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Research Paper

Study of Aquatic Sedimentation Using Electromagnetic Modeling in Flood Hazard Mitigation Scheme

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Abstract

The accumulation of sediment in aquatic environments can lead to an increase in flood risk due to raised floodplains and water levels. Electromagnetic modeling techniques, such as Time Domain Electromagnetic (TDEM) resistivity or lithological conductivity contrast, can be utilized to detect changes in the subsurface. In this study, we investigated the use of TDEM in flood hazard mitigation schemes by developing a 1-D forward modeling program for the central loop configuration in an aquatic environment using the Adaptive Born Forward Mapping (ABFM) method. The program was tested in various environmental conditions, i.e., freshwater, brackish water, and saltwater, to determine its response. The objective is to prevent natural disasters, particularly flooding caused by sedimentation. The TDEM models can generate images of sediment thickness, providing a sensitive response in saltwater environments and enabling the detection of changes in depth compared to other aquatic environments. Overall, this study demonstrated the potential of TDEM as a valuable tool in flood hazard mitigation schemes.

Keywords: *ABFM; electromagnetic modeling; flood risk; flood hazard mitigation; sedimentation; TDEM.*

Introduction

The electromagnetic method is a popular geophysical technique used to image subsurface conditions based on conductivity contrast. It has various applications, including geological hazard mitigation [1,2], caving mitigation [3], water subject modeling [4-6], mineral exploration [7], and environmental investigation [8-10]. Electromagnetic methods are generally classified into two types based on the time and frequency domains. In frequency-domain electromagnetic (FDEM) methods, data is measured by recording the presence of a signal with a specific frequency. In contrast, time-domain electromagnetic (TDEM) methods use a square or circular loop placed on the surface to emit a direct short-current pulse that stops after a certain period.

In aquatic environments, sediment accumulation and weathering can lead to rising water levels and potential flood hazards. The TDEM method is commonly used in such aquatic modeling [5,6,10], but conductivity poses a challenge. In this study, we modeled TDEM responses in different water types to evaluate its sensitivity to water level and sediment thickness.

The TDEM method is a controlled source electromagnetic technique that injects currents into the subsurface and turns them off for a specific period to measure the resulting response [11-15]. Modeling of TDEM data has been done using genetic algorithms [12,14,15]. Genetic algorithms (GAs) are a class of optimization algorithms that mimic the process of natural selection in order to find the optimal solution to a problem. In TDEM (Time-Domain Electromagnetic) data modeling, genetic algorithms can be used to optimize the inversion process and improve the accuracy of the model [12,14,15].

TDEM data modeling involves simulating electromagnetic waves and their propagation through geological structures to determine the electrical conductivity distribution of the subsurface. The goal is to fit the model to the observed data and determine the most likely subsurface structure. To use genetic algorithms in TDEM data

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modeling, the first step is to define the objective function. This function evaluates the fitness of the model and determines how well it fits the observed data. The genetic algorithm then uses this function to evolve the population of candidate models over multiple generations until it converges to the optimal solution. At each generation, the genetic algorithm generates a new population of models by combining and mutating the most fit individuals from the previous generation. These new models are then evaluated using the objective function, and the fittest individuals are selected for the next generation. This process continues until the algorithm converges to the optimal solution or reaches a predefined stopping criterion. Overall, genetic algorithms can be a powerful tool in TDEM data modeling as they can efficiently search the large space of possible subsurface structures and provide more accurate results than traditional optimization techniques [12,14,15]. However, they require careful parameter tuning and can be computationally expensive.

Data

The TDEM data response depends on physical properties such as medium conductivity and thickness. We used synthetic data generated from a conceptual model to determine the 1-D TDEM response, as shown in Figure 1.

The model comprises geological and geophysical profiles of a subsection system of water-containing environments (freshwater, brackish water, and saline water) with synthetic lithology, which we refer to as sedimentary layers. The geological concept model has five layers: water, soil, clay, medium sand gravel, and sandstone as bedrock. From top to bottom S1 consists of: a 3-m thick layer of soil (resistivity 25 ohm.m) and a 12-m thick layer of sandstone (resistivity 700 ohm.m).

