Referee # 3 Comments (Report 1):

The authors must replot the sections of MT data

See the attached file

The language must be reviewed before publications.

Response:

Dear Anonymous Referee,

We greatly appreciate the time and effort you dedicated to evaluating our work and providing constructive feedback. Your comments have been invaluable in helping us refine and enhance the quality and clarity of our study.

In response to your suggestions, we have made substantial revisions throughout the manuscript. All major changes based on your feedback have been highlighted in the track-changes version of the revised manuscript.

Specifically, the MT data sections have been replotted as recommended, please refer to the updated figures in the revised version. Additionally, the language throughout the manuscript has been thoroughly reviewed and improved to ensure clarity and readability.

Once again, we sincerely thank you for your insightful review and thoughtful comments, which have significantly strengthened our paper.

Comment:

Most of figures not clear, some questions

Response:

Thank you for your comment. In response to the feedback from all reviewers, all figures have been carefully rechecked and improved to enhance their clarity and readability. We have ensured that the revised figures effectively convey the necessary information and meet publication standards.

Comment 1:

Why the length of profiles does not have the same?

Response 1:

Thank you for raising this important point. A detailed explanation regarding the variation in profile lengths has been provided in the revised manuscript. Please refer to the Discussion section under the new subheading titled **"4.13 Rationale for variable CSAMT profile extents"** for clarification:

New Version (Track Changes Copy: Page 46; Line 775-784), (Clean Copy: Page 44; Line 742-751):

4. Discussion: 4.13 Rationale for variable CSAMT profile extents

"The variation in CSAMT profile lengths reflects site-specific logistical and geological constraints encountered during field deployment. Factors such as terrain accessibility, infrastructure (e.g., roads, buildings), and the need to capture key geological features (e.g., faults, lithological boundaries) influenced the extent of each profile. In some cases, shorter profiles were required due to rugged topography or land access limitations, while longer profiles were employed where feasible to ensure adequate coverage across broader structural domains. Despite the variation in length, all profiles were designed to achieve sufficient depth penetration and resolution for reliable resistivity–permeability modeling, as validated through borehole calibration."

Comment 2:

The scale of resistivity not clear can you put it in linear scale?

Response 2:

Thank you for your suggestion. The resistivity scale has been changed from logarithmic to linear to improve clarity. Please see the updated Fig. 3 in the revised manuscript:

New Version (Track Changes Copy: Page 16; Line 316), (Clean Copy: Page 15; Line 295)

Comment 3:

The depth of boreholes is very shallow with respect to MT sections for correlation

Response 3:

Thank you for your observation. This point has been addressed with supporting explanation in the Discussion section of the revised manuscript. Please see the subsection titled **"4.14 Addressing the borehole–CSAMT depth discrepancy"** for details on the correlation between shallow boreholes and deeper MT sections:

New Version (Track Changes Copy: Page 46-47; Line 785-798), (Clean Copy: Page 44-45; Line 752-765)

4. Discussion: 4.14 Addressing the borehole–CSAMT depth discrepancy

"Although the borehole data used for calibration were limited to depths of 0–200 m, this interval encompasses key lithological units, granite, hornstone, and sandstone, and captures a representative range of resistivity and k conditions. These near-surface measurements provided a robust basis for developing the empirical resistivity–permeability (k–ρ) relationship, which was subsequently applied across the full depth range of the CSAMT profiles (~1300 m). While direct validation at greater depths is not currently possible due to the absence of deep borehole data, the extrapolation of the calibrated model is supported by consistent geological structure, hydrochemical data, and stratigraphic continuity reported by the Geological Survey of China down to ~1000 m. Furthermore, strong spatial alignment between resistivity, inferred k, and mapped lithological boundaries lends confidence to the model's deeper projections. We acknowledge this depth mismatch as a limitation, but emphasize that the approach enables meaningful k estimation in data-scarce regions. Future studies incorporating deep drilling and in-situ petrophysical logging will be essential to further refine model accuracy at greater depths."

Referee # 4 Comments (Report 2):

This manuscript uses controlled-source audio-frequency magnetotellurics (CSAMT) resistivity inversions and borehole information to create an empirical relationship between apparent resistivity and permeability of an area within the Jinji region in China. This empirical relationship allowed them to estimate 2D and 3D fields of permeability for the whole region and interpret areas where groundwater has the potential to be present. As the authors point out, their approach has the potential to cut down on the need for costly borehole tests. It allows for a more thorough assessment of aquifer potential, providing a tool in deep groundwater exploration. I have read the manuscript with interest. The manuscript requires considerable work. The authors need to provide clarifications in parts of their methods and conclusions, and rephrase parts of their manuscript to correct for misleading statements. Below, I have listed comments, hoping they may help improve the manuscript's quality.

Response:

Dear Anonymous Referee,

We sincerely thank you for your detailed, thoughtful, and highly professional review of our manuscript. We greatly appreciate the time and effort you dedicated to evaluating our work and providing constructive feedback. Your comments were invaluable in helping us refine and improve the quality and clarity of our study.

In response to your suggestions, we have made substantial revisions throughout the manuscript. All major changes based on your feedback have been highlighted in the track-changes version of the revised manuscript.

Once again, we truly appreciate your insightful review and constructive comments, which have significantly strengthened our paper.

Specific Comments

Comment 1:

The authors should be mindful and careful while presenting their results and conclusions, as some of the sentences throughout the text can be misleading. Below are some of the examples:

Comment 1). Lines 42 to 45 in the abstract state, "The results demonstrate that CSAMT can effectively charact.erize deep subsurface variability and generate **accurate**, spatially continuous hydrogeological models in hard rock terrains, particularly where drilling data are limited or **unavailable**."

i). First, all these resistivity-based geophysical methods rely on ground data, such as boreholes, to aid in their interpretation. In fact, the authors use borehole data to construct their empirical model. So, it is misleading to say that this approach will work in areas where ground data is **unavailable**. Consider rephrasing this part.

ii). Secondly, CSAMT relies on ill-posed inversions. Thus, stating that this geophysical method can provide an "**accurate**" hydrogeological model of the deep subsurface can also be misleading, especially if there is not enough information at depths of 1 km to validate these results. Consider rephrasing this part of the statement as well.

iii). Finally, the abstract and conclusions are misleading, as they emphasize the importance of using CSAMT for characterizing hydraulic parameters, specifically permeability, but they fail to mention the crucial role of ground information in fitting the empirical model and validating their results. I urge the authors to consider adding these silver linings to their study, as borehole information is essential in their research and is not mentioned until later in the manuscript.

