Referee # 5 Comments (Report 1):

Title: Novel insights into deep groundwater exploration by geophysical estimation of hard rock permeability

In general, this is a detailed and well-structured research paper that presents a novel application of the CSAMT method. The following comments are a critical analysis of the revisions needed.

Response:

Dear Anonymous Referee,

We sincerely thank you for your thorough and highly professional review of our manuscript. We greatly value the time and effort you dedicated to assessing our work and for providing such constructive and insightful feedback. Your comments have been instrumental in improving the clarity, rigor, and overall quality of the study.

In light of your suggestions, we have undertaken substantial revisions across the manuscript. All major changes informed by your feedback are clearly indicated in the track-changes version of the revised submission.

We are truly grateful for your careful evaluation and constructive recommendations, which have significantly strengthened our work.

1. Comments in the Research Paper and Proposed Solutions

The paper is strong methodologically but has several limitations, primarily related to data, validation, and certain assumptions.

Comment point:

Limited & Shallow Borehole Calibration

Description:

The entire empirical model (the core of the study) is built on 116 core samples from only 6 boreholes, all within 0-200 m depth. The model is then extrapolated to 1300 m without direct validation at those depths.

How to Address:

Acknowledge this more explicitly as the primary limitation. Future work must include deep boreholes (>500 m) for sampling and pumping tests to validate the extrapolated k-values. Use probabilistic modeling to show the uncertainty increases with depth due to a lack of calibration.

Response:

This point has been addressed in the newly added subheading (Section 4.7) of the Discussion.

Track Changes Copy: Page 42, Line 676-691 (New Fig. 13: Page 51)

Clean Copy: Page 41-42, Line 658-673 (New Fig. 13: Page 49)

4.7 Limited and shallow borehole calibration

A key limitation of this study lies in the depth extent of the calibration dataset. The empirical resistivity–permeability relationship was developed using 116 core samples from six boreholes, all restricted to depths between 0 and 200 m. Extrapolating this relationship to 1300 m depth introduces uncertainty, as no direct calibration exists at greater depths. To address this limitation, we incorporated a probabilistic modeling framework that quantifies the increase in uncertainty with depth. The model results (Fig. 13) clearly illustrate that while near-surface permeability estimates are relatively well constrained, the confidence intervals expand significantly beyond ~200 m due to the lack of direct sampling.

Future work should therefore prioritize the acquisition of deep borehole data (>500 m), including core sampling, hydraulic pumping tests, and packer testing, to directly validate the extrapolated permeability values. In addition, the integration of advanced downhole geophysical logging with geostatistical and probabilistic approaches will provide stronger constraints on subsurface heterogeneity at depth. Such efforts will be essential to improve confidence in deep permeability predictions, reduce geological uncertainty, and enhance the reliability of groundwater resource assessments in complex crystalline terrains.

Comment point:

Uncertainty in Deep Fluid Properties

Description:

The paper assumes that low resistivity at depth is due to fresh water in fractures. However, without hydrochemical data from deep aquifers (>1 km), high salinity could also cause low resistivity, leading to an overestimation of permeability.

How to Address:

State this as a key assumption and limitation. Recommend future studies including deep fluid sampling to measure salinity. A brief sensitivity analysis could be presented: "If fluid resistivity (ρf) were halved (due to salinity), the inferred k would change by a factor of X."

Response:

This point has been addressed in the subheading (Section 4.11) of the Discussion.

Track Changes Copy: Page 45-46, Line 747-772

Clean Copy: Page 44-45, Line 729-750

4.11 Salinity effects and uncertainty in deep fluid properties

The influence of factors beyond lithology, particularly groundwater salinity, on CSAMT-derived resistivity warrants consideration. Electrical resistivity is inherently sensitive to porosity, fracture density, mineral alteration, fluid saturation, and salinity. In this study, *k* calibration was based on core samples from 0–200 m depths across six boreholes. While this limits direct calibration at greater depths, hydrochemical data from the Geological Survey of China, spanning 800–1,000 m depth, consistently indicate fresh groundwater, suggesting salinity is not the cause of deeper low-resistivity zones. We interpret these zones, especially in sandstone and hornstone, as reflecting high saturation and pore connectivity rather than saline fluids. This is further supported by the absence of resistivity anomalies typically associated with brackish water, and the strong alignment between resistivity, *k*, and lithological boundaries.

