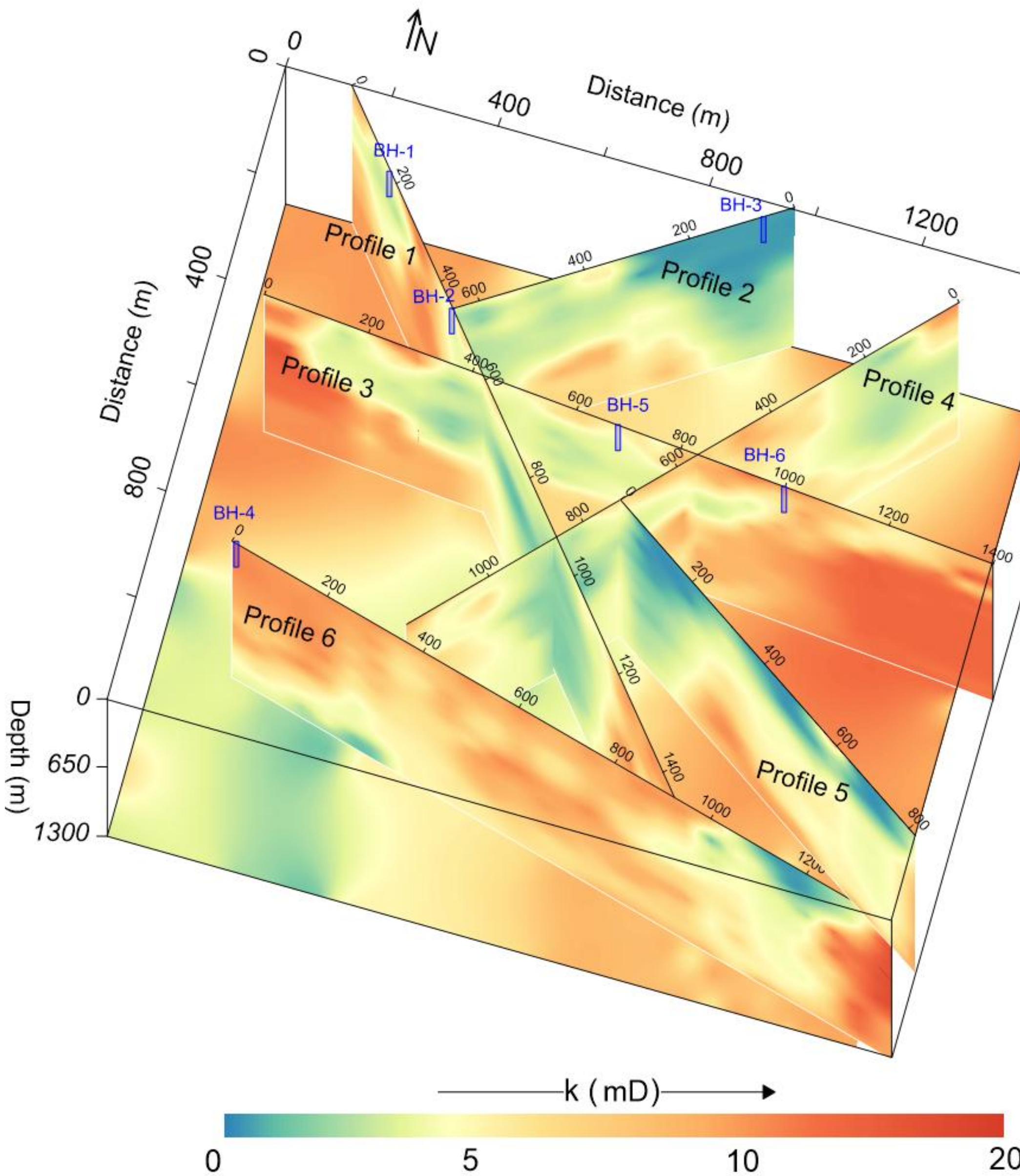

Fig. 8 The integrated 2D k models derived from the incorporation of geophysical and drilling data, with k represented on a color bar spanning from green to red