Response 1:

Response 1):

Such misleading statements have been removed from the manuscript, such as:

Old Version (Page 2; Line 42-45):

Abstract: "The results demonstrate that CSAMT can effectively characterize deep subsurface variability and generate **accurate**, spatially continuous hydrogeological models in hard rock terrains, particularly where drilling data are limited or **unavailable**."

Changed to:

New Version (Track Changes Copy: Page 3; Line 56-60), (Clean Copy: Page 2; Line 40-45):

Abstract: "*The results show that, when calibrated with borehole data, CSAMT can reliably capture deep subsurface variability and produce spatially continuous hydrogeological models in hard rock terrains, particularly in areas with limited borehole coverage. While CSAMT inversion is inherently ill-posed, the incorporation of ground-truth data significantly enhances model robustness and interpretability*."

And

New Version (Track Changes Copy: Page 47/48; Line 810-817), (Clean Copy: Page 46; Line 777-784):

Conclusions: "*While borehole drilling remains the conventional means of evaluating hydraulic parameters, its high cost, limited spatial coverage, and logistical challenges restrict its broader applicability. Our approach leverages co-located CSAMT and borehole data to construct an empirical resistivity–permeability relationship, enabling the generation of spatially continuous hydrogeological models that extend beyond the reach of direct sampling.*
Although the CSAMT method is inherently based on ill-posed inversion and relies on assumptions during model construction, the integration of borehole-derived ground truth allows for the calibration and partial validation of subsurface predictions."

Comment 2):

In lines 39 to 40 and other parts of the manuscript, the authors state that this study introduces, for the first time, the use of CSAMT to estimate the distribution of permeability. While this reviewer could not find other work specifically using CSAMT to estimate hydraulic properties and state variables, there have been other studies where resistivity-based geophysical methods have been used with this objective (e.g., Daily et al., 1992; Herckenrath et al., 2012, 2013; Hinnell et al., 2010; Pollock & Cirpka, 2012), using techniques known as hydrogeophysical inversions (A. Binley et al., 2010, 2015; Ferré et al., 2009). I encourage the authors to look into this literature and acknowledge these advances in their introduction, and discuss how the advances provided in this manuscript extend this body of literature.

Response 2):

The necessary revisions have been made as suggested:

Old Version (Page 2; Line 33-42):

Abstract: "In contrast, geophysical methods offer a non-invasive, cost-effective, and efficient alternative, enabling large-scale assessment of subsurface hydrogeological conditions with minimal surface disruption. Previous geophysical studies have employed empirical approaches, particularly vertical electrical sounding (VES), to estimate permeability. However, these methods are confined to shallow depths, homogeneous settings, and one dimensional interpretation, making them insufficient for application in highly heterogeneous hard rock environments. This study introduces, for the first time, the use of controlled-source audio-frequency magnetotellurics (CSAMT) to estimate two and three dimensional permeability distributions at depths exceeding 1 km in complex geological settings, including sedimentary, igneous, and metamorphic rocks."

Changed to:

New Version (Track Changes Copy: Page 3; Line 46-56), (Clean Copy: Page 2; Line 31-40):

Abstract: "*Geophysical methods offer a promising non-invasive alternative, enabling broader spatial coverage with reduced surface disturbance. While previous studies have used empirical approaches, such as vertical electrical sounding (VES), to estimate k, these techniques are typically constrained to shallow depths (typically <200 m), homogeneous conditions, and one-dimensional interpretations. This study advances the application of resistivity-based geophysical methods by demonstrating, for the first time, the use of controlled-source audio-frequency magnetotellurics (CSAMT) to estimate two- and three-dimensional k distributions to depths exceeding 1 km across complex geological settings, including sedimentary, igneous, and metamorphic formations. In doing so, it extends the scope of earlier hydrogeophysical research, which has largely focused on shallower or more uniform subsurface environments*."

And

Old Version (Page 8-10; Line 175-221):

Introduction: "Numerous studies have investigated empirical and semi-empirical correlations between these two parameters, with the objective of utilizing resistivity as a proxy for estimating hydraulic conductivity or permeability in regions with limited data (De Lima and Niwas, 2000;

Hubbard and Rubin, 2002; Niwas and De Lima, 2003; Singh, 2005; Soupios et al., 2007; Jardani et al., 2007; Sinha et al., 2009; Majumdar and Das, 2011; Nwosu et al., 2013; Hasan et al., 2021; Asfahani, 2023). Niwas and De Lima (2003) developed an analytical model linking formation resistivity to transmissivity in porous media. Similarly, Jardani et al. (2007) demonstrated the feasibility of employing geophysical inversions to infer permeability distributions in heterogeneous aquifers. Recent studies have applied these approaches to fractured and hard-rock environments; however, such correlations are less common and frequently constrained by site-specific geological variability (Soupios et al., 2007; Hasan et al., 2021; Asfahani, 2023). Despite recent advancements, the development of robust, high-resolution 2D and 3D permeability models from resistivity data, particularly in geologically complex environments at significant depths, remains a major challenge. To date, no previous studies have successfully achieved this, underscoring the critical need for improved integration of geophysical measurements with sparse borehole data. The relationship between resistivity measurements and borehole-derived data provides an efficient and cost-effective method for estimating aquifer properties over extensive spatial areas and varied depth profiles. This study, for the first time, demonstrates a novel application of the CSAMT technique to create high-resolution two and three dimensional permeability models reaching depths of around 1300 m in a geologically complex and heterogeneous environment characterized by sandstone, granite, and hornstone. A selected number of boreholes were strategically drilled at critical points within the study area. Following this, several CSAMT survey lines were conducted, encompassing both the borehole locations and their surrounding zones. By linking resistivity data from the CSAMT surveys with permeability measurements obtained from borehole core testing, we derived a reliable empirical relationship between resistivity and permeability. This correlation was then applied throughout the entire CSAMT dataset, allowing for the generation of detailed 2D and 3D permeability models even in regions lacking direct borehole data. The method provides a cost-effective and comprehensive framework for evaluating deep groundwater potential, significantly minimizing the reliance on extensive and expensive drilling operations.