However, because no fluid data are available below 1 km, the role of salinity cannot be entirely excluded, representing a key assumption and limitation of this study. A sensitivity analysis indicates that if fluid resistivity (ρf) were halved due to salinity, the apparent formation resistivity (ρ) would decrease by ~50%. Substituting this reduced resistivity into our resistivity–permeability relationship (Eq. 3) yields higher permeability (*k*) values, as *k* increases exponentially with decreasing ρ. Specifically, halving ρf would increase inferred *k* by approximately a factor of 2 at 1000 Ωm, 7 at 2000 Ωm, and 18 at 3000 Ωm. These results demonstrate that salinity effects are modest at shallow depths but may become significant at greater depths. Future investigations should therefore incorporate deep borehole sampling, fluid logging, and hydrochemical analyses to directly constrain fluid resistivity and reduce uncertainty in *k* extrapolation.

Comment point:

Storage Parameters Neglected

Description:

The study focuses exclusively on permeability (k) for "water-bearing capacity." A complete aquifer assessment requires storage parameters (storativity, specific yield). The potential volume of water, not just its transmissivity, is critical for resource management.

How to Address:

Explicitly state that the study characterizes transmissivity/flow potential, not storage capacity. Recommend that future work integrate methods to estimate porosity (e.g., from geophysical logs, nuclear magnetic resonance) to provide a more comprehensive resource evaluation.

Response:

This point has been addressed in the subheading (Section 4.13) of the Discussion.

Track Changes Copy: Page 48-49, Line 813-840

Clean Copy: Page 46-47, Line 777-795

4.13 Limitations of storage characterization

A complete aquifer assessment requires evaluation of both permeability (*k*) and storage parameters such as storativity, specific yield, and specific storage. This study focused primarily on delineating spatial variations in *k*, referred to here as "water-bearing capacity," using CSAMT-derived resistivity calibrated with borehole data. While this approach provides valuable insights into transmissivity and flow potential, it does not directly constrain aquifer storage capacity.

Due to the absence of deep pumping tests and detailed formation logs, storage parameters could not be quantified. Instead, our interpretations rely on qualitative geological and geophysical inference. Permeable units like sandstone and hornstone likely possess higher porosity due to their granular textures and fracture networks, unlike the denser granite. This is supported by groundwater level data from six boreholes and regional water table records, which indicate aquifers in fractured, low-resistivity zones. These zones align spatially with permeable features in both CSAMT/*k* models and borehole data.

We acknowledge that the current study characterizes relative transmissivity rather than absolute storage capacity, representing a key limitation. Future work should therefore integrate porosity and storage characterization through deep borehole testing, in-situ hydrochemical and geophysical logging (e.g., nuclear magnetic resonance), and aquifer hydraulic analysis to provide a more comprehensive basis for groundwater resource evaluation in complex hard rock terrains.

Comment point:

Scale Discrepancy

Description:

There's an inherent scale difference between a small core plug (cm-scale) used for lab k-measurements and the CSAMT resolution (10s of m). A core sample might miss a major fracture right next to it, while CSAMT would detect it. This can lead to scatter in the k-ρ relationship.

How to Address:

Discuss this scale effect as a reason for the observed scatter in the empirical data (Fig. 5). The readers know that the lab k represents the "matrix" property, while CSAMT-derived k represents a larger "effective" property that includes fractures.

Response:

This point has been addressed in the newly added subheading (Section 4.9) of the Discussion.

Track Changes Copy: Page 43-44, Line 707-727

Clean Copy: Page 42-43, Line 689-709

4.9 Scale effects in permeability estimation

While core plug measurements and CSAMT-derived resistivity are broadly compatible for establishing an empirical k–ρ relationship, it is important to acknowledge the differences in sampling scale. Core-derived permeability (k) values, measured on centimeter-scale samples, largely capture matrix properties of the rock. These may underestimate flow capacity where nearby fractures or heterogeneities are missed. In contrast, CSAMT inversions, with an effective resolution of ~50 × 50 m, represent a bulk effective property that integrates both matrix and fracture contributions across larger volumes.

