Water Research Program

Improved forecasting of water content spatial distribution and aquifer potential assessment using geostatistical and hydro-geophysical methods.

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Abstract

In the Western United States, mountainous regions capture approximately 70% of precipitation, though they account for only 30% of the land area. This makes rainfall, snowfall, and snowmelt critical contributors to both surface water flow and aquifer recharge, especially in states like Wyoming, where most of the population relies on these water sources. This study enhances aquifer potential predictions by integrating time-lapse geophysical observations with geostatistical methods. We developed a new methodology based on Bayesian theory to estimate key subsurface properties, such as porosity and water saturation, which are essential for understanding groundwater dynamics. By continuously updating our model as new data becomes available, we improve predictions of the water holding capacity of aquifer recharge zones. This enables more effective water resource management by state agencies, helping to plan for population growth, mitigate water security threats, and better manage annual water usage under varying precipitation conditions. Our methodology was applied to a dataset measured in the Laramie Range. This approach has broader applicability to similar regions in other Wyoming municipalities.

Objectives

This project has three key objectives:

1. Methodology Development: To develop a novel methodology that integrates geostatistical techniques with hydro-geophysical measurements, particularly seismic velocities and electrical resistivity, to evaluate aquifer recharge potential in groundwater recharge zones. This methodology aims to improve understanding of subsurface hydrological variables that govern aquifer recharge.

2. Quantifying Uncertainty: One of the major challenges in hydrologic modeling is the uncertainty in predictions due to the inability to directly measure many key subsurface properties. We apply a Bayesian geostatistical framework to estimate the spatial distributions of crucial subsurface properties, such as porosity and water saturation, and to quantify the associated uncertainty.

3. Supporting Water Management: The ultimate goal is to improve the ability of state agencies, such as the Wyoming Water Development Commission and the National Weather Service, to manage water resources effectively. By providing better predictions of groundwater recharge and resilience, this project provides support for more informed decision-making, planning for future growth, and hazard management.

Methodology

The study uses a multidisciplinary approach combining geophysical measurements, geostatistical simulations, and Bayesian inversion techniques to estimate aquifer potential. The primary data sources are time-lapse geophysical observations, including seismic velocities and electrical resistivity, collected from key aquifer recharge zones in Wyoming’s mountainous regions. These geophysical measurements are sensitive to the subsurface properties of interest, such as porosity, i.e., the amount of pore space available for water, and water saturation, i.e., the amount of water within the pore space.

The novel methodology includes a) Geophysical data collection; b) Geostatistical simulations and Bayesian inversion; c) Continuous model updating; and d) Validation and testing. First, seismic and resistivity data are collected over time at strategic locations within the target catchments. Seismic velocities provide indirect information about rock stiffness, which relates to pore volume, while resistivity helps to estimate water content in the subsurface. Then, geophysical data are integrated into a geostatistical model using Bayesian inverse theory. This method allows the creation of multiple realizations of subsurface properties, which are updated as new data becomes available. The result is a probabilistic model that predicts the most likely distributions of porosity and water saturation while accounting for uncertainties. Finally, as additional data are collected over time (e.g., during different seasons), the model is continuously refined and updated. This ensures that the predictions are based on the most current and accurate information, improving the ability to forecast aquifer potential and recharge dynamics. The methodology was tested and validated using datasets from the Laramie Range, WY, a site that relies heavily on both surface water and groundwater. This dataset provides the basis for comparing predictions against real-world observations and refining the model for future use in similar regions.

The measured data and the results of the computational models are shown in Figures 1-5. Figure 1 shows the site location. Datasets were collected along ten transects near Pilot Peak (PP; Figure 1) and along ten transects near Government Gulch (GG; Figure 2c), both in the Laramie Range, Wyoming, USA, in July 2022 (Figure 1). Additionally, time-lapse ERT datasets were collected at a transect near PP from 08/15/2022 to 08/16/2023 and at a transect near GG from 12/31/2021 to 08/14/2022, both at a 24-hour data acquisition frequency (Figure 1). Figures 2 and 3 show the seismic and electrical data acquisitions. Data in Figures 2 and 3 have been processed using Monte Carlo inversion methods to predict the elastic and electrical rock and fluid properties in the subsurface in terms of seismic velocity and electrical resistivity and quantify their uncertainty.

Principal Findings

The results from the geophysical and geostatistical integration indicate significant improvements in the ability to predict groundwater recharge and assess aquifer resilience. By coupling time-lapse geophysical data with Bayesian statistical models, we are able to provide spatially explicit predictions of key subsurface properties, including porosity and water saturation. These properties are critical for understanding groundwater flow and the potential for aquifer recharge.