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

Changed to:

New Version (Track Changes Copy: Page 8-9; Line 165-203), (Clean Copy: Page 7-8; Line 144-182):

Introduction: *"Empirical and semi-empirical models have been developed to estimate hydraulic properties from geophysical measurements, particularly in data-sparse regions (Niwas and De Lima, 2003; Singh, 2005; Soupios et al., 2007; Hasan et al., 2021; Asfahani, 2023). In parallel, resistivity-based methods and hydrogeophysical inversion techniques have been developed to more rigorously estimate hydraulic parameters by integrating petrophysical relationships within geophysical modeling frameworks (Daily et al., 1992; Ferré et al., 2009; Binley et al., 2010; Hinnell et al., 2010; Herckenrath et al., 2012; Pollock and Cirpka, 2012; Herckenrath et al., 2013; Binley et al., 2015). These approaches have improved resolution in parameter estimation, particularly in shallow, unconsolidated, or relatively homogeneous settings. However, applications to deep, fractured, and lithologically complex environments remain limited, especially in terms of producing volumetric k models at kilometer-scale depths. Despite these advances, generation of detailed 2D and 3D k maps from resistivity data in deep, hard-rock terrains is constrained by limited borehole control, significant geological heterogeneity, and the ill-posed nature of geophysical inversion. In such contexts, integrating resistivity data with* *borehole measurements presents a practical, cost-effective solution for characterizing aquifer properties over large areas and depth ranges. This study builds on prior hydrogeophysical research and introduces a novel application of the CSAMT method for volumetric k modeling in a complex, fractured hard-rock setting. While previous studies have applied resistivity-based techniques to estimate hydraulic properties, this is the first to utilize CSAMT for constructing the detailed 2D and 3D k modeling beyond 1000 m depth in geologically heterogeneous terrains comprising hornstone, granite, and sandstone. Few available drilling tests were used to calibrate CSAMT-derived resistivity with laboratory-measured k, allowing the resulting empirical relationship to be applied across the broader survey domain. Several CSAMT profiles were conducted along and beyond the borehole locations, and the calibrated resistivity–permeability correlation was used to generate spatially continuous subsurface models in regions lacking direct borehole data. This integration resulted in a robust, data-constrained workflow capable of revealing k variations across diverse rock units and lithological boundaries. The method offers a practical and scalable alternative to extensive drilling campaigns, enabling a more detailed and cost-efficient evaluation of deep groundwater potential in structurally complex terrains.*

Ultimately, this work extends the scope of hydrogeophysical methods by demonstrating the feasibility of applying CSAMT for deep hydraulic parameter estimation in hard rock. It bridges a critical methodological gap in hard-rock hydrogeology and sets the foundation for future CSAMT-based volumetric modeling in similarly challenging environments. This study aims to develop and apply a geophysical-based approach for mapping the spatial distribution of k in deep, hard-rock settings. By integrating CSAMT data with targeted borehole measurements, this research enhances 2D and 3D hydrogeological assessments across heterogeneous lithologies in structurally complex terrains. It also minimizes reliance on extensive drilling, demonstrating the value of non-invasive geophysical techniques as a cost-effective alternative for deep groundwater exploration.”

Comment 3):

In line 98, the authors say that “Permeability is a crucial parameter for characterizing the ability of geological formations to store and transmit water.” This is partially correct, as permeability refers to the ease with which a fluid moves through a porous medium. However, this parameter is not a measure of the porous medium's ability to store water. Storage is better characterized by porosity. Consider correcting this statement.

Response 3):

Old Version (Page 5; Line 98-99):

Introduction: "Permeability is a crucial parameter for characterizing the ability of geological formations to store and transmit water."

Changed to:

New Version (Track Changes Copy: Page 5; Line 100-102), (Clean Copy: Page 4; Line 84-86):

Introduction: *"Permeability (k) is a key parameter that describes the ease with which fluids can move through a porous medium, while the capacity to store water is more directly characterized by porosity".*

Comment i:

A similar statement is presented in lines 114-115: "… while still enabling accurate evaluation of groundwater storage capacity within prospective rock formations." Are the authors aiming to characterize other parameters besides permeability? Please clarify.

Response i:

Old Version (Page 5-6; Line 113-115):

Introduction: "Alternatively, it is essential to develop methods that minimize the reliance on costly drilling while still enabling accurate evaluation of groundwater storage capacity within prospective rock formations."

Changed to:

New Version (Track Changes Copy: Page 5-6; Line 112-114), (Clean Copy: Page 5; Line 94-95):

Introduction: *"Alternatively, it is essential to develop methods that minimize reliance on costly drilling while still enabling reliable estimation of permeability within prospective rock formations."*

Comment 4):

In line 173, the authors state, "Numerous parameters significantly affect permeability." Which parameters affect permeability? Consider being more specific.

Response 4):

Old Version (Page 8; Line 173-174):

Introduction: "Numerous parameters significantly affect permeability, highlighting the utility of resistivity measurements as indicators for evaluating groundwater flow potential".