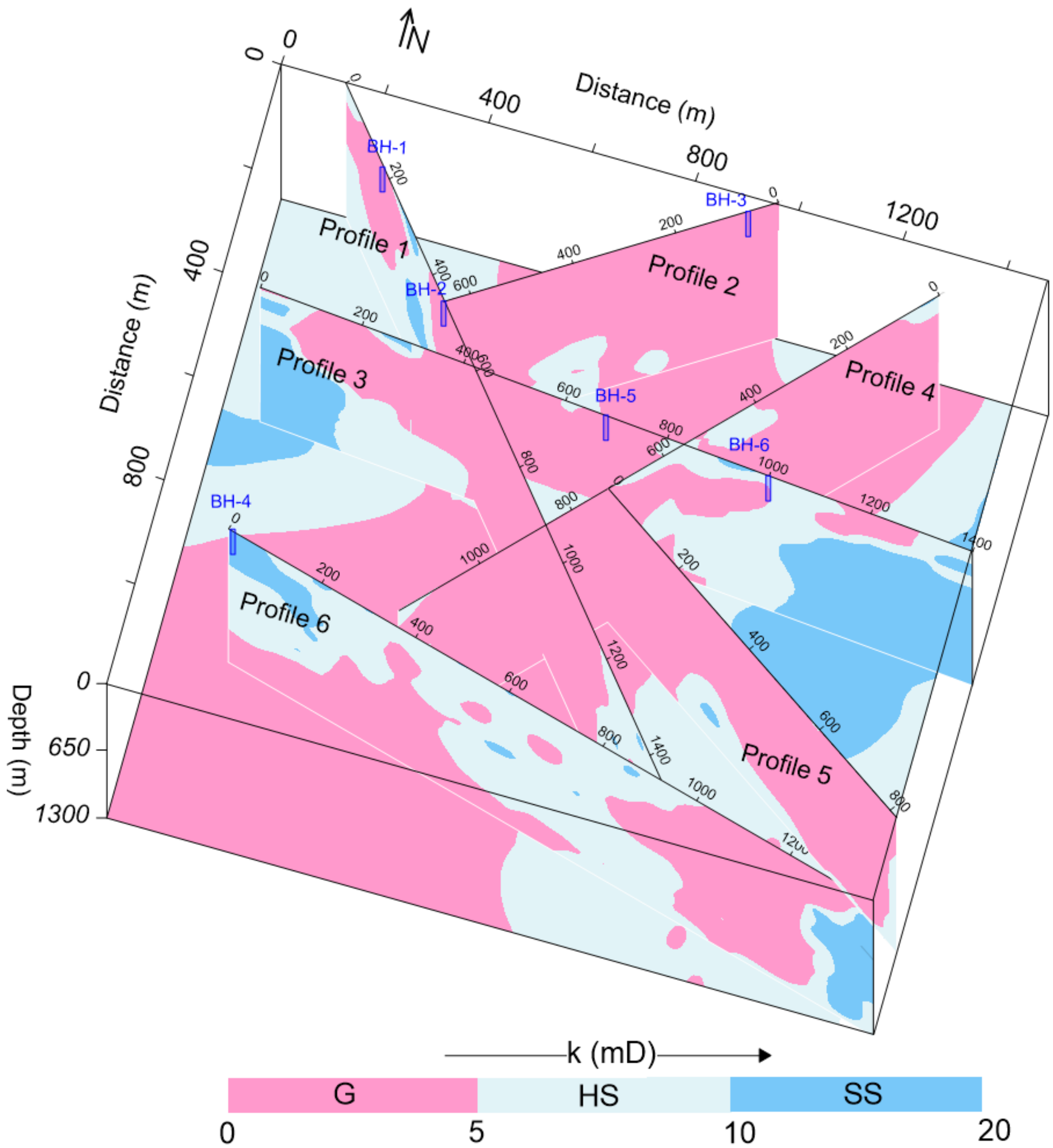

Fig. 9 Analysis of the integrated 2D k models (derived from designated k ranges) for three groundwater potential aquifers: low potential aquifer (LPA), medium potential aquifer (MPA), and high potential aquifer (HPA), associated with three geological formations: granite (G), hornstone (HS), and sandstone (SS), respectively

