

Magnetotelluric Imaging of Deep Aquifers in Seawater-Intrusion Areas of the Ganges-Brahmaputra Delta, Coastal Bangladesh

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SUMMARY

Marine incursions in the tidal dominated regions of the southwestern Ganges-Brahmaputra delta (GBD) exacerbate the challenge of freshwater access for agriculture and domestic uses. Furthermore, arsenic pollution and intensive aquifer extraction limit the potable water supply for high population-density areas. In SW Bangladesh, the shallow groundwater aquifer is saline leading to considerable water stress due to the lack of potable water during the dry season. Although tube wells and DC resistivity surveys have been conducted extensively to evaluate these saline shallow aquifers, they fail to assess the underlying deep groundwater systems. Here we apply the broadband magnetotelluric (MT) method to investigate the potential deep fresh aquifers along the Pusur River in SW Bangladesh from Khulna to the coast. The high-quality broadband MT responses reveal an extensive resistive freshwater distribution in the upper kilometer of the 120 km long profile. We use Archie's law along with hydrogeologic constraints to estimate groundwater salinity. Our estimated salinity model shows a south-dipping freshwater wedge on the northern part of the profile and a smaller low-salinity body close to the river mouth. While these two deep freshwater bodies may connect with the groundwater recharge system, low flow rates and ¹⁴C age dates up to 30,000 years suggest that they are primarily the remnants of preserved Pleistocene groundwater. Based on Holocene sediment thickness data from tube wells, we suggest that the discontinuity between the two bodies is due to the NW-SE-oriented incised Ganges paleovalley that cut through the central part of the profile during the last sea-level lowstand. Our results provide the first detailed extent of deep fresh groundwater in coastal Bangladesh and salinity information relevant for planning of future deep wells in freshwater-stressed SW Bangladesh.

Keywords: magnetotellurics, fresh aquifers, deep groundwater, coastal Bangladesh

INTRODUCTION

Seawater intrusion and arsenic pollution are severe problems of shallow aquifers in Bangladesh. These issues drive the search for potable supplies to mitigate water stress in overpopulated areas. Tubewells have been installed to extract groundwater as deep aquifers are one of the safe water sources (van Geen et al., 2003, Ravenscroft et al., 2013). However, little is known about the extension of deep aquifers and hydrogeological processes controlling their distribution. To image the deep groundwater systems in coastal Bangladesh, we used the broadband magnetotelluric (MT) method, a passive electromagnetic (EM) method for resolving spatial distribution of subsurface resistivity. EM techniques are powerful tools to map resistivity/conductivity variations in groundwater settings since EM signals can be sensitive to variations in fluid salinity as well

as between pore fluids and the host lithology (Gustafson et al., 2019, Micallef et al., 2020, Attias et al., 2020).

In our survey, we collected 25 land MT stations along riverbanks and fields adjacent to the Pusur River, a distributary of the Ganges River, southwestern Bangladesh. We deployed Phoenix ultra-wideband MT systems overnight to collect responses in the period spanning from 10⁻³ to 10³ s, allowing for sensitivity to resistivity structures at multiple depth ranges. The Pusur MT transect is 120-km long extending from Khulna City to the coastline, passing through the Sundarbans Mangrove Forest (Fig. 1). We also collected 23 MT stations adjacent to the Tetulia River, a tributary of the lower Meghna. The analysis of the Tetulia MT transect is ongoing; here we focus on the Pusur transect. In addition to MT data, we conducted land and continuous river-borne transient EM (TEM)

survey. However, the TEM data only constrains the shallow resistivity up to 100 m deep and thus are not considered here.

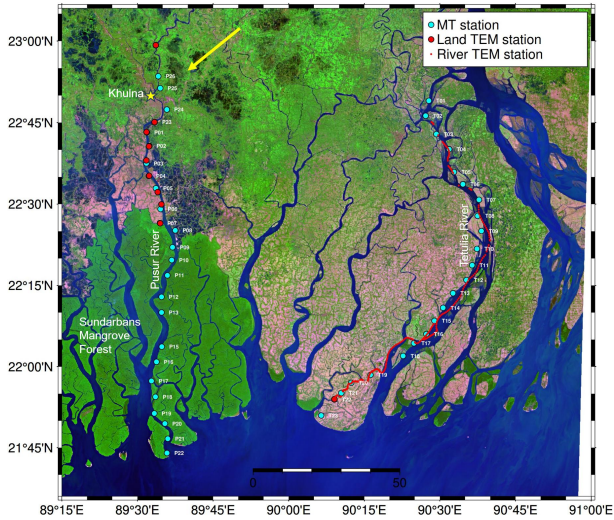


Figure 1. Study location in the southwestern Ganges-Brahmaputra delta (GBD), Bangladesh. The yellow arrow indicates the Pusur MT transect presented in this work.