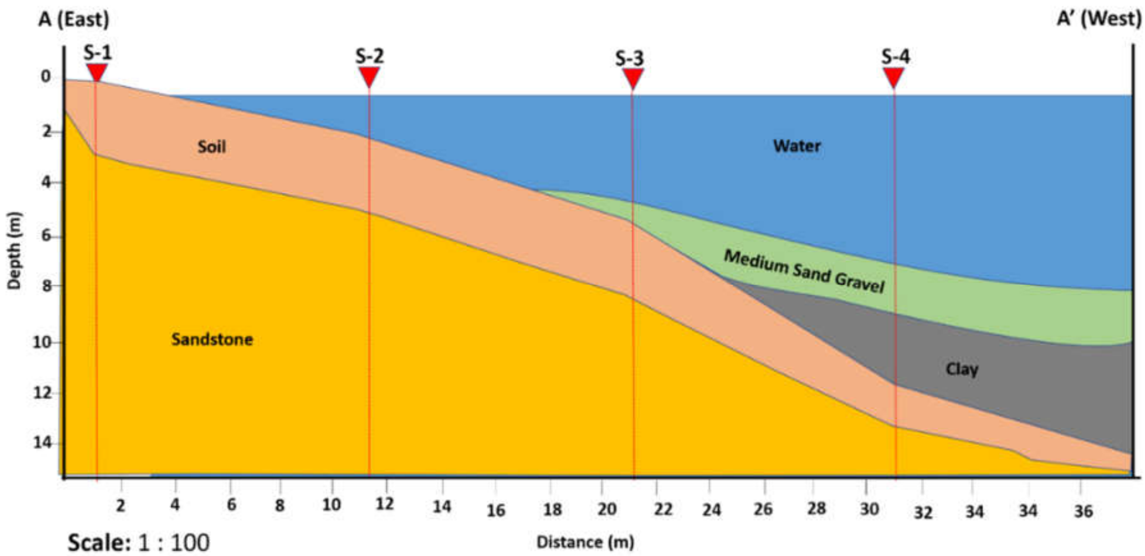

Figure 1 Geological conceptual model.

From top to bottom S2 consists of: a 2-m thick layer of water (resistivity 4.5 ohm.m), a 3-m thick layer of soil (resistivity 25 ohm.m), and a 10-m thick layer of sandstone (resistivity 700 ohm.m). From top to bottom S3 consists of: a 5-m thick layer of water (resist. 4.5 ohm.m), a 1-m thick layer of medium sand gravel (resist 140 ohm.m), a 3-m layer thick of soil, a 7-m thick layer of sandstone. From top to bottom S4 consists of: a 6-m thick layer of water, a 2-m thick layer of medium sand gravel, a 3-m thick layer of clay (resist 50 ohm.m), a 1-m thick layer of soil, a 2-m thick layer of sandstone. We simulated different water conditions for each model with the same geological features and divided the models into four sampling points (S-1, S-2, S-3, and S-4) to obtain responses at different water layer thicknesses. Table 1 shows the geological and geophysical parameters used in the study.

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Table 1 Conceptual model parameters.

Lithology	Resistivity (ohm.m)
Sandstone	700
Soil	25
Clay	50
Medium Sand gravel	140
Freshwater	10
Brackish water	4.5
Saline water	0.3

Method

In TDEM, a secondary magnetic field is generated due to the variation of the magnetic field over time in a central loop configuration. During the implementation of this method, the secondary magnetic field and its derivative are measured. Assuming that the medium is a homogeneous half-space, the secondary magnetic field can be estimated using Eq. (1):

$$\frac{\partial H_z}{\partial t} = \frac{-I}{\mu_0 \sigma a^3}\left[3\, erf(\theta a) - \frac{2}{\sqrt{\pi}}(3 + 2\theta^2 a^2)e^{-\theta^2 a^2}\right] \quad (1)$$

where θ and the error function are determined by Eq. (2) and (3):

$$\theta = \sqrt{\frac{\mu_0 \sigma}{4t}} \quad (2)$$

$$\mathrm{erf}(\theta a) = \frac{1}{\sqrt{\pi}}\int_{-\theta a}^{\theta a} e^{-t^2}\, dt \quad (3)$$

The secondary derived magnetic field can be transformed into apparent resistivity using Eq. (4):

$$\rho_a \approx \frac{I^{0.667}(\mu_0)^{1.667} a^{1.333}}{20^{0.667}\pi^{0.333} t^{1.667}}\left(\frac{-\partial H_z}{\partial t}\right)^{0.667} \quad (4)$$

The TDEM response at each observation point is obtained through forward modeling, using the Adaptive Born Forward Mapping (ABFM) method. This method describes how the response changes as a function of the subsurface conductivity contrast. The forward modeling process is carried out through a floating process, and the apparent conductivities are unknown until the response from the forward modeling is calculated. Thus, an initiation model is needed. The apparent conductivity is calculated as a function of time, denoted by index j for each layer, using Eq. (1). This method does not require deconvolution or other non-unique transformations [7,8].

