

1 **Novel insights into deep groundwater exploration by geophysical estimation of**
2 **hard rock permeability**

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23 **Abstract**

24 Deep groundwater exploration in hard rock terrains is essential in regions with the potential for
25 deep aquifers, especially where water scarcity threatens sustainable development and long-term
26 water security. However, such exploration remains a global challenge due to the geological
27 complexity and the limitations of traditional investigation methods. Accurate estimation of
28 hydraulic parameters, particularly permeability (k), is vital for effective groundwater
29 management and reliable prediction of future scenarios. Conventionally, permeability is
30 measured through borehole investigations. While widely adopted, these methods are intrusive,
31 expensive, time-consuming, and limited to point-scale measurements. Their effectiveness is
32 often restricted to areas with relatively uniform geological settings, and they are generally
33 inadequate for assessing deep groundwater systems. In contrast, geophysical methods offer a
34 non-invasive, cost-effective, and efficient alternative, enabling large-scale assessment of
35 subsurface hydrogeological conditions with minimal surface disruption. Previous geophysical
36 studies have employed empirical approaches, particularly vertical electrical sounding (VES), to
37 estimate permeability. However, these methods are confined to shallow depths, homogeneous
38 settings, and one dimensional interpretation, making them insufficient for application in highly
39 heterogeneous hard rock environments. This study introduces, for the first time, the use of
40 controlled-source audio-frequency magnetotellurics (CSAMT) to estimate two and three
41 dimensional permeability distributions at depths exceeding 1 km in complex geological settings,
42 including sedimentary, igneous, and metamorphic rocks. The results demonstrate that CSAMT
43 can effectively characterize deep subsurface variability and generate accurate, spatially
44 continuous hydrogeological models in hard rock terrains, particularly where drilling data are
45 limited or unavailable. Our approach cuts down on the need for costly borehole tests and allows

46 for a more thorough assessment of aquifer potential. This research provides a major
47 breakthrough in deep groundwater investigation and helps with better scientific planning and
48 long-term groundwater resource management in challenging hard rock areas.

49 **Keywords:** Permeability; Geophysical methods; Hydraulic parameters; Groundwater; Hard rock;
50 Hydrogeological models

51 **1 Introduction**

52 Metamorphic and igneous rocks make up the majority of Earth's crust, covering roughly one-
53 third of the planet's surface ([Amiotte Suchet et al., 2003](#)). Research on groundwater in hard rock
54 terrains primarily aims to delineate subsurface geological features, such as fault systems and
55 fracture networks, which are essential for understanding groundwater occurrence and movement
56 ([Fernando and Pacheco, 2015](#); [Hasan et al., 2021](#)). A crucial parameter in these studies is aquifer
57 potential, which refers to the ability of rock formations to store and transmit water. This
58 parameter is essential for the monitoring and evaluation of groundwater resources ([Majumdar
59 and Das, 2011](#); [Nwosu et al., 2013](#); [Qian et al., 2024](#)). The aquifer potential is influenced by
60 various geological and environmental factors, such as lithology, structural configuration, fault
61 and joint density, mineralogical composition, weathering degree, and water infiltration depth
62 ([Dell'Oca et al., 2020](#); [Abbas et al., 2022](#)). Accurately characterizing the lateral and vertical
63 heterogeneity of aquifer properties within complex and massive rock units remains one of the
64 primary challenges in hard rock hydrogeology ([Courtois et al., 2010](#); [Dewandel et al., 2006](#)). A
65 thorough assessment of aquifer potential is particularly important in geologically varied
66 environments, where conventional methods frequently prove inadequate due to the complexity of
67 subsurface formations and the scarcity of direct data ([Robinson et al., 2016](#); [Worthington et al.,](#)

68 2016; Zhu et al., 2017). These uncertainties often lead to inefficient or unsustainable
69 groundwater development, worsening water scarcity and environmental degradation (Dewandel
70 et al., 2006; Refsgaard et al., 2012; Lachassagne et al., 2021). Refining cost-effective and
71 reliable methods for assessing subsurface hydrogeological conditions is a fundamental challenge
72 in the study and management of hard rock aquifers.

73 Groundwater at depths greater than 500 m is typically less affected by surface
74 hydrological processes and frequently contains brackish or saline water (Gleeson et al., 2016;
75 Margat and van der Gun, 2013; Ferguson et al., 2023). Its exploration is increasingly recognized
76 as strategically important in certain geological and environmental contexts. In the Jinji region
77 (study area), various site-specific factors require a targeted examination of these deeper reserves.
78 First, surface water availability is both scarce and unreliable, increasing the importance of deep
79 aquifers as a potential supplementary source of freshwater. Second, the shallow subsurface is
80 largely composed of fresh granite, a rock type known for its inherently low porosity and
81 permeability, thus offering limited groundwater potential (Dewandel et al., 2006; Lachassagne et
82 al., 2021). In contrast, favorable water-bearing zones such as fractured granite, sandstone, and
83 hornstone are typically found at much greater depths. Third, recent national water initiatives in
84 China have underscored the need for deep subsurface exploration, especially in structurally
85 complex terrains, to uncover underutilized aquifers that could contribute to more resilient water
86 supply systems in the face of increasing demand and climatic uncertainties (MOHURD, 2021;
87 Qian et al., 2024). Comprehensive assessments of deep groundwater are therefore essential for
88 identifying these hidden but strategically valuable water sources, evaluating their recharge
89 characteristics, and integrating them into sustainable long-term management plans (Courtois et
90 al., 2010; Refsgaard et al., 2012). As pressures on surface and shallow subsurface water sources

91 intensify, deeper aquifer systems may serve as a critical buffer, ensuring more reliable water
92 access amid growing environmental and socio-economic challenges.

93 Multiple studies have recorded the swift depletion of global groundwater reserves,
94 underscoring an increasing concern for water sustainability (Rodell et al., 2009; Wada et al.,
95 2010; Laghari et al., 2012; Jasechko et al., 2024). In light of this significant issue, thorough and
96 precise assessments of groundwater resources are crucial for their effective management and
97 sustainable utilization. A comprehensive understanding of hydraulic properties is essential for
98 these assessments. Permeability is a crucial parameter for characterizing the ability of geological
99 formations to store and transmit water. This factor is crucial for aquifer analysis in various
100 hydrogeological contexts globally (Dewandel et al., 2006; Gerke et al., 2011; Allègre et al., 2016;
101 Fiandaca et al., 2018; Mudunuru et al., 2022; Esmailpour et al., 2023; Yan et al., 2024; Carbillet
102 et al., 2024). The aquifer potential of geological layers is usually determined by permeability
103 (Zhang et al., 2004; Pellet et al., 2024). De Lima and Niwas (2000), Soupios et al. (2007), Hasan
104 et al. (2021), and Yang and Zhang (2024) all state that borehole testing is the standard method
105 for measuring aquifer parameters. While boreholes contribute valuable geological data,
106 generating a comprehensive 2D analysis through drilling alone is often time-consuming and
107 challenging (Hubbard and Rubin, 2002; Niwas and De Lima, 2003). Borehole methods are
108 limited by high costs, time-intensive procedures, bulky equipment requirements, and challenging
109 deployment in rugged terrain, while also providing only localized data with limited capability to
110 image lateral and deep subsurface structures (Singh, 2005; Lin et al., 2018; Asfahani, 2023).
111 Uncertainty in groundwater resource estimation can arise from the limited availability of
112 borehole data, as the constraints of drilling make it difficult to conduct frequent and widespread
113 borehole investigations. Alternatively, it is essential to develop methods that minimize the

114 reliance on costly drilling while still enabling accurate evaluation of groundwater storage
115 capacity within prospective rock formations.

116 A diverse range of groundwater studies has effectively incorporated geophysical methods
117 to improve subsurface characterization (Bentley and Gharibi, 2004; Yadav and Singh, 2007; Fu
118 et al., 2013; Vouillamoz et al., 2014; Robinson et al., 2016; Lin et al., 2018; Abbas et al., 2022;
119 Kouadio et al., 2023; Zhang et al., 2024). These methods provide notable benefits compared to
120 traditional drilling, especially regarding cost-efficiency, rapid deployment, minimal
121 environmental impact, and ease of field implementation (Hu et al., 2013; Lin et al., 2018; Di et
122 al., 2020; Fusheng et al., 2022; Hasan and Shang, 2022). Geophysical tools offer significant
123 practical advantages, including strong vertical and lateral imaging capabilities, which enhance
124 their effectiveness in capturing the hydrogeological complexity of diverse subsurface conditions
125 (Niwas and De Lima, 2003; Fu et al., 2013; Hasan et al., 2021; Wynn et al., 2016; Kouadio et al.,
126 2023). Resistivity-based methods are pivotal in contemporary groundwater exploration, owing to
127 their sensitivity to diverse subsurface conditions and materials (Bentley and Gharibi, 2004;
128 Camporese et al., 2011; Robinson et al., 2016). The main methods in this category are vertical
129 electrical sounding (VES), electrical resistivity tomography (ERT), and controlled-source audio-
130 frequency magnetotellurics (CSAMT) (Soupios et al., 2007; Di et al., 2020; Zhang et al., 2024).
131 VES has been utilized for one dimensional profiling, especially in areas with horizontally layered
132 aquifers (Niwas and De Lima, 2003; Soupios et al., 2007; Majumdar and Das, 2011; Nwosu et
133 al., 2013; Hasan et al., 2021; Asfahani, 2023). This method is particularly appropriate for small-
134 scale applications (less than 200 m depth), providing low operational costs and reduced logistical
135 requirements. However, its lateral resolution is limited, and its performance can be compromised
136 in geologically complex settings with highly resistive or conductive layers. ERT, by contrast,

137 enables two and three dimensional imaging up to intermediate depths (~300 m) with
138 significantly improved resolution. It is particularly effective for characterizing complex
139 geological settings, such as fractured zones or karst systems, and is widely used for detailed
140 assessments of aquifer geometry and contamination (Bentley and Gharibi, 2004; Camporese et
141 al., 2011; Lin et al., 2018; Abbas et al., 2022; Hasan and Shang, 2022). Nonetheless, it requires
142 greater field effort, careful electrode spacing, and, like VES, may encounter challenges in highly
143 resistive or conductive environments. CSAMT, a more advanced method, is ideally suited for
144 deep investigations (hundreds to thousands of meters), especially in hard rock terrains. It
145 provides two and three dimensional subsurface imaging with strong sensitivity to deep
146 conductive structures, making it highly effective for delineating deep-seated aquifers and
147 geothermal systems (Smith and Booker, 1991; Simpson and Bahr, 2005; Bai et al., 2010; Fu et
148 al., 2013; Hu et al., 2013; Wang et al., 2015; Wynn et al., 2016; Zhang et al., 2021; Kouadio et
149 al., 2023). While CSAMT typically offers lower spatial resolution than ERT, it excels in deep
150 structural mapping, performs well in areas with high cultural noise due to its controlled-source
151 signals, and can be further enhanced when integrated with empirical or model-based approaches
152 (Zonge and Hughes, 1988; An et al., 2016; Hasan et al., 2025). The choice among these
153 resistivity techniques depends on various factors, including investigation depth, target resolution,
154 geological complexity, logistical constraints, cost, field conditions, and resistivity contrast (Di et
155 al., 2020; Hasan and Shang, 2022). Given these considerations, particularly the need to
156 investigate deep aquifer systems in hard rock environments, CSAMT was determined to be the
157 most suitable method for the present study.

