Application of Electrical Resistivity Tomography and Ground Penetrating Radar to assess salinity in a coastal aquifer with tidally-driven saline recirculation cell

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EGU General Assembly 2020

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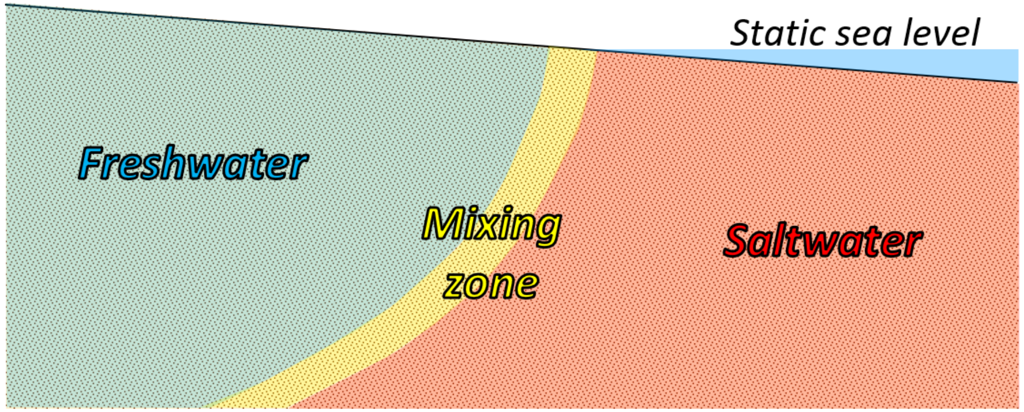
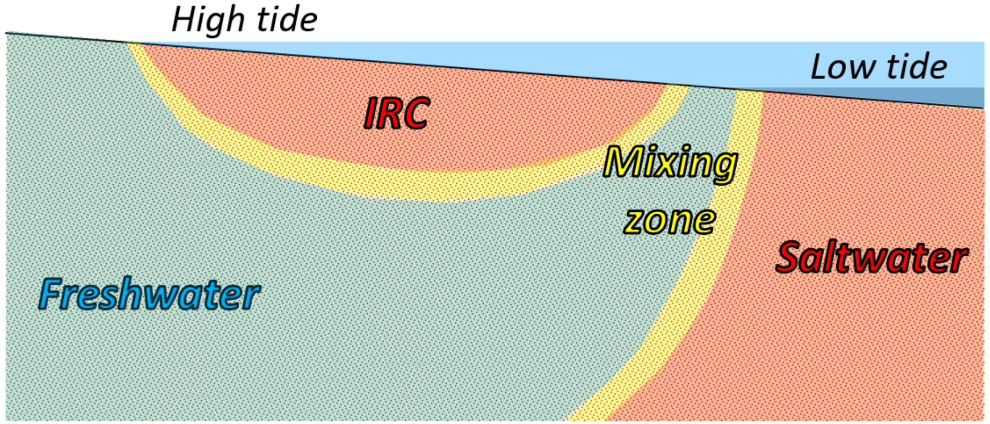
Introduction

- Saltwater intrusion (SI) is a major issue worldwide, as coastal aquifers act as the primary source of drinking water for more than one billion people
- With climate change and projected population increases in coastal areas, SI problem is anticipated to become more pressing over the next decades
- Density differences cause freshwater to float on seawater creating the classical saltwater intrusion saline wedge
- Oceanic forcing (waves and tides) often control coastal groundwater dynamics causing the emergence of an upper saline intertidal recirculation cell (IRC)