This scale difference provides a natural explanation for the scatter observed in the k–ρ dataset (Fig. 5). For example, a core extracted from intact granite may record low k, while the corresponding CSAMT block encompasses a fracture corridor that increases the effective k. Conversely, a core intersecting a fracture may yield anomalously high k compared to the surrounding bulk medium resolved by CSAMT. Thus, while the fine-scale core data were essential for establishing point-specific calibration with resistivity values, the observed scatter reflects the complementary strengths of the two approaches: core testing constrains intrinsic rock matrix properties, and CSAMT captures fracture-controlled heterogeneity and connectivity at the field scale. Together, they provide a more robust characterization of hydraulic behavior than either method alone. Future work should strengthen this multi-scale integration by including intermediate-scale datasets such as borehole geophysics and aquifer-scale pumping tests. Such efforts would further bridge the gap between matrix-scale and bulk-scale measurements, reducing uncertainty in k modeling for complex crystalline terrains.

Comment point:

Model Extrapolation & Edge Effects

Description:

The 3D model is built by interpolating 2D lines. The reliability of the model decreases significantly in areas between lines and at the edges, where there is no data constraint.

How to Address:

The black dots on Figs. 10/11 are a good start. Strengthen this by discussing the interpolation method (e.g., kriging parameters) and explicitly stating that the model is most reliable near the boreholes and survey lines and should be used with caution elsewhere.

Response:

This point has been addressed in the subheading (Section 4.12) of the Discussion.

Track Changes Copy: Page 46-48, Line 773-812

Clean Copy: Page 45-46, Line 751-776

4.12 Uncertainty from model extrapolation and edge effects

The 3D permeability (*k*) model was constructed by interpolating between 2D CSAMT inversion profiles calibrated with borehole-derived *k* values from six reference locations. Given the limitations in survey geometry and computational cost, full 3D inversion of the resistivity data was not feasible. Instead, we implemented a geostatistical framework using ordinary kriging, which integrated cross-sectional profiles and applied the resistivity–permeability relationship across the model volume. The interpolation was guided by variogram models tuned to reflect the spatial continuity of lithological units and constrained by borehole control points, thereby maintaining geological consistency. While this approach provides a volumetric representation of *k* that highlights the distribution of permeable zones, its reliability is scale- and data-density dependent. The model is most robust in the central areas where CSAMT lines intersect and are directly supported by borehole data. In contrast, reliability diminishes in regions between widely spaced profiles and toward the model edges and corners, where no direct constraints exist. Sensitivity analyses, based on alternative variogram structures and comparisons with inverse distance weighting, consistently revealed greater variability and uncertainty in these peripheral zones.

To address this, uncertainty contours were added to Figs. 10 and 11, delineating areas of higher and lower confidence. The black dots marking borehole and survey line positions serve as reference anchors, making it clear that interpolation quality decreases with increasing distance from these control points. As such, interpretations in boundary regions should be treated with caution, particularly where model predictions extend beyond the convex hull of available data. We emphasize that the current model provides a reliable first-order framework for *k* distribution in the study area, but future improvements should prioritize denser CSAMT line coverage and, where feasible, the use of full 3D inversion techniques. Such approaches would better capture lateral continuity, minimize edge effects, and enhance confidence in the extrapolated 3D structure.

Comment point:

Site-Specific Empirical Relationship

Description:

The derived equation k = 15.373(e)^0.002(p) is highly specific to the Jinji area's unique geology and mineralogy. Applying it directly to other regions without calibration would be invalid.

How to Address:

Emphasize this more strongly in the abstract and conclusion. The key contribution is the methodology, not the specific equation. The paper should recommend that the approach be followed—collecting local calibration data—rather than using the provided constants.

Response:

This point has been addressed in the abstract.

Track Changes Copy: Page 2-3, Line 37-42, 47-49

Clean Copy: Page 2-3, Line 37-42, 47-49

Abstract

….The method relies on an empirical resistivity–permeability relationship calibrated using 116 core samples from six boreholes (0–200 m). While the specific equation derived in this study is site-specific to the Jinji area and should not be directly transferred elsewhere, the broader methodology, integrating CSAMT resistivity with local borehole calibration, offers a transferable framework for *k* estimation in other complex geological settings.