158 In fractured rock environments, including granitic, metamorphic, and sandstone
159 formations, fluid movement is primarily influenced by the arrangement and connectivity of

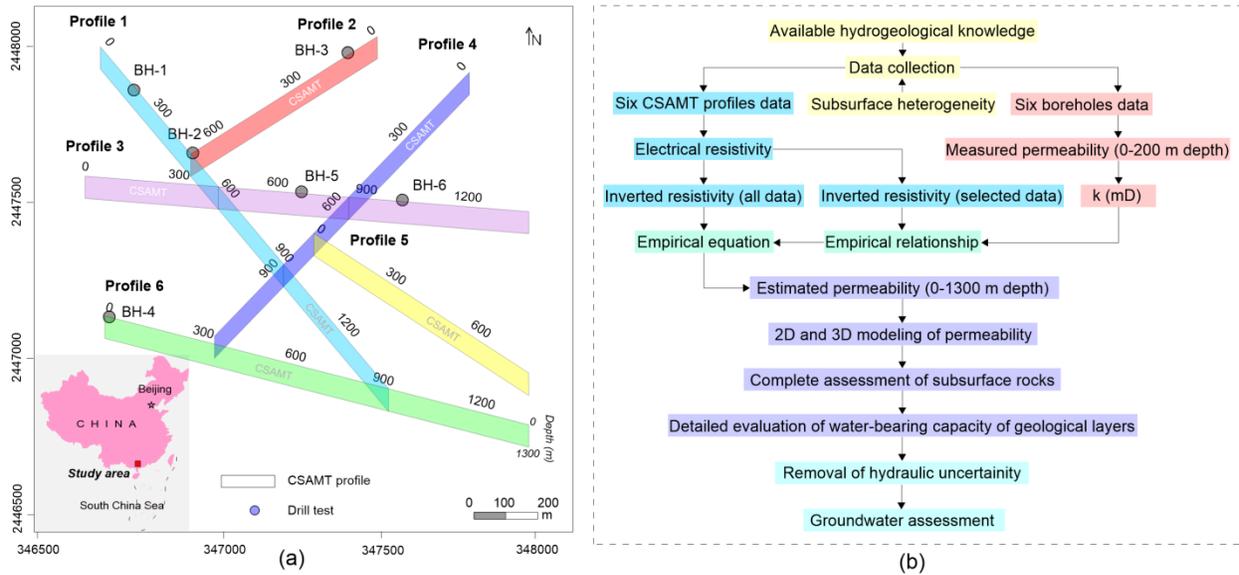
160 fractures, rather than the inherent porosity of the rock matrix. A precise assessment of hydraulic
161 behavior in these environments necessitates the application of integrated methodologies. Recent
162 studies emphasize the necessity of integrating geophysical and hydrogeological methods to
163 accurately identify and characterize hydraulic properties (McKeown et al., 1999; Medici et al.,
164 2023). Interdisciplinary approaches are crucial for improving the precision of flow modeling and
165 for guiding groundwater management and geo-energy development in structurally complex
166 terrains. Resistivity-based methods are essential in groundwater investigations for their ability to
167 delineate subsurface structures and identify areas with water-bearing potential. Recent
168 hydrogeophysical studies have focused on the correlation between electrical resistivity and
169 permeability, as both are closely related to the fluid content and physical structure of subsurface
170 materials. Electrical resistivity, which reflects a material's resistance to the flow of electrical
171 current, is influenced by various factors. These include rock type, porosity, weathering extent,
172 connectivity of the pore network, saturation level, structural features like faults and fractures, and
173 the salinity of pore fluids. Numerous parameters significantly affect permeability, highlighting
174 the utility of resistivity measurements as indicators for evaluating groundwater flow potential
175 (Singh, 2005; Sinha et al., 2009; Hasan et al., 2021). Numerous studies have investigated
176 empirical and semi-empirical correlations between these two parameters, with the objective of
177 utilizing resistivity as a proxy for estimating hydraulic conductivity or permeability in regions
178 with limited data (De Lima and Niwas, 2000; Hubbard and Rubin, 2002; Niwas and De Lima,
179 2003; Singh, 2005; Soupios et al., 2007; Jardani et al., 2007; Sinha et al., 2009; Majumdar and
180 Das, 2011; Nwosu et al., 2013; Hasan et al., 2021; Asfahani, 2023). Niwas and De Lima (2003)
181 developed an analytical model linking formation resistivity to transmissivity in porous media.
182 Similarly, Jardani et al. (2007) demonstrated the feasibility of employing geophysical inversions

183 to infer permeability distributions in heterogeneous aquifers. Recent studies have applied these
184 approaches to fractured and hard-rock environments; however, such correlations are less
185 common and frequently constrained by site-specific geological variability (Soupios et al., 2007;
186 Hasan et al., 2021; Asfahani, 2023). Despite recent advancements, the development of robust,
187 high-resolution 2D and 3D permeability models from resistivity data, particularly in geologically
188 complex environments at significant depths, remains a major challenge. To date, no previous
189 studies have successfully achieved this, underscoring the critical need for improved integration
190 of geophysical measurements with sparse borehole data. The relationship between resistivity
191 measurements and borehole-derived data provides an efficient and cost-effective method for
192 estimating aquifer properties over extensive spatial areas and varied depth profiles. This study,
193 for the first time, demonstrates a novel application of the CSAMT technique to create high-
194 resolution two and three dimensional permeability models reaching depths of around 1300 m in a
195 geologically complex and heterogeneous environment characterized by sandstone, granite, and
196 hornstone. A selected number of boreholes were strategically drilled at critical points within the
197 study area. Following this, several CSAMT survey lines were conducted, encompassing both the
198 borehole locations and their surrounding zones. By linking resistivity data from the CSAMT
199 surveys with permeability measurements obtained from borehole core testing, we derived a
200 reliable empirical relationship between resistivity and permeability. This correlation was then
201 applied throughout the entire CSAMT dataset, allowing for the generation of detailed 2D and 3D
202 permeability models even in regions lacking direct borehole data. The method provides a cost-
203 effective and comprehensive framework for evaluating deep groundwater potential, significantly
204 minimizing the reliance on extensive and expensive drilling operations.

205 This study introduces several important advancements in the assessment of deep
206 groundwater resources. It is the first to estimate permeability beyond depths of 1,000 m within a
207 hard-rock environment and to develop detailed two and three dimensional permeability models
208 through geophysical techniques. The innovative use of CSAMT for volumetric hydraulic
209 parameter estimation represents a notable methodological breakthrough. Carried out in a
210 geologically intricate setting dominated by sandstone, granite, and hornstone, where such deep
211 assessments were previously unattempted, this work also highlights the effective integration of
212 limited borehole data to generate high-resolution hydrogeological models. This strategy offers a
213 practical and cost-efficient alternative to widespread deep drilling, significantly decreasing the
214 number of boreholes required to achieve similar spatial detail in permeability mapping. The
215 primary aim of this study is to develop and implement a geophysical-based approach for
216 accurately predicting the spatial distribution of permeability in deep, hard rock environments. By
217 integrating CSAMT data with strategically selected borehole measurements, this research
218 enhances the two and three dimensional assessment of hydrogeological properties across various
219 rock types in geologically complex settings, reduces reliance on extensive and costly drilling,
220 and highlights the advantages of using non-invasive geophysical techniques as a more efficient
221 alternative for deep groundwater exploration.

222 **2 Methods**

223 This study integrates limited drilling data with the CSAMT method to estimate permeability (k)
224 for both two dimensional and three dimensional assessments of groundwater resources across the
225 entire project area (Fig. 1a). The main stages of the methodology are summarized in the
226 flowchart shown in Fig. 1b.



227

228 **Fig. 1.** (a) Location of the project site, showing six boreholes (BH-1 to BH-6) and six CSAMT survey
 229 profiles (1–6); (b) Flowchart illustrating the methodology for generating 2D and 3D permeability (k)
 230 models to enable comprehensive assessments of groundwater resources across extensive areas

231 **2.1 Study area and hydrogeological settings**

232 This study is part of a broader suite of major national-level initiatives in South Guangdong of
 233 China, each targeting distinct aspects of deep subsurface exploration. These include both the
 234 investigation of deep groundwater resources, as undertaken in this study, and the development of
 235 deep-underground engineering infrastructure, such as the Jiangmen Underground Neutrino
 236 Observatory (JUNO), China's next-generation neutrino detector (Hasan et al., 2025). While each
 237 project addresses distinct hydrogeological and geotechnical challenges, they are collectively
 238 aligned with China's broader strategic agenda for deep subsurface resource development and
 239 sustainable utilization. This study was conducted in the Jinji region of South Guangdong, a
 240 geologically diverse and structurally complex area prioritized for deep groundwater exploration
 241 (Fig. 1a). Situated within a subtropical monsoonal climate zone, the region experiences intense

242 seasonal rainfall, with an average annual precipitation of approximately 1981 mm. The
243 topography is defined by low, eroded hills and moderately elevated mountains, with elevations
244 ranging from 39 to 539.9 m above sea level. The study area features diverse topography, ranging
245 from mild slopes to sharply inclined terrain, and is characterized by dense vegetation cover. The
246 northern portion is comparatively flat, whereas the southern region is more mountainous,
247 distinguished by notable elevations such as Dashishan, Qilongding, Jixinshan, and Xikeng. The
248 Yongkouwei River, located in the northeastern section at approximately 7.5 m above sea level, is
249 a crucial component of the region's surface water drainage system.

250 The Jinji region exhibits a complex geological evolution shaped by various tectono-
251 magmatic events, particularly during the Caledonian (Silurian–Devonian), Indosinian (Late
252 Triassic), and Yanshanian (Jurassic–Cretaceous) orogenic phases. The geodynamic episodes
253 have resulted in a diverse lithological landscape, mainly consisting of granite, sandstone, and
254 hornstone (hornfels) (Qin, 2017; Yang et al., 2021). Extensive granitic intrusions indicate deep
255 crustal magmatism linked to continental collision and subduction processes. Hornstone
256 exemplifies contact metamorphism resulting from the intersection of intrusive bodies with pre-
257 existing sedimentary layers. Paleogene formations, primarily consisting of fluvial and lacustrine
258 deposits, overlay these units and signify a subsequent phase of basin sedimentation. The region is
259 characterized by the Kaiping concave fault-fold system, a significant deformation zone formed
260 through recurrent crustal stress and magmatic processes. This structural framework encompasses
261 various fault types, including reverse, thrust, and strike-slip, indicative of a prolonged history of
262 crustal shortening and lateral displacement. Compressional folds that developed during the
263 Caledonian and Indosinian periods were subsequently modified by strike-slip faulting in the
264 Yanshanian phase. The prevalent northeast-trending orientation of these features aligns with

265 regional stress patterns and significantly influences the subsurface architecture (Qin, 2017; Yang
266 et al., 2021). Fracture networks, consisting of joints and fissures, are widespread in granite,
267 sandstone, and hornstone units. The brittle features, characterized by variations in spacing,
268 orientation, and continuity based on lithology and structural history, function as essential
269 conduits for groundwater flow. Their spatial alignment with major fault systems highlights a
270 significant relationship between structural geology and hydrogeology, with critical implications
271 for subsurface fluid dynamics in this fractured terrain.

272 This study primarily examines the vertical stratification of aquifer-bearing formations in
273 the Jinji region. Highly productive groundwater zones are linked to deeply buried sandstone
274 formations that possess well-developed fracture systems conducive to water storage and flow.
275 The sandstone units are covered by a substantial granite layer with low permeability, which
276 serves as a confining cap that limits vertical recharge from the surface. A hornstone (hornfels)
277 stratum is situated between these two layers, exhibiting intermediate hydraulic properties while
278 providing limited connectivity between the overlying granite and the deeper sandstone. This
279 configuration effectively isolates deep sandstone aquifers from near-surface hydrological
280 processes, making them inaccessible to conventional shallow geophysical or drilling techniques.
281 Targeted deep exploration is essential for the accurate identification and characterization of
282 concealed aquifers, as well as for guiding their sustainable management in this structurally
283 complex hard rock environment.

284 **2.2 CSAMT survey**

285 **2.2.1 Theoretical background**

286 The application of CSAMT in hard rock studies is well documented, as evidenced by various
287 publications (Simpson and Bahr, 2005; Bai et al., 2010; Fu et al., 2013; Wang et al., 2015; Wynn
288 et al., 2016; Di et al., 2020; Zhang et al., 2021; Kouadio et al., 2023; Hasan et al., 2025). In such
289 studies, a distant transmitter emits regulated electric signals into the earth, while a receiving
290 station monitors the electric and magnetic fields (Zonge and Hughes, 1988; Zhang et al., 2021).
291 A mathematical relationship exists between reflection depth and frequency in subsurface
292 structures, where different fields exhibit varied propagation depths (Borah and Patro, 2019). This
293 method utilizes the varying electrical conductivities of different rock types to monitor alterations
294 in magnetic field strength and primary field potential (Cagniard, 1953; Zonge and Hughes,
295 1988). The frequency components of the signal are obtained from the time series of
296 electromagnetic field fluctuations through the application of Fourier transforms (Simpson and
297 Bahr, 2005). A regulated artificial field source is employed in CSAMT. Electrodes positioned
298 one to two kilometers apart can measure the electromagnetic field component of an electric
299 dipole source. The wires connecting the batteries to the current electrodes and the transmitter can
300 be established. The typical distances between field source transmitters and receivers range from
301 5 to 10 km, although this may vary depending on the depth of investigation and geological
302 conditions. A method for determining subsurface resistivity involves calculating the ratio of the
303 magnitudes of the electric and magnetic fields measured in two orthogonal directions. Numerous
304 studies, such as those by Fu et al. (2013), Zhang et al. (2021), and Hasan et al. (2024), have
305 identified various factors affecting resistivity variations in connection with subsurface geological
306 conditions. These factors include lithological variations in stratigraphic structures, fault-induced
307 fragmentation, water saturation, rock types, pore fluid characteristics, and porosity. The vertical
308 resolution in CSAMT, indicating the capacity to differentiate between neighboring subsurface

309 layers, generally varies from 5% to 20% of DOI (depth of investigation), which spans
310 approximately 20 to 1000 meters. At shallower depths (e.g., 20–100 m), vertical resolution is
311 higher (closer to 5%), enabling better differentiation between thin layers. At greater depths (up to
312 1000 m), resolution may degrade toward the 20% mark due to signal attenuation and broader
313 averaging of resistivity data. This makes CSAMT a valuable tool for identifying significant
314 lithological contrasts, fault zones, and resistivity anomalies related to geological structures. The
315 propagation frequency and subsurface resistivity are the basis of DOI. According to [Borah and](#)
316 [Patro \(2019\)](#), a lower frequency and higher resistivity typically result in a higher DOI. The
317 distance between stations determines the lateral resolution; typically, this is between ten and two
318 hundred meters. According to [Simpson and Bahr \(2005\)](#), increasing the distance between stations
319 enhances the strength and reliability of the received signal. At every station, a portable receiver
320 processes, amplifies, filters, and records the incoming signal. In order to pick up sent signals,
321 electrode pairs, which include magnetic-field sensors and short grounded dipoles, are utilized.
322 Effective survey planning plays a crucial role in minimizing the impact of metal fence, radio
323 transmitter, power line, and other potential sources of interference that could affect the accuracy
324 of CSAMT data. Plan, three-dimensional, fence, and cross-sectional views are all potential ways
325 to display the modeled resistivity data.