SI without oceanic forcing



SI with oceanic forcing



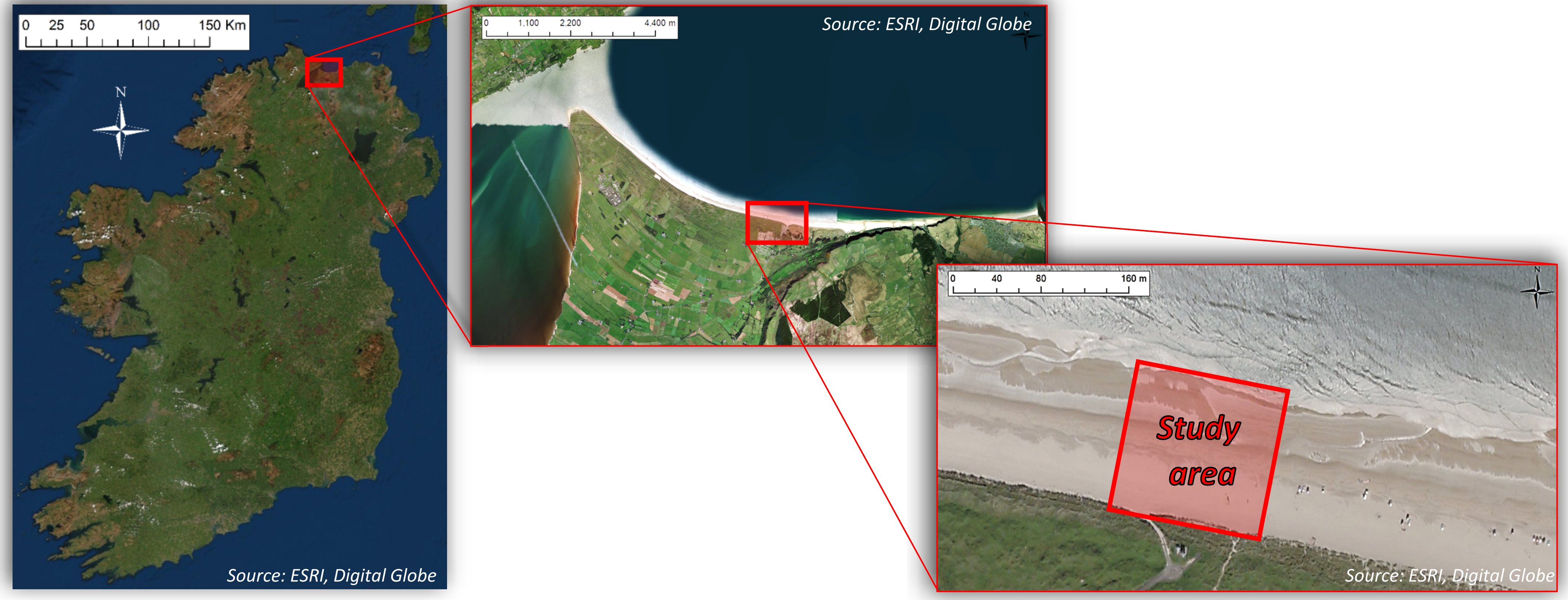
Aims and objectives

- The aim of this study is to test the applicability and utility of geophysical techniques to characterize and assess salinity of coastal aquifers where tides induce an IRC
- Non-invasive geophysical methods are usually used to characterise coastal aquifers. However, discerning between types of geological formations and water quality can be ambiguous if ground heterogeneities are present
- Several techniques were applied to characterize and assess salinity of the relatively homogeneous coastal sand aquifer underlying Benone Strand at Magilligan (Northern Ireland) where tides induce an IRC:
  - ✓ Electrical Resistivity Tomography (ERT)
  - ✓ Groundwater sampling
  - ✓ Ground Penetrating Radar (GPR)