$$\sigma_a(t_j) = \sum_{k=1}^{L} \sigma_k F_{jk} \quad (5)$$

σ_k in Eq. (5) the conductivity model for each layer *k*. The Fréchet kernel equation (F_{jk}), which evaluates the change with depth *(z)*, is used to obtain the apparent conductivity of the conductivity model. The Fréchet kernel function is expressed in Eq. (6):

$$F\left(z_k, t_j, \sigma_a(t_j)\right) = f(x) = \begin{cases} \frac{z_k}{D_j}\left(2 - \frac{z_k}{D_j}\right), for\ z_k \le D_j \\ 1, for\ z_k > D_j \end{cases} \quad (6)$$

where the variable D_j is defined as in Eq. (7):

$$D_j = \sqrt{\frac{c t_j}{\mu_0 \sigma_a(t_j)}} \quad (7)$$

The ad-hoc scaling is denoted by c and the free-space magnetic permeability is represented by µ0, which are 1.2 and $4\pi \times 10^{-7}$, respectively. For our modeling, we used an α value of 0.4 and a current I of 10 A. Reference [6] suggests that a good forward modeling result can be obtained after at least five to ten iterations. In this study, we applied twenty iterations to obtain the most optimal result. During this process, an initial value of the conductivity model σ_a^k is required. We set the average conductivity model as the initial σ_a^k value, and the iteration process was carried out using Eq. (8):

$$\sigma_a^k = \alpha\sigma_a^{k+1} + (1+\alpha)\sigma_a^k \quad (8)$$

Results

TDEM Response in Different Water Types

In this study, we obtained four models for each water type, which are shown in Figures 2 through 4. Figures 2, 3, and 4 show the Time Domain Electro Magnetic (TDEM) response in dB/dt for the different water types (fresh, brackish, and saline water) with the S1 soil and sandstone layer as control. The purpose of the figures is to demonstrate how the TDEM response varies with changes in water type and to establish a baseline or control measurement for comparison with other layers. The figures provide useful information for understanding the electrical properties of the subsurface materials and how they affect the TDEM response. By comparing the TDEM response in different water types and layers, we can better interpret the geophysical data and improve our understanding of the subsurface conditions. The TDEM response is described by red dots, and the depth of the sedimentary layer model is shown by a blue line. The S-1 point consists of soil and sandstone, where the conductivity contrast between these sediment types is significant. We set the soil depth as 3 meters. The lithology of S-2 is water (2 meters), soil (3 meters), and sandstone. The S-3 point has the following characteristics: water (5 meters), medium sand gravel (1 meter), soil (3 meters), and sandstone. The S-4 point consists of water (7 meters), medium sand gravel (2 meters), clay (4 meters), soil (1.5 meters), and sandstone.

Our results show that minor changes in depth do not significantly affect the TDEM response. Therefore, from model S-2 (2 meters of water depth) to S-4 (7 meters of water depth), all model responses show significant changes. Comparison between the responses of S-2, S-3, and S-4 shows that changes in sediment thickness can be detected using this method.