Key findings include:

- Enhanced Prediction Accuracy: The combined use of seismic and resistivity data allows for better predictions of subsurface properties, especially in areas with sparse direct measurements.

- Uncertainty Quantification: The Bayesian framework helps to quantify the uncertainty in predictions, providing decision-makers with more reliable information on the range of possible outcomes.

- Aquifer Resilience Assessment: By predicting changes in groundwater recharge under different climatic and extraction scenarios, the model can assess the resilience of aquifers to increased withdrawals due to population growth or reduced snowmelt.

- Improved Water Resource Management: The continuous model updates provide real-time predictions, improving water resource management and enabling better planning for future growth and climate variability.

Significance

The significance of this research lies in its potential to improve the management of water resources in regions that rely heavily on aquifers for municipal water supplies. Wyoming, like much of the Western U.S., faces increasing water security challenges due to population growth and changing precipitation patterns. The innovative combination of geophysical observations with geostatistical methods offers several key benefits:

1. Better Water Resource Management: The ability to accurately predict aquifer recharge and resilience allows state and federal agencies to make better-informed decisions about water

allocations, extraction limits, and long-term planning. This is particularly important for areas experiencing rapid growth or facing future water shortages due to changing climate conditions.

2. Real-Time Updates for Dynamic Management: The continuous updating of the geostatistical model as new data becomes available provides dynamic and real-time insights into aquifer conditions, enabling more responsive and adaptive management practices.

3. Educational and Training Benefits: The project also contributes to the training and education of graduate and undergraduate students in advanced hydrological and geophysical techniques. By involving students in the data collection, analysis, and modeling processes, the project fosters the development of future experts in water resource management.

4. Applicability to Other Regions: While this study focuses on the Laramie Range, the methodology is applicable to other regions where aquifers are a critical resource. The ability to extend this model to different geophysical environments could lead to improved water management strategies in other water-scarce regions.

In summary, this project will not only advance scientific understanding of aquifer dynamics but also provide practical tools for managing water resources in a changing world.

Research outcomes

The main results of the research were published in two manuscripts publications. In Li et al. (2024a), a stochastic framework is implemented based on a statistical approach where multiple realizations of stochastically perturbed initial models and travel time picks are generated and the uncertainty in the predicted velocity models is quantified. The two sources of uncertainty are first studied independently and then the combined effect is investigated. The results show that both sources affect the posterior uncertainty, but the uncertainty in the initial model has a greater effect than picking error on the uncertainty of the posterior velocity model. In addition, joint analysis of both sources of uncertainty shows that the uncertainty in the inverted model depends on predicted velocity values, depths, velocity gradients and ray coverages. In Li et al. (2024b), a statistical approach based on the stochastic perturbation and inversion of multiple realizations of resistance data is applied to study the uncertainty in the predicted resistivity models. The work investigates the effect of data uncertainty on the inverted resistivity model for individual data sets and it quantifies the effect of variation in data quality over time on the inverted time-lapse resistivity results. The results from 20 campaigns and 2 time-lapse electrical resistivity data sets show that reciprocal error is positively correlated with both contact resistance and ground's apparent resistivity, thus the significance of lowering electrode contact resistance during fieldwork needs to be considered along with the ground's apparent resistivity. The results using the statistical approach show that uncertainty in the posterior resistivity model depends on the ground's resistivity and measurement error in the input data. The time-lapse results provide additional insight that model uncertainty is the highest at the driest months of the year, corresponding to the highest measured contact resistance and reciprocal error. Finally, Prof. Dario Grana presented the results at the 15th International Conference on Geostatistics for Environmental Applications

(Grana et al., 2024). In the presentation, it was demonstrated how uncertainty is estimated for each modeling step and propagated from the input data to the posterior distribution. The talks aimed to convey that seismic velocity and electric resistivity inversion processes are mostly affected by two types of uncertainty: a) the lack of accurate knowledge of the initial model and the inversion regularization parameters adopted to constrain the inversion and reduce the non-uniqueness of the solution, and b) the limited precision of the measured data due to measurement and data processing errors. Consequently, the accuracy and precision of the results of the rock and fluid property inversion depend on the uncertainty in the predictions of seismic velocity and electric resistivity as well as the accuracy of the rock physics model approximation.