Changed to:

New Version (Track Changes Copy: Page 8; Line 160-163), (Clean Copy: Page 7; Line 139-142):

Introduction: *"Permeability is influenced by numerous parameters, including porosity, fracture density and orientation, grain size distribution, degree of weathering, pore connectivity, and saturation level, highlighting the utility of resistivity measurements as indicators for evaluating groundwater flow potential."*

Comment 2:

This reviewer acknowledges the current length of the manuscript. However, I encourage the authors to mention other important electromagnetic-based geophysical methods in the introduction briefly. Such as Magnetotellurics (MT) and time-domain electromagnetics (TDEM), which allow for deep vertical exploration. Can these same results be achieved with such geophysical methods?

Response 2:

Old Version (Page 6-7; Line 128-157):

Introduction: "The main methods in this category are vertical electrical sounding (VES), electrical resistivity tomography (ERT), and controlled-source audio-frequency magnetotellurics (CSAMT) (Soupios et al., 2007; Di et al., 2020; Zhang et al., 2024). VES has been utilized for one dimensional profiling, especially in areas with horizontally layered aquifers (Niwas and De Lima, 2003; Soupios et al., 2007; Majumdar and Das, 2011; Nwosu et al., 2013; Hasan et al., 2021; Asfahani, 2023). This method is particularly appropriate for small-scale applications (less than 200 m depth), providing low operational costs and reduced logistical requirements. However, its lateral resolution is limited, and its performance can be compromised in geologically complex settings with highly resistive or conductive layers. ERT, by contrast, enables two and three dimensional imaging up to intermediate depths (~300 m) with significantly improved resolution. It is particularly effective for characterizing complex geological settings, such as fractured zones or karst systems, and is widely used for detailed assessments of aquifer geometry and contamination (Bentley and Gharibi, 2004; Camporese et al., 2011; Lin et al., 2018; Abbas et al., 2022; Hasan and Shang, 2022). Nonetheless, it requires greater field effort, careful electrode spacing, and, like VES, may encounter challenges in highly resistive or conductive environments. CSAMT, a more advanced method, is ideally suited for deep investigations (hundreds to thousands of meters), especially in hard rock terrains. It provides two and three dimensional subsurface imaging with strong sensitivity to deep conductive structures, making it highly effective for delineating deep-seated aquifers and geothermal systems (Smith and Booker, 1991; Simpson and Bahr, 2005; Bai et al., 2010; Fu et al., 2013; Hu et al., 2013; Wang et al., 2015; Wynn et al., 2016; Zhang et al., 2021; Kouadio et al., 2023). While CSAMT typically offers lower spatial resolution than ERT, it excels in deep structural mapping, performs well in areas with high cultural noise due to its controlled-source signals, and can be further enhanced when integrated with empirical or model-based approaches (Zonge and Hughes, 1988; An et al., 2016; Hasan et al., 2025). The choice among these resistivity techniques depends on various factors, including investigation depth, target resolution, geological complexity, logistical constraints, cost, field conditions, and resistivity contrast (Di et al., 2020; Hasan and Shang, 2022). Given these considerations, particularly the need to investigate deep aquifer systems in hard rock environments, CSAMT was determined to be the most suitable method for the present study."

Changed to:

New Version (Track Changes Copy: Page 6-7; Line 123-150), (Clean Copy: Page 5-6; Line 104-131):

Introduction: *"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). VES offers a budget-friendly solution for shallow 1D (one-dimensional) profiling (typically <200 m) but lacks lateral resolution in complex settings (Niwas and De Lima, 2003; Majumdar and Das, 2011). ERT offers improved 2D (two-dimensional) and 3D (three-dimensional) imaging up to ~300 m depth, making it suitable for fractured and karst systems; though it requires more field effort and is less effective in extreme resistivity conditions (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 provides excellent depth penetration (up to tens of kilometers) and is widely used in regional-scale studies and geothermal exploration, though it requires long acquisition times and is sensitive to cultural noise (Simpson and Bahr, 2005). TDEM offers a compromise between resolution and depth, reaching several hundred meters with rapid deployment, but can be constrained by near-surface conductivity and limited sensitivity at greater depths (Bauer-Gottwein et al., 2010). CSAMT, by contrast, bridges the gap between these methods. With controlled-source signals and frequency tuning, CSAMT enables high-resolution 2D and 3D imaging of conductive structures over 1,000 m depth, even in culturally noisy and geologically complex settings (Smith and Booker, 1991; Zhang et al., 2021). Although its spatial resolution is generally lower than ERT, CSAMT offers superior performance for deep hydrogeological investigations, especially when integrated with borehole data and empirical modeling (Zonge and Hughes, 1991; Wang et al., 2015). 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 delineate deep aquifer structures in a hard rock setting, CSAMT was selected as the most suitable method, offering a practical balance of depth penetration, imaging capability, and field adaptability."*

Comment 1):

Incidentally, Magnetotelluric information has been used for the interpretation of circulation patterns in mountain systems (Jiang et al., 2014), and has the potential for detecting regional groundwater flow paths that supply water to lowland aquifers (Gonzalez-Duque et al., 2024). Consider this information for discussing the results in light of groundwater assessments and security.

Response 1):

The relevant information has been included in the Discussion section of the revised version.

New Version (Track Changes Copy: Page 39-40; Line 615-641), (Clean Copy: Page 37-38; Line 582-608):

4. Discussion: 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 with precision and where other resistivity methods (VES and ERT) may fall short. While other electromagnetic methods such as MT and TDEM are also capable of probing deep subsurface structures, achieving comparable results with these methods 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). However, MT's lower resolution in the upper crust and dependency on natural field conditions often limit its effectiveness in detailed, site-specific k modeling, particularly when borehole calibration is sparse. Similarly, TDEM is widely used for near-surface to intermediate-depth investigations and offers rapid deployment, but its signal strength and resolution tend to decrease in highly resistive formations, making it less

suitable for imaging deep, fractured zones in hard rock. Therefore, while MT and TDEM are powerful methods for broad-scale groundwater assessment, they are less suited to the high-resolution, volumetric modeling of k in varied lithologies beyond 1km depth. In contrast, CSAMT's controlled-source design, moderate-to-deep depth penetration, and strong signal-to-noise ratio in resistive environments make it better aligned with the goals of this study. The approach bridges the gap between large-scale geophysical surveys (e.g., MT or TDEM) and localized drilling, enabling spatially continuous 2D and 3D hydrogeophysical models essential for evaluating deep aquifer potential. While MT or TDEM may complement such studies at regional scales, achieving this level of resolution and lithological detail in a hard rock context currently remains more feasible with CSAMT."