Benone beach 27/02/19

Study area

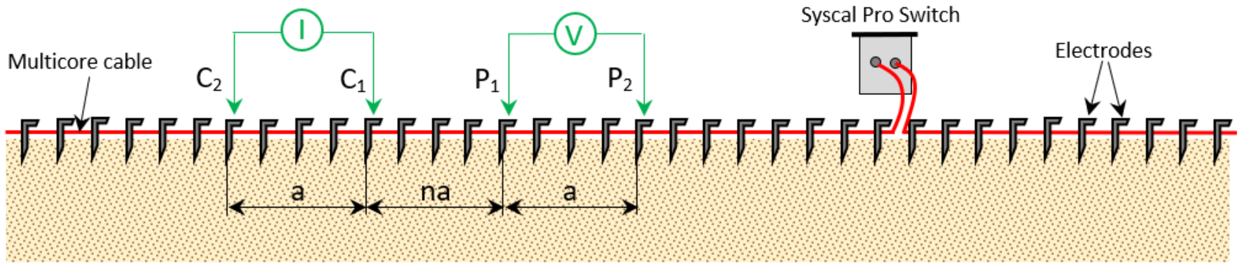
- This study was conducted in the intertidal zone of Benone beach located at Magilligan, in the northwest of County Londonderry (Northern Ireland, UK)
- Benone is a mildly sloping sandy beach in which its width can vary more than 150 m between low and high tide



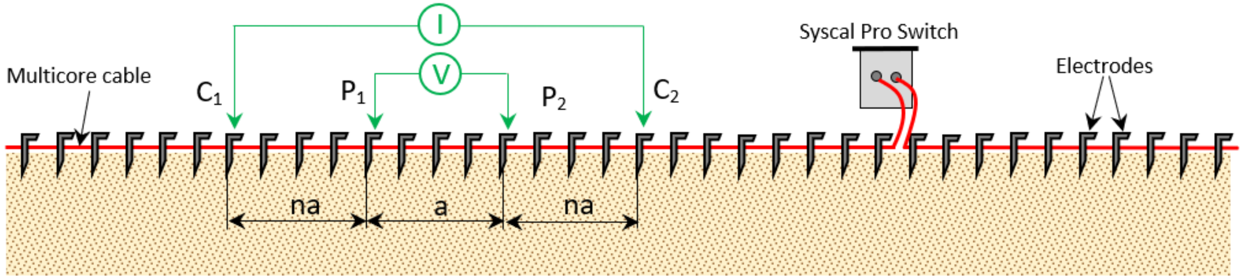
Electrical Resistivity Tomography

- ERT is a geophysical technique for imaging subsurface structures from electrical resistivity measurements usually made at the surface
- The resistivity of most types of sediments and rocks depend on the water content (concentration of dissolved salts)
- 2D ERT profiles were generated at Benone beach using the SYSCAL Pro 72 ERI system (Iris Instruments) with two different array configurations:
  - ✓ Dipole-Dipole array (good horizontal resolution & data coverage)
  - ✓ Wenner Schlumberger array (reasonably good horizontal & vertical resolutions)

Dipole-Dipole array



Wenner-Schlumberger array



P_1, P_2: potential electrode; C_1, C_2: current electrode; a: X grid spacing; n: separation factor between current and potential electrodes (related to the depth level)