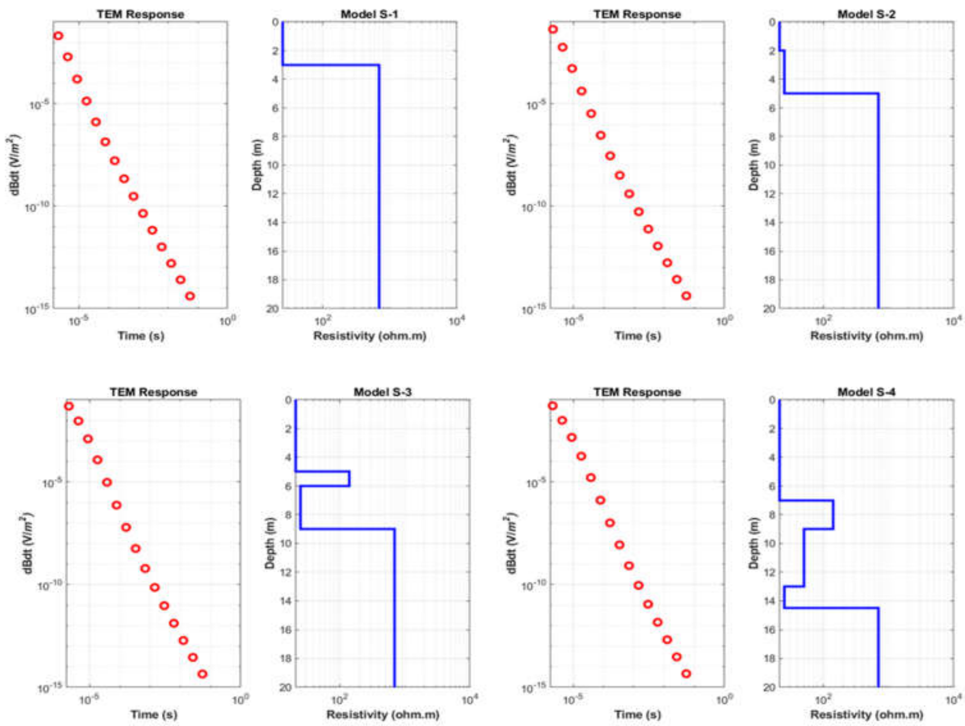

Figure 2 TDEM response in freshwater.

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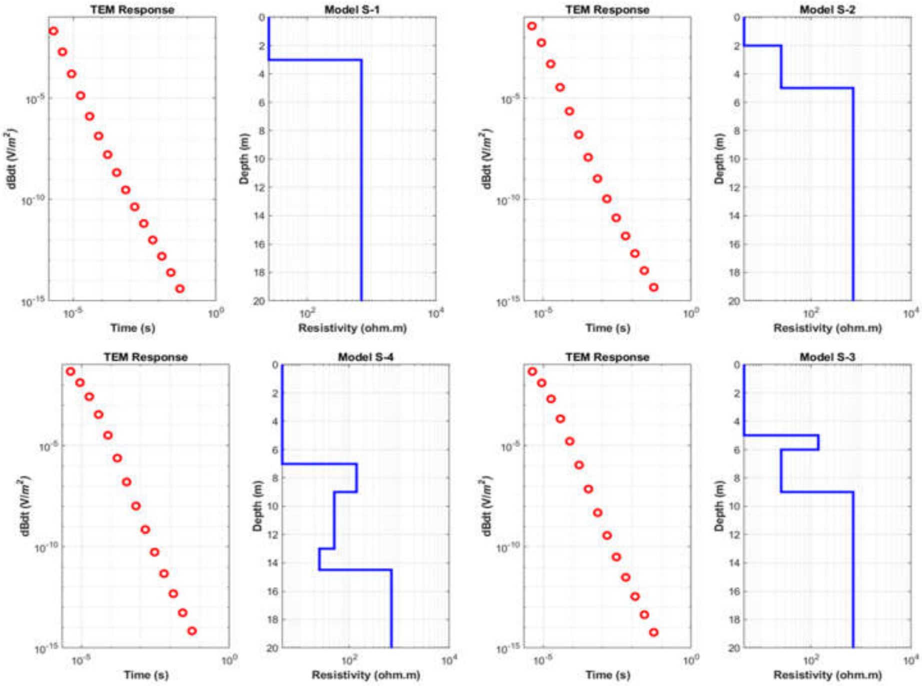

Figure 3 TDEM response in brackish water.