Comment 3:

As the authors state in lines 196 to 198, "A selected number of boreholes were strategically drilled at critical points within the study area. Following this, several CSAMT lines were conducted, encompassing both the borehole locations and their surrounding zones." How were the locations of these boreholes determined? Is there a certain number of boreholes needed for the method framed in this study to work? What would happen if the authors removed one borehole from their research and validated it at that point? Would you get the same field of permeabilities? These are questions that arise from the approach taken that the authors should address in the text.

Response 3:

Old Version (Page 9; Line 196-198):

Introduction: "A selected number of boreholes were strategically drilled at critical points within the study area. Following this, several CSAMT survey lines were conducted, encompassing both the borehole locations and their surrounding zones."

A separate subsection has been added to the Discussion, providing detailed information on this point:

New Version (Track Changes Copy: Page 45-46; Line 763-774), (Clean Copy: Page 43-44; Line 730-741):

4. Discussion: 4.12 Optimizing borehole placement for CSAMT calibration

"Borehole placement in this study was strategically guided by geological mapping, hydrological relevance, and preliminary geophysical data to ensure representative coverage of key lithologies and structures. These boreholes served both to calibrate resistivity–permeability relationships and to validate the CSAMT-derived k models. While there's no fixed number of required boreholes, our results show that a small but well-distributed set across major lithological and structural zones yields reliable model performance. A leave-one-out validation confirmed that the model maintains coherent spatial trends, though with slightly reduced accuracy in geologically complex areas. This highlights both the importance of strategic calibration point distribution and the robustness of the CSAMT-based approach, even with limited borehole data. Future efforts could improve efficiency by adapting borehole placement based on preliminary CSAMT results, optimizing both calibration and cost."

Comment 4:

In the sentence from lines 486 to 488, the authors state that "The resistivity-porosity can be indirectly extended to infer permeability, especially when combined with other petrophysical models (Andrew Binley & Kemna, 2005; Revil & Cathles III, 1999)." The citation of Binley & Kemna (2005) is misleading because it focuses on direct current resistivity and explains some physical concepts that are not directly related to the sentence. Consider removing this citation from the paragraph.

Response 4:

The citation of Binley & Kemna (2005) has been removed.

Old Version (Page 24; Line 486-488):

Methods: "The resistivity-porosity relationship can be indirectly extended to infer permeability, especially when combined with other petrophysical models (Binley et al., 2005; Revil & Cathles, 1999)."

Changed to:

New Version (Track Changes Copy: Page 18; Line 370-372), (Clean Copy: Page 17; Line 343-345):

Methods: *"As such, the resistivity–porosity relationship can be leveraged to infer k indirectly, especially when supplemented with additional petrophysical frameworks (Revil & Cathles, 1999)."*

Comment 5:

Similarly, the statement in lines 493 to 495 could potentially have misleading references. First, in Jardani et al. (2007) there are no empirical or semi-empirical models that connect electrical resistivity to permeability. Consider removing it. Also, this author could not find the citation (Jiang et al., 2014), with the reference presented below. Consider adding the DOI number in all the references.

Jiang, Y., Wu, X., and Shi, Z.: A novel model to estimate permeability from formation resistivity, Journal of Petroleum Science and Engineering, 124, 15–23, 2014

Response 5:

The references Jardani et al. (2007) and Jiang et al. (2014) have been replaced with more appropriate sources: Glover (2009) and Yan et al. (2024). DOIs for all references have been provided in the reference list.

Old Version (Page 24; Line 493-495):

Methods: "The application of this equation alongside Archie's law facilitates the development of empirical or semi-empirical models that connect electrical resistivity to permeability (Jiang et al., 2014; Jardani et al., 2007)."

Changed to:

New Version (Track Changes Copy: Page 19; Line 383-386), (Clean Copy: Page 18; Line 352-353):

Methods: *"The application of this equation alongside Archie's law facilitates the development of empirical or semi-empirical models that connect electrical resistivity to k (Glover, 2009; Yan et al., 2024)."*

Comment 6:

The presentation of the Kozeny-Carman equation in this study seems out of place. While it is important to stress how this equation is used in the field, there is no use of the equation in the study. Consider emphasizing the practical application of the relationship and removing the equation if it is not used.

Response 6:

The Kozeny-Carman equation has been removed, and the text has been revised to focus on its practical application in the context of the current study.

Old Version (Page 23; Line 477-480):

Methods: "The Kozeny-Carman equation is another widely accepted model that links permeability to porosity and specific surface area (Bear, 1972; Carman, 1956). While it does not directly involve resistivity, it is often used alongside petrophysical models to interpret hydrogeological characteristics based on geophysical data (Paterson & Wong, 2005; Clennell, 1997)."

Old Version (Page 24-25; Line 489-504):

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

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

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

Although these formulations offer a robust theoretical foundation, their direct application in complex geological contexts, particularly in heterogeneous hard rock such as granite, sandstone, and hornstone, is frequently limited. This results mainly from differences in mineral composition, pore connectivity, and structural anisotropy (Roa-García et al., 2010; Singh et al., 2020). Our present study establishes a localized empirical relationship between resistivity and permeability through co-located measurements obtained from deep boreholes and CSAMT profiles to address these challenges. Such correlation facilitates the development of high-resolution 2D and 3D permeability models in the Jinji area (study area), thereby improving the comprehension of subsurface hydrogeology in contexts where traditional methods fall short."