Electrical Resistivity Tomography

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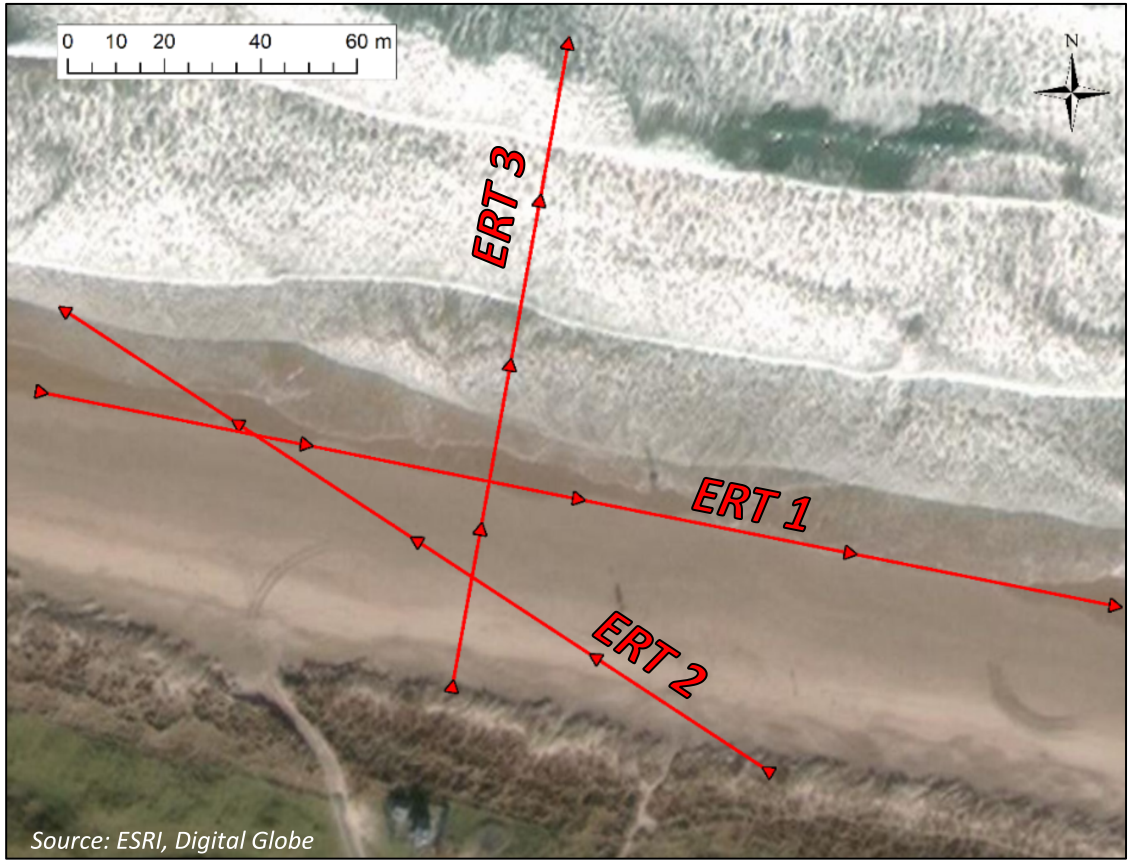
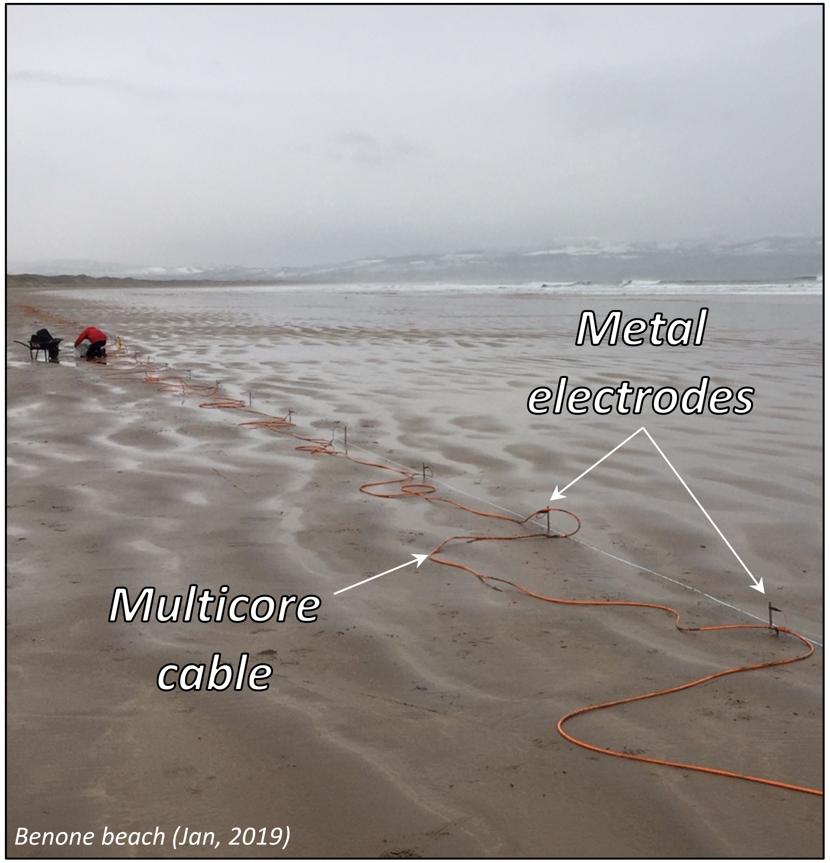
- ERT profiles were generated parallel, perpendicular and diagonal to the shoreline
- The software RES2DINV (Loke, 2006) was used to determine the true resistivity distribution from field measured apparent resistivities



