

Mapping bar-sand coastal aquifer structure and saltwater intrusion mechanisms using Electrical Resistivity Tomography: a case study from Binh Thuan coast, south-central Vietnam

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Abstract

Coastal aquifers in bar-sand systems are highly vulnerable to saltwater intrusion, yet their internal structure and contamination patterns remain poorly constrained along many tropical shorelines. This study presents electrical resistivity tomography (ERT) surveys conducted along an approximately 95 km stretch of the Binh Thuan coast, south-central Vietnam — a region formed by Holocene and Pleistocene marine bar-sand and aeolian dune deposits overlying Cretaceous igneous basement. Eight ERT profiles (total length 1,755 m) were acquired using a Dipole-Dipole array with a minimum electrode spacing of 5 m and a maximum separation factor of $n = 7$, providing model depths of up to 57 m. Data were inverted using the smoothness-constrained least-squares method in RES2DINV. The resulting resistivity cross-sections reveal a consistent two- to three-layer structure: an upper layer of dry to freshwater-saturated sand ($> 40 \Omega\cdot\text{m}$), an intermediate transition zone, and a basal conductive unit ($< 20 \Omega\cdot\text{m}$) interpreted as saline-water-saturated sediments. Four distinct saltwater intrusion mechanisms are identified: (i) direct marine intrusion at the shoreline and river mouth, consistent with the Ghyben–Herzberg principle; (ii) saline contamination from shrimp-farming operations via surface seepage and open-channel drainage; (iii) relic saline contamination from former titanium-ilmenite placer mining; and (iv) compound low resistivity at the river mouth driven by the combination of tidal intrusion, clay-rich sediments, and shrimp-farm drainage. Hydrochemical measurements from eight wells corroborate the resistivity interpretation, with TDS values ranging from 67 to 3,059 mg/l. ERT proves an effective tool for rapid, non-invasive mapping of aquifer geometry and saltwater intrusion mechanisms in coastal bar-sand environments.

1 Introduction

Coastal aquifers in sandy barrier and bar systems constitute a critical freshwater resource for millions of people worldwide, particularly in arid and semi-arid tropical regions where surface water availability is highly seasonal (Post et al. 2018). However, these shallow, unconfined aquifers are inherently vulnerable to saltwater intrusion — a process driven by the density contrast between freshwater and seawater and exacerbated by sea-level rise, reduced recharge, and excessive groundwater extraction (Werner et al. 2013; Ketabchi et al. 2016). In Vietnam, the south-central coastal zone features an almost continuous 192 km belt of Holocene aeolian dunes and Pleistocene marine bar-sand deposits (NAWAPI 2017). These formations host the primary freshwater aquifers for local communities, yet systematic mapping of their subsurface structure and saltwater intrusion extent remains limited.

Traditional hydrogeological investigation methods — borehole drilling, pumping tests, and water sampling — provide precise but spatially sparse information and are costly to deploy along extended coastlines (Kirsch 2006). Electrical resistivity tomography (ERT) has emerged as a powerful non-invasive tool for imaging shallow subsurface resistivity structures, with particular effectiveness in coastal hydrogeological settings where the strong resistivity contrast between freshwater-saturated sediments (typically $10\text{--}200 \Omega\cdot\text{m}$) and saline-water-saturated sediments ($< 5 \Omega\cdot\text{m}$) provides clear geophysical targets (Loke et al. 2013; Costall et al. 2020). ERT has been successfully applied to delineate saltwater intrusion in a wide range of coastal environments, including sandy beaches and barrier islands, river

deltas, and volcanic island aquifers. In the Binh Thuan province itself, ERT surveys along the Luy River coastal plain revealed that saltwater intrusion extends considerably further inland and at greater depth than previously estimated, with the deeper Pleistocene aquifer systematically saline on the low-lying left bank while the sand-dune complex on the right bank hosts a thick freshwater lens (Cong-Thi et al. 2021). Complementary hydrochemical analysis confirmed that freshening of connate seawater is the dominant long-term process in those alluvial aquifers, with salinization driven by upconing and agricultural exploitation during the dry season (Dieu et al. 2022). The present study addresses a different but complementary coastal setting: the Holocene and Pleistocene bar-sand barrier system along the open shoreline, where the freshwater–saltwater interface geometry is more directly controlled by the Ghyben–Herzberg equilibrium and by anthropogenic saline sources at the surface.

In the study area, four distinct mechanisms of saline contamination are identified: (1) direct seawater intrusion driven by tidal fluctuation and the Ghyben–Herzberg equilibrium (Herzberg 1901; Badon Ghyben 1889); (2) saline contamination from shrimp-farming operations through surface seepage and open-channel drainage; (3) relic saline contamination from former titanium-ilmenite placer mining operations that used seawater for mineral separation; and (4) compound low resistivity at the river mouth, where tidal intrusion, clay-rich sediments, and shrimp-farm drainage act in combination. Distinguishing these mechanisms has direct management implications, as each requires a different remediation strategy.

This paper presents ERT surveys along eight profiles distributed across four coastal sub-areas – Bau Trang beach, Hon Rom beach, Tien Thanh beach, and the Song Phan river mouth – together with in situ hydrochemical measurements from eight shallow wells and grain-size analysis of aquifer sediments. Our objectives are: (i) to characterize the subsurface resistivity structure of the bar-sand aquifer system; (ii) to delineate the spatial extent of saltwater intrusion; and (iii) to identify and distinguish the dominant intrusion mechanisms operating in each sub-area.

2 Hydrogeological setting

2.1 Geographical and geomorphological context

The study area extends along approximately 95 km of coastline from Bau Trang beach in the north to the Song Phan river mouth in the south, within the former Binh Thuan province – now part of the newly merged Lam Dong province, Vietnam (Fig. 1). The region lies between latitudes 10°43'N and 11°06'N and longitudes 107°51'E and 108°29'E. The coastal morphology is dominated by a near-continuous belt of aeolian dune ridges and beach-ridge barrier systems. A marine terrace 4–5 m above mean sea level extends almost continuously along this shoreline (Dao Manh Tien 2006) and is backed landward by dune and red-sand massifs rising to several tens of metres. Ground-surface elevations along the ERT profiles reflect this contrast, ranging from + 0.2 to + 4.4 m where the lines run on the terrace (BT-01, TT-04, SP-01) to + 11.0 m (TT-01) and + 26.2 m (HR-03) where they climb onto the dune body (Table 2). These coastal sand bodies separate the open East Vietnam Sea from a series of back-barrier lagoons, estuaries, and wetlands.

2.2 Geological framework

The Quaternary sedimentary sequence was mapped by NAWAPI (2017) and forms the primary hydrogeological framework. From oldest to youngest, the relevant stratigraphic units are:

Pre-Quaternary basement

Along the coastal strip surveyed here the basement consists of Cretaceous igneous rocks – andesite of the Nha Trang Formation and granodiorite to granite of the Deo Ca complex – as recorded by three boreholes within the study area (Table 1) and by shallow-seismic mapping of the nearshore zone between Ca Na and Vung Tau (Dao Manh Tien 2006). Middle Jurassic sandstone, siltstone, and shale of the La Nga Formation (J_2In), poorly permeable (hydraulic conductivity ~ 0.27 m/day), form the lower confining unit further inland (NAWAPI 2017). Both basement lithologies are electrically resistive, a point that bears directly on the interpretation of the deep conductive zones discussed in Sect. 4.5.6.

Pleistocene sediments (qp)

Red aeolian sands of the Phan Thiet Formation (aQ_1^{2pt}), up to 80 m thick, and marine bar-ridge sands (mbQ_1^{2-3pt}), 60–70 m thick; hydraulic conductivities 1.5–7.2 m/day (NAWAPI 2017). The Pleistocene dune-sand complexes along the coast host particularly thick freshwater-bearing sequences, reaching up to 80–100 m in their elevated central parts, which sustain extensive freshwater bodies in close proximity to the shoreline (Nguyen Minh Khuyen 2015).