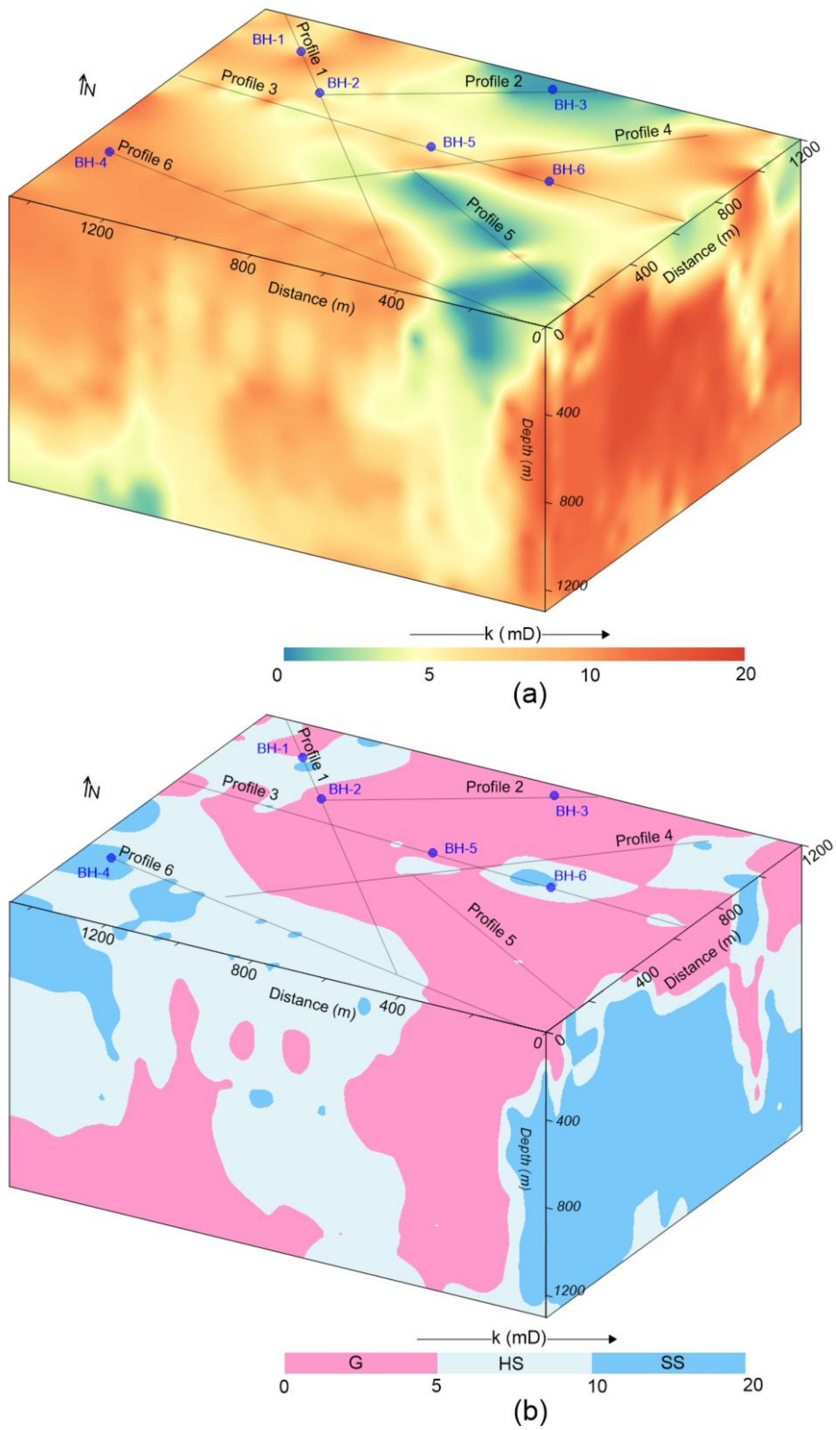

Fig. 10 The 3D k models, generated from the correlation of CSAMT and borehole data (with k represented on a color scale ranging from green to red), correspond to three groundwater potential aquifers: low potential aquifer (LPA), medium potential aquifer (MPA), and high

potential aquifer (HPA), associated with three geological strata: granite (G), hornstone (HS), and sandstone (SS), respectively, for (a) the external view of the 3D k model, and (b) the analysis of the 3D k model from an external perspective