Changed to:

New Version (Track Changes Copy: Page 19; Line 377-393), (Clean Copy: Page 17-18; Line 346-360):

Methods: *"The Kozeny–Carman equation, though not used explicitly in this study, provides a widely accepted theoretical foundation that connects k to porosity and specific surface area (Carman, 1956; Bear, 1972). While it does not incorporate resistivity directly, this model is often used in hydrogeophysical studies to support the interpretation of petrophysical relationships that bridge electrical and hydraulic properties (Chapuis and Aubertin, 2003). Its relevance lies in the broader theoretical justification for using porosity, derived or inferred from resistivity, as a predictor of k. The application of this equation alongside Archie's law facilitates the development of empirical or semi-empirical models that connect electrical resistivity to k (Glover, 2009; Yan et al., 2024).*

However, direct application of these equations to complex geological environments, such as fractured granite, sandstone, and hornstone, remains limited due to heterogeneities in mineral composition, pore connectivity, and structural anisotropy. To mitigate such constraints, our approach empirically develops a localized, site-calibrated correlation involving k and resistivity, grounded in co-located deep borehole and CSAMT data. This empirical link supports high-resolution spatial modeling of k in both 2D and 3D for the Jinji area, offering enhanced insight into subsurface hydrogeological conditions where traditional models may not be applicable."

Comment 7:

The empirical relationship found in the study (Equation 4 and Figure 5) is interesting and seems to have a pronounced change around 1,000 Ω ·m. This relationship reminds me of previous permeability models fitted to depth that use an exponential model to calculate permeability near the surface and a potential model after a depth threshold (e.g., Ingebritsen & Manning, 2010; Manning & Ingebritsen, 1999; Saar & Manga, 2004). Have the authors considered using a similar modeling approach for their empirical relationship? Is their new model better than these previous approximations that depend on depth? Consider adding some discussion.

<u>Response 7:</u>

A new subheading has been added in the Discussion section to provide a detailed explanation of this point.

New Version (Track Changes Copy: Page 42-43; Line 701-719), (Clean Copy: Page 40-41; Line 668-686):

4. Discussion: 4.8 Inflection in the resistivity–permeability relationship: a depth analogue

"The empirical resistivity–permeability (k–ρ) relationship developed in this study exhibits a sharp decline in k with increasing resistivity and a clear inflection near 1,000 Ωm. This mirrors classic depth–permeability (k–z) trends (e.g., Manning and Ingebritsen, 1999; Saar and Manga, 2004; Ingebritsen and Manning, 2010), where k decreases exponentially at shallow depths and follows a power-law pattern deeper down. However, unlike those models that use depth alone, our resistivity-based approach captures additional controls such as lithology, porosity, fluid content, and fracturing, making it a more localized and physically representative proxy, especially in heterogeneous hard rock settings.

Depth was considered but not used as the primary variable due to strong lateral variations in resistivity and k caused by geological complexity. For instance, in the Jinji area, surface granite shows high resistivity and low k, consistent with standard crustal profiles. However, deeper hornstone and sandstone units exhibit lower resistivity and higher k, contrary to typical depth trends, likely due to localized faulting, thermal alteration, and contact metamorphism that enhance fracture connectivity. The resemblance between our k–ρ curve and established k–z models reinforces its physical validity. The observed transition near 1,000 Ωm *may reflect a shift from conductive, fractured zones to compact, resistive rock masses. While hybrid models incorporating depth may be useful in future work, our resistivity-based method provides a more reliable and site-specific approach for k estimation in structurally complex terrains."*

Comment 8:

I recommend adding more information on the reasoning behind selecting the thresholds for resistivity to define each of the primary lithologies, as picking other thresholds can potentially change the conclusions of the manuscript.

Response 8:

To address this point, we have introduced a new subheading in the Discussion section with a detailed explanation.

New Version (Track Changes Copy: Page 40-41; Line 642-670), (Clean Copy: Page 38-39; Line 609-637):

4. Discussion: 4.4 Calibrated resistivity thresholds for lithological and hydraulic discrimination

"We developed a robust empirical relationship between resistivity and k using 116 co-located data pairs, 62 from granite, 31 from sandstone, and 23 from hornstone, spanning 35–4,765 Ωm and 0.01–19.9 mD, respectively. The strong correlation ($R^2 = 0.96$) ensures reliable k prediction and minimizes lithological bias. The lithological classification derived from the resistivity–permeability relationship in this study is both geologically plausible and empirically supported by borehole data and field observations. Specifically, granite showed high resistivity (>700 Ωm) and low k (0–5 mD), hornstone had intermediate resistivity (350–700 Ωm) and moderate k (5–10 mD), and sandstone was marked by low resistivity (<350 Ωm) and higher k (10–20 mD). These ranges align with the distinct hydrogeological behaviors of each lithology under the site-specific structural and mineralogical conditions. The resistivity thresholds were selected through an integrated approach combining lithological logs from boreholes, established empirical resistivity values reported in the literature, and the geoelectrical contrasts identified in CSAMT

profiles. For instance, the high resistivity of granite reflects its dense, low-porosity matrix and limited fluid content, whereas the lower resistivity of sandstone and hornstone corresponds to increased pore connectivity and higher saturation, often enhanced by structural features or thermal alteration. To ensure robust classification, the resistivity thresholds were calibrated using co-located borehole observations from multiple calibration sites and iteratively refined to maximize agreement between observed lithology and the modeled resistivity–permeability domains. While we acknowledge that resistivity can vary within a given lithology due to localized factors such as fluid saturation, mineral alteration, or fracture density, sensitivity analyses indicated that moderate adjustments to the threshold values had minimal impact on the overall lithological classification or the interpretation of k trends. This suggests that the chosen thresholds are well-suited to the structurally complex Jinji area. Nevertheless, we emphasize that these resistivity–permeability associations are localized and should be recalibrated to account for site-specific conditions before use elsewhere. Although site-specific, the approach demonstrates how minimal calibration data can support high-resolution 2D/3D k modeling in data-scarce settings. Future studies could benefit from probabilistic classification schemes or machine learning approaches to further refine lithological mapping in geologically heterogeneous terrains."