REGULARIZED 2D INVERSION

We used MARE2DEM, a freely available 2D non-linear regularized inversion code (Key 2016), to resolve the primary resistivity structures required by the MT responses. The applied regularized inversion provides a robust smooth model by equilibrating the trade-off between model roughness and minimizing data misfit. We parameterized the inversion using a dense quadrilateral grid in the top 2 km to resolve groundwater systems located there, while a sparser parameter grid extends from 2 km to 10 km deep to image any deep structures required by the longer period data. Where the southern end of the transect approaches the Bay of Bengal, we added an adjacent ocean region with resistivity of 0.3 Ωm. Since the MT signals of five stations in the vicinity of Khulna City are lower quality due to cultural noise, we excluded the two northernmost stations (P25 and P26) from the inversion and set an error floor of 10% for P01, P02, and P03. The error floor of other stations is 5%. Our preferred 2D resistivity model with the RMS misfit of 1.005 is shown in Figure 2.

SALINITY ESTIMATION

To identify the distribution of fresh aquifers, we used Archie’s Law (1942) and an assumed porosity to estimate the pore-fluid resistivity, which we then converted to salinity using the Practical Salinity Scale 1978 (PSS78) (Lewis and Perkin, 1978). In the estimation, we imposed an exponential

decrease in porosity as a function of depth using Athy’s law (Athy, 1930). Table 1 lists the parameters used in our salinity calculation. Figure 3 shows the inferred salinity model.

Table 1. Parameters in the salinity calculation.

Parameter	Value/Function
Pore-fluid resistivity(ρ_f)	$\rho_{bulk} \times \phi^m$ (Archie’s Law)
Cementation factor (m)	1.6
Porosity ($\phi(z)$)	$\phi_o \times \exp(-cz)$ (Athy’s Law)
Surface porosity (ϕ_o)	0.4
Compaction factor (c)	0.146 km ⁻¹
Geothermal gradient*	28.5°C/km
Salinity (S)	f(P, T, ρ_f) (PSS78)

*geothermal gradient from Zahid and Uddin (2005)

BAYESIAN 1D INVERSION

To estimate the non-linear uncertainty of the inverted model parameters, we applied the 1D Bayesian sampling method described in Ray et al. (2013) and Blatter et al. (2019), referred to as the parallel tempered reversible jump Markov chain Monte Carlo (PTRJ-MCMC) algorithm. Compared to the regularized inversion, the Bayesian inversion results allow us to quantify uncertainty the model uncertainty in light of the non-uniqueness of EM geophysical data. This approach treats the model parameters as random variables and estimates their probability density functions (PDF). Resistivity structures with higher probability can be interpreted as more likely required by the MT data, and vice versa. Figure 4 shows the Bayesian 1D models obtained for stations P01 and P16.

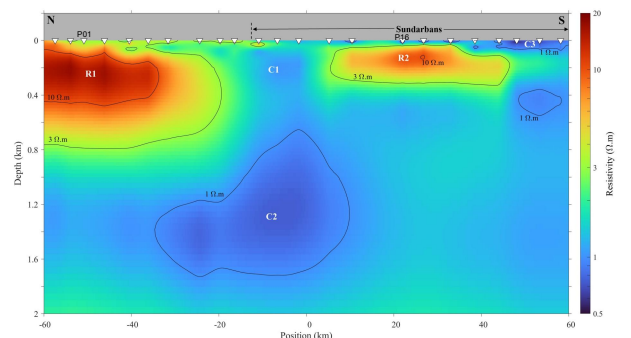


Figure 2. 2D regularized inverse resistivity model along the Pusur River. Black lines delineate the resistivity contours. Features with R and C labels denote resistive and conductive bodies referred to in the text.

RESULTS

Our resistivity and salinity model (Fig. 2 & 3) shows the landward resistor R1 representing a deep freshwater zone spanning 30 km and reaching ~500 m depth. The seaward resistor R2, located within the Sundarbans spans 35 km and extends to 250-m depth. The conductor C1 separates two

resistive zones, R1 and R2, while C2 illustrates deeper sediments infiltrated by conductive brackish to saline groundwater. C3 is associated with shallow seawater intrusion, which can extend up to ~100 km landward during the dry seasonal monsoon.

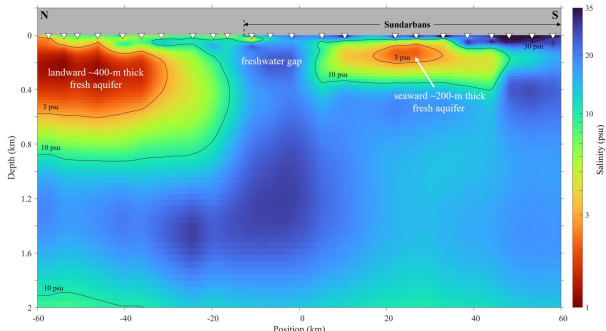


Figure 3. 2D salinity model derived from bulk resistivity (Fig. 2). Black lines show the salinity contours. In this study, freshwater zones: <3 psu; saltwater: >30 psu; 10 psu marks the transition between low- and high-salinity zones.