…. It provides a scalable methodology for sustainable groundwater resource management, while emphasizing the need for local calibration in any new application.

This point has been addressed in the conclusions.

Track Changes Copy: Page 52, Line 897-901

Clean Copy: Page 50, Line 852-856

Conclusions

…It is important to note that the empirical relationship (Eq. 3) derived in this study is site-specific to the Jinji region's geological and hydrogeochemical conditions. Its constants should not be generalized to other regions without new calibration data. The key contribution of this work is therefore the methodology, a workflow for integrating CSAMT with borehole calibration, rather than the specific coefficients of the empirical equation…

Comment point:

Justification for CSAMT over MT/TDEM

Description:

The justification for choosing CSAMT over other deep EM methods like MT or TDEM is somewhat brief and could be more quantitative.

How to Address:

Expand the comparative analysis in the introduction/discussion. Include a table comparing depth, resolution, cost, and cultural noise immunity for VES, ERT, CSAMT, TDEM, and MT to visually justify the choice of CSAMT for this specific purpose.

Response:

This point has been addressed in the Introduction.

Track Changes Copy: Page 5-6, Line 96-131 (New Table 1: Page 9)

Clean Copy: Page 5-6, Line 96-130 (New Table 1: Page 9)

Introduction

….Geophysical methods are widely and effectively employed to enhance subsurface characterization in groundwater studies (Daily et al., 1992; Jardani et al., 2007; Hinnell et al., 2010; Fu et al., 2013; Jiang et al., 2014; Kouadio et al., 2023). Compared to conventional drilling, these techniques offer significant advantages in cost, deployment speed, environmental impact, and spatial extent (Hu et al., 2013; Fusheng et al., 2022). Their ability to image subsurface variations in both vertical and lateral dimensions makes them particularly effective in heterogeneous terrains (Hasan et al., 2025). Among them, resistivity-based methods are widely used due to their sensitivity to lithology, porosity, fractures, and fluid content (Hasan et al., 2021; Asfahani, 2023). Common techniques include electrical resistivity tomography (ERT), vertical electrical sounding (VES), and electromagnetic methods such as magnetotellurics (MT), time-domain electromagnetics (TDEM), and controlled-source audio-frequency magnetotellurics (CSAMT) (Soupios et al., 2007; Bauer-Gottwein et al., 2010; Pollock and Cirpka, 2012; Jiang et al., 2014; Di et al., 2020). A comparative summary of these methods (Table 1) highlights their relative strengths and limitations in terms of depth penetration, spatial resolution, sensitivity to cultural noise, and cost. VES is cost-effective but limited to shallow one-dimensional profiling (<200 m) (Niwas and De Lima, 2003; Majumdar and Das, 2011). ERT improves resolution and enables 2D/3D imaging up to ~300 m but requires intensive fieldwork and is less effective in extreme resistivity environments (Abbas et al., 2022; Hasan and Shang, 2022). For deeper targets, electromagnetic methods such as TDEM, MT, and CSAMT are often employed (Bauer-Gottwein et al., 2010; Di et al., 2020; Gonzalez-Duque et al., 2024). MT achieves the greatest depth penetration (up to tens of kilometers) but often sacrifices resolution in the upper crust and is highly susceptible to cultural noise (Simpson and Bahr, 2005). TDEM provides rapid deployment and intermediate depth coverage (hundreds of meters) but suffers reduced sensitivity in resistive hard rock (Bauer-Gottwein et al., 2010). By contrast, CSAMT bridges these approaches: with a controlled source and frequency tuning, it achieves intermediate-to-deep penetration (>1000 m) with improved resolution in resistive hard rock settings and strong immunity to cultural noise (Smith and Booker, 1991; Zonge and Hughes, 1991; Wang et al., 2015; Zhang et al., 2021). The choice between resistivity and electromagnetic techniques is contingent upon parameters like investigation depth, resolution requirements, geological complexity, and logistical constraints (Majumdar and Das, 2011; Hasan et al., 2025). Given the objectives of this study, to characterize deep fractured aquifers in crystalline and sedimentary rocks under complex geological conditions, CSAMT was selected as the most suitable technique. Its combination of depth penetration, resolution, and robustness against noise provides a practical balance between regional coverage and site-specific imaging, enabling the development of 2D and 3D permeability models that are otherwise difficult to achieve with alternative methods.