Comment 9:

One of the main concerns with the results is the direct linking between the lithology permeability and the apparent or bulk resistivity obtained from the CSAMT inversion. As the authors mentioned several times through the manuscript (e.g., lines 170-173), "Electrical resistivity […] is influenced by various factors. These include rock type, porosity, weathering extent, connectivity of pore network, saturation levels, structural features like faults and fractures, and the salinity of pore fluids." However, there is no mention of these other factors in their study. Do the authors know the salinity of the water after 1 km? How do the authors validate that the resistivity results they see at these depths are specifically due to the porous media characteristics and not to the presence of brackish or saline water or a combination of both? Idealized simulations on mountainous systems suggest that the salinity of water, combined with the lithologic characteristics, can change the bulk resistivity inversions and, thus, their interpretation

(Gonzalez-Duque et al., 2024). I recommend that the authors discuss these potential limitations in their study, as not accounting for these changes could lead to misinterpretations.

Response 9:

A new subheading has been added to the Discussion section to offer a detailed explanation of this point.

New Version (Track Changes Copy: Page 43-44; Line 720-733), (Clean Copy: Page 41-42; Line 687-700):

4. Discussion: 4.9 Salinity effects and limitations of deep calibration

"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, due to the lack of salinity data below 1 km, the role of deep fluid conductivity cannot be fully ruled out, a limitation of the current study. Future work should include deep borehole sampling and in-situ fluid logging to better constrain this relationship."

Comment 1):

Additionally, the authors mention doing a 2D and 3D groundwater assessment of the water-bearing capacity of the rock mass for groundwater evaluation using solely the permeability fields. A water-bearing assessment should also include the storage capacity of these lithological units that can be related to other hydraulic parameters, such as porosity. Did the authors calculate porosity, specific yield, and specific storage as well? Do they have information on water levels in the area to validate where the aquifer is located? I recommend clarifying these definitions and correcting the text when needed.

Response 1):

The explanation and clarification of this point have been provided under a new subheading in the Discussion section.

New Version (Track Changes Copy: Page 44-45; Line 748-762), (Clean Copy: Page 43; Line 715-729):

4. Discussion: 4.11 Limitations of storage characterization

"A complete groundwater assessment requires evaluating both k and storage parameters. This study focused on delineating spatial variations in k, referred to here as "water-bearing capacity", using CSAMT-derived resistivity calibrated with borehole data. While we emphasize k, we acknowledge that key storage parameters such as porosity, specific yield, and specific storage remain unmeasured due to the absence of deep aquifer tests and formation logs. However, geological and geophysical evidence allows for qualitative 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. Our current interpretation focuses on relative transmissivity, not absolute storage capacity, a limitation we acknowledge. Future work should include porosity and storage measurements through deep borehole testing, in-situ logging, and hydraulic analysis to support more comprehensive aquifer characterization in complex hard rock settings."

Comment 10:

It is not clear to this author how the 3D model was calculated. Did the authors perform a 3D inversion, or are these values interpolated? What is the certainty in their estimations at the corners, where no data is present? Please provide clarification and a discussion on the potential uncertainty behind these estimations. I recommend that these estimations of uncertainty or sensitivity be shown as contours in the figures with 3D interpretations.

Response 10:

A detailed explanation of this point has been provided under a new subheading in the Discussion section.

New Version (Track Changes Copy: Page 44; Line 734-747), (Clean Copy: Page 42-43; Line 701-714):

4. Discussion: 4.10 Model construction and uncertainty in 3D permeability mapping

"The 3D k model was developed by interpolating between 2D CSAMT inversion profiles calibrated with borehole-derived k from six reference locations. Due to limitations in survey geometry and computational cost, full 3D inversion was not feasible. Instead, a geostatistical framework using ordinary kriging integrated cross-sections and applied the resistivity–permeability relationship across the volume, constrained by lithological boundaries and borehole data. While this approach provides a volumetric view of k, model reliability declines toward the edges and corners where data density is limited. Sensitivity analyses, based on variogram adjustments and comparisons of interpolation algorithms, revealed elevated uncertainty in these peripheral zones. To convey this, uncertainty contours were added to the 3D figures (Figs. 10 and 11), delineating areas of reduced confidence. The model's core, where CSAMT lines intersect and borehole constraints exist, offers the highest reliability. Boundary regions should be interpreted with caution. Future work with denser CSAMT coverage or full 3D inversion would enhance model accuracy and reduce edge-related uncertainties."

Comment 11:

It is not clear how the matching percentages in section 3.5 are calculated. I recommend adding this equation for interpretation purposes.

Response 11:

Such equation has been added.

New Version (Track Changes Copy: Page 36; Line 569-576), (Clean Copy: Page 34; Line 536-543):

Results: "*To clarify the basis of the percentage matching values, the following explicit equation was used to quantify the agreement between CSAMT-derived k values and borehole-based k estimates:*

$$\text{Percentage Matching} = \left(\frac{Ns}{Nl}\right) \times 100 \qquad (4)$$

Here, N_s *represents the smaller of the two k values, either from the CSAMT model or borehole data, at a given depth, while* N_l *is the larger. This ratio offers a normalized agreement metric, where 100% indicates a perfect match and lower values reflect greater divergence. Comparisons were made at multiple depth intervals across six calibration boreholes."*

Comment 12:

I encourage the authors also to consider releasing the tables with the permeability and sounding information for reproducibility.

Response 12:

We appreciate the reviewer's suggestion regarding data transparency and reproducibility. A total of 142 CSAMT soundings were conducted along six profiles, with each sounding spaced at 50 m intervals. Each sounding includes multiple resistivity values from surface to 1300 m depth, resulting in hundreds of permeability (k) estimates. Given the extensive dataset and the current length constraints of the manuscript, it is not feasible to list all permeability values corresponding to each resistivity data point.

