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Uncertainty Quantification of the Fresh-Saltwater Interface from Time-Domain Electromagnetic Data

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Geophysical methods provide a cost-effective way to characterize the subsurface for hydrogeological projects, but they rely on solving an inverse problem. Traditionally, deterministic approaches are used, which face challenges related to non-uniqueness of the solution. In contrast, stochastic methods offer uncertainty quantification but generally require higher computational resources. Bayesian Evidential Learning (BEL) has been proven as a reliable alternative to solve the inverse problem stochastically. BEL bypasses full stochastic inversion by learning a direct relationship between data and model parameters, allowing to approximate the posterior distribution at a lower computational cost. However, as with most Monte Carlo techniques, BEL efficiency depends on the number of inversion parameters.

In this contribution, we show that incorporating prior physical knowledge about the imaged processes into the parameterization of model parameters efficiently reduces the number of unknowns, and subsequently the computational burden of BEL. Using time-domain electromagnetic data (TEM), we characterize the fresh - saltwater transition zone in the Flemish coastal aquifer. This transition can be sharp, gradual or very smooth depending on the local hydrogeological context. Conventional blocky or smooth deterministic inversions then often misrepresent this transition zone as too sharp or too gradual. To address this, we explicitly incorporate the transition zone in the parameterization, with two variables: its depth and its thickness, assuming a linear increase of conductivity within this thickness. The transition zone is underlying a freshwater zone with constant conductivity and overlying a saline zone, also with constant conductivity. This retains the compactness of blocky or layered inversion while allowing sharp or gradual interfaces like voxel-based methods.

To assess the reliability and robustness of the method, we invert these parameters stochastically using BEL with Thresholding (BEL1D-T). Results indicate this approach effectively captures uncertainty for synthetic and field data. The transition zone remains largely uncertain due to the limited sensitivity of the TEM set-up to the relatively shallow transition observed in the Belgian coastal area. Yet, our probabilistic method achieves this without the heavy computational cost of traditional stochastic approaches. The result also shows that the uncertainty can be efficiently reduced when prior information on the presence of confining layer (e.g., clay layer) is further introduced in the parameterization.

Keywords: time-domain electromagnetics, inverse problem, uncertainty quantification, fresh-saltwater interface (FSI)