Holocene sediments (qh)

Aeolian dune sands (vQ_2^3), 2–30 m thick; beach and foreshore sands (mQ_2^3), 1–3 m thick; and estuarine-lagoonal silty clays (amQ_2^3) near river mouths. The Holocene aquifer is unconfined, with water tables typically 1.5–3.5 m below the surface and hydraulic conductivities of 0.02–4.24 m/day (mean 1.55 m/day) (NAWAPI 2017).

Three boreholes drilled within the study area during the 1:100,000 marine geological survey of the south-central Vietnam shelf provide independent stratigraphic control (Fig. 1, Table 1; Dao Manh Tien 2006). All three were collared at mean sea level on the coastal terrace, 1.2–4.5 km from the nearest ERT profiles, and are used here as regional stratigraphic context rather than for profile-specific calibration. They show a consistent three-part section: 4.6–6.6 m of clean, well-rounded and well-sorted marine sand of Holocene age (quartz 80–95%); beneath it a Pleistocene sequence of silty–clayey sand containing 20–30% silt and clay, with kaolin pods, laterite nodules and volcanic ash; and crystalline basement at 22.7–27.5 m below sea level. Every unit is of marine origin, consistent with the bar-sand framework adopted in this study.

Table 1

Representative Quaternary stratigraphy of the Binh Thuan coastal strip from three boreholes within the study area (Dao Manh Tien 2006). Depths are given relative to mean sea level; all three boreholes were collared at 0 m. Distances are to the nearest ERT profile

Unit	BV40 – Hong Phong (2.2 km from HR-03)	BV42 – Tien Thanh (1.2–1.9 km from TT lines)	BV43 – Tan Thuan (4.5 km from SP-01)	Typical character
Holocene marine sand (Q ₂)	0 to – 4.6 m	0 to – 4.8 m	0 to – 6.6 m	Clean, well-rounded, well-sorted fine to coarse sand; quartz 80–95%; 1–10% shell debris
Pleistocene (Q ₁)	–4.6 to – 22.7 m	–4.8 to – 27.5 m	–6.6 to – 26.4 m	Silty–clayey sand with 20–30% silt and clay; kaolin pods, laterite nodules, volcanic ash
Pre-Quaternary basement	–22.7 m: andesite, Nha Trang Fm (K)	–27.5 m: granodiorite, Deo Ca complex (K)	–26.4 m: granite, Deo Ca complex (K)	Resistive crystalline rock

2.3 Hydrogeological units

Holocene aquifer (qh)

Thickness 1–40 m (mean ~ 14 m). Groundwater is fresh (TDS < 1,000 mg/l) in areas away from the coast, but saline (TDS > 1,000 mg/l) covers ~ 212 km² (35.6% of outcrop area) near river mouths and low-lying coastal areas.

Pleistocene aquifer (qp)

Larger areal extent (~ 1,700 km² freshwater zone), borehole yields 1.0–9.15 l/s. Saline water restricted to ~ 66 km² (4% of outcrop). Main target for water supply development.

2.4 Saltwater intrusion status

Saltwater intrusion affects approximately 222 km² across five coastal zones: the downstream plain of the Song Phan–Phan Thiet river system (~ 81 km²), the Dong Giang–Long Song river mouth area (~ 56 km²), the Luy River coastal plain (~ 41 km²), the coastal zone from Tan Hai to Cape Ke Ga (~ 17 km²), and the Dinh River mouth (~ 27 km²) (NAWAPI 2017). TDS in contaminated zones commonly ranges from 1.5 to 4.0 g/l; an extreme value of 44.0 g/l was recorded at borehole LK4B north of Phan Thiet city, attributed to buried connate saline water (NAWAPI 2017). In addition to natural tidal intrusion, anthropogenic activities have contributed significantly to salinization: titanium-ilmenite placer mining operations have used seawater for mineral separation, causing localized but severe saline contamination of adjacent aquifers; and shrimp aquaculture ponds on coastal sand flats have infiltrated saline water into shallow groundwater over extensive areas (Nguyen Minh Khuyen 2015). Recent ERT investigations in the

adjacent Luy River alluvial plain documented saltwater intrusion extending at least 15 km inland, with a formation factor of 2.2–2.8 (Archie's Law) and a resistivity threshold of approximately $7 \Omega \cdot \text{m}$ corresponding to a TDS boundary of $\sim 3 \text{ g/l}$ for the clay-bearing alluvial sediments of the Luy River (Cong-Thi et al. 2021) – a threshold that differs from that derived for the clean bar-sand setting of the present study.

3 Data acquisition and methods

3.1 ERT data acquisition

ERT surveys were carried out along eight profiles across four coastal sub-areas: Bau Trang beach (BT-01, BT-02), Hon Rom beach (HR-03), Tien Thanh beach (TT-01, TT-02, TT-04), and the Song Phan river mouth (SP-01, SP-02) using a SYSCAL-Pro 72-electrode resistivity system (IRIS Instruments, France). The Dipole-Dipole array was selected for its high sensitivity to lateral resistivity variations (Loke 2021). A multi-spacing acquisition scheme was employed: the initial electrode spacing was $a = 5 \text{ m}$, and to increase both the signal amplitude and the investigation depth the spacing was progressively increased to $a = 10, 15, 20, 25, 30, 35, 40, 45$ and, on the three 265 m lines, 55 m where profile length permitted, with the separation factor n decreasing accordingly to maintain coverage within the fixed profile length. The instrument was programmed for separation factors up to $n = 12$; after quality filtering the retained data extend to $n = 7$. Each reading was stacked between three and six times using a 500 ms current injection at a transmitter voltage of 800 mV. This multi-spacing strategy yielded model depths of up to 57 m below the surface. Profile lengths ranged from 125 m (TT-02) to 265 m (BT-01, BT-02, TT-04), giving a total surveyed length of 1,755 m and 5,685 data points retained for inversion (Table 2). Wenner–Schlumberger data were acquired along most profiles as well; only the Dipole-Dipole results are presented here, and the joint interpretation of the two arrays will be reported separately.

Lines BT-01, BT-02, HR-03, TT-01, TT-02, and SP-02 were oriented NW–SE, perpendicular to the shoreline. Line TT-04 was oriented NE–SW, parallel to the shoreline, to characterize lateral variability along the beach ridge. Line SP-01 was oriented NW–SE, perpendicular to the Song Phan riverbank. Contact resistance was reduced by pouring saline water around each electrode stake, bringing values to 500–2,000 Ω . The standard deviation of stacked measurements ranged from 0.26% to 1.98% (mean 1.00%), confirming good field data quality. Measured apparent resistivity spanned 0.08 to 18,012 $\Omega \cdot \text{m}$, both extremes being recorded in the Bau Trang sub-area – the minimum at BT-01 and the maximum in the dry aeolian dune sands of BT-02. After removal of noisy data points the range carried forward to inversion was 1.0–4,948 $\Omega \cdot \text{m}$.