Student support

The projected supported and contributed to the training of three students: a) Tanner Adam (BS student in Geology), b) Alexandra Peterson (MS student in Geophysics), and c) Ang Li (PhD student in Geophysics). All students participated in the field work for the acquisition of the geophysical dataset during the summer, under the supervision of Prof. Andrew Parsekian. In addition, Ang Li worked on the computational models for geostatistical simulations and inversions and applied the models to the measured dataset, under the supervision of Prof. Dario Grana.

References

- Li, A., Grana, D., Parsekian, A.D. and Carr, B., 2024a. Uncertainty Quantification in Tomographic Inversion of Near-Surface Seismic Refraction Data. Mathematical Geosciences, 56(1), pp.77-101.
- Li, A., Grana, D., Parsekian, A.D. and Carr, B., 2024b. Quantification of uncertainty in electrical resistivity tomography. Geophysics, in review.
- Grana, D., Parsekian, A.D, Li, A., and Oladeji, E., 2024. Uncertainty Quantification of Rock and Fluid Properties in Near Surface Geophysics Studies. 15th International Conference on Geostatistics for Environmental Applications, Chania, Greece.

Figures

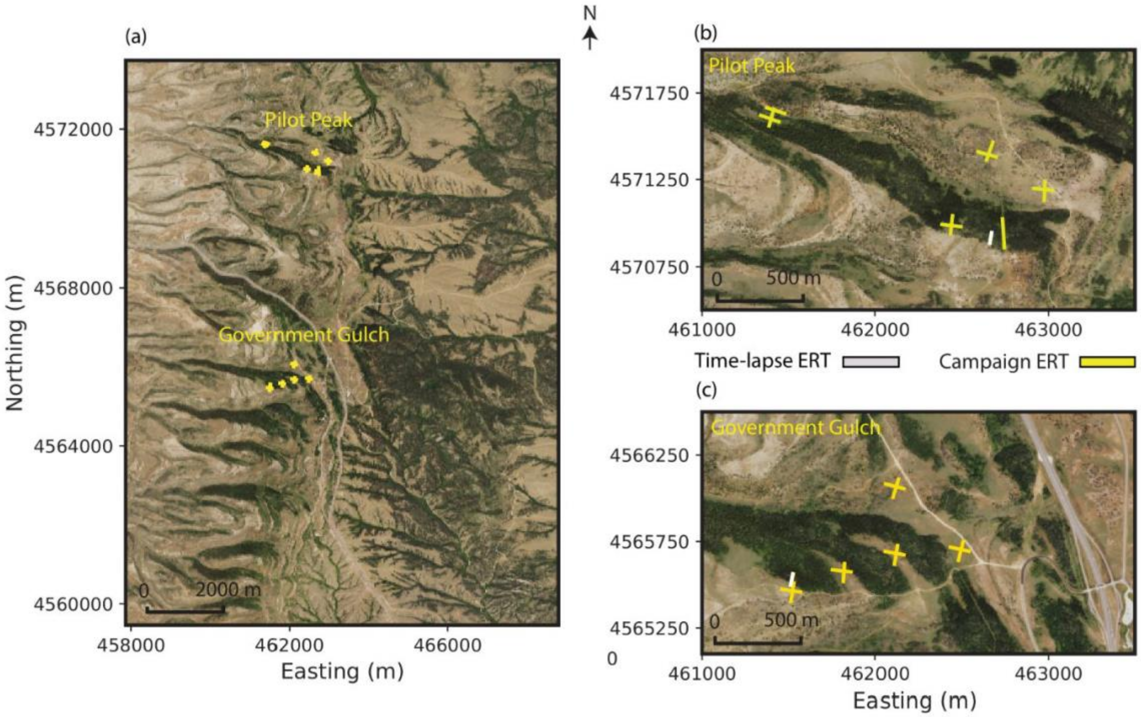

Figure 1: Field site at Pilot Peak (PP) and Government Gulch (GG) near Laramie, Wyoming (a). Electrical resistivity tomography campaign (yellow) and time-lapse (grey) transects at Pilot Peak (b) and at Government Gulch (c).