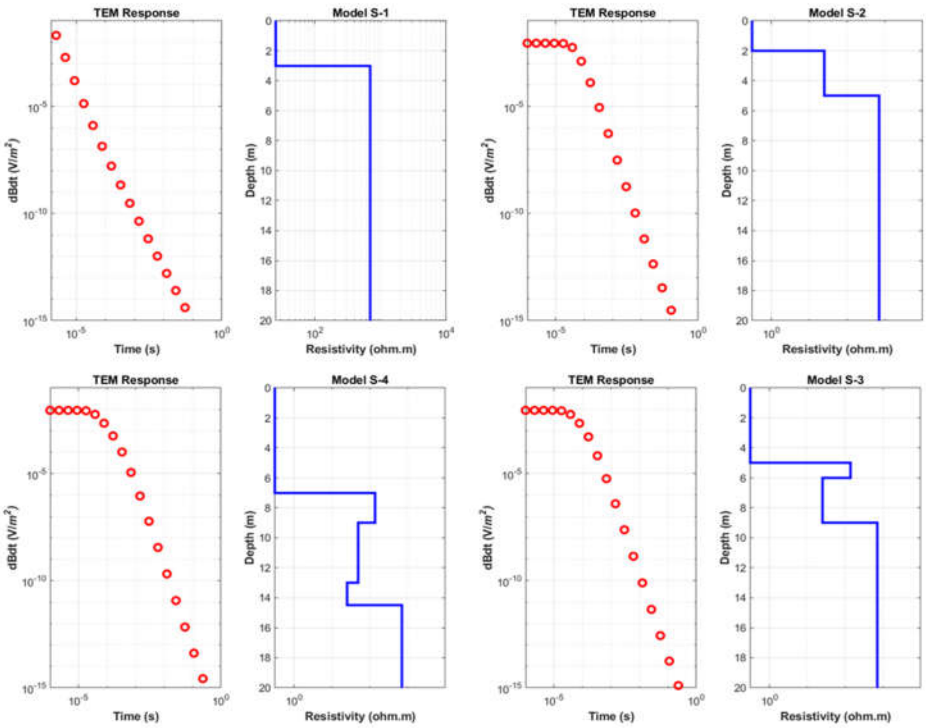

Figure 4 TDEM response in saline water.

Comparison TDEM Response in the Different Sedimentary Thickness

Here, we present the TDEM response to an increase in the sediment thickness layer for the same water type but with different sediment thicknesses, as shown in Figure 5. The red, blue, and black lines represent the response at each point. The water and lithology thickness increase from points S-1 to S-4. Our findings are consistent with the theory, where a thicker sedimentary layer results in a higher response. Comparison of the response at points S-2 and S-4 indicates that the response is significantly more sensitive for brackish and saline water. This information is crucial for approximate assessment of sediment thickness in sedimentation studies. Excessive sedimentation can increase the potential for water level rise and lead to flood hazards.

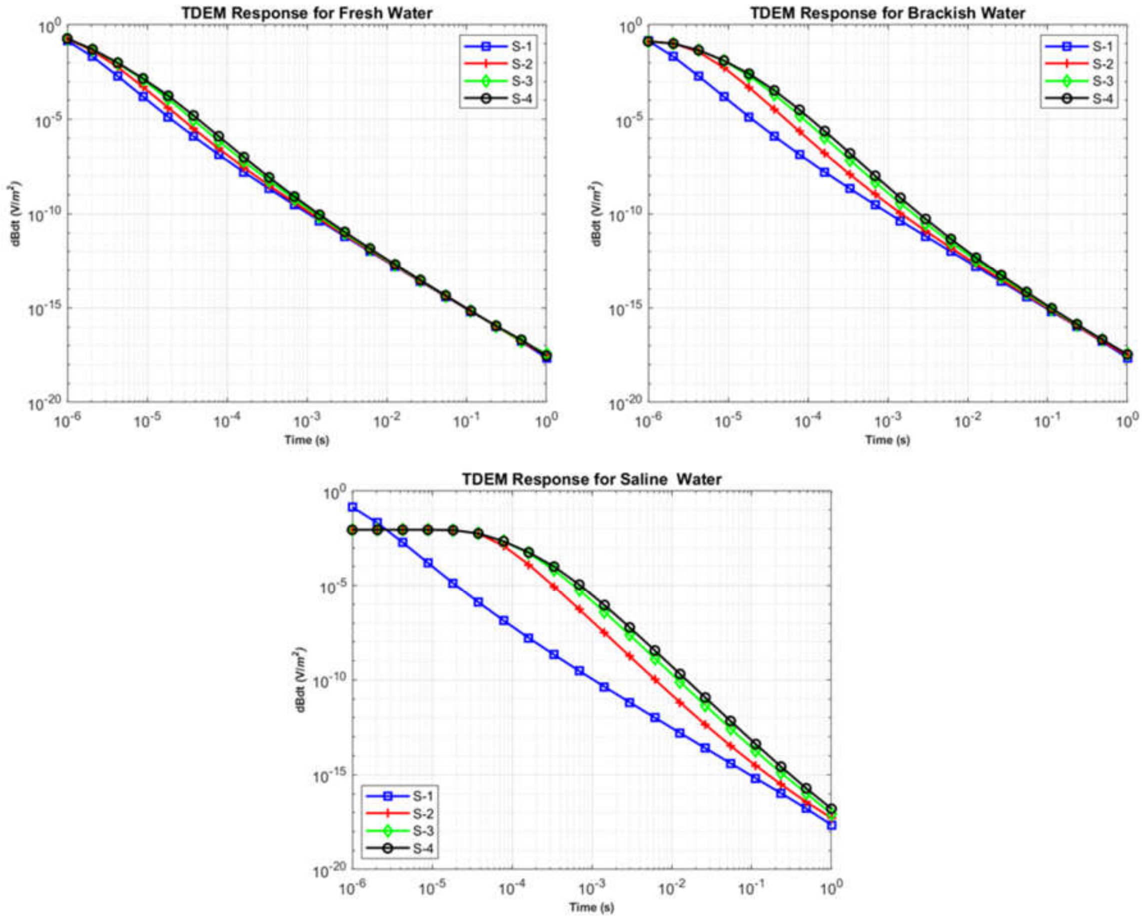

Figure 5 Comparison TDEM response for each model.