Table 2

ERT acquisition and inversion parameters for the eight survey profiles. Elev. = range of ground-surface elevation above mean sea level along the profile; a = electrode spacings used; n max = maximum separation factor retained after quality filtering; Data pts = number of apparent-resistivity measurements used in the inversion; pa = range of measured apparent resistivity before removal of noisy data points; SD = standard deviation of stacked measurements; RMS = final inversion misfit

No	Line	Elect.	Length (m)	Direction	Elev. (m a.s.l.)	a (m)	n max	Data pts	pa ($\Omega\cdot\text{m}$)	SD (%)	RMS (%)
1	BT-01	54	265	NW–SE	+ 0.2 to + 7.9	5–55	7	542	0.08–8,786	1.98	7.90
2	BT-02	54	265	NW–SE	0.0 to + 8.8	5–55	7	1,113	6.3–18,012	0.44	6.69
3	HR-03	50	245	NW–SE	+ 0.1 to + 26.2	5–45	7	512	0.61–4,948	1.25	8.04
4	TT-01	34	165	NW–SE	+ 3.8 to + 11.0	5–40	7	354	0.13–3,178	0.53	6.68
5	TT-02	26	125	NW–SE	+ 2.7 to + 9.1	5–40	7	225	7.5–1,814	0.26	6.56
6	TT-04	54	265	NE–SW	+ 1.2 to + 4.4	5–55	7	1,456	1.2–196	0.98	4.10
7	SP-01	45	220	NW–SE	+ 2.1 to + 2.9	5–45	7	965	1.0–12.5	1.97	4.07
8	SP-02	42	205	NW–SE	+ 0.6 to + 9.1	5–45	7	518	7.8–6,525	0.55	7.95

3.2 ERT data inversion

Apparent resistivity data were inverted using RES2DINV (Loke 2021; Loke and Barker 1996). The forward problem was solved using the finite-element method, and the inverse problem using Gauss–Newton optimization with both Robust data constraint and Robust model constraint (Loke and Barker 1996; Loke et al. 2003; Menke 2018). Inversion parameters are listed in Table 3. Inversion was terminated after 15 iterations, or earlier when the relative change in RMS error between successive iterations fell below the convergence limit, which occurred at iteration 13 for TT-04 and iteration 7 for SP-01. Final RMS misfits ranged from 4.07% to 8.04% (mean 6.50%; Table 2). Topography was incorporated using the damped finite-element method, and all model sections are plotted against elevation relative to mean sea level.

To assess which parts of the models are constrained by the data rather than by the regularization, the depth-of-investigation (DOI) index of Oldenburg and Li (1999) was computed for the two profiles carrying the deepest interpretations, TT-04 and SP-01. Each data set was inverted twice using constant reference models differing by a factor of 100 – 1.586 and 158.6 $\Omega\cdot\text{m}$ for TT-04, and 0.385 and 38.5 $\Omega\cdot\text{m}$ for SP-01, that is 0.1 and 10 times the respective mean measured apparent resistivity – and the index $R(x, z) = [m_1(x, z) - m_2(x, z)] / (m_{1,\text{ref}} - m_{2,\text{ref}})$ was evaluated, where m denotes $\log_{10}$ resistivity. All four runs converged to comparable misfits (RMS 4.40–4.73%). Cells for which R approaches zero are determined by the data, whereas cells for which R approaches unity are determined by the reference model. Oldenburg and Li (1999) place the transition between data-driven and reference-model-driven parts of the model in the range $R = 0.2\text{--}0.4$. No single cut-off is adopted here, because the depth of investigation inferred from such indices is sensitive to the threshold chosen (Deceuster et al. 2014); the measured values are reported instead, together with the relative comparison between profiles, which is threshold-independent. Because R does not asymptote to unity within the extended models used for this test (maxima of 0.43 and 0.61), a consequence of the smoothness constraint coupling deep cells to shallower, data-constrained ones, the index is interpreted here as a relative measure; normalizing by its maximum leads to the same conclusions.

Table 3
Inversion parameter settings used in RES2DINV for all survey profiles

Parameter	Value
Initial damping factor	0.15
Minimum damping factor	0.02
Damping factor optimized at each iteration	Yes
Higher damping factor for the first layer	No
Apply HDF for blocks at side of model (edge effect)	Yes
Type of forward modeling method	Finite element
Horizon mesh size	4 nodes
Vertical mesh size	Finer mesh
Error convergence limit	1.0%
Percentage RMS for convergence	1.50%
Maximum number of iterations	15
Ratio of first layer thickness to unit electrode spacing	0.375
Rate of layer thickness increase with depth	1.1
Width of model cell	0.5 × unit electrode spacing
Type of data inversion constraint	Robust data constraint
Type of model inversion constraint	Robust model constraint
Optimization method	Standard Gauss–Newton
Type of initial model	Homogeneous half-space
Logarithm of apparent resistivity used	Yes

3.3 Hydrochemical data acquisition

In situ hydrochemical parameters — electrical conductivity (EC), total dissolved solids (TDS), pH, and temperature — were measured at eight existing shallow production wells (W1–W8; Fig. 1) using a WTW Multi 3430 meter (Xylem, Germany), with measurement accuracies of $\pm 0.5\%$ for EC and TDS, ± 0.004 units for pH, and $\pm 0.4^\circ\text{C}$ for temperature. Results are listed in Table 4.

Table 4
In situ hydrochemical measurements at eight wells (W1–W8) in the study area (referenced to T = 25°C). Original well identifiers given in parentheses

Well	EC (μS/cm)	TDS (mg/l)	pH
W1	4,780.0	3,059.2	6.8
W2	748.0	478.7	6.8
W3	357.0	228.5	7.3
W4	189.5	121.3	5.8
W5	105.1	67.3	5.6
W6	363.0	232.3	6.5
W7	743.0	475.5	5.9
W8	147.0	94.1	6.6

3.4 Grain-size analysis

Grain-size distribution of sediment samples from well W6 on line TT-04 at depths of 0, 1.0, and 1.8 m was determined by laser diffraction using a Horiba LA-960 analyzer (Horiba Ltd., Japan; range 10 nm to 5 mm). Samples were dispersed in water with ultrasonic agitation prior to measurement. Grain-size classes follow the Wentworth (1922) scale; results are reported as volume percentages (Table 5).

Table 5
Grain-size distribution of sediment samples from well W6, line TT-04, at three depth intervals (Wentworth 1922 classification; Horiba LA-960 laser diffraction). Values are volume percentages

Grain-size class	Diameter (mm)	0 m	1.0 m	1.8 m
Very coarse sand	1.0–2.0	4.5%	3.9%	0.1%
Coarse sand	0.5–1.0	37.0%	35.7%	11.1%
Medium sand	0.25–0.5	51.4%	52.9%	70.2%
Fine sand	0.125–0.25	7.0%	7.5%	18.2%
Very fine sand	0.063–0.125	0.1%	0.1%	0.5%
Silt	< 0.063	0.0%	0.0%	0.0%
Clay	< 0.002	0.0%	0.0%	0.0%
Total sand fraction	—	100.0%	100.1%	100.1%

4 Results and discussion

4.1 Bau Trang area (lines BT-01 and BT-02)

Line BT-01

The inverted resistivity cross-section of line BT-01 (length 265 m) reveals model resistivities between 0.9 and 212 $\Omega\cdot\text{m}$ (Fig. 2a). Along the uppermost 5 m at the landward end (stations 0–40 m), a near-surface layer of very low resistivity (1.3–3 $\Omega\cdot\text{m}$, dark blue) coincides with the position of active shrimp-farming ponds. Across most of the shallow zone (0–10 m, stations 40–265 m), resistivity rises to 2–30 $\Omega\cdot\text{m}$ (blue to green). The main body of the section (depth 5–30 m) is dominated by 4–20 $\Omega\cdot\text{m}$ (blue to green). At the seaward portion (stations 160–265 m, depth 5–25 m), a broad zone of 1.5–14 $\Omega\cdot\text{m}$ (blue to cyan) expands progressively with depth toward the sea. Below approximately 35 m depth across the entire profile, resistivity stabilizes at 15–40 $\Omega\cdot\text{m}$ (green).

Line BT-02

The inverted cross-section of line BT-02 (length 265 m) shows model resistivities between 7.9 and 3,643 $\Omega\cdot\text{m}$ (Fig. 2b). The entire upper 10–20 m is dominated by very high resistivity ($> 608 \Omega\cdot\text{m}$, dark red to purple), forming a thick laterally continuous layer corresponding to coarse-medium dune sand, dry as observed in the field. Immediately below this high-resistivity cap, resistivity drops to 15–90 $\Omega\cdot\text{m}$ (green to yellow-green) in the depth range 15–35 m. At the seaward end (stations 160–265 m, depth 10–30 m), a well-defined zone of 8–45 $\Omega\cdot\text{m}$ (cyan to green) forms a tongue-shaped body that wedges out in the landward direction. Below 35 m depth across the whole profile, resistivity returns to 30–145 $\Omega\cdot\text{m}$ (yellow-green).