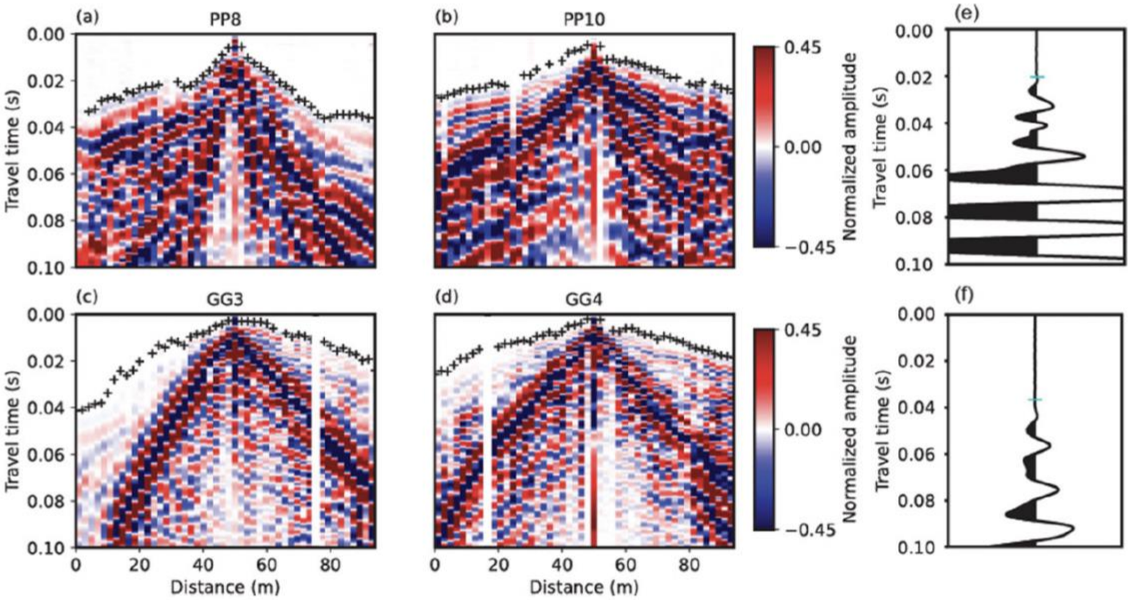

Figure 2: Normalized seismic waveform data for a seismic source location at 50 m for 4 seismic lines (a, d), and two seismic traces (e, f) extracted from line PP10 at 80 m and from line GG3 at 8 m, respectively, with first-arrival picks shown in blue.