Discussion

TDEM Sensitivities Comparison

Figure 6 illustrates the TDEM response for different water types with the same thickness. At the S-2 point, the freshwater and the brackish water exhibit nearly identical responses at shallow depths, but they differ at greater depths. Thus, at greater depths, we found that freshwater and brackish water have the same response, indicating that the TDEM is sensitive enough to detect different water types. The figure also shows how the upper layer affects the lower layer since the response is a function of time. At greater depths, freshwater and brackish water have almost completely overlapping responses in contrast to saline water.

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If the sedimentary layer does not significantly change, it is challenging to conclude that it has changed based solely on the TDEM response. This is also demonstrated by the water response at S-3 and S-4, where the thickness changes by only 2 meters. Therefore, the inversion process from the TDEM response to depth information is required to evaluate the changes.

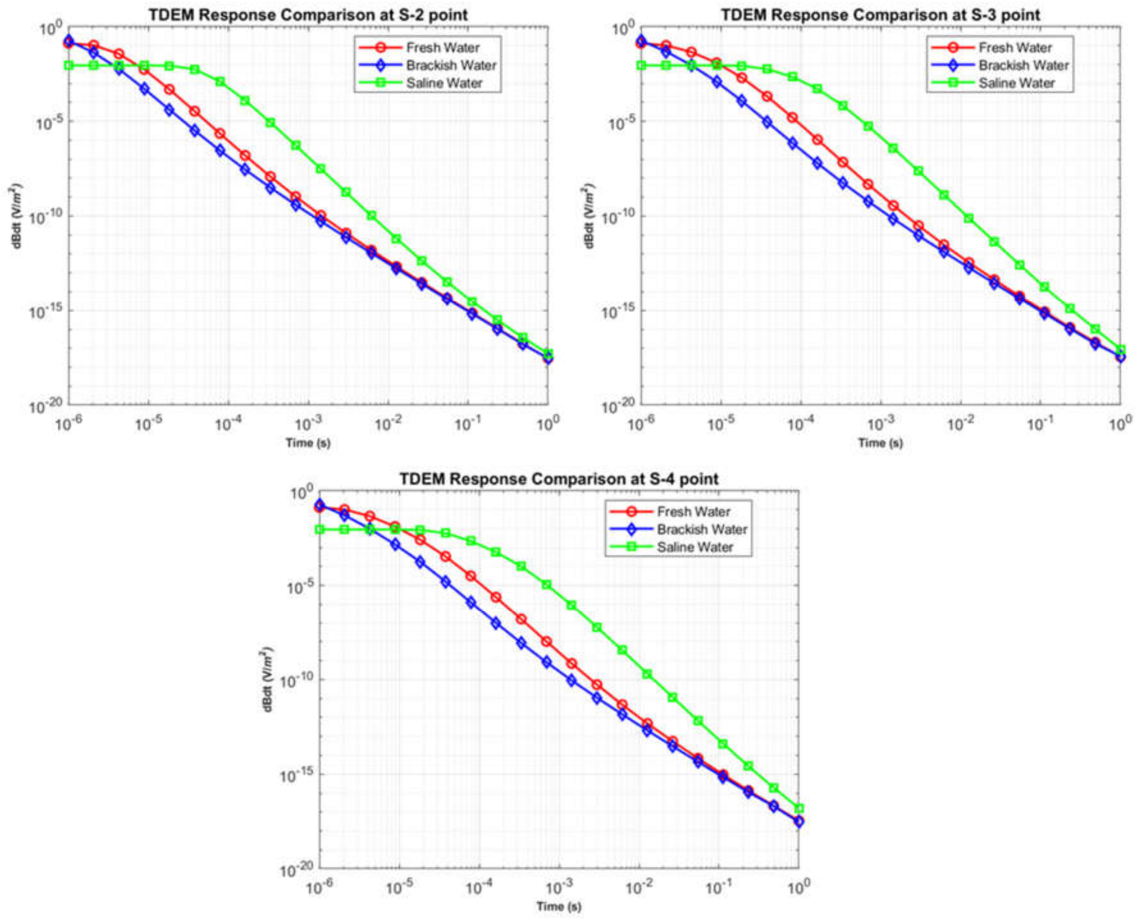

Figure 6 Comparison of the TDEM response for each model.