4.2 Hon Rom area (line HR-03)

Line HR-03

The inverted cross-section of line HR-03 (length 245 m) is characterized by a markedly asymmetric topographic profile: the landward end (station 0 m) sits at +26.2 m elevation, descending steeply to near sea level at the seaward end (Fig. 3). Model resistivities span 4.4 to 7,536 $\Omega\cdot\text{m}$. The entire shallow zone (0–10 m below surface across the full profile length) is dominated by very high resistivity ($> 608 \Omega\cdot\text{m}$, dark red to purple), corresponding to coarse-medium dune sand, dry as observed in the field. Within this high-resistivity body, at stations 100–140 m and at approximately 10 m depth below the surface, a localized zone of markedly lower resistivity ($\sim 200\text{--}400 \Omega\cdot\text{m}$, orange) appears as a distinct anomaly embedded within the surrounding very high-resistivity block ($> 608 \Omega\cdot\text{m}$), spatially coinciding with the position of an old titanium-ilmenite placer mining site. Below the surface high-resistivity layer, the main body of the section (depth 10–35 m, stations 0–200 m) is characterized by 40–600 $\Omega\cdot\text{m}$ (yellow-green to orange). At the seaward end (stations 180–245 m, depth 10–40 m), a distinct low-resistivity zone, falling to 4.4 $\Omega\cdot\text{m}$ at its core (blue) and typically 14–30 $\Omega\cdot\text{m}$ (cyan to green), deepens and expands toward the seaward tip of the section, independent of the ore-processing anomaly.

4.3 Tien Thanh beach area (lines TT-01, TT-02, TT-04)

Line TT-01

The inverted cross-section of line TT-01 (length 165 m) shows model resistivities between 7.7 and 2,042 $\Omega\cdot\text{m}$ (Fig. 4a, top). A continuous high-resistivity layer ($> 202 \Omega\cdot\text{m}$, orange to deep red) of 3–5 m thickness from station 0 to ~ 120 m corresponds to coarse-medium dune sand, dry as observed in the field. Below this surface layer (depth 5–20 m, stations 0–120 m), resistivity is 40–202 $\Omega\cdot\text{m}$ (yellow-green). Toward the seaward end, a zone of reduced resistivity extends from station ~ 75 m to the end of the line and from near-surface to ~ 40 m depth, falling to 7.7 $\Omega\cdot\text{m}$ at its core (cyan); it is interpreted as the seawater wedge. The deepest portion (> 25 m, all stations) shows uniformly 15–40 $\Omega\cdot\text{m}$ (green). Well W4 (TDS = 121 mg/l) is located at approximately station 140 m.

Line TT-02

The inverted cross-section of line TT-02 (length 125 m) shows model resistivities between 16 and 2,495 $\Omega\cdot\text{m}$ (Fig. 4b, middle). A thin high-resistivity surface layer ($> 202 \Omega\cdot\text{m}$, orange to deep red) of 2–3 m thickness is present across the full profile length. Below this layer (depth 3–15 m), 40–202 $\Omega\cdot\text{m}$ (yellow-green) dominates across the central and landward portions (stations 0–80 m). At the seaward end (stations 65–110 m) and at 20–32 m depth, a zone of reduced resistivity (16–50 $\Omega\cdot\text{m}$, green) corresponds to the seawater wedge. Elsewhere the deepest portion (> 15 m) shows 50–120 $\Omega\cdot\text{m}$ (yellow-green).

Line TT-04

Line TT-04 (length 265 m, NE–SW parallel to the shoreline) shows model resistivities between 1.7 and 258 $\Omega\cdot\text{m}$ (Fig. 4c, bottom). A surface layer (0–5 m) of 40–202 $\Omega\cdot\text{m}$ (yellow to orange) across the full profile length corresponds to coarse-medium dune sand, dry as observed in the field. Below the surface layer (depth 5–30 m, stations 0–160 m), the section is dominated by 15–40 $\Omega\cdot\text{m}$ (green to dark green), consistent with the fresh groundwater recorded at well W6 (TDS = 232 mg/l) located at station ~ 72 m, and well W5 (TDS = 67 mg/l) located ~ 50 –60 m west of the profile. In marked contrast, at the northeastern end (stations 160–265 m, depth 0–20 m), a localized low-resistivity zone, falling to 1.7 $\Omega\cdot\text{m}$ at its core (dark blue) and typically 4–24 $\Omega\cdot\text{m}$ (blue to green), appears at shallow depth, despite being at a similar distance from the sea as the southwestern end of the profile. This asymmetry demonstrates that the low resistivity here cannot be attributed to marine intrusion alone, and coincides spatially with the drainage area of a shrimp-farming operation. At the base of the entire section (depth > 30 m, all stations), resistivity decreases to 4.5–20 $\Omega\cdot\text{m}$ (blue to green), forming a laterally continuous conductive layer. This deep conductive body, entirely below the depth sampled by well W6 (screen depth ~ 2 m), is interpreted as saline water at the base of the freshwater lens and is discussed further in Section 4.5.6.

4.4 Song Phan river mouth area (lines SP-01 and SP-02)

Line SP-01

The inverted cross-section of line SP-01 (length 220 m, perpendicular to the Song Phan riverbank) stands out by its uniformly very low resistivity, model resistivities of only 0.8 to 19 $\Omega\cdot\text{m}$ across the entire section (Fig. 5a). No high-resistivity surface layer is present. In the shallow zone (0–10 m) the section divides sharply at station 56 m, the point from which the profile runs immediately alongside the shrimp-farm ponds. Landward of that point (stations 0–56 m) the median resistivity is 7.4 $\Omega\cdot\text{m}$ (cyan to green); alongside the ponds (stations 56–184 m) it falls to 1.98 $\Omega\cdot\text{m}$ (dark blue) and declines further to 1.28 $\Omega\cdot\text{m}$ over the last 36 m toward the river mouth (overall range 0.8–16.5 $\Omega\cdot\text{m}$). The contrast is sharpest at 5–10 m depth, where the medians are 11 $\Omega\cdot\text{m}$ landward of station 56 m, 2.4 $\Omega\cdot\text{m}$ alongside the ponds and 1.1 $\Omega\cdot\text{m}$ over the last 36 m of the line, and it is confined to the uppermost ~ 12 m: below about 17 m the pattern reverses, the landward segment falling to 2.4–3.8 $\Omega\cdot\text{m}$ while the central part of the section rises to 5–16 $\Omega\cdot\text{m}$. The deepest portion (> 30 m) reaches 13–16 $\Omega\cdot\text{m}$ (cyan to green). Well W7 (TDS = 476 mg/l) is located at station 0, where the shallow resistivity is highest.

Line SP-02

The inverted cross-section of line SP-02 (length 205 m, ~ 1.5 km south of SP-01) shows model resistivities between 9.5 and 6,142 $\Omega\cdot\text{m}$ (Fig. 5b). Three resistivity layers are identified. The uppermost layer (0–3 m depth) is characterized by high to very high resistivity (202–1,835 $\Omega\cdot\text{m}$, orange to dark red), corresponding to coarse-medium dune sand, dry as observed in the field; however, this layer is thin (3–5 m) and laterally discontinuous — it is absent in the interval stations 70–100 m where the underlying layer outcrops at the surface. Beneath this surface layer, the second layer dominates the cross-section with intermediate to high resistivity (40–202 $\Omega\cdot\text{m}$, orange to yellow), locally decreasing to 15–40 $\Omega\cdot\text{m}$ (green) at a few points. This layer shows strongly variable thickness: in the landward portion (stations 0–110 m) it is 5–10 m thick, whereas in the interval stations 110–160 m it extends to depths of 30–35 m, forming a prominent resistive body that accounts for most of the section volume in this segment. A third layer, characterized by high resistivity (> 608 $\Omega\cdot\text{m}$, red), is present only beneath the landward portion of the profile (stations 0–100 m) at depths below the second layer. Well W8 (TDS = 94 mg/l) at the landward end confirms predominantly fresh groundwater conditions at this location, consistent with the overall high-resistivity character of the section.