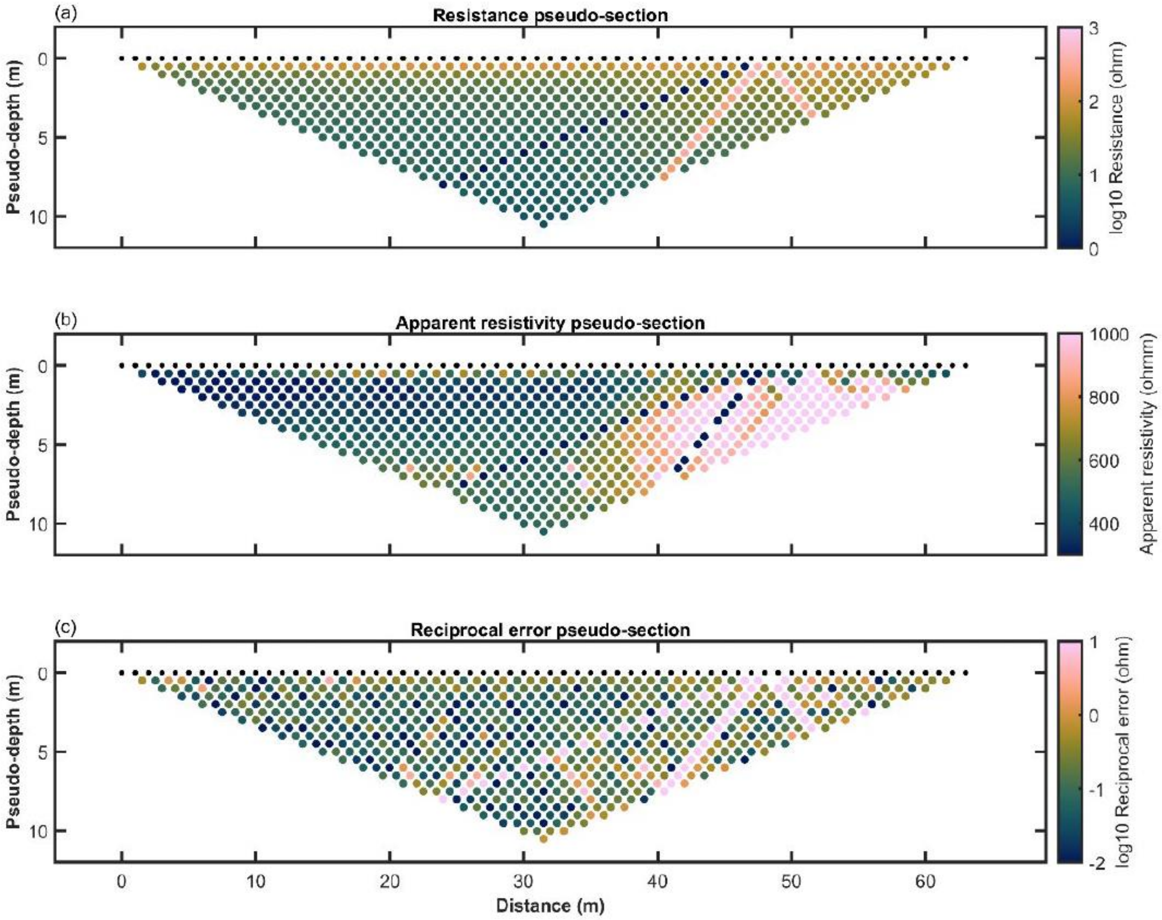

Figure 3: DC resistivity pseudo-sections for resistance (a), apparent resistivity (b), and reciprocal error (c) for a time-lapse dataset measured on 12/21/2021 at Government Gulch.

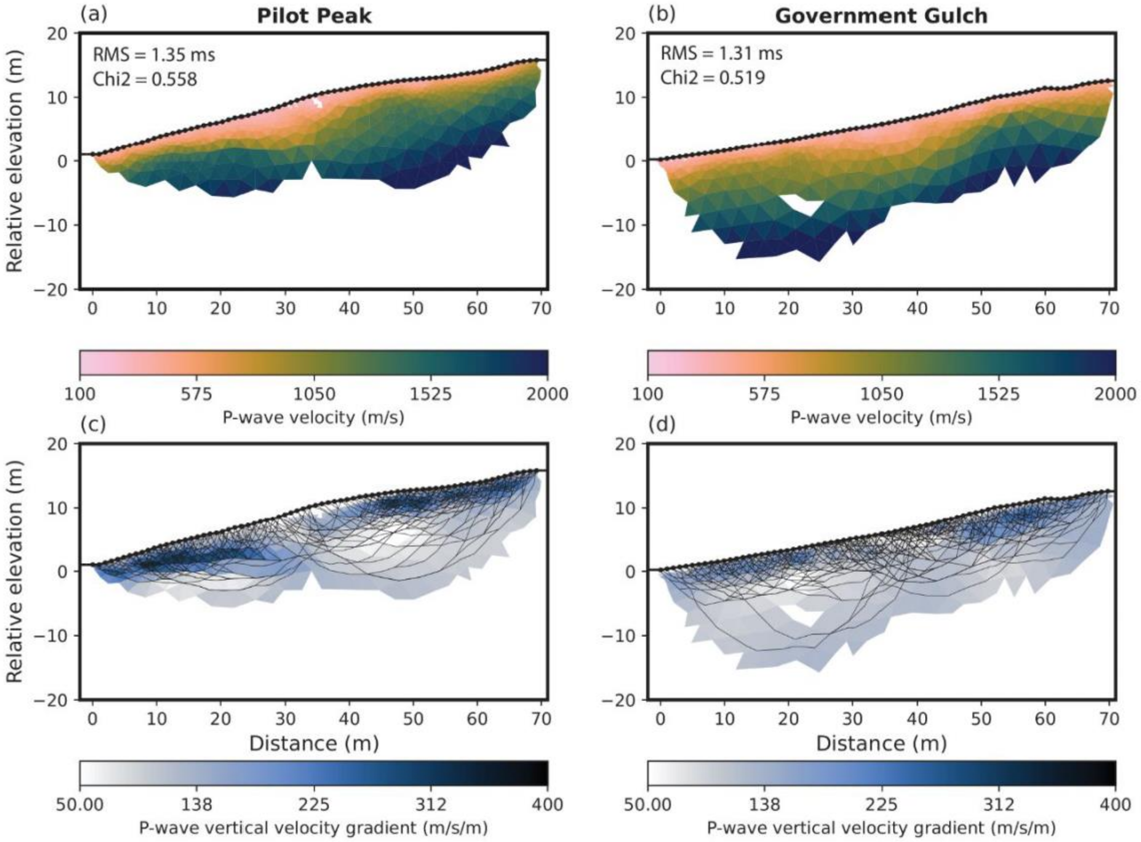

Figure 4: P-wave tomography inversion results for the lines that are co-located with the timelapse electrical resistivity transects at Government Gulch and Pilot Peak: P-wave velocity model (a and b), calculated vertical velocity gradient and ray path (c and d) (ray path thicknesses are used for visualization). Black dots represent geophone locations along the hillslope.