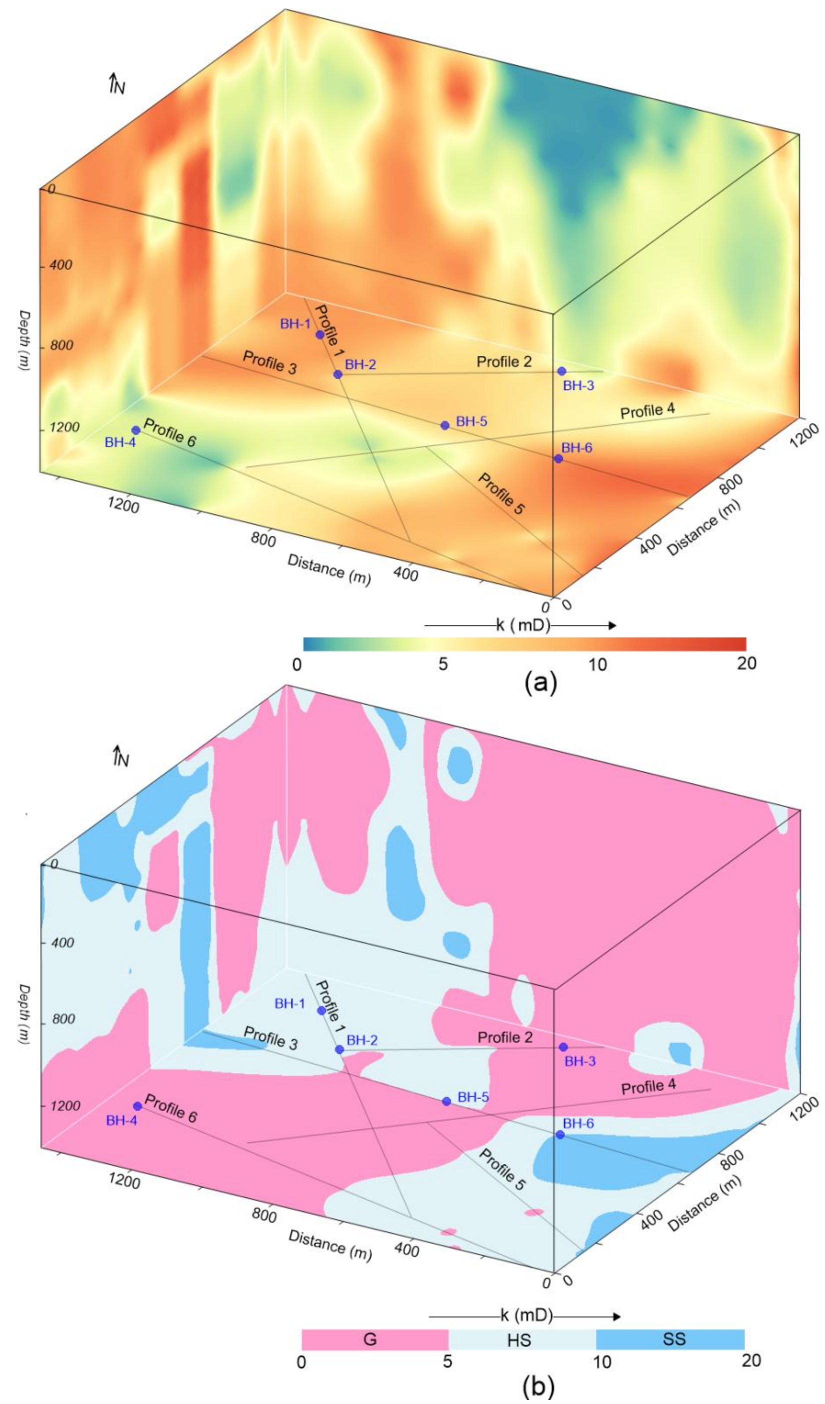

Fig. 11 The 3D k models, obtained from the correlation of CSAMT and borehole data (with k represented on a color scale ranging from green to red), illustrate three groundwater potential aquifers: low potential aquifer (LPA), medium potential aquifer (MPA), and high potential aquifer (HPA), associated with three geological strata: granite (G), hornstone (HS), and sandstone (SS), respectively, for (a) the internal view of the 3D k model, and (b) the analysis of the 3D (internal perspective) k model