4.5 Discussion

4.5.1 Resistivity–TDS calibration and petrophysical framework

The petrophysical relationship linking bulk formation resistivity to pore-water TDS is approximated using Archie's Law (Archie 1942): $p_{\text{bulk}} = a \cdot p_w \cdot \phi^{-m}$. For clean, well-sorted coastal sands ($a = 1$, $m = 1.5\text{--}2.0$, $\phi = 0.35\text{--}0.40$; Keller and Frischknecht 1966) the formation factor $F = \phi^{-m}$ ranges from about 4.0 to 8.2, and a working value of $F \approx 4\text{--}6$ gives the following thresholds: bulk resistivities below ~ 10 $\Omega\cdot\text{m}$

correspond to TDS > ~ 3,000 mg/l (highly saline); below ~ 25 $\Omega\cdot\text{m}$ to TDS > ~ 1,500 mg/l (saline by the Vietnamese groundwater standard); above ~ 50 $\Omega\cdot\text{m}$ to TDS < ~ 500 mg/l (fresh); and the intermediate range 25–50 $\Omega\cdot\text{m}$ represents brackish to moderately saline conditions where interpretive uncertainty is higher. Two wells lie directly on the survey profiles and allow these thresholds to be tested. Well W4 on line TT-01 (TDS = 121 mg/l, EC = 189 $\mu\text{S}/\text{cm}$, pw = 53 $\Omega\cdot\text{m}$) corresponds to model cells of 80–120 $\Omega\cdot\text{m}$, and well W6 on line TT-04 at station ~ 72 m (TDS = 232 mg/l, EC = 363 $\mu\text{S}/\text{cm}$, pw = 28 $\Omega\cdot\text{m}$) to model cells of 40–60 $\Omega\cdot\text{m}$. Both wells therefore fall on the fresh side of the thresholds, as expected. The observed bulk resistivities are, however, systematically lower than the Archie prediction for clean sand (209–431 $\Omega\cdot\text{m}$ at W4 and 109–225 $\Omega\cdot\text{m}$ at W6) by a factor of roughly two to four. Two effects plausibly contribute: the smoothness-constrained inversion tends to underestimate the resistivity of thin resistive layers, and the boreholes described in Sect. 2.2 show 20–30% silt and clay below about 5 m depth, which adds surface conductivity not accounted for by the simplified Archie relationship. The TDS values inferred from resistivity should therefore be read as upper bounds on salinity rather than as precise estimates.

Grain-size analysis of sediment samples from well W6 on line TT-04 (Table 5) supports the applicability of Archie's Law in the shallow part of the section. Laser diffraction analysis reveals sediment composed entirely of well-sorted medium to coarse sand, with no detectable silt or clay fraction in any of the three samples, which were taken at 0, 1.0 and 1.8 m depth. Within this shallow interval the absence of fine-grained material minimizes surface conductivity contributions to bulk resistivity, so the simplified Archie relationship is appropriate. The analysis does not constrain the deeper section, and the boreholes of Table 1 indicate that silt and clay become a significant component below about 5 m. This contrasts with the clay-bearing alluvial sediments of the Luy River plain in the same province, where surface conductivity has been shown to be up to 40 times larger than that of clay-free sand, necessitating combined ERT and induced polarization approaches (Cong-Thi et al. 2024).

4.5.2 Mechanism 1 – Direct marine and tidal intrusion (Ghyben–Herzberg)

The zones of reduced resistivity at the seaward ends of profiles BT-01, BT-02, HR-03, TT-01 and TT-02 – falling to 0.9, 7.9, 4.4, 7.7 and 16.0 $\Omega\cdot\text{m}$ respectively – are interpreted as saltwater intruding from the sea; by the thresholds of Sect. 4.5.1 all five correspond to brackish to saline pore water. In the Tien Thanh profiles (TT-01, TT-02), the geometry of the conductive zone – deepening progressively from the seaward toward the landward end – is consistent with the Ghyben–Herzberg freshwater–saltwater interface: $z \approx 40 h_f$, where z is the depth to the saltwater interface below sea level and h_f is the freshwater head above sea level (Badon Ghyben 1889; Herzberg 1901). The thick dune-sand cap of BT-02 (> 608 $\Omega\cdot\text{m}$, 10–20 m) sustains a high freshwater hydraulic head that confines the saline wedge (8–45 $\Omega\cdot\text{m}$) to depths of 10–30 m at the seaward end, preventing near-surface salinization there. At the Song Phan river mouth, dry-season river discharge falls to approximately 1 m^3/s (NAWAPI 2017), allowing tidal water to penetrate several kilometres upstream and laterally into adjacent Holocene aquifer sands, contributing to the low-resistivity signature of SP-01.

4.5.3 Mechanism 2 — Saline contamination from shrimp-farming operations

The near-surface very low resistivity zones ($1\text{--}3\ \Omega\cdot\text{m}$) at the landward end of BT-01 (stations 0–40 m, depth 0–5 m) and at the northeastern end of TT-04 (stations 160–265 m, depth 0–20 m) are attributed to saline contamination from shrimp-farming operations, manifesting through two distinct pathways directly observed in the field. The first pathway is surface seepage: saline water seeps laterally from shrimp-pond embankments onto the ground surface, forming visible drainage rills that subsequently infiltrate into the sandy subsurface. This was directly observed during fieldwork at line BT-01, where saline seepage water formed shallow channels across the beach surface adjacent to the pond area, consistent with the very low resistivity anomaly ($1\text{--}3\ \Omega\cdot\text{m}$) at the landward end of BT-01. The second pathway is open-channel discharge: pond effluent is released toward the sea through open drainage canals, allowing saline wastewater to percolate into the shallow aquifer. This was observed at line TT-04, where an open drainage system discharges shrimp-farm wastewater toward the shoreline. A critical observation is that line TT-04 runs parallel to the shoreline, meaning both ends of the profile are at approximately the same distance from the sea. The southwestern end (stations 0–160 m) is characterized by intermediate to high resistivity ($15\text{--}202\ \Omega\cdot\text{m}$) and fresh groundwater (well W6, TDS = 232 mg/l), while the northeastern end (stations 160–265 m) shows anomalously low resistivity ($2\text{--}7\ \Omega\cdot\text{m}$). Since both ends are equidistant from the sea, this lateral contrast cannot be explained by differential marine intrusion, and is instead attributed to the shrimp-farm drainage at the northeastern end. Well W5 (TDS = 67 mg/l), located $\sim 50\text{--}60$ m west of the profile and further from the drainage area, confirms that the aquifer remains fresh in the absence of this anthropogenic input. Well W6, positioned closer to the sea, records higher salinity (TDS = 232 mg/l) than W5. Such anthropogenic salinization has been documented more broadly along the Binh Thuan coastline (Nguyen Minh Khuyen 2015; Cong-Thi et al. 2021).