326 **2.2.2 Survey design and procedures**

327 CSAMT data were collected along six profiles (Profiles 1–6), with a station spacing of 50 m
328 between successive measurement points. The selection and location of 6 CSAMT profiles were
329 chosen based on several factors, including geological targets and objectives, surface geology and
330 mapping data, topography and terrain accessibility, orientation relative to structures, spacing and
331 coverage requirements, resistivity contrast expectations, integration with other data (boreholes),

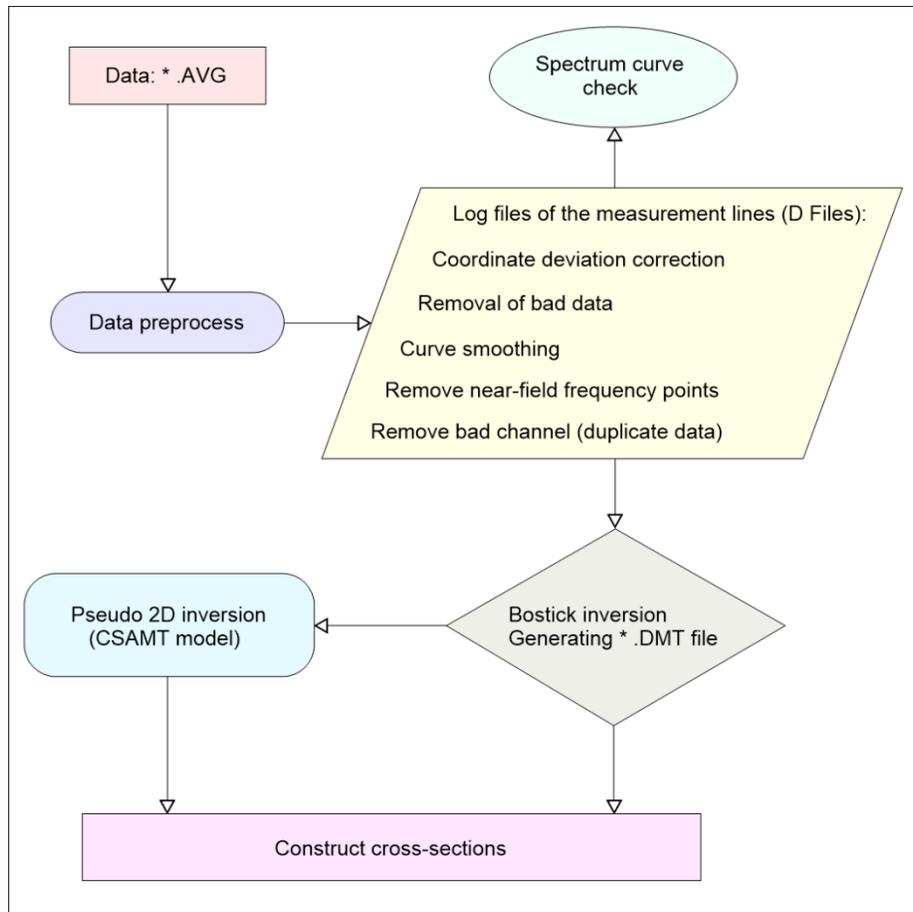
332 environmental and regulatory constraints, and source-receiver geometry requirements, etc.
333 Carefully selected survey profiles enhanced the ability to resolve critical subsurface features and
334 minimized ambiguities in the geophysical interpretation. The depth of investigation (DOI) in the
335 CSAMT survey was about 1300 meters. We performed scalar measurements using the
336 Transverse Magnetic (TM) mode, recording bidirectional magnetic and electric field
337 components, both perpendicular and parallel to the survey line. For EMAP observations,
338 measurement stations were arranged sequentially and placed approximately 50 m from the
339 electrodes. The configuration utilized Gain Mode X1 along with a 50 Hz linear filter.
340 Transmission current varied with frequency, ranging from 2.6–4.5 A at 7680 Hz to a peak of 12–
341 18 A at 1 Hz. CSAMT data were collected using a V8 multifunction receiver coupled with a
342 TXU-30 transmitter, both produced by Phoenix Geophysics, Canada. The TXU-30 is a versatile,
343 high-power transmitter with a maximum output capacity of 30 kilowatts. It enables geophysical
344 operation with transmission voltages up to 1000 V, delivering currents up to 20 A at 1000 V and
345 up to 40 A at 500 V. This GPS-enabled transmitter is ideal for deep investigation since it is
346 compatible with common household three-phase 220 volt alternators. There were 34 separate
347 frequency points utilized, spanning the range of 1–7680 Hz. In addition to collecting data, the V8
348 multifunction receiver may monitor data sent by other secondary receiving units. The principal
349 receiver's three channels and tracks make this possible. The distances between the transmitter
350 and receiver stations ranged from 9.3 to 12.5 km. Non-polarized electrodes were used to record
351 the electric field signals. Magnetic signals were captured using the AMTC-30 inductive sensor,
352 specifically designed for high-frequency AMT/CSAMT applications, with an operational range
353 from 10,000 Hz to 0.1 Hz. At each site, two orthogonal components of the electric field and three
354 orthogonal components of the magnetic field were acquired, allowing for the computation of the

355 full impedance tensor. Positional data for all measurements were obtained using a Trimble XH
356 dual-frequency GPS receiver, manufactured in the United States. Using the Hi-Tech V30GNSS
357 RTK apparatus, we measured the CSAMT lines for object recognition. Modern navigational aids
358 allow for pinpoint accuracy on the order of sub-meter precision. The computer calculated the
359 coordinate values of each survey line and survey point using the given direction and distance,
360 and then sent them to the GPS or RTK. Survey line measurement points were identified using
361 RTK or GPS navigation systems. The spatial distribution of inspection points was consistently
362 maintained, with system quality assessments showing variability within a 3–5% range along the
363 measurement lines. The system quality assessment met the following design criteria: a root-
364 mean-square (RMS) error of less than $\pm 5\%$, an allowable error of less than 10 between
365 consecutive profile points, a relative elevation tolerance of 1.67 mm, and a planar tolerance of
366 2.33 mm. Due to the absence of anthropogenic and electrical interference at the survey site, the
367 collected data was of exceptionally high quality. Site characteristics were interpreted based on
368 the analysis of the CSAMT data (An and Di, 2016; Hasan et al., 2025). After eliminating skewed
369 data, a detailed curve analysis was performed..

370 **2.2.3 Processing workflow**

371 Static correction and spatial filtering using a Hanning window are essential preprocessing steps
372 in CSAMT data analysis, aimed at improving data quality and enhancing the reliability of
373 subsurface resistivity models. Static correction mitigates the impact of near-surface resistivity
374 inhomogeneities, which can distort electric field measurements and result in static shifts, leading
375 to vertical displacements in apparent resistivity curves that misrepresent deeper subsurface
376 conditions. To improve data quality, measured electric fields were calibrated against a stable
377 baseline or averaged field, thereby reducing the impact of shallow subsurface layers and isolating

378 signals from deeper sources. Simultaneously, spatial filtering techniques were employed to
379 mitigate noise resulting from environmental and instrumental interference. The Hanning (Hann)
380 window demonstrated notable effectiveness in suppressing spectral leakage and smoothing
381 fluctuations while preserving underlying trends. The Hanning window, when applied in spatial
382 filtering, executed weighted averaging among adjacent measurement stations, preserving
383 coherent spatial patterns and reducing high-frequency noise. This method markedly enhanced the
384 stability and interpretability of the resulting inversion models. For the data processing step, we
385 used the CMTPro Version software produced by Phoenix Geophysics ([Phoenix Geophysics](#)
386 [CMTPro, 2020](#)). This program combines V8 and tracking data, and source current into CMT
387 files, corrects electrode coordinates, automatically smoothes observed curves, and generates files
388 in the AVG format, among other things. [Fig. 2](#) shows a flow diagram of the CSAMT-SW
389 method ([Phoenix Geophysics CSAMT-SW, 2020](#)) that was used to conduct the 2D inversion
390 ([Rodi and Mackie, 2001](#); [Wang et al., 2015](#)).

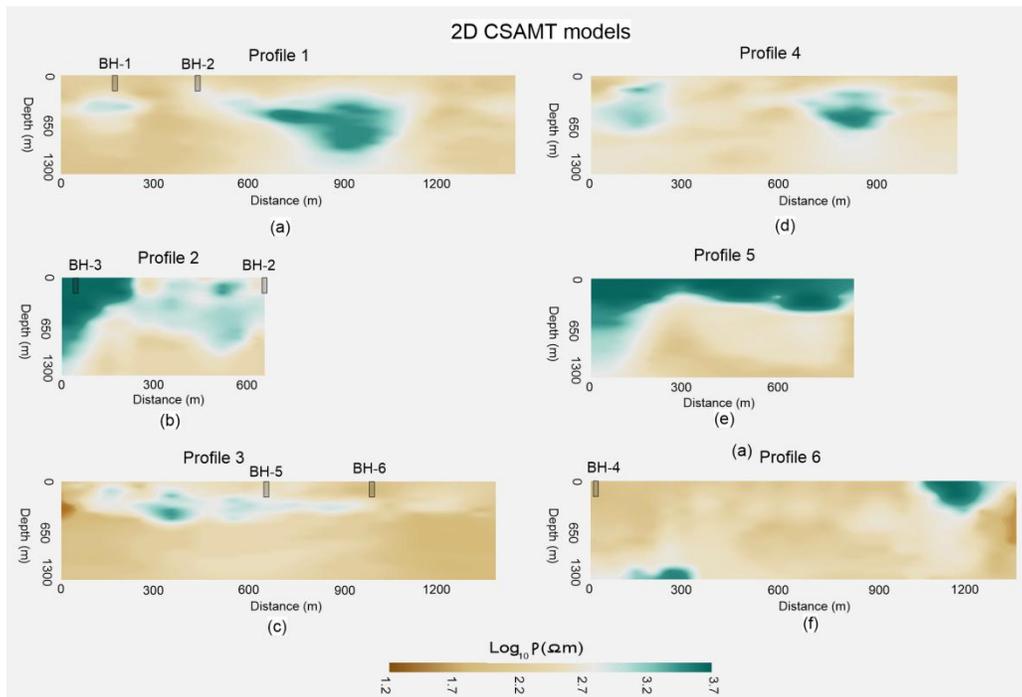


391

392 **Fig. 2.** Illustration of the 2D inversion process of CSAMT data using Bostick inversion

393 Here are the main components of the CSAMT-SW: 1. Data format conversion from AVG
 394 to D; 2. Editing and generating CHK elevation files, and converting them to format D; 3.
 395 Manually checking the file D for corrupted sectors, filling in the gaps, removing near-field data,
 396 and skipping to certain spots; 4. Inversion outcomes from different static correction methods
 397 were very similar when compared; the D file was utilized for smoothing processing; 5. D, H, K,
 398 and Z are the four static correction results files for various correction approaches; 6. Generating
 399 text files through BOSTICK inversion combined with near-field correction; 7. Using quasi-2D
 400 inversion combined with the CSAMT global field model (ID), which integrates both near and
 401 transition fields, finite-depth layers representing resistivity variations can be generated directly

402 from the measured CSAMT data. After applying Bostick inversion (Fusheng et al., 2022), the
 403 output data in D format were saved as *_BOS.DAT and *_BSS.DAT files, respectively. The
 404 processed data, formatted according to the requirements of the CSAMT 2D inversion model,
 405 were stored in a newly created *_M.DMT text file. The inversion process continued until either
 406 the maximum number of iterations, set at five, or the target RMS error was reached. At this point,
 407 the resulting models were fitted to the observed data using the inversion method. A trustworthy
 408 2D resistivity model (Zhang et al., 2021) of CSAMT was produced, considering the local
 409 geology and dataset quirks, by employing the most appropriate processing and inversion
 410 procedures to reduce model errors. The final inversion models (Fig. 3), through delineation of
 411 resistivity variations, significantly enhanced our understanding of the subsurface geological
 412 framework.



413

414 **Fig. 3.** Construction of 2D CSAMT models along six geophysical profiles: (a) Profile 1, (b) Profile 2, (c)
415 Profile 3, (d) Profile 4, (e) Profile 5, and (f) Profile 6. Resistivity values increase from brown to green on
416 the color scale.

417 **2.3 Permeability estimation framework**

418 **2.3.1 Laboratory-based permeability determination from borehole core samples**

419 Permeability (k) is a fundamental hydrogeological parameter that describes the capacity of a
420 porous medium, such as rock or sediment, to transmit water. This concept is crucial for
421 comprehending fluid dynamics in aquifers and is extensively utilized in groundwater evaluations
422 (Allègre et al., 2016; Fiandaca et al., 2018; Mudunuru et al., 2022; Esmailpour et al., 2023;
423 Carbillet et al., 2024). The permeability of a formation indicates the extent to which fluids can
424 move through pore spaces or interconnected fractures, serving as a critical factor in subsurface
425 hydrodynamics at different depths. k is typically determined via pumping tests or direct testing
426 of rock cores collected from boreholes, a method that is both expensive and logistically
427 demanding. Permeability is affected by various geological and physical factors, including
428 porosity, lithological composition, saturation level, faulting, jointing, and diagenetic processes
429 such as compaction and mineral alteration (Dewandel et al., 2006; Yan et al., 2024).