To address this, we have summarized key data in Table 2, which presents 18 representative datasets (3 k values at different depths from each of the 6 selected soundings near boreholes), including both measured and estimated permeability values. Additionally, Figure 4 shows the 116 measured permeability values (black dots) from six boreholes, alongside the nearby selected soundings.

Furthermore, the comprehensive distribution of permeability values derived from all 142 soundings is visualized in the 2D and 3D predicted k models presented in the manuscript.

Technical Corrections

Besides the comments described above, I have a few technical recommendations for the manuscript.

Comment 1):

Part of the methods and results in the manuscript feel redundant. Information that is presented in tables is described in multiple ways in the text. I encourage the authors to condense the information to reduce the overall length of the manuscript. As an example, the 2D and 3D groundwater assessment and the depth-wise groundwater assessments sections can be condensed into one, reducing the description of specific depths for each profile (which can be seen in the figures) and following a storyline that avoids repetition.

Response 1):

We thank the reviewer for the thoughtful feedback. The original manuscript was not excessively long; however, after incorporating the valuable suggestions from all reviewers, the overall length increased. In response, we conducted a thorough revision to streamline the content, removing redundant or non-essential text and retaining only the most relevant information for readers.

As a result, the manuscript length has been reduced significantly, from approximately 15,000 words to under 10,000 words (excluding references). We have only two tables, both of which contain essential information not fully described in the text. The accompanying explanations are brief and have minimal impact on overall length.

All figures have been carefully selected and are necessary for clarity and comprehension; removing any of them would compromise the quality of the presentation. Regarding the structure of the Results section, while we understand the suggestion to merge the 2D, 3D, and depth-wise permeability modeling subsections, we found that doing so made the content less accessible and more difficult to follow. Therefore, we opted to retain the three subheadings but have shortened and refined each of them for clarity and conciseness.

Importantly, not only the Methods and Results sections, but all sections including References (reduced from 120 to 75) of the manuscript have been revised to minimize length while ensuring that essential scientific details are preserved. Given the scope and multidisciplinary nature of the study, we believe the current length is appropriate and justified.

Comment 2):

In the abstract (line 37), when the authors refer to "shallow depths," I recommend clarifying what they mean by that, specifically whether it is greater than 200 m, 500 m, or 1 km.

Response 2):

In geophysical exploration, shallow depth typically refers to depths less than 200 meters, as most VES, ERT, and drilling investigations are limited to this range.

The shallow depth range is given in the revised manuscript, such as:

New Version (Track Changes Copy: Page 3; Line 49-50), (Clean Copy: Page 2; Line 34).

New Version (Track Changes Copy: Page 6; Line 128), (Clean Copy: Page 5; Line 109).

Comment 3):

A citation is missing at the end of the sentences between lines 167 and 170.

Response 3):

Citations added

New Version (Track Changes Copy: Page 7; Line 152-155), (Clean Copy: Page 6; Line 133-136):

Introduction: *"Accurate hydraulic assessment in such settings benefits from integrated geophysical and hydrogeological approaches to better capture spatial variability and improve flow modeling (Hasan et al., 2021; Abbas et al., 2022)."*

Comment 4):

Similarly, a citation is missing in the sentence between lines 170 and 173.

Response 4):

Citations added

New Version (Track Changes Copy: Page 7; Line 155-158), (Clean Copy: Page 6-7; Line 136-139):

Introduction: *"Resistivity-based techniques are particularly valuable for delineating subsurface structures and identifying water-bearing zones. Because electrical resistivity is sensitive to porosity, saturation, fracture density, and fluid salinity, it is increasingly used to infer k in heterogeneous geological settings (Mudunuru et al., 2022; Yan et al., 2024)."*

Comment 5):

Figure 1a shows the profiles taken in the study region. However, there is no information related to topography, geology, and/or water bodies. Consider adding this information on the figure to give context to the reader, especially if this information is provided in lines 242 to 249 and the paragraph beginning in line 250.

Response 5):

Fig. 1a has been revised according to the reviewer's suggestions:

New Version (Track Changes Copy: Page 10), (Clean Copy: Page 9)

The suggested information has been incorporated into the text.

New Version (Track Changes Copy: Page 11, Line 222-238), (Clean Copy: Page 10, Line 201-217)

Study area and hydrogeological settings: *"Topography ranges from low hills to mountainous terrain (39–539.9 m elevation), with dense vegetation and varied slopes. The northern part is relatively flat, while the south includes prominent features such as the Dashishan and Qilongding Mountains. Surface drainage is primarily controlled by the Yongkouwei River in the northeast.*

Geologically, the Jinji area has evolved through successive tectono-magmatic processes linked to the Yanshanian, Indosinian, and Caledonian mountain-building phases, resulting in a *lithologically diverse landscape of granite, sandstone, and hornstone (Qin, 2017). Granite intrusions reflect deep crustal magmatism, while hornstone indicates contact metamorphism. Overlying Paleogene sediments record later basin development. Tectonic structuring in the area is largely influenced by the Kaiping fault-fold complex, which includes reverse, thrust, and strike-slip faults formed under prolonged crustal compression and later modified by strike-slip tectonics. These northeast-trending structures govern subsurface architecture and groundwater flow pathways (Yang et al., 2021). Fractures and joints are widespread in granite, sandstone, and hornstone, varying by lithology and tectonic history. These brittle features act as primary conduits for groundwater, with their alignment along major faults highlighting the tight coupling between structural geology and hydrogeology."*

Comment 6):

Remove one of the periods (dots) in line 369.

Response 6):

Removed:

New Version (Track Changes Copy: Page 14, Line 291), (Clean Copy: Page 13, Line 270)

Comment 7):

In line 746, consider changing "%match" to "percent match."

Response 7):

"%match" in **Old Version (Page 43, Line 746)**

Changed to

"percent match." **in New Version (Track Changes Copy: Page 36, Line 587), (Clean Copy: Page 34, Line 554)**

Comment:

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Response:

The suggested references from the list above have been incorporated, and some references were removed as per the reviewer’s recommendation.