4.5.4 Mechanism 3 — Relic saline contamination from titanium-ilmenite mining

A third anthropogenic saline contamination source is identified at line HR-03, associated with the former titanium-ilmenite placer mining operation. Prior to exploitation, the mining area had a topography similar to the surrounding dune landscape. Large volumes of sand were excavated during ore extraction, lowering the ground surface by 10–15 m relative to the surrounding terrain — creating a topographic depression that traps saline water from the ore-separation process. Line HR-03 transects the edge of this former mine at stations 100–140 m, at an elevation approximately 7–12 m above the excavated mine floor where well W1 is located. During ore extraction, seawater was pumped directly into the open pit for mineral separation — a practice documented along the Binh Thuan coast that has caused severe localized salinization of adjacent aquifers (Nguyen Minh Khuyen 2015). The resulting low-resistivity anomaly ($\sim 202\ \Omega\cdot\text{m}$) embedded within the surrounding very high-resistivity dune-sand block ($> 608\ \Omega\cdot\text{m}$) at stations 100–140 m and ~ 10 m depth is interpreted as a relic saline plume that has migrated laterally from the mine depression into the adjacent undisturbed dune sand. This interpretation is supported by

well W1 at the excavated mine floor (TDS = 3,059 mg/l – confirming severe saline contamination at the mine centre), while wells W2 (TDS = 479 mg/l) and W3 (TDS = 229 mg/l) at progressively greater distances from the mine demonstrate that the surrounding dune-sand aquifer remains predominantly fresh, and that the saline plume is spatially confined to the former mining area.

4.5.5 Mechanism 4 – Compound low resistivity at Song Phan river mouth (SP-01)

The uniformly very low resistivity throughout line SP-01 (0.8–19 $\Omega\cdot\text{m}$), contrasting sharply with all other profiles, is explained by the combined effect of three factors. First, saline infiltration from the active shrimp-farming ponds is evidenced by a step in shallow resistivity that coincides with the pond margin. The profile runs immediately alongside the ponds between stations 56 and 184 m; over that interval the median resistivity of the 0–10 m layer is 1.98 $\Omega\cdot\text{m}$, against 7.4 $\Omega\cdot\text{m}$ landward of station 56 m where no pond adjoins the line – a 3.7-fold decrease across the pond boundary. The contrast is sharpest at 5–10 m depth, where the medians are 11 $\Omega\cdot\text{m}$ landward of the pond margin against 2.4 $\Omega\cdot\text{m}$ alongside the ponds, and it is confined to the uppermost ~ 12 m; below about 17 m the pattern reverses. This depth distribution is that expected for downward seepage from surface ponds rather than from a deep-seated source. Second, direct field observations of road cuttings near SP-01 reveal that the near-surface sediments consist predominantly of clay and silty clay, unlike the clean bar-sand lithology of the Tien Thanh and Bau Trang profiles. The presence of clay minerals increases surface conductivity and lowers bulk resistivity independently of pore-water salinity (Cong-Thi et al. 2024), explaining the absence of any high-resistivity surface layer in SP-01 and making Archie-based TDS estimation unreliable for this profile. The magnitude of the effect can be gauged at well W7 (TDS = 476 mg/l, EC = 743 $\mu\text{S}/\text{cm}$, pw = 13.5 $\Omega\cdot\text{m}$), where Archie with $F = 4\text{--}6$ predicts a bulk resistivity of 54–81 $\Omega\cdot\text{m}$ while the model gives a shallow median of 7.4 $\Omega\cdot\text{m}$ – a discrepancy of seven- to elevenfold, against only two- to fourfold on the clean bar-sand profiles of Sect. 4.5.1. Third, the proximity of SP-01 to the Song Phan river estuary exposes the aquifer to tidal intrusion during the dry season (Cong-Thi et al. 2021). Within the pond interval the shallow median continues to decline steadily toward the estuary, from 3.5 $\Omega\cdot\text{m}$ at stations 56–72 m to 1.2 $\Omega\cdot\text{m}$ at stations 168–184 m, and the lowest values of the whole section (0.9–1.2 $\Omega\cdot\text{m}$ at 5–10 m depth) occur over the last 36 m of the line, beyond the pond margin. Because the ponds extend to within 36 m of the seaward end, however, the pond and estuarine contributions overlap spatially and cannot be separated geometrically on this profile; the estuarine component is inferred from the persistence of the gradient beyond the ponds and from the setting, rather than from an isolated anomaly. The combined contribution of these three factors produces the anomalously uniform low resistivity across the entire SP-01 cross-section. The DOI analysis shows that this is nevertheless the least well constrained model in the data set. $|R|$ remains below 0.19 down to about 46 m depth and reaches 0.23 only in the lowermost metres, at the lower edge of the 0.2–0.4 transition range of Oldenburg and Li (1999); at the same depth the value for TT-04 is 0.09, so SP-01 is a factor of 2.4 less well constrained – an expected outcome for a profile that is uniformly conductive and therefore limits current penetration. No interpretation is placed on the base of this section; the mechanisms inferred above rest on the shallow and intermediate parts of the model ($|R| \leq 0.12$ above about 32 m depth), which are well resolved.

4.5.6 Freshwater lens geometry and deep saline water

Several profiles reveal a three-layer vertical resistivity structure — a high-resistivity surface layer (coarse-medium dune sand, dry above the water table and freshwater-saturated below), an intermediate-resistivity zone, and a low-resistivity basal layer — consistent with a freshwater lens floating on denser saline water at depth (Post and Abarca 2010). The intermediate zone is interpreted here as partly lithological in origin: the boreholes of Table 1 place a Pleistocene silty-clayey sand unit, with 20–30% silt and clay, immediately beneath the clean Holocene sand, and its elevated surface conductivity lowers bulk resistivity independently of pore-water salinity. This structure is most clearly expressed in BT-02, where the thick high-resistivity dune cap ($> 608 \Omega\cdot\text{m}$, 10–20 m) sustains a robust freshwater hydraulic head, confining the saline wedge ($7\text{--}40 \Omega\cdot\text{m}$) to the seaward and deepest portions of the section only. In TT-04, which runs parallel to the shoreline on the low marine terrace (ground surface + 1.2 to + 4.4 m), a laterally continuous conductive basal layer ($4.5\text{--}20 \Omega\cdot\text{m}$) extends below about – 28 m across the full 265 m profile. The DOI index confirms that this feature is resolved by the measurements rather than imposed by the inversion: $|R| \leq 0.04$ at the top of the conductive layer (~ 28 m depth) and ≤ 0.09 at the base of the displayed section (~ 53 m depth), that is less than half the lower bound of the 0.2–0.4 transition range of Oldenburg and Li (1999), and R reaches 0.2 only below about 140 m, some 2.5 times the imaged depth. Because the nearest borehole (BV42, 1.4 km distant) encountered resistive granodiorite basement at – 27.5 m, and crystalline basement would appear resistive rather than conductive, the observed $4.5\text{--}20 \Omega\cdot\text{m}$ values require saline pore fluid — either within a Quaternary trough deeper than at BV42, or within a deeply weathered, saline-saturated basement surface. Although the shoreline-parallel orientation of TT-04 precludes direct imaging of the Ghyben–Herzberg wedge geometry, the persistent presence of this body at uniform depth along the entire profile is consistent with Ghyben–Herzberg equilibrium at this location. The resistivity contrast between the freshwater lens ($> 40 \Omega\cdot\text{m}$) and this deep saline zone ($< 20 \Omega\cdot\text{m}$) provides a robust geophysical target for monitoring lens thickness through time-lapse ERT surveys planned for subsequent phases of this investigation.

5 Conclusions

1. Aquifer structure: The subsurface resistivity structure consistently reveals a two- to three-layer geometry: an upper unsaturated or freshwater-saturated clean sand layer ($> 40\text{--}202 \Omega\cdot\text{m}$), an intermediate zone that the borehole record attributes principally to Pleistocene silty-clayey sand and that in places also carries the freshwater–saltwater transition, and in several profiles a deep low-resistivity basal unit ($< 20 \Omega\cdot\text{m}$) interpreted as saline-water-saturated sediments. The thick high-resistivity dune cap at BT-02 ($> 608 \Omega\cdot\text{m}$, 10–20 m) represents the most prominent freshwater reserve in the study area.

2. Spatial variability: The extent and severity of saltwater intrusion varies markedly across the 95 km transect. The Song Phan river mouth (SP-01) exhibits the most severe contamination ($0.8\text{--}19 \Omega\cdot\text{m}$ throughout) reflecting a compound effect of tidal intrusion, shrimp-farm drainage, and clay-enhanced

conductivity. Bau Trang (BT-02) hosts the thickest continuous freshwater dune-sand cover. Tien Thanh beach (TT-01, TT-02) exhibits the clearest Ghyben–Herzberg wedge geometry.