430 In this study, the initial permeability data from the Jinji region were limited to just six
431 boreholes. A suite of laboratory analyses was conducted on rock core samples obtained from the
432 deep boreholes to enhance the dataset's robustness. The research concentrated on three primary
433 lithologies: sandstone, hornstone (hornfels), and granite. The samples covered depths reaching
434 200 m. A total of 116 laboratory measurements were collected, comprising 31 from sandstone,
435 23 from hornstone, and 62 from granite. These measurements offer significant insights into the

436 vertical distribution of permeability across various strata, thereby enhancing the hydrogeological
437 characterization of the region (Neuzil, 1994; Zhang et al., 2020).

438 Coring was performed utilizing a wireline rotary system equipped with triple-tube barrels
439 to achieve minimal disturbance and optimal recovery of intact samples (ISRM, 2007). Core
440 samples were promptly vacuum-sealed and stored under controlled humidity to maintain in-situ
441 moisture conditions and the integrity of microfracture networks. Before testing, cores were
442 sectioned into standardized cylindrical specimens, generally measuring 50 mm in diameter and
443 100 mm in length, and examined to eliminate any visibly fractured or altered areas.

444 Two distinct laboratory techniques were utilized according to the anticipated permeability
445 range of each rock type. A steady-state flow method was employed for sandstone, which
446 typically demonstrates higher permeability, in accordance with ASTM D5084-21 guidelines
447 (ASTM, 2021). A constant hydraulic gradient was applied under fully saturated conditions, and
448 the corresponding volumetric flow rate was recorded. Permeability was determined through the
449 application of Darcy's Law:

$$450 \quad k = \frac{Q \cdot \mu \cdot L}{A \cdot \Delta P} \quad (1)$$

451 where Q is the flow rate (m^3/s), μ is the fluid viscosity ($\text{Pa}\cdot\text{s}$), L is the sample length (m), A is the
452 cross-sectional area (m^2), and ΔP is the applied pressure difference (Pa).

453 The transient pulse decay method was employed for granite and hornstone, both of which
454 exhibit low permeability, adhering to the procedure originally outlined by Brace et al. (1968) and
455 subsequently refined by Hsieh et al. (1981). This method involves introducing a brief pressure
456 pulse at one end of the saturated specimen and monitoring the rate of pressure decay over time.
457 Tests were performed under confining pressures reaching 30 MPa to replicate in-situ stress

458 conditions and to examine the stress-sensitive behavior of crystalline rocks, where fracture
459 closure can notably influence permeability (Faybishenko et al., 2000; Niu et al., 2016).

460 Each lithology underwent testing under both dry and saturated conditions to assess the
461 influence of moisture content on permeability. Measurements were replicated to ensure data
462 reliability, and statistical analyses were employed to evaluate variability within and among
463 lithological groups (Zhao et al., 2018). The permeability data were organized by depth and
464 lithology to create vertical permeability profiles, which served as a crucial input for analyzing
465 the hydrostratigraphic framework of the subsurface. Granite demonstrated the lowest
466 permeability, indicative of its dense, unfractured crystalline structure. Hornstone exhibited
467 intermediate permeability values, probably resulting from localized tectonic or thermally induced
468 fractures. Conversely, sandstone layers at increased depths exhibited markedly higher
469 permeability, aligning with their function as the primary aquifer units in the study region (Wang
470 et al., 2014; Liu et al., 2021).

471 **2.3.2 Permeability-resistivity relationship (Archie and Kozeny-Carman equation)**

472 Several foundational studies have established empirical and theoretical relationships between
473 electrical resistivity and hydraulic properties such as permeability. The Archie equation,
474 introduced by Archie (1942), is widely used in clean, saturated sedimentary formations. It relates
475 formation resistivity to porosity and water saturation but assumes the absence of clay minerals
476 and thus has limitations in more complex lithologies (Waxman & Smits, 1968; Glover, 2015).
477 The Kozeny-Carman equation is another widely accepted model that links permeability to
478 porosity and specific surface area (Bear, 1972; Carman, 1956). While it does not directly involve
479 resistivity, it is often used alongside petrophysical models to interpret hydrogeological
480 characteristics based on geophysical data (Paterson & Wong, 2005; Clennell, 1997).

481 Archie's law (Archie, 1942) relates the bulk electrical resistivity of a fully saturated
482 porous medium to its porosity and fluid resistivity. It is commonly expressed as:

$$483 \quad \rho_b = a \cdot \rho_f \cdot \phi^{-m} \quad (2)$$

484 where, ρ_b is the bulk resistivity, ρ_f is the fluid resistivity, ϕ is the porosity, a and m are empirical
485 constants. Although Archie's law does not directly estimate permeability, porosity is often used
486 as a proxy because of its influence on fluid flow. The resistivity-porosity relationship can be
487 indirectly extended to infer permeability, especially when combined with other petrophysical
488 models (Binley et al., 2005; Revil & Cathles, 1999).

489 The Kozeny–Carman equation establishes a theoretical relationship between permeability
490 (k) and porosity (ϕ), expressed as follows:

$$491 \quad k = \frac{C \cdot \phi^3}{(1-\phi)^2 \cdot S^2} \quad (3)$$

492 In this equation, k denotes permeability, ϕ represents porosity, S is the specific surface area, and
493 C is a structural constant reflecting pore geometry and tortuosity. The application of this
494 equation alongside Archie's law facilitates the development of empirical or semi-empirical
495 models that connect electrical resistivity to permeability (Jiang et al., 2014; Jardani et al., 2007).

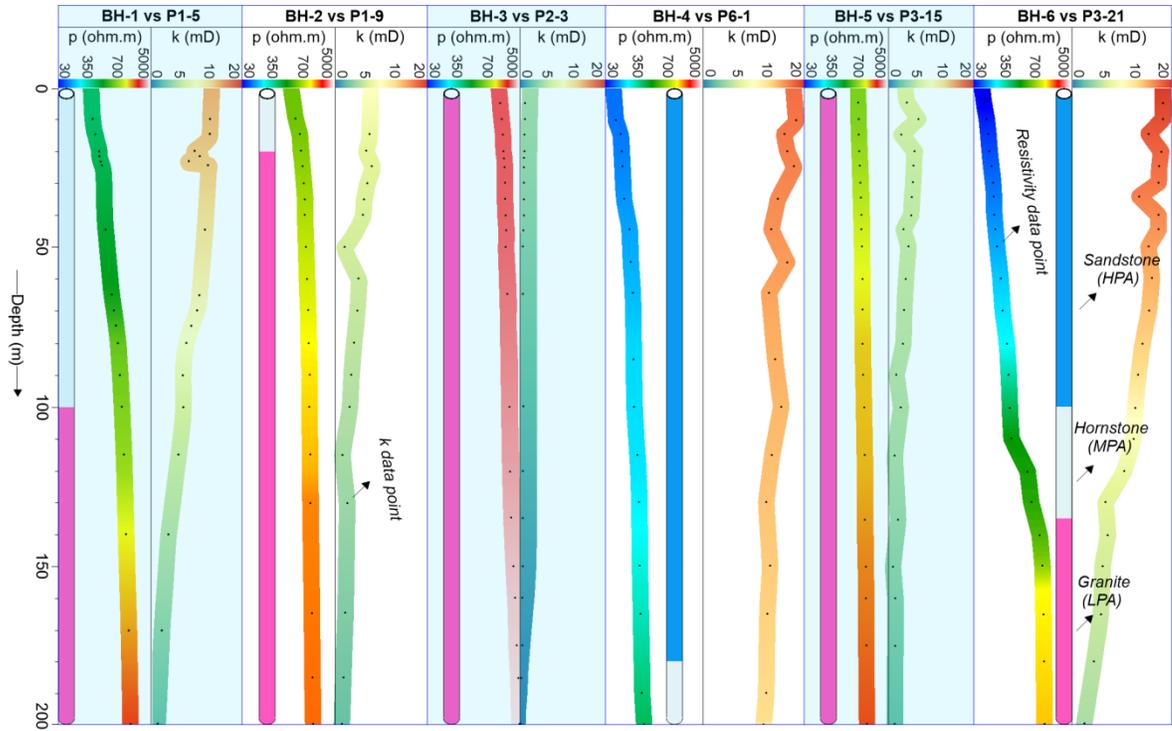
496 Although these formulations offer a robust theoretical foundation, their direct application
497 in complex geological contexts, particularly in heterogeneous hard rock such as granite,
498 sandstone, and hornstone, is frequently limited. This results mainly from differences in mineral
499 composition, pore connectivity, and structural anisotropy (Roa-García et al., 2010; Singh et al.,
500 2020). Our present study establishes a localized empirical relationship between resistivity and
501 permeability through co-located measurements obtained from deep boreholes and CSAMT
502 profiles to address these challenges. Such correlation facilitates the development of high-

503 resolution 2D and 3D permeability models in the Jinji area (study area), thereby improving the
504 comprehension of subsurface hydrogeology in contexts where traditional methods fall short.

505 **2.3.3 Spatial permeability modeling from CSAMT data**

506 To estimate permeability (k) across the entire study area, we implemented a multi-stage
507 approach integrating borehole core analysis with CSAMT-derived resistivity data. In the first
508 stage, a total of 116 laboratory-based permeability measurements were acquired from six
509 boreholes (from BH-1 to BH-6), drilled to depths ranging from 0 to 200 m (Fig. 4). These
510 measurements were obtained from intact rock core samples representing three principal
511 lithologies: granite, hornstone, and sandstone.

512 In the second stage, each of the 116 borehole-derived k values was empirically correlated
513 with corresponding resistivity values extracted from CSAMT soundings co-located with the
514 borehole sites. The spatial correspondence between boreholes and CSAMT sounding points was
515 carefully matched (Fig. 4). For example: P1-5 represents the fifth CSAMT sounding at 200 m
516 along survey line 1 near borehole BH-1; P1-9 corresponds to the ninth sounding at 400 m on line
517 1 near borehole BH-2; P2-3 denotes the third sounding at 100 m along line 2 near BH-3; P6-1
518 indicates the first sounding at 0 m on line 6 adjacent to BH-4; P3-15 and P3-21 represent the
519 fifteenth (700 m) and twenty-first (1000 m) soundings along line 3, near boreholes BH-5 and
520 BH-6, respectively.



521

522 **Fig. 4.** Comparison of 116 CSAMT-based resistivity (ρ) data points with corresponding drilling-based
 523 permeability (k) values at depths of 0–200 m across six borehole locations (BH-1 to BH-6). The data were
 524 used to evaluate high potential aquifers (HPA) in sandstone, medium potential aquifers (MPA) in
 525 hornstone, and low potential aquifers (LPA) in granite. Each dot represents a resistivity or permeability
 526 data point. Sounding labels indicate specific CSAMT locations: P1-5 (5th point on Line 1), P1-9 (9th on
 527 Line 1), P2-3 (3rd on Line 2), P6-1 (1st on Line 6), and P3-15 and P3-21 (15th and 21st on Line 3.)

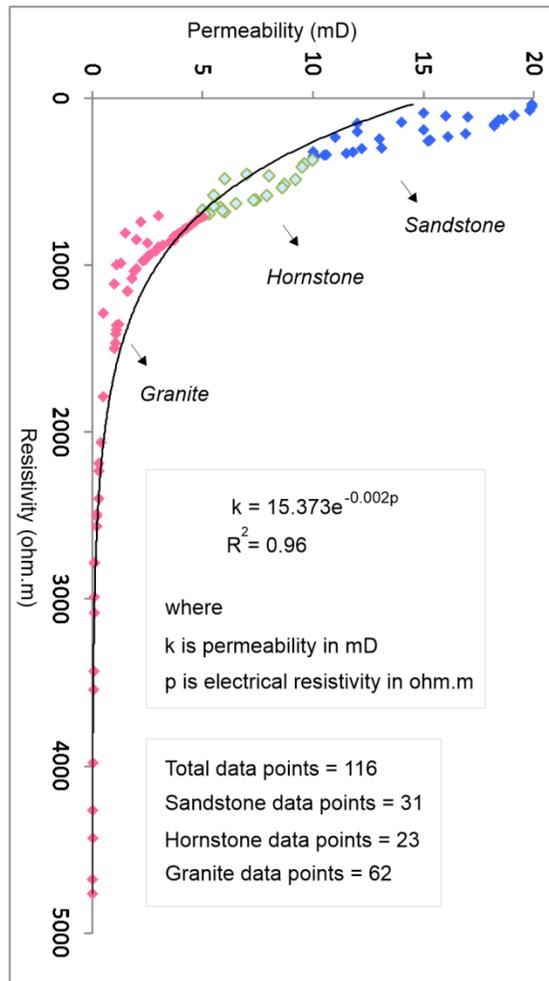
528 In the third stage, all 116 paired measurements of permeability (k) and resistivity (ρ)
 529 were utilized to develop an empirical model. An exponential relationship was derived between
 530 permeability (k in millidarcies or mD) and electrical resistivity (ρ in Ω m), expressed as follows
 531 (Fig. 5):

532

$$k = 15.373(e)^{-0.002(\rho)} \quad (4)$$

533 This site-specific empirical model was then applied to the entire suite of CSAMT resistivity data
534 collected along six survey profiles to estimate spatial variations in permeability across the
535 broader study area. Using this relationship, we generated predictive 2D and 3D permeability
536 models that capture the hydraulic behavior of three major lithological units: low potential aquifer
537 (LPA): associated with low-permeability granite, medium potential aquifer (MPA): hosted
538 within fractured hornstone (hornfels), high potential aquifer (HPA): corresponding to more
539 porous sandstone units.