Synthetic Apparent Resistivity Curves

In this section, we show the changes in apparent resistivity for all water types. The resistivity curves for freshwater, brackish water, and saline water are shown in Figures 7, 8, and 9, respectively. The responses at each sampling point are indicated by the blue, red, green, and black lines on each curve. The apparent resistivity curve decreases in a thicker layer of water because the medium has a higher relative conductivity compared to other media around it. The most significant changes occur in saline water when compared with the response at S-1.

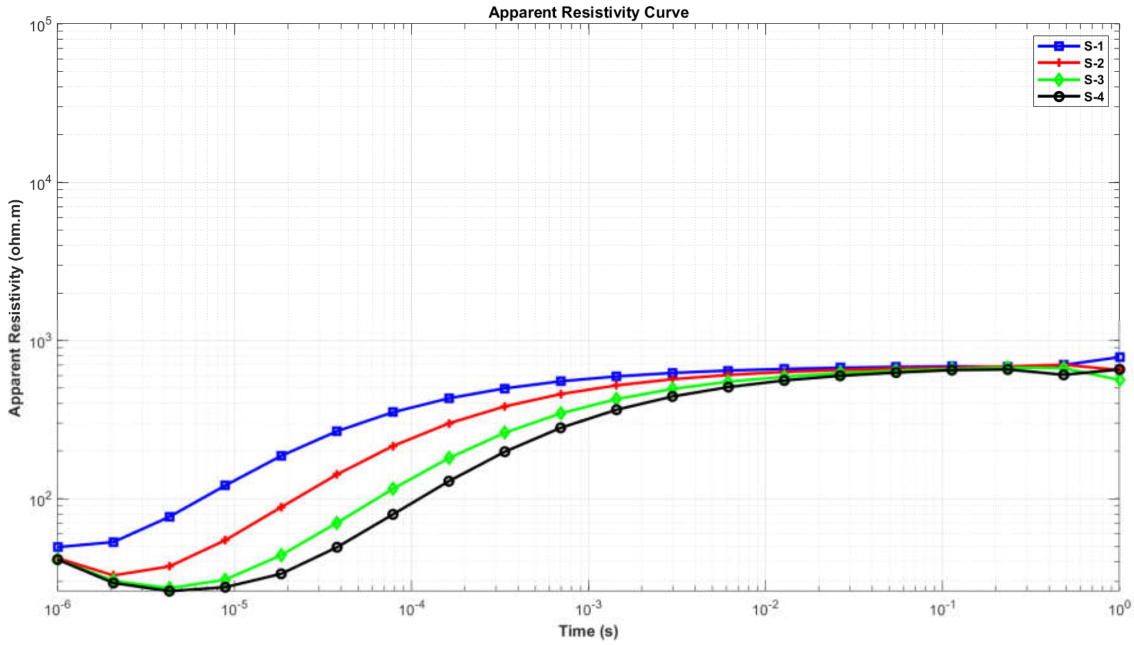

Figure 7 Apparent resistivity curve of freshwater.