3. Four salinization mechanisms identified: ERT imaging, supported by hydrochemical data from eight wells (W1–W8), distinguishes: (i) direct marine intrusion forming a Ghyben–Herzberg wedge at the seaward ends of profiles; (ii) anthropogenic contamination from shrimp-farming via surface seepage (BT-01) and open-channel drainage (TT-04); (iii) relic saline contamination from former titanium-ilmenite mining at HR-03; and (iv) compound low resistivity at the river mouth driven by tidal intrusion, shrimp-farm drainage, and clay-rich sediments. Grain-size analysis confirms the clean bar-sand character of the Tien Thanh aquifer sediments, validating Archie's Law for petrophysical interpretation there.

4. ERT effectiveness: The multi-spacing Dipole-Dipole scheme – with electrode spacing progressively increasing from 5 to 55 m – proved well-suited to this environment, providing both near-surface resolution and model depths of up to 57 m. The wide dynamic range of measured apparent resistivity (0.08–18,012 $\Omega\cdot\text{m}$) and the low stacking noise (mean SD = 1.00%) confirm the suitability of the method for rapid, cost-effective baseline mapping over kilometre-scale coastal transects. Depth-of-investigation analysis (Oldenburg and Li 1999) shows the imaged sections to be data-constrained over their full displayed depth on TT-04 ($|R| \leq 0.09$), and down to about 46 m on SP-01 ($|R| \leq 0.19$).

5. Management implications: Tidal intrusion at river mouths can be partly mitigated by maintaining minimum ecological river flows during the dry season. Shrimp-pond contamination requires regulatory control of pond siting, lining, and drainage management. Freshwater lens depletion calls for managed aquifer recharge and extraction rate limits. The baseline data presented here provide a foundation for time-lapse ERT monitoring and coupled hydrogeological modelling of the aquifer system.

Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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Author Contribution

Conceptualization and field investigation: T.H.T., N.N.T.; Data acquisition and processing: N.N.T., T.H.T., B.V.N., N.V.D., T.T.T.H.; Formal analysis and interpretation: N.N.T., T.H.T.; Writing – original draft: N.N.T.;

Writing — review and editing: all authors; Funding acquisition: T.H.T. All authors read and approved the final manuscript.

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Data Availability

The ERT inversion files (.INV) and hydrochemical data supporting the results of this study are available from the corresponding author upon reasonable request.

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Figures



Figure 1

Location map of the study area and positions of the eight ERT survey profiles, with inset satellite images showing the detailed layout of each survey sub-area. Red lines ERT profiles; green dots measurement wells (W1–W8); white arrows shrimp-farm locations; yellow triangles boreholes BV40, BV42 and BV43 (Dao Manh Tien 2006)

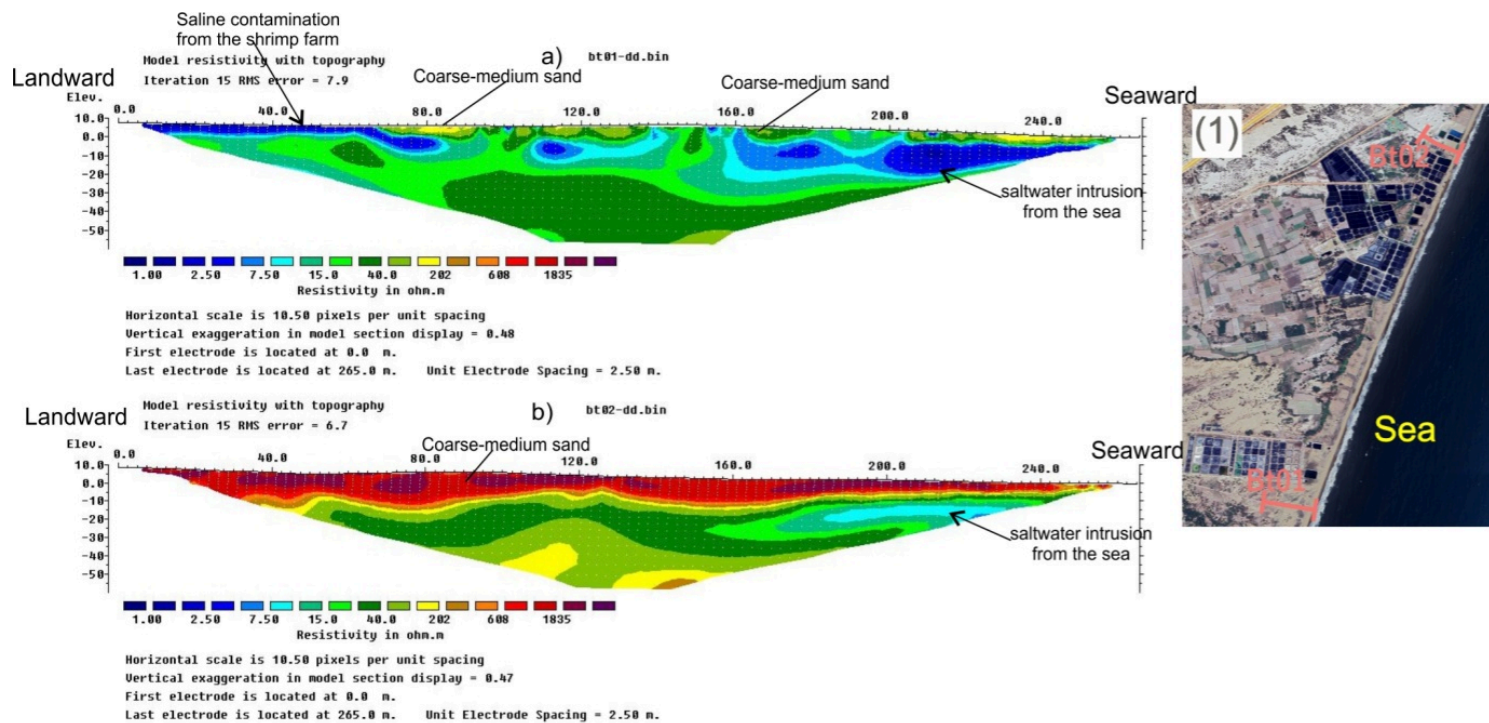


Figure 2

Inverted resistivity cross-sections of lines BT-01 (a) and BT-02 (b), Bau Trang area. Colour scale 1–1,835 $\Omega \cdot m$ (logarithmic). Landward end at station 0 m (left), seaward end at station 265 m (right). Model resistivities above 1,835 $\Omega \cdot m$ are saturated at the top of the colour scale

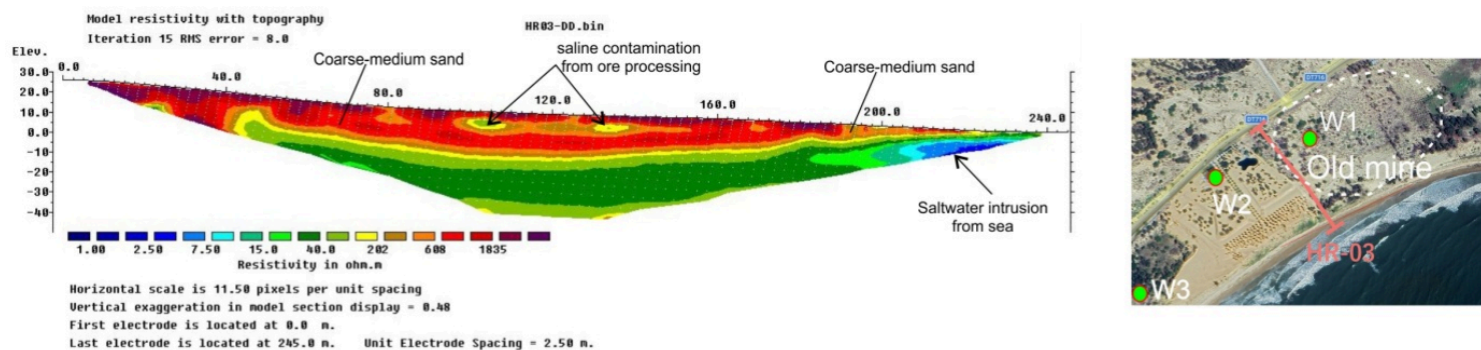


Figure 3

Inverted resistivity cross-section of line HR-03, Hon Rom area. Colour scale 1–1,835 $\Omega \cdot m$ (logarithmic). Landward end at station 0 m (left, elevation +26.2 m), seaward end at station 245 m (right, near sea level). Green dots: wells W1 (HR3-01), W2 (HR3-02), W3 (HR3-03). Model resistivities above 1,835 $\Omega \cdot m$ are saturated at the top of the colour scale