540 These models provide a depth-resolved assessment of subsurface permeability from the
541 surface down to approximately 1300 m. Final 2D and 3D spatial visualizations were developed
542 using Geosoft Oasis montaj and SKUA-GOCAD modeling platforms ([Webring, 1981](#); [Mira
543 Geoscience Ltd., 1999](#); [Hasan et al., 2024](#)), enabling the visualization of permeability
544 distributions across all six CSAMT profiles and improving hydrogeological characterization in
545 structurally complex hard rock terrain.



546

547 **Fig. 5.** Empirical relationship derived from 116 data points comparing CSAMT-based resistivity and
548 drilling-based permeability at depths of 0–200 m, across three lithologies: sandstone (31 data points),
549 hornstone (23 data points), and granite (62 data points).

550 **3 Results**

551 **3.1 Cross-validation of geophysical and borehole parameters**

552 [Table 1](#) summarizes the integrated dataset from six boreholes and six CSAMT profiles, which
553 were used to delineate the subsurface into three distinct hydrogeological units, based on
554 variations in electrical resistivity and corresponding permeability (k) values. The development of

555 these subsurface models mainly depends on borehole data, CSAMT-derived resistivity
 556 measurements, and the regional geological framework. The stratigraphy was categorized into
 557 three primary lithologies: sandstone, hornstone, and granite. Classification criteria were
 558 established as follows: sandstone was defined by resistivity values below 350 Ωm and a
 559 permeability range of 10–20 mD; hornstone exhibited resistivity values between 350 and 700
 560 Ωm with a k range of 5–10 mD; and granite was characterized by resistivity values exceeding
 561 700 Ωm and permeability values ranging from 0 to 5 mD. Based on our evaluations of the
 562 subsurface hydrogeological model's aquifer potential zones, we found that sandstone contains the
 563 high potential aquifer (HPA), hornstone contains medium potential aquifer (MPA), and granite
 564 has low potential aquifer (LPA). Aquifers with the largest yields or the best water-bearing
 565 capacity are indicated by sandstone, whereas aquifers with the lowest yields or the worst water-
 566 bearing capacities are denoted by granite. Groundwater development is best facilitated by
 567 sandstone in the study area, whereas groundwater extraction is most hindered by granite.

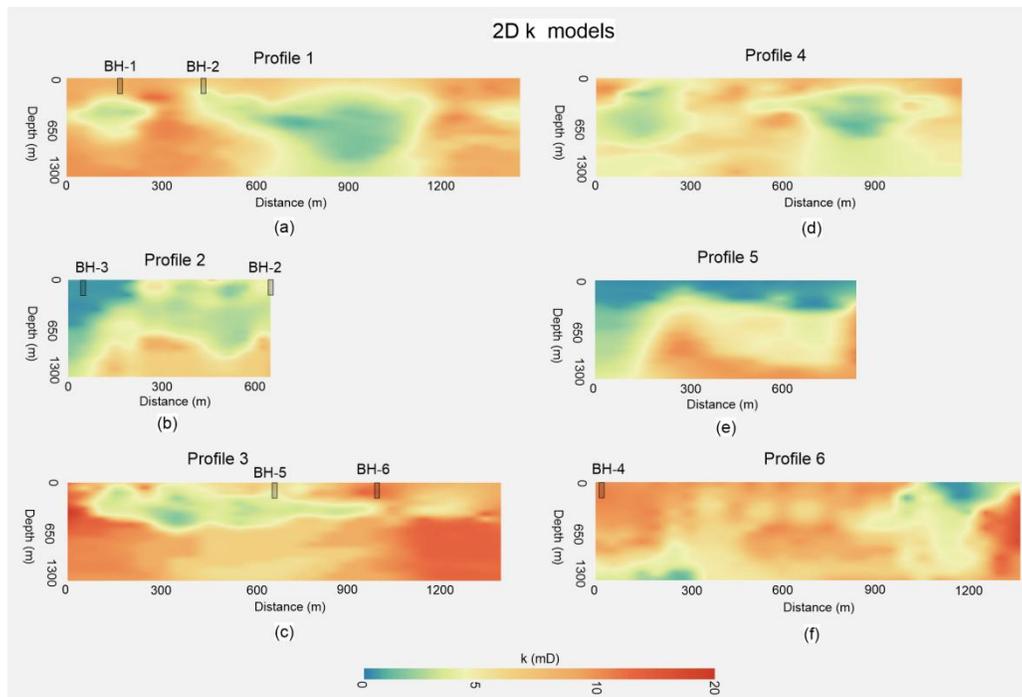
568 **Table 1**

569 Integrating distinct ranges of electrical resistivity and permeability (k) enables a comprehensive
 570 assessment of groundwater potential across various hard rock types

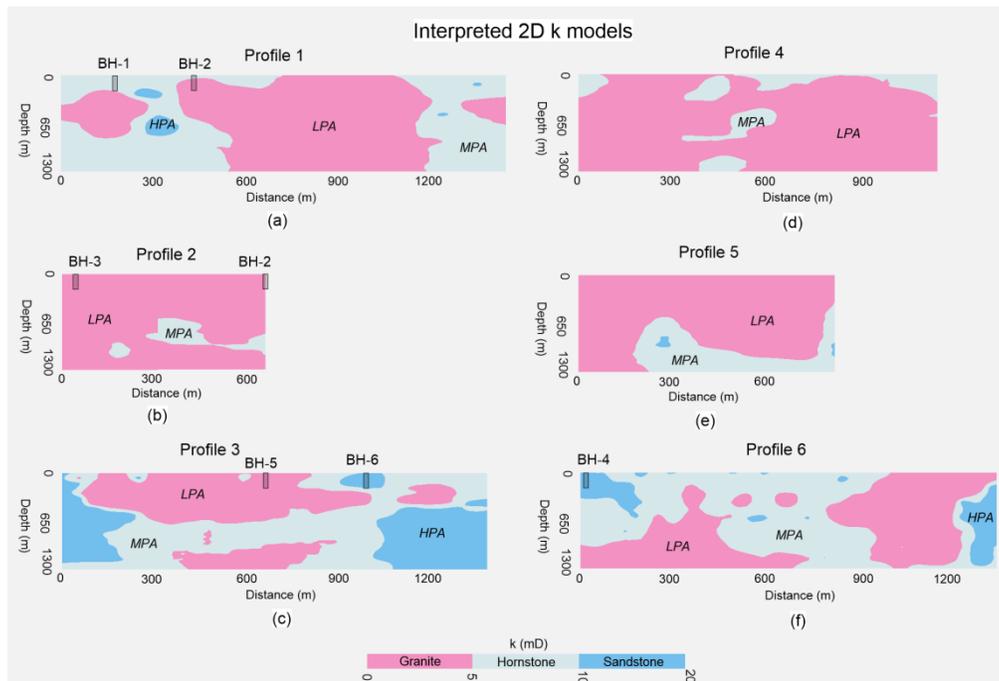
Resistivity (Ωm)	k (mD)	Type of rock	Aquifer potential
< 350	10–20	Sandstone	High potential aquifer (HPA)
350–700	5–10	Hornstone	Medium potential aquifer (MPA)
>700	0–5	Granite	Low potential aquifer (LPA)

571 **3.2 2D groundwater assessments**

572 Using geophysical-borehole correlation as its basis, Eq. (4) efficiently converts two dimensional
573 CSAMT models (Fig. 3) into two dimensional k models (Fig. 6). The interpreted 2D k models
574 shown in Fig. 7, in comparison with the limited borehole experiments, allow for an accurate and
575 comprehensive assessment of the groundwater resources in hard rock across the whole research
576 area, from 0 to 1300 m deep.



577
578 **Fig. 6.** The predicted 2D k models along six geophysical profiles: (a) Profile 1, (b) Profile 2, (c) Profile 3,
579 (d) Profile 4, (e) Profile 5, and (f) Profile 6. k values increase from blue to red on the color scale.



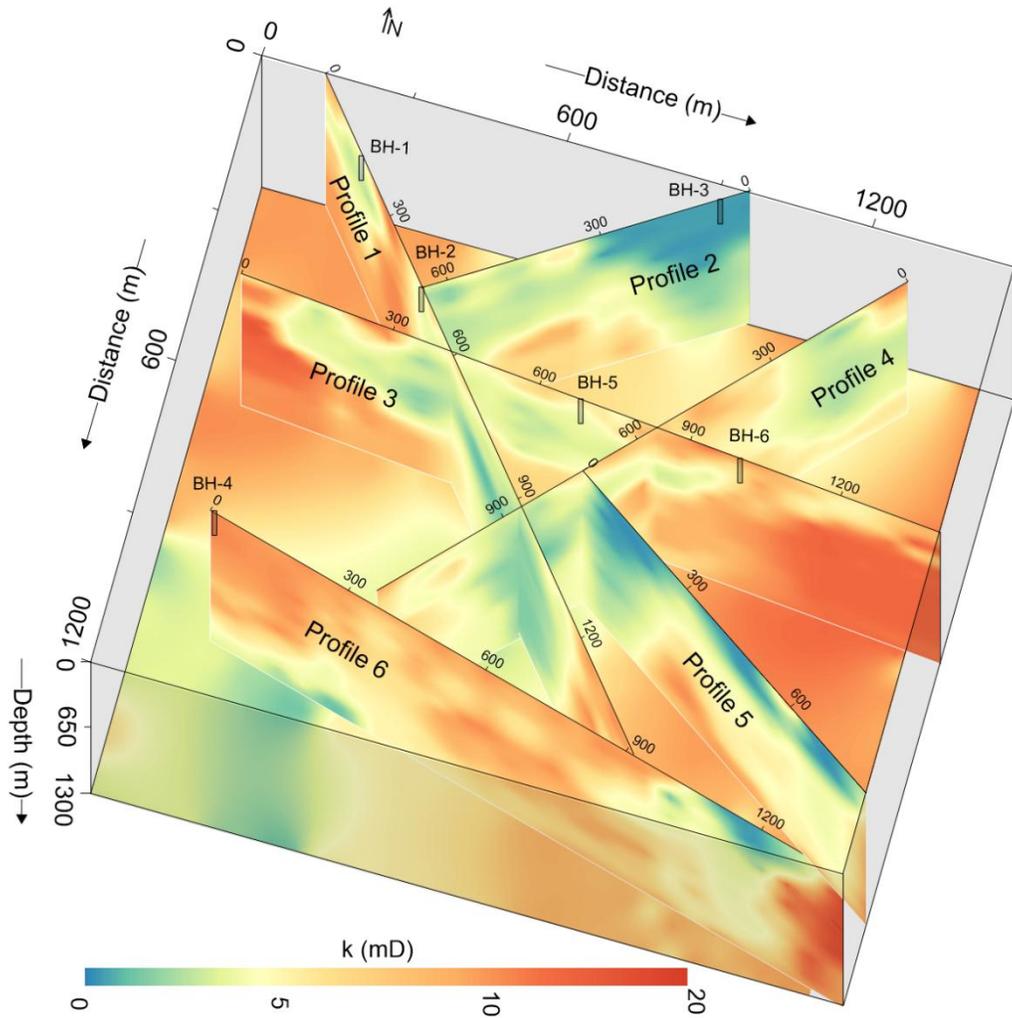
580

581 **Fig. 7.** The interpretation of the predicted 2D k models along six geophysical profiles: (a) Profile 1, (b)
 582 Profile 2, (c) Profile 3, (d) Profile 4, (e) Profile 5, and (f) Profile 6. Sandstone is represented in blue,
 583 hornstone in light blue, and granite in pink

584 The integrated 2D k models (Fig. 8) and their interpretation (Fig. 9) offers a more
 585 comprehensive and detailed two dimensional evaluations of groundwater resources within the
 586 highly heterogeneous geological settings of sandstone, hornstone, and granite. Line 1 of the
 587 survey has had the following geological layers marked out for the purpose of groundwater
 588 evaluation: A sandstone layer of high potential aquifer, 85 to 305 m thick, is visible between 245
 589 and 380 m of distance, at depths ranging from 205 to 400 m. From 0 to 1300 m below surface, at
 590 concentrations of 0 to 525 m and 1185 to 1445 m away, the remaining portion of the profile is
 591 composed of a medium potential aquifer embedded in sandstone. Distances of 0–285 m within
 592 290–790 m depth, 385–1185 m between 0–1300 m depth, and 1305–1450 m within 390–745 m
 593 depth were used to assess granite aquifers with poor potential. Along profile 2, the geological