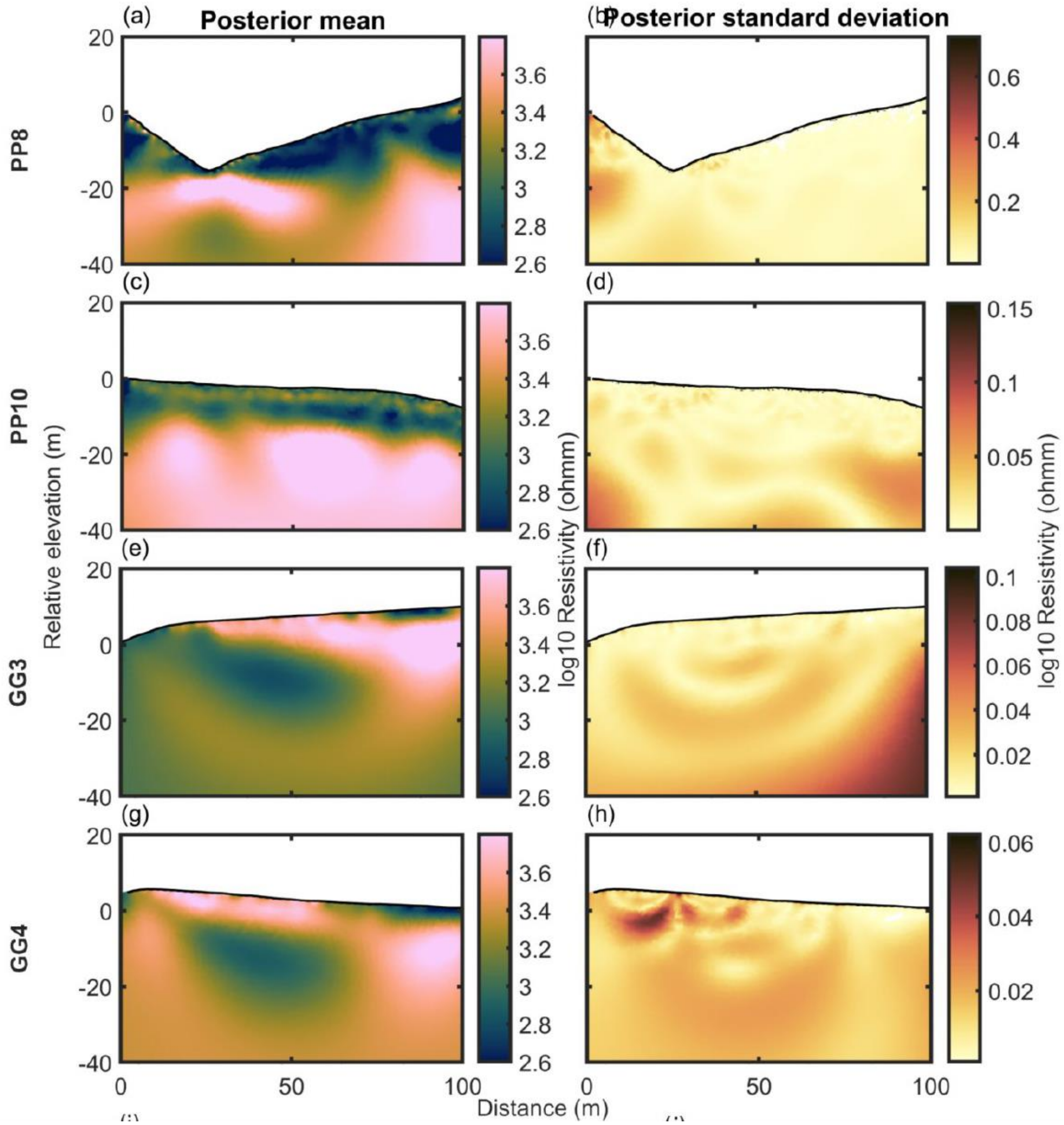

Figure 5: Posterior model of resistivity for 4 lines (a-c-e-g) and standard deviation of geostatistical realizations (b-d-f-h) obtained by perturbing the resistance data.