We propose that the deep fresh aquifers are primarily fossil water emplaced during the Pleistocene sea-level lowstand and later sealed by an impermeable paleosol layer (Hoque *et al.*, 2014). This layer formed at the top of the exposed Pleistocene during the Last Glacial Maximum and protected the deep fresh aquifers from vertical mixing with dense seawater above as sea level rose. The landward aquifer connects to the recharge source in upper Ganges delta, while the seaward aquifer potentially connects to a source in West Bengal. Some recharge may occur, but the recharge rate is extremely low due to flat topography of the GBD. Nearby groundwater radiocarbon ages increase with depth up to 30,000 years (Khan *et al.*, 2019). The 20-km long conductor C1 formed by the incision of a paleochannel that carved a deep valley during low sea-level in the Pleistocene. As sea-level rose in the Holocene, seawater flooding and rapid sedimentation occurred within the paleovalley and formed the high-salinity gap in freshwater (Fig. 3).

The 1D Bayesian models delineate the probability of two fresh aquifers R1 and R2 corresponding to P01 and P16 stations, respectively. These high probability resistivity structures are consistent with the resolved primary features in the 2D regularized model. At both stations, the resistors are overlain by a thin shallow conductive layer, a Holocene aquifer, and underlain by a thick deep conductor (Fig. 4). For example, the high PDF of resistor R1 at P01 localizes around 8-10 Ωm and extends from 50 to 750 m depth, whereas the high PDF of R2 is only ~250-m thick at 10 Ωm value. Although most primary resistivity structures in two inversion

schemes are in good agreement, the differences between them are interesting for further discussion. For instance, the regularized inversion results illustrate a smooth transition between conductor and resistor, which poorly fits with high probability regions in Bayesian models. We also note that MT data are unable to resolve the magnitude of highly resistive layers due to response saturation. This is reflected where the Bayesian 95th percentiles run up close to the prior upper bound ($10^3 \Omega\text{m}$); conversely, the lower limit of resistivities compatible with the data (here defined by the 5th percentile) is more clearly resolved by the data.

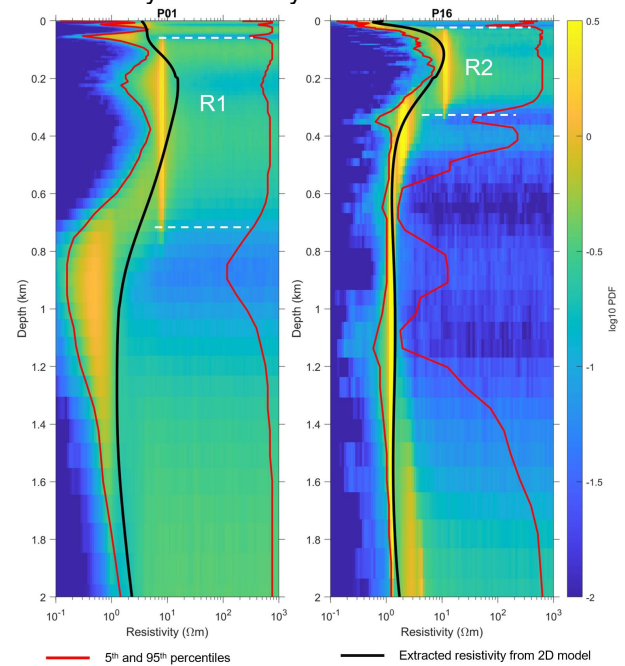


Figure 4. 1D Bayesian inversion models obtained from the MT data at stations P01 and P16, which show the resistive fresh aquifers R1 and R2, respectively (see Fig. 2). Warm and cold colors indicate high and low probability of resistivity structures, respectively.

CONCLUSIONS

Our EM survey carried out along the Pusur River, GBD demonstrates that broadband MT data can image deep aquifers in seawater-intrusion regions. The MT data significantly expands the depth of investigation compared to the conventional near-surface EM methods applied in groundwater exploration, such as TEM and DC resistivity soundings. A combination of regularized and Bayesian inversion methods improves our understanding of the resolved resistivity structures. The inversion models indicate two deep fresh paleowater systems formed during the last Pleistocene sea-level lowstand. The two aquifers are intersected by a high-salinity gap in freshwater formed by the incision of paleovalley. Thus, the interaction between sea-level and sedimentological processes plays a crucial role in the distribution of

deep aquifers along the Pusur River. Our results provide the first detailed extent of deep fresh groundwater and salinity information relevant for future deep wells in coastal Bangladesh.

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