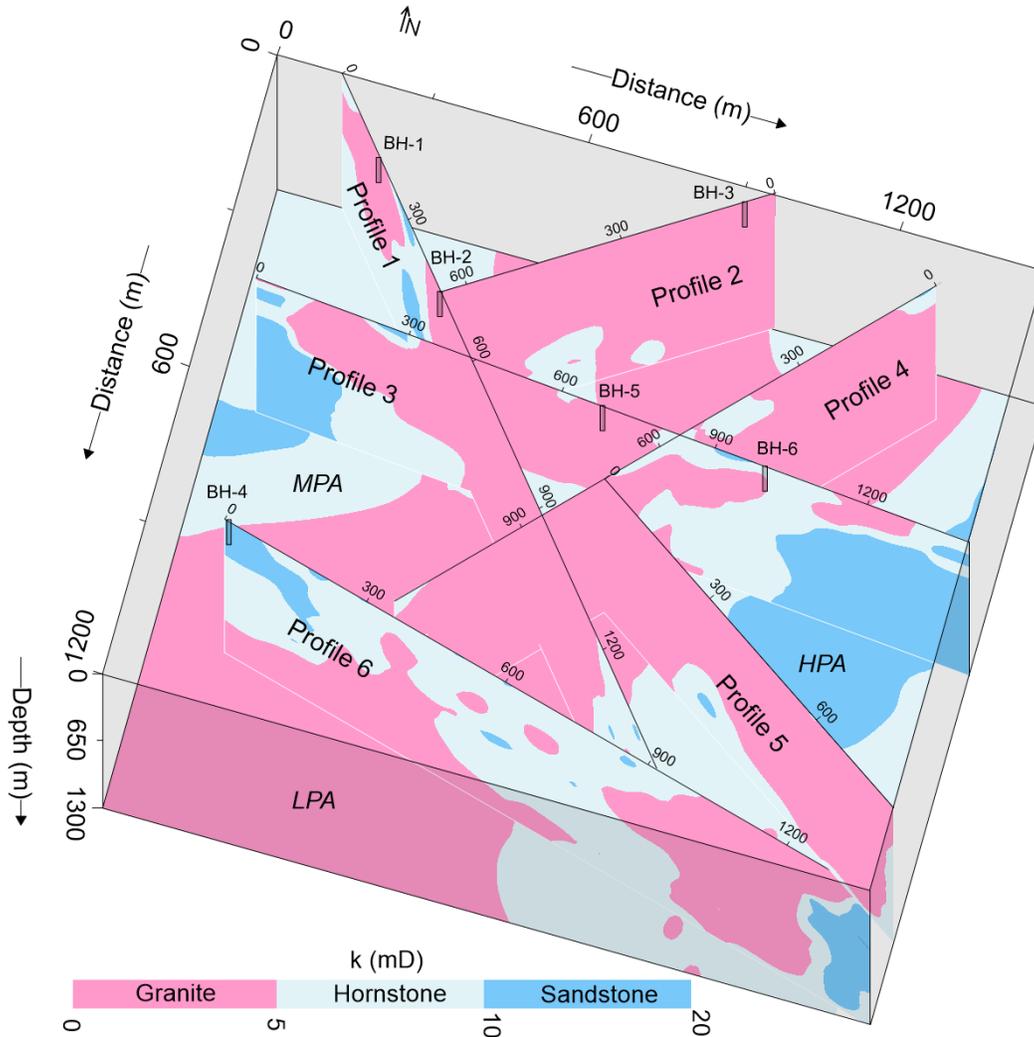
594 layers that were employed for groundwater assessment are described as follows: A hornstone
595 layer 140–380 m thick encloses a medium potential aquifer 490–1105 m below ground, more
596 precisely between 145–215 m and 290–645 m distance. We did not detect any sandstone
597 associated with the high potential aquifer along this profile. Along this profile, granite from low
598 potential aquifers predominates, with the exception of the zones evaluated by medium potential
599 hornstone aquifers; granite is located at 0–700 m distance between 0–1300 m depths. Along
600 profile 3, the following geological layers have been characterized for the purpose of groundwater
601 evaluation: A hornstone-containing medium potential aquifer is evaluated at depths between 0
602 and 1300 m and within a range of 0 to 1400 m distance. Sandstone-associated high potential
603 aquifers are located between 0 and 250 m distance and between 0 and 1190 m depths; 905 and
604 1065 m away between 0 and 205 m deep; and 1040 and 1390 m distance and between 490 and
605 1305 m depths. Distances of 80–1015 m between 0–590 m depths, 395–845 m between 915–
606 1300 m depth, and 1100–1300 m between 200–500 m depth are used to assess the possible
607 aquifers contained beneath granite. Here is the breakdown of the geological layers in profile 4 for
608 the purpose of groundwater assessment: The hornstone medium potential aquifer is checked at
609 distances of 0–105 m and depths of 0–340 m. There is a layer about 290 m thick hornstone at 0–
610 1300 m depth between 340 and 645 m distances, with depths of 0–300 m between 595 and 790
611 m profile spread, and 0–345 m deep between 1015 and 1145 m distance. No sandstone that could
612 contain a high potential aquifer is being investigated along this profile. The low potential aquifer
613 associated with granite is delineated at most portions of the profile at 0–1145 m distance between
614 0–1300 m depths, excluding the areas with medium potential aquifer of hornstone. The
615 geological layers that were considered for the groundwater assessment along profile 5 are as
616 follows: Between 190 and 845 m beneath the granite, there is hornstone associated with a

617 medium potential aquifer, which is located between 390 and 1325 m below the surface. Two
618 small sandstone patches of high yield aquifer can also be seen along this profile. One is at 790–
619 960 m depth for 290 m distances, while the other is at 815 m, between 1045 and 1135 m depth.
620 Within the depth range of 0–1300 m, granite from low potential aquifers is assessed at a distance
621 of 0–190 m, and between 0 and 1025 m, at a distance of 790–815 m. Here are the geological
622 layers that can be used for groundwater assessment along profile 6: To assess the high potential
623 aquifer linked to sandstone, distances of 0–190 m between depths of 0–490 m and 1245–1345 m
624 between depths of 215–1225 m are utilized. Distances of 0–690 m within depths of 390–1300 m
625 and 790–1360 m within 0–1190 m depths are used to evaluate low yield aquifer granite. Between
626 0 and 1300 m depth and 0 and 1350 m distance, the hornstone of the medium potential aquifer
627 dominates the rest of the profile. In the southeastern and northwest regions, there are a lot of
628 medium to high potential aquifers, according to the results of the integrated 2D k models shown
629 in [Fig. 8](#) and [9](#). On the other hand, in the central areas, groundwater resources are scarce or
630 nonexistent.



631

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



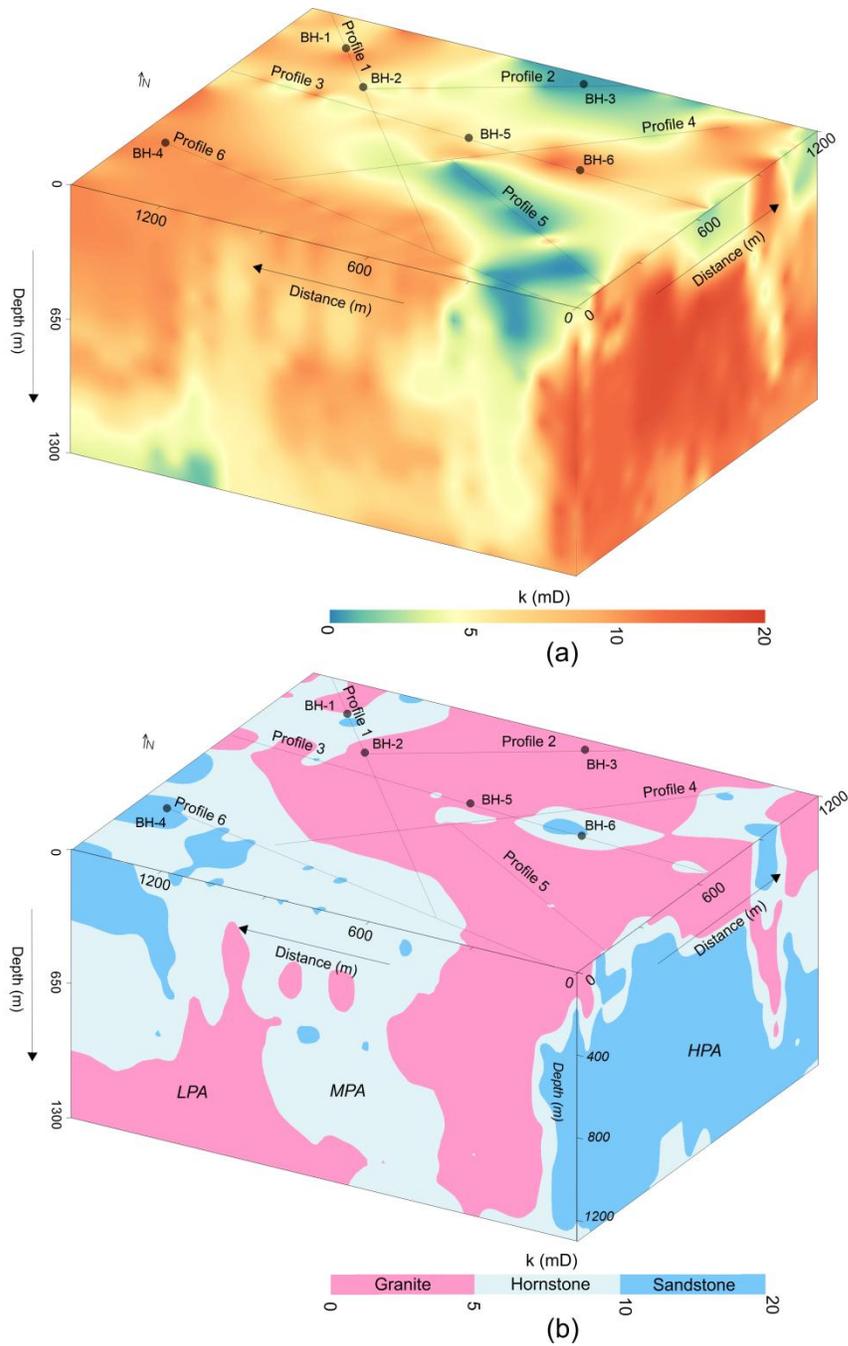
634

635 **Fig. 9** Analysis of 2D permeability (k) models, based on defined k ranges, for three groundwater potential
 636 aquifers: low potential aquifer (LPA), medium potential aquifer (MPA), and high potential aquifer (HPA),
 637 corresponding to the granite, hornstone, and sandstone formations, respectively

638 **3.3 3D groundwater assessments**

639 A thorough assessment of the water-bearing capacity of the rock mass for groundwater
 640 evaluation was conducted using the 3D k external visualization depicted in Fig. 10 (a, b). The
 641 granite of low potential aquifer was evaluated at the ground surface along profile 1 at distances
 642 of 85–215 m and 385–1175 m, surveyed line 2 at 0–655 m, CSAMT line 3 at 0–45 m, 95–175 m,

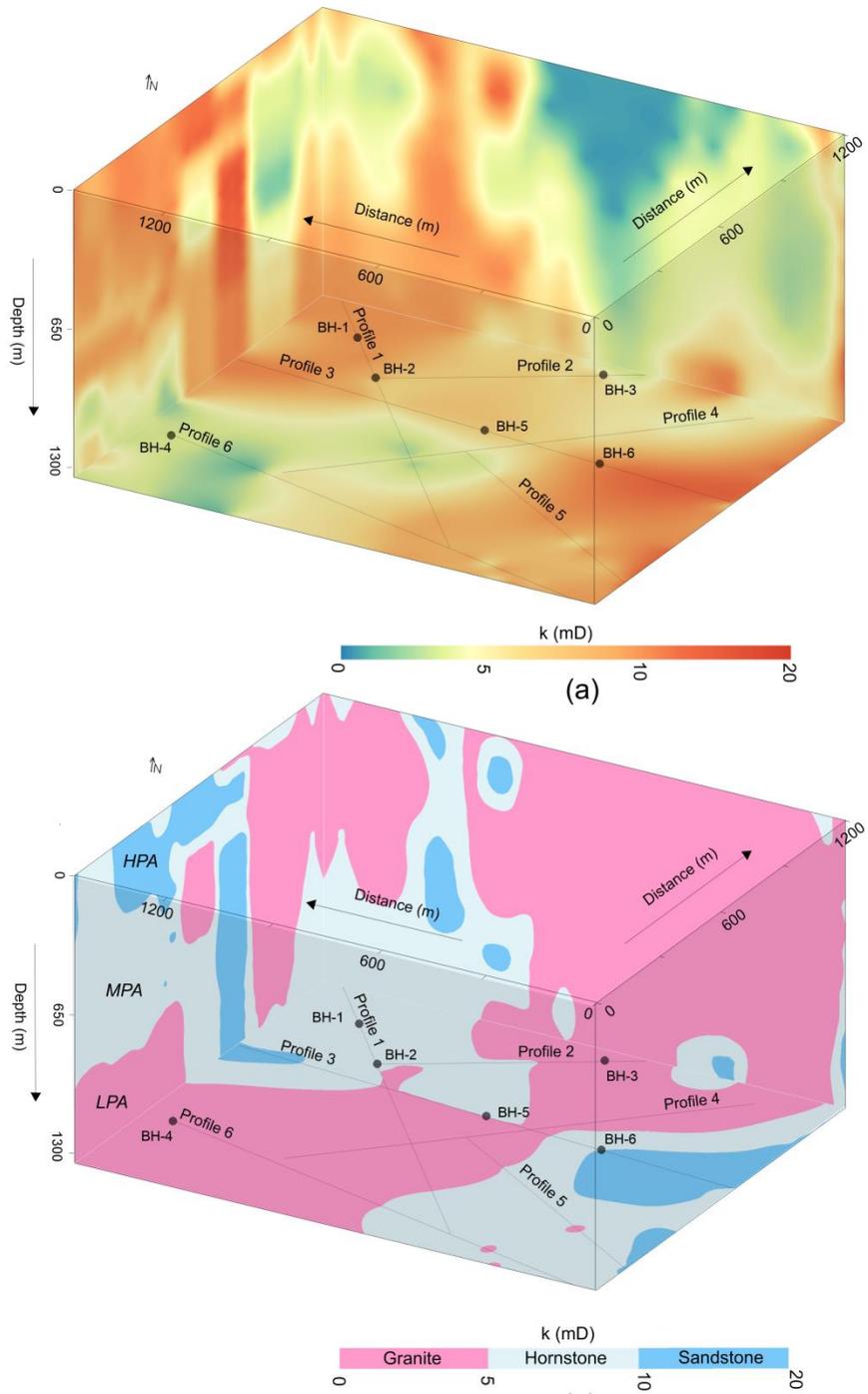
643 265–585 m, 605–845 m, and 1145–1315 m, line 4 at 90–390 m, 490–615 m, and 745–1115 m,
644 line 5 at 0–815 m, and surveyed line 6 at 1045–1345 m. A medium potential aquifer within
645 hornstone was identified along profile 1 at distances of 0–95 m, 190–260 m, 295–415 m, and
646 1185–1425 m; along profile 3 at 40–105 m, 215–275 m, 580–605 m, 850–910 m, 1010–1155 m,
647 and 1310–1410 m; along profile 4 at 45–90 m, 390–490 m, 590–685 m, and 1115–1185 m; and
648 along line 6 at 90–190 m, 215–275 m, 315–485 m, 505–605 m, and 635–1045 m. The sandstone
649 with significant aquifer potential was assessed across many locations: profile 1 at distances of
650 265–310 m, line 3 at 235–255 m and 915–1010 m, profile 4 within 0–45 m, and profile 6 at 0–90
651 m, 210–25 m, 275–305 m, 515–525 m, and 605–635 m. [Fig. 10](#) indicates that elevated aquifer
652 yield is predominantly concentrated in the southern regions.