This point has been addressed in the subheading (Section 4.3) of the Discussion.

Track Changes Copy: Page 38-39, Line 588-625

Clean Copy: Page 38-39, Line 584-607

4.3 Comparative advantages of CSAMT for deep hard rock aquifer characterization

CSAMT, developed in the 1970s, remains uniquely valuable for deep subsurface exploration, particularly in resistive and fractured hard rock environments. Its ability to image at intermediate-to-deep depths (hundreds to over a thousand meters) with relatively high resolution and controlled signal strength enhances its ability to delineate lithological contacts and fluid-bearing formations where other resistivity methods (VES and ERT) may fall short. While electromagnetic methods such as MT and TDEM are also capable of probing deep subsurface structures, achieving comparable results in similarly complex hard rock settings presents notable challenges. MT, which relies on natural variations in electromagnetic fields, can reach even greater depths than CSAMT and has been successfully applied in regional-scale hydrogeological investigations, such as identifying deep groundwater circulation paths in mountain systems (Jiang et al., 2014) and tracing flow systems that recharge lowland aquifers (Gonzalez-Duque et al., 2024).

As summarized in Table 1, MT provides exceptional penetration (tens of kilometers) but has reduced resolution in the upper crust and is highly sensitive to cultural noise, limiting its suitability for detailed *k*-modeling at the site scale. TDEM, while rapid and effective for intermediate depths, suffers loss of sensitivity in highly resistive formations, making it less effective for fractured granite and hornstone settings. In contrast, CSAMT's controlled-source design and strong immunity to cultural noise provide a balance of depth penetration and resolution well-suited for site-specific groundwater studies in hard rock terrains.

Thus, the comparative analysis (Table 1) underscores why CSAMT is the most appropriate method for this study: it bridges the gap between large-scale regional techniques (MT, TDEM) and shallow, high-resolution methods (VES, ERT), enabling robust 2D and 3D hydrogeophysical modeling essential for evaluating deep aquifer potential.

2. Grammatical and Linguistic Errors and Improvements

The paper is generally well-written but has occasional errors in article usage, word choice, and sentence flow. Here are some specific examples and suggestions for improvement.

Category 1: Missing Definite/Indefinite Articles (a, an, the)

This is the most frequent issue.

1. Original (P2, L24): `Deep groundwater exploration in hard rock terrains is critical in regions where deep aquifers may offer long-term water security amidst increasing scarcity.`

Suggestion: `...amidst an increasing scarcity.`

Response:

Corrected:

Track Changes Copy: Page 2, Line 25

Clean Copy: Page 2, Line 25

2. Original (P2, L28): `Conventional borehole-based methods for measuring k are invasive, costly, time-consuming, and limited to sparse, point-scale observations...`

Suggestion: `...limited to sparse, point-scale observations...` (This is actually correct. An example of an error is below).

Response:

Unchanged:

Track Changes Copy: Page 2, Line 29-30

Clean Copy: Page 2, Line 29-30

3. Original (P4, L68): `Its strategic importance is increasingly recognized, particularly in geologically and environmentally constrained settings'.

Suggestion: `...in geologically and environmentally constrained settings.` (The hyphens are needed here).

Response:

Corrected:

Track Changes Copy: Page 4, Line 68-69

Clean Copy: Page 4, Line 68-69

4. Original (P9, L184): `This research integrates inadequate drilling information with the geophysical data...`.

Suggestion: `This research integrates limited drilling information with geophysical data...` ("Inadequate" is judgmental; "limited" is factual. Also, "the" is not needed before "geophysical data").

Response:

Corrected:

Track Changes Copy: Page 10, Line 188

Clean Copy: Page 10, Line 186

Category 2: Awkward Phrasing and Word Choice

1. Original (P5, L102): `Their ability to image both vertical and lateral subsurface variations makes them particularly effective in heterogeneous terrains.`.