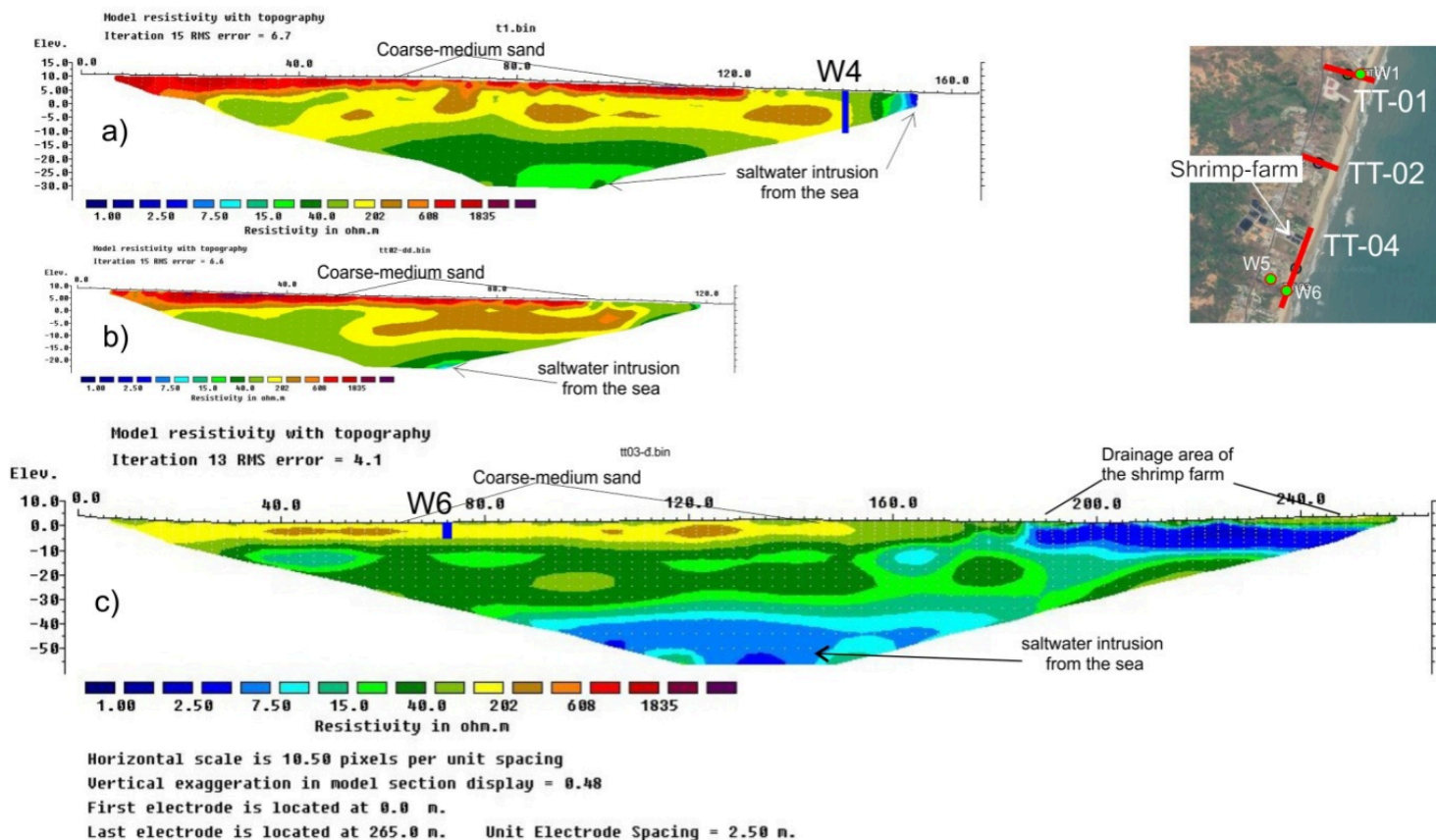


Figure 4

Inverted resistivity cross-sections of lines TT-01 (top), TT-02 (middle), and TT-04 (bottom), Tien Thanh beach area. Colour scale 1–1,835 $\Omega \cdot m$. For TT-01 and TT-02, landward end at station 0 m (left). TT-04 is oriented parallel to the shoreline (NE–SW). Model resistivities above 1,835 $\Omega \cdot m$ are saturated at the top of the colour scale

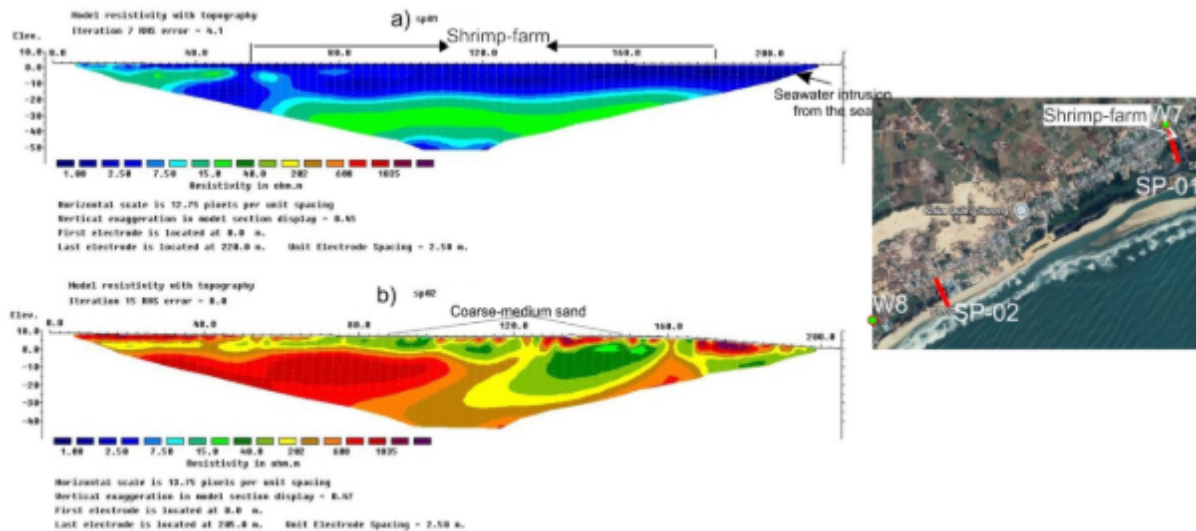


Figure 5

Inverted resistivity cross-sections of lines SP-01 (a) and SP-02 (b), Song Phan river mouth area, with satellite imagery of the sub-area at right. Colour scale 1–1,835 $\Omega\cdot\text{m}$ (logarithmic). Landward end at station 0 m (left) for both profiles. The horizontal bar on (a) marks the interval over which the profile runs immediately alongside the shrimp-farm ponds (stations 56–184 m); green dots: wells W7 and W8. Model resistivities above 1,835 $\Omega\cdot\text{m}$ are saturated at the top of the colour scale