653

654 **Fig. 10.** The 3D k models, generated from the correlation of CSAMT and borehole data (with k
 655 represented on a color scale ranging from green to red), correspond to three groundwater potential
 656 aquifers: low potential aquifer (LPA), medium potential aquifer (MPA), and high potential aquifer (HPA),
 657 associated with three geological strata: granite, hornstone, and sandstone, respectively, for (a) the external
 658 view of the 3D k model, and (b) the analysis of the 3D k model from an external perspective

659 [Fig. 11](#) (a, b) presents a comprehensive evaluation of the aquifer potential of the rock
660 mass for groundwater assessment, using a 3D internal perspective. At a subterranean depth of
661 1300 m, the low aquifer yield of granite was assessed using profile 1 across a distance of 515–
662 1215 m, profile 2 across 0–290 m, profile 3 across 390–690 m, profile 4 across 0–1145 m,
663 profile 5 across 0–195 m and 565–595 m, and profile 6 across lengths of 0–690 m and 1075–
664 1115 m. Hornstone associated to a medium potential aquifer was identified by profile 1 at
665 intervals of 0–540 m and 1215–1445 m, surveyed line 2 at 295–675 m, surveyed line 3 at 175–
666 395 m, 445–815 m, and 915–1035 m, profile 5 at 205–565 m and 610–815 m, and surveyed line
667 6 at 685–1080 m and 1110–1355 m. An aquifer with high potential, situated within sandstone,
668 was evaluated along profile 3 at intervals of 0–205 m and 1010–1400 m, as well as along line 5
669 at 810–815 m. Medium to high potential aquifers, located at a depth of 1300 m, are
670 predominantly found in the southeastern and northwestern regions, whilst the central areas are
671 primarily characterized by low potential aquifers. [Fig. 11](#) illustrates the results of the 3D K
672 analysis, indicating that the northeastern and southwestern regions are primarily composed of
673 granite with negligible aquifer yield. The water retention capacity of the rock mass is enhanced
674 when observed from an aerial perspective. This enables a precise assessment of the aquifer
675 potential of geological strata for thorough groundwater analysis via 3D k modeling.



676

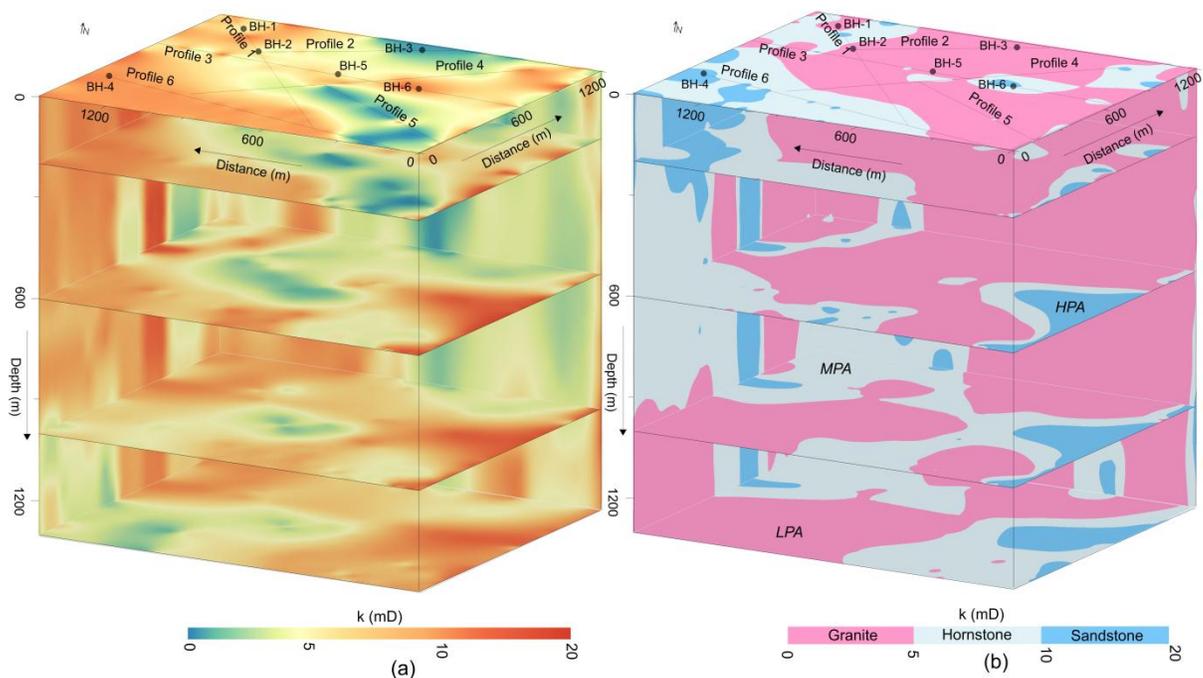
677 **Fig. 11.** The 3D k models, obtained from the correlation of CSAMT and borehole data (with k
 678 represented on a color scale ranging from green to red), illustrate three groundwater potential aquifers:
 679 low potential aquifer (LPA), medium potential aquifer (MPA), and high potential aquifer (HPA),

680 associated with three geological strata: granite, hornstone, and sandstone , respectively, for (a) the internal
681 view of the 3D k model, and (b) the analysis of the 3D (internal perspective) k model

682 **3.4 Depth-wise groundwater assessments**

683 Because of the scarcity of borehole data, it is not possible to use the observed k (borehole-based
684 k) to determine the water-bearing capacity of rock masses located below 200 m deep. The
685 evaluation of hard rock groundwater resources was made efficient, precise, and comprehensive
686 by creating a high link between drilling and CSAMT data. Because of this, k could be quickly
687 and accurately determined up to depths of 1300 m. From 2D/3D groundwater yield insights, we
688 were able to derive anticipated k values at 0, 200, 600, 1000, and 1300 m depths (Fig. 12).
689 Evaluation of groundwater at a depth of 1300 m was based on the following criteria: The
690 southwest and northeastern regions are assessed for granite, which constitutes over 45% of the
691 subsoil in low potential aquifer locations. Near the granite formation in the northwest and
692 southeast, we looked into hornstone, which comprised 40% of the medium potential aquifer. In
693 the eastern region, subsurface assessments were conducted on high-yield sandstone for over 15%
694 of the total. For groundwater evaluation at a depth of 1000 m, the following standards were
695 applied to understand the subsurface: The subsoil around the high potential aquifers in the
696 southeast consisted of 14% sandstone. Near the granite in the southeast and northwest areas, 38%
697 of the hornstone belonged to a medium potential aquifer. There were three boundaries, in the
698 middle, to the northeast, and to the southwest, in the subsurface, which was 52% granite and had
699 a poor aquifer yield. We examined the hydrogeological conditions at 600 m below ground using
700 the following criteria: in the central and northern areas, a low-yielding granite aquifer constituted
701 55% of the subsurface; hornstone in the west part was more common, accounting for 32% of the
702 subsurface and indicating a medium-yielding aquifer; and in the southeastern regions, sandstone

703 was the most studied, constituting 13% of the subsoil and indicating a high-yielding aquifer. To
 704 assess the hydrogeological conditions at a depth of 200 m, the following criteria were used:
 705 Granite with a low potential aquifer constituted 64% of the total in the center and northern parts.
 706 Hornstone with a medium yield aquifer comprised 26% of the underground in the southern
 707 regions. Research in the west focused on sandstone that made up 10% of the subsoil and had a
 708 high potential aquifer. Surface measurements taken at a depth of 0 m allowed us to determine the
 709 following hydrogeological conditions: While a medium potential aquifer is contained within 22%
 710 of the southwesterly surface's hornstone, and granite with 69% of the subsurface in the middle
 711 part. The sandstone, which is primarily located in the southwest, contains a high potential aquifer
 712 and is studied on 9% of the surface. Fig. 12 shows that as we descend then thickness of the
 713 granite from low yield aquifers decreases. Midway through, when depth drops to 600 to 700 m,
 714 groundwater conditions are at their worst. In the northwest, southeast, and southwest areas, there
 715 are rock masses that could represent aquifers, especially at depths lower than 700 m.



716

717 **Fig. 12.** (a) Geophysical permeability (k) imaging at depths of 0, 200, 600, 1000, and 1300 m, with k
718 values represented on a color scale ranging from green to red. (b) Evaluation of CSAMT-derived k values
719 (based on defined k ranges) at various depths for different aquifer types: low potential aquifer (LPA) in
720 granite, medium potential aquifer (MPA) in hornstone, and high potential aquifer (HPA) in sandstone

721 **3.5 Validation of predicted vs. measured permeability**

722 Groundwater evaluations across the study area benefit significantly from the precise and
723 systematic estimation of water-bearing capacity derived from CSAMT-based permeability (k).
724 As shown in [Fig. 6–12](#), granite dominates the central, northeastern, and southwestern zones,
725 while hornstone, commonly classified as a type of metamorphosed sandstone, appears
726 predominantly in the southeastern, western, and northwestern regions. Sandstone is extensively
727 characterized in the eastern zones, with more limited data coverage in the west. Accurate
728 assessment of groundwater potential using only borehole data is challenging due to
729 inconsistencies in subsurface geological mapping. While drilling-based k values align with
730 CSAMT-predicted k at select points around 200 m depth near boreholes, spatial extrapolation
731 remains uncertain across larger areas. This mismatch underscores the difficulty of reliably
732 assessing aquifer properties based solely on sparse drilling, especially in complex lithological
733 settings.

734 [Table 2](#) summarizes the percentage agreement between measured (drill-based) and
735 predicted (CSAMT-based) k values. Agreement was evaluated by comparing matched depth
736 intervals for each borehole–sounding pair using [Eq. \(4\)](#). For instance: BH-1 paired with P1-5
737 shows matching percentages of 73%, 63%, and 100% at depths of 10 m, 40 m, and 170 m,
738 respectively. BH-2 and P1-9 exhibit matches of 80%, 77%, and 85% at 20 m, 60 m, and 185 m
739 depths. BH-3 with P2-3 yields lower agreement: 67%, 40%, and 30% at 10 m, 85 m, and 200 m

740 depths. BH-4 and P6-1 show strong correspondence with 70%, 86%, and 78% at 15 m, 100 m,
 741 and 180 m depths. BH-5 and P3-15 demonstrate high agreement of 80%, 94%, and 85% at 30 m,
 742 135 m, and 200 m depths. BH-6 and P3-21 produce matches of 61%, 74%, and 71% at 45 m, 165
 743 m, and 180 m depths, respectively.

744 These results reveal a generally high degree of consistency between observed and
 745 predicted k values, with discrepancies likely arising from local heterogeneities or measurement
 746 uncertainties. Notably, even when the %match is low, the k values from both methods tend to
 747 classify the location into the same aquifer potential zone (low, medium, or high), reinforcing the
 748 reliability of the CSAMT-based approach for broader regional assessments.