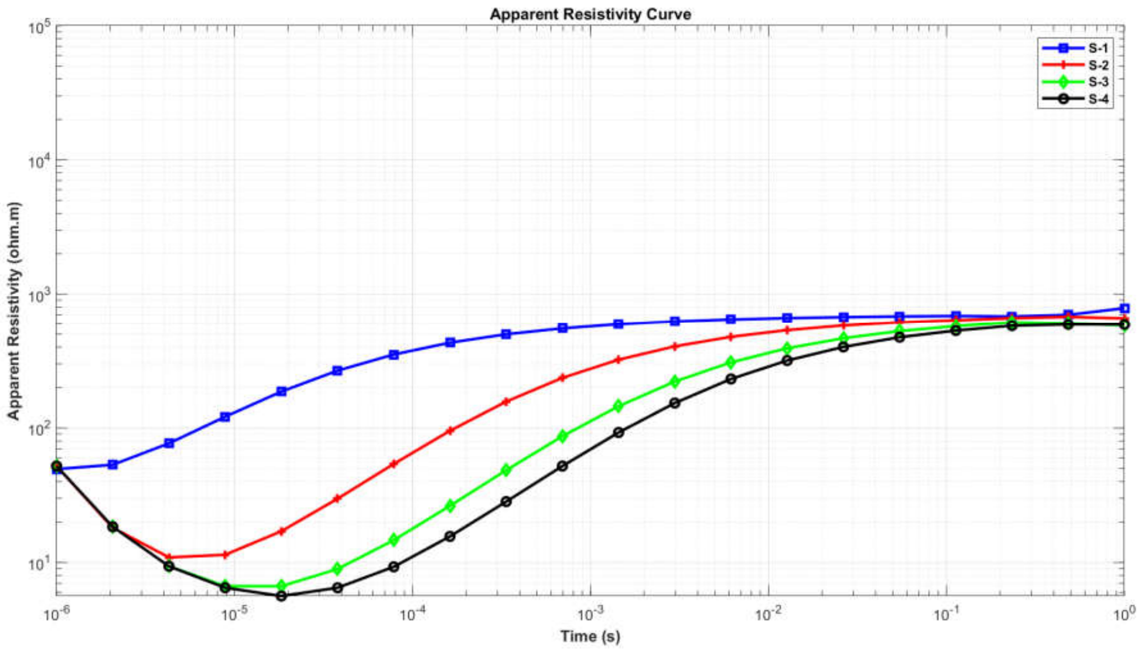

Figure 8 Apparent resistivity curve of brackish water.

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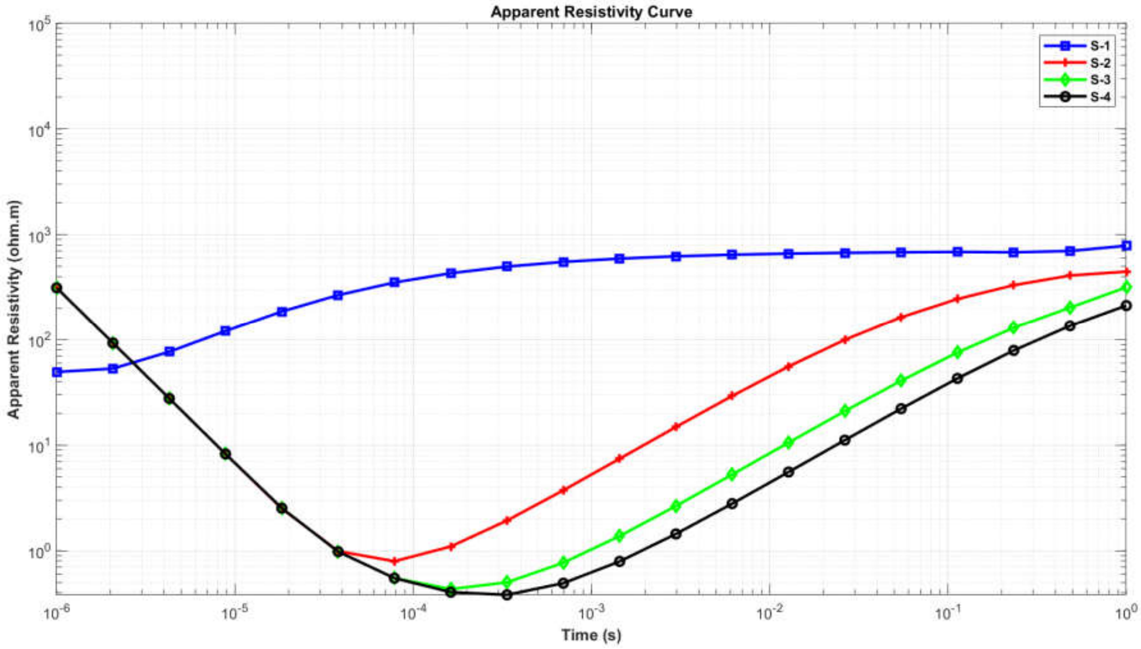

Figure 9 Apparent resistivity curve of saline water.

Conclusion

Overall, the TDEM method can provide useful information for sedimentary assessment in flood hazard studies. It can detect changes in sediment thickness and distinguish between different water types. However, it should be noted that if sedimentary thickness is not significantly changed, it may not be possible to conclude that it has changed based solely on the TDEM response. In such cases, an inversion process from TDEM response to depth information may be necessary. Overall, the TDEM method is a valuable tool for assessing sedimentary conditions and can help in predicting and managing flood hazards.

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