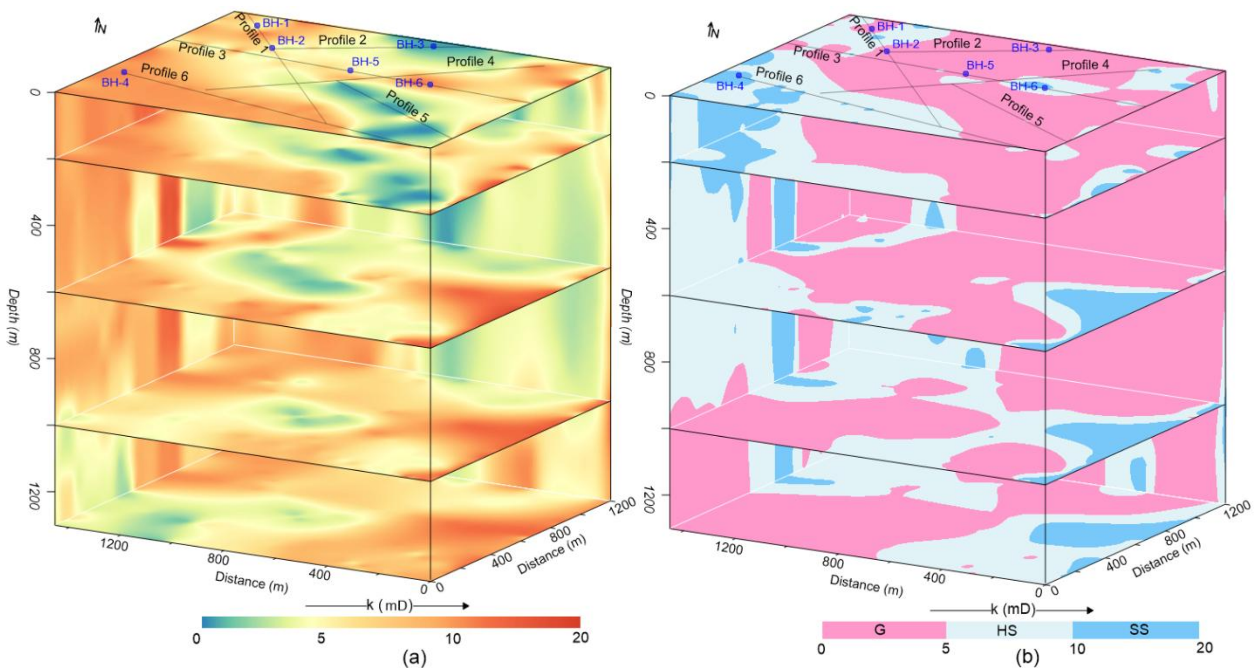

Fig. 12 (a) Geophysical-based k imaging at various depths (0, 200, 600, 1000, and 1300 m) with inner 3D view is represented by K on a color bar that goes from green to red, (b) Assessment of geophysical-derived k (using specified k ranges) at different depths for various types of aquifers: low potential aquifer (LPA) granite (G), medium potential aquifer (MPA) hornstone (HS), and high potential aquifer (HPA) sandstone (SS)