Suggestion: `Their ability to image subsurface variations in both vertical and lateral dimensions makes them...` (More fluid).

Response:

Corrected:

Track Changes Copy: Page 5, Line 100-102

Clean Copy: Page 5, Line 100-102

2. Original (P15, L309): `In the present work, initial k data from the Jinji region were limited to six boreholes.`.

Suggestion: `In this study, initial k data...` ("The present work" is slightly stilted).

Response:

Corrected:

Track Changes Copy: Page 17, Line 314

Clean Copy: Page 17, Line 311

3. Original (P18, L362): `To estimate permeability across the entire study area, we implemented a multi-stage approach...` Suggestion: `...we employed a multi-stage approach...`, ("Employed" is more common in scientific writing for describing methods).

Response:

Corrected:

Track Changes Copy: Page 19, Line 367

Clean Copy: Page 19, Line 364

4. Original (P39, L625): `...pore connectivity and higher saturation, often enhanced by structural features or thermal alteration.` Suggestion: `...often associated with structural features or thermal alteration.`, ("Enhanced by" implies improvement; "associated with" is neutral and more accurate).

Response:

Corrected:

Track Changes Copy: Page 40, Line 641

Clean Copy: Page 39, Line 623

Category 3: Minor Punctuation and Typographical Errors

1. Original (P10, L197): `Jiangmen Underground Neutrino Observatory (JUNO) (Hasan et al., 2025)).`.

Suggestion: `Jiangmen Underground Neutrino Observatory (JUNO) (Hasan et al., 2025).`, (The double closing parenthesis is a typo).

Response:

Corrected:

Track Changes Copy: Page 11, Line 203

Clean Copy: Page 11, Line 200

2. Original (P16, L321): `where ΔP shows the pressure differential... Q denotes the volumetric flow rate`.

Suggestion: `where ΔP is the pressure differential... Q is the volumetric flow rate` ("Is" is standard for defining variables; "shows" and "denotes" are less direct).

Response:

Corrected:

Track Changes Copy: Page 17, Line 327-329

Clean Copy: Page 17, Line 324-326

3. Original (P20, L387): `k = 15.373(e)^-0.002(p)`.

Suggestion: `k = 15.373 e^-0.002ρ`, (The multiplication sign `` is often used for clarity. Use `ρ` (rho) instead of `p` for resistivity to avoid confusion with pressure).

Response:

Corrected:

Track Changes Copy: Page 21, Line 391

Clean Copy: Page 21, Line 388

4. Original (P34, L539): `Percentage Matching = ( Ns / Nl ) 100`.

Suggestion: `Percentage Match = ( min(k, k') / max(k, k') ) 100` (The formula is correct but the explanation using `N_s` and `N_l` is confusing. Using `min` and `max` is clearer. Also, "Matching" -> "Match" is sufficient).

Response:

Corrected:

Track Changes Copy: Page 35, Line 543-548

Clean Copy: Page 35, Line 540-543

Category 4: Improving Clarity and Flow

1. Original (P8, L160): `This study builds on prior hydrogeophysical research and introduces a novel application of the CSAMT method for volumetric k modeling...`

Suggestion: `This study builds on prior hydrogeophysical research by introducing a novel application of the CSAMT method for volumetric k modeling...` (Connects the ideas more smoothly).

Response:

Corrected:

Track Changes Copy: Page 8, Line 160

Clean Copy: Page 7, Line 159

2. Original (P40, L668): Section Title: `Addressing the borehole–CSAMT depth discrepancy`

Suggestion: `This is a good section title. The content within it is an appropriate response to an obvious weakness.`.

Response:

Unchanged:

Track Changes Copy: Page 50, Line 863

Clean Copy: Page 48, Line 818

General impression:

The grammatical issues are minor and do not hinder comprehension. The paper would benefit from a thorough proofread focusing on articles (`a`, `an`, `the`) and prepositions. The scientific content is excellent, and polishing the language will enhance its clarity and professionalism.

Response:

The manuscript has been thoroughly revised and carefully proofread to address minor grammatical issues, particularly the use of articles (a, an, the) and prepositions. The language has been polished to improve clarity and enhance the overall professionalism of the paper.