749 **Table 2**

750 Percentage match and deviation between drilling-derived permeability (k) and CSAMT-derived
 751 permeability (k') for 18 selected data points out of the total 116

CSAMT data points (selected)			Drilling data			%Matching	Difference between k' and k
CSAMT sounding number	Resistivity (Ω m)	Predicted k' using Eq. (4)	Borehole name	Depth (m)	Measured k	k' vs k	
P1-5	392	7.0	BH-1	10	9.6	73	2.6
P1-5	515	5.5	BH-1	40	8.7	63	3.2
P1-5	1080	1.8	BH-1	170	1.8	100	0.0
P1-9	669	4.0	BH-2	20	5.0	80	1.0
P1-9	863	2.7	BH-2	60	3.5	77	0.8
P1-9	1354	1.02	BH-2	185	1.2	85	0.18
P2-3	2187	0.2	BH-3	10	0.3	67	0.1

P2-3	2988	0.04	BH-3	85	0.1	40	0.06
P2-3	4765	0.003	BH-3	200	0.01	30	0.007
P6-1	50	13.9	BH-4	15	19.9	70	6.0
P6-1	200	10.3	BH-4	100	12.0	86	1.7
P6-1	348	7.7	BH-4	180	9.9	78	2.2
P3-15	792	3.3	BH-5	30	4.1	80	0.8
P3-15	1157	1.5	BH-5	135	1.6	94	0.1
P3-15	1412	0.91	BH-5	200	1.07	85	0.16
P3-21	165	11.1	BH-6	45	18.2	61	7.1
P3-21	708	3.7	BH-6	165	5.0	74	1.3
P3-21	846	2.8	BH-6	180	2.0	71	0.8

752

753 **4 Discussion**

754 The integration of geophysical methods into groundwater research has gained significant traction
755 in recent years, offering scalable and cost-effective alternatives to traditional drilling. While
756 borehole investigations remain the most direct method for assessing permeability (k), they are
757 often constrained by high costs, logistical complexity, and limited spatial coverage, particularly
758 in deep, geologically heterogeneous terrains. Our study presents a novel and reliable framework
759 for indirect 2D and 3D permeability modeling to depths exceeding 1 km, achieved by integrating
760 CSAMT with borehole-derived data in a lithologically complex setting. This methodology
761 addresses critical hydrogeological challenges in our study area, where surface water resources
762 are limited and shallow granite exhibits low permeability. By contrast, deeper fractured granite,
763 hornstone, and sandstone formations demonstrate significantly greater groundwater potential.

764 The resulting deep aquifer characterizations are aligned with China's national water security
765 initiatives and provide valuable input for sustainable groundwater management in the context of
766 increasing water stress and climate variability. Building on this foundation, our previous research
767 (Hasan and Shang, 2022; Hasan et al., 2025) applied similar geophysical strategies in
768 geotechnical engineering, where 2D and 3D modeling of Rock Quality Designation (RQD) and
769 rock mass integrity coefficient (K_v), two key geomechanical parameters, was conducted using
770 empirical correlations between borehole core data and resistivity derived from ERT/CSAMT.
771 These methods were instrumental in site evaluations for major national infrastructure projects,
772 including the Accelerator Driven System (ADS) in Huizhou and the Jiangmen Underground
773 Neutrino Observatory (JUNO), located approximately 700 m below ground in South Guangdong,
774 adjacent to the present study area. The successful deployment of this geophysical approach in
775 both hydrogeological and geotechnical domains underscores its reliability, scalability, and
776 interdisciplinary value for large-scale subsurface characterization.

777 CSAMT, introduced in the 1970s, remains uniquely valuable for deep subsurface
778 exploration, particularly in resistive, hard rock environments. Unlike conventional geophysical
779 techniques, CSAMT excels at delineating lithological boundaries and fluid-bearing zones.
780 Recent advances in instrumentation and inversion techniques have significantly enhanced its
781 resolution and depth penetration, enabling applications such as ours that extend its use beyond
782 historical limits. The novelty of this study lies not in the use of CSAMT or resistivity–
783 permeability relationships themselves, both of which are well-established, but in their integrated,
784 site-specific application to a geologically complex and deeply fractured hard rock environment
785 This is the first study to successfully model permeability at depths of up to 1300 m in granite,

786 sandstone, and hornstone using a data-driven approach validated by high-resolution borehole
787 data.

788 In this study, we established an empirical relationship between resistivity and
789 permeability using 116 co-located data pairs across the three dominant lithologies in the study
790 area: 62 for granite, 31 for sandstone, and 23 for hornstone. The dataset spans a resistivity range
791 of 35 to 4,765 Ωm and a permeability range of 0.01 to 19.9 mD, and is evenly distributed across
792 the geological formations, thereby minimizing lithological bias and ensuring robust calibration.
793 The derived correlation yielded a high coefficient of determination ($R^2 = 0.96$), indicating strong
794 predictive capability. The lithological classification emerging from this resistivity–permeability
795 relationship is both geologically consistent and empirically validated by field observations and
796 borehole data: low-permeability granite ($>700 \Omega\text{m}$; $k = 0\text{--}5$ mD), moderate-permeability
797 hornstone ($350\text{--}700 \Omega\text{m}$; $k = 5\text{--}10$ mD), and high-permeability sandstone ($<350 \Omega\text{m}$; $k = 10\text{--}$
798 20 mD). These ranges reflect the distinct hydrogeological behavior of each unit under site-
799 specific geological conditions. We emphasize, however, that these resistivity– k associations are
800 localized and must be recalibrated for application in other regions with different geological
801 settings. The strength of our approach lies in its ability to significantly reduce the reliance on
802 extensive borehole drilling and direct permeability measurements, which are both cost-
803 prohibitive and operationally challenging, particularly in deep or structurally complex terrains.
804 By using a limited number of boreholes for calibration, our method enables the construction of
805 high-resolution 2D and 3D permeability models over large areas using CSAMT-derived
806 resistivity. If extensive borehole data were readily available or required, the added value of our
807 geophysical integration would diminish, along with its cost-effectiveness and broader
808 applicability. Thus, the novelty and practical relevance of our approach stem from its ability to

809 enhance subsurface characterization in data-scarce environments while minimizing invasive
810 testing.

811 The fitted relationship between resistivity and permeability (k) in our study (shown in
812 Fig. 5) is inherently influenced by several factors, including the geological setting, lithological
813 variability, data distribution, and the accuracy of both resistivity and permeability measurements.
814 The broad dynamic range observed in our dataset, resistivity values from 35 to 4,765 Ωm and
815 permeability values from 0.01 to 19.9 mD, provides a solid foundation for resolving trends
816 across all three dominant lithologies: sandstone, granite, and hornstone. This wide spread is
817 particularly beneficial for characterizing high-resistivity rocks such as granite, where
818 permeability remains consistently low and varies only slightly. In such cases, even large
819 differences in resistivity correspond to minor changes in k , resulting in a smoother inverse trend.
820 Conversely, in the lower resistivity range (e.g., $<1500 \Omega\text{m}$) where permeability exceeds 1 mD,
821 small changes in resistivity correspond to larger variations in k , resulting in a more scattered and
822 nonlinear trend in the correlation. This behavior is expected and reflects real geological
823 variability.

824 To ensure accuracy and reduce uncertainty, we implemented a robust workflow across all
825 stages of data acquisition, processing, inversion, and modeling. For CSAMT, we employed
826 careful survey design, optimized electrode configurations, and applied advanced filtering and
827 static shift corrections. Inversion incorporated multidimensional modeling with borehole-
828 constrained a priori information to improve resolution and reduce non-uniqueness. The
829 permeability data from borehole cores were collected under controlled conditions, using high-
830 quality, undisturbed samples from six boreholes, thereby reducing lab-to-field scale

831 discrepancies. These efforts, combined with integrated lithological data, yielded a reliable
832 permeability model capable of informing groundwater assessments across the study domain.

833 Matching between measured and predicted permeability (k vs. k') was also rigorously
834 validated (Table 2). Among 18 selected points from boreholes, 10 showed a difference of less
835 than 1 mD, with only two exceeding 4 mD. Despite minor deviations, all points were accurately
836 classified by lithology. This confirms the empirical model's reliability and its utility for regional-
837 scale k prediction, even in areas lacking direct measurements. The geophysical model effectively
838 compensates for sparse drilling data, offering a scalable and cost-effective tool for
839 hydrogeological evaluation in hard rock terrains.

840 While pumping tests provide average hydraulic conductivity over large volumes of
841 subsurface material, making them suitable for establishing 1D correlation with spatially averaged
842 geophysical data, they are less appropriate for high-resolution 2D or 3D modeling. In contrast,
843 our objective was to develop detailed 2D and 3D permeability models that reflect the spatial
844 heterogeneity of the subsurface. Achieving this level of resolution requires point-specific
845 permeability measurements at varying depths, which align more precisely with the localized
846 nature of resistivity values derived from CSAMT data. To meet this requirement, we employed
847 rock core analysis rather than traditional pumping tests. Rock core testing offers the advantage of
848 extracting permeability data at discrete depths and locations, providing a direct and fine-scale
849 match with CSAMT-derived resistivity. This approach enhances the accuracy of the resistivity–
850 permeability relationship and allows for more reliable permeability modeling in complex
851 geological settings. Scale compatibility between CSAMT-derived resistivity and borehole-
852 derived permeability (k) values was carefully addressed. The typical lateral resolution of

853 CSAMT ($\sim 50 \times 50$ meters) closely matches the spatial scale of the core-based permeability data
854 used in this study.

855 Furthermore, our findings were cross-validated against existing geological data from both
856 local and national surveys, revealing strong alignment with the established stratigraphy and
857 hydrogeological characteristics of the region. This consistency reinforces the validity of our
858 integrated geophysical–borehole approach, which offers a scientifically robust and practically
859 scalable framework for estimating permeability in structurally complex and data-scarce terrains.
860 While the methodology is rooted in established geophysical principles, the innovation of this
861 study lies in its comprehensive, site-specific implementation, combining deep permeability
862 modeling, field-based verification, and empirical calibration specifically tailored to the local
863 geological context. Overall, the results underscore the considerable potential of geophysical
864 techniques, particularly CSAMT, in supporting sustainable groundwater exploration and
865 management at significant depths

866 **5 Conclusions**

867 This study presents an innovative, non-invasive approach to deep groundwater exploration using
868 controlled-source audio-frequency magnetotellurics (CSAMT). For the first time, CSAMT has
869 been applied to indirectly estimate two and three dimensional permeability (k) distributions in
870 geologically complex hard rock terrains, extending to depths of up to 1300 m. While borehole
871 drilling remains the conventional method for evaluating hydraulic parameters, it is often costly,
872 logistically challenging, and limited in spatial coverage. Our approach significantly reduces
873 reliance on boreholes while providing a more detailed and spatially extensive hydrogeological
874 assessment. Using co-located CSAMT and borehole data, we developed a robust empirical

875 equation to estimate permeability based on resistivity values. This equation was applied across
876 the study area to generate high-resolution k models that align closely with the known geology
877 and stratigraphy. Specifically, sandstone, classified as a high potential aquifer (HPA), exhibited
878 resistivity below 350 Ωm and permeability ranging from 10–20 mD. Hornstone, as a medium
879 potential aquifer (MPA), showed resistivity between 350–700 Ωm and k values of 5–10 mD.
880 Granite, representing a low potential aquifer (LPA), had resistivity above 700 Ωm with k ranging
881 from 0–5 mD. These trends confirm the expected relationship between lower resistivity and
882 higher permeability, validating the physical basis of our model.

883 Our 2D/3D permeability models further revealed that the most promising zones for deep
884 groundwater occur in central regions below 700 m and around granite formations down to 1300
885 m. The close alignment between the modeled permeability and regional hydrogeological features
886 highlights the reliability and predictive power of this method. By bridging the gap between
887 sparse borehole data and robust hydrogeological models, CSAMT offers a cost-effective and
888 scalable alternative for evaluating groundwater potential in hard rock regions. Looking forward,
889 future research could enhance this method by refining the empirical models using broader
890 hydrogeological datasets and integrating other geophysical parameters. This would deepen our
891 understanding of the relationship between aquifer properties and geophysical signals, ultimately
892 improving the reliability of groundwater assessments in challenging geological settings.

893 **Code availability**

894 Software application or custom code supports the published claims and complies with field
895 standards

896 **Data availability**

897 Data available on request from the corresponding author

898 **Author contributions**

899 MH conceptualized the research goals and developed the methodology. MH and LS found the
900 funding for the project. MH developed the code and prepared its visualization, and LS provided
901 programming support and analysis tools. MH prepared the original draft.

902 **Declaration of competing interest**

903 The authors declare that they have no conflict of interest.

904 **Acknowledgements**

905 The authors wish to acknowledge the institutions that facilitated the research for this study: the
906 State Key Laboratory of Mountain Hazards and Engineering Resilience, Institute of Mountain
907 Hazards and Environment, Chinese Academy of Sciences, and China-Pakistan Joint Research
908 Center on Earth Sciences, CAS-HEC, Islamabad, Pakistan.

909 **Financial support**

910 This research was financially supported by the National Natural Science Foundation of China's
911 Research Fund for International Young Scientists (RFIS-I) (Grant No. 42350410442), and
912 International Science and Technology Cooperation Program of Shanghai Cooperation
913 Organization, Science and Technology Department, Xinjiang, China (Grant No. E202301005).

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