Source: ESRI, Digital Globe



Benone beach (Jan, 2019)

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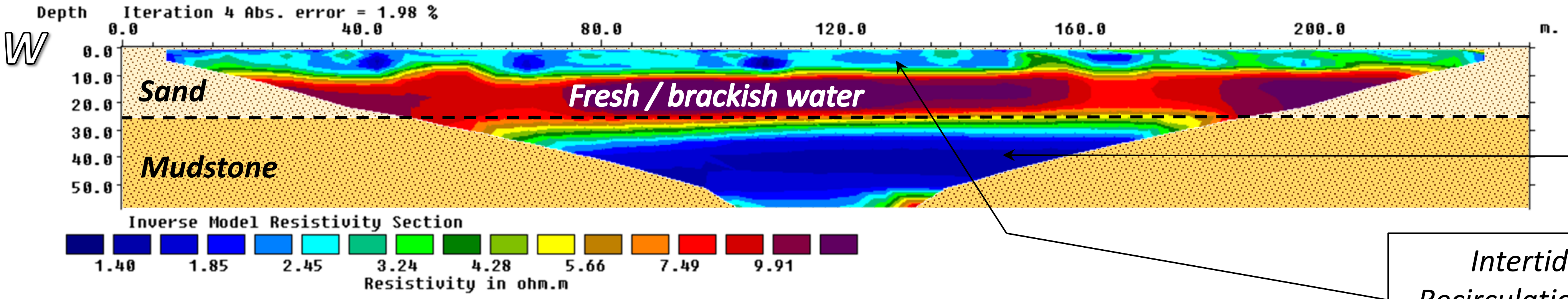
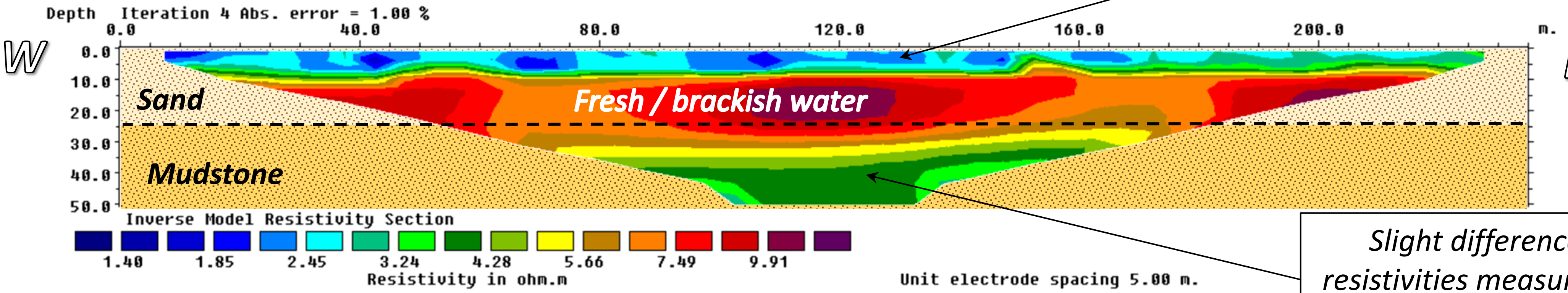
Electrical Resistivity Tomography

- ERT 1 (parallel to the coastline). Electrode spacing = 5 m. Total length = 235 m
  - ✓ Dipole-Dipole array



  - ✓ Wenner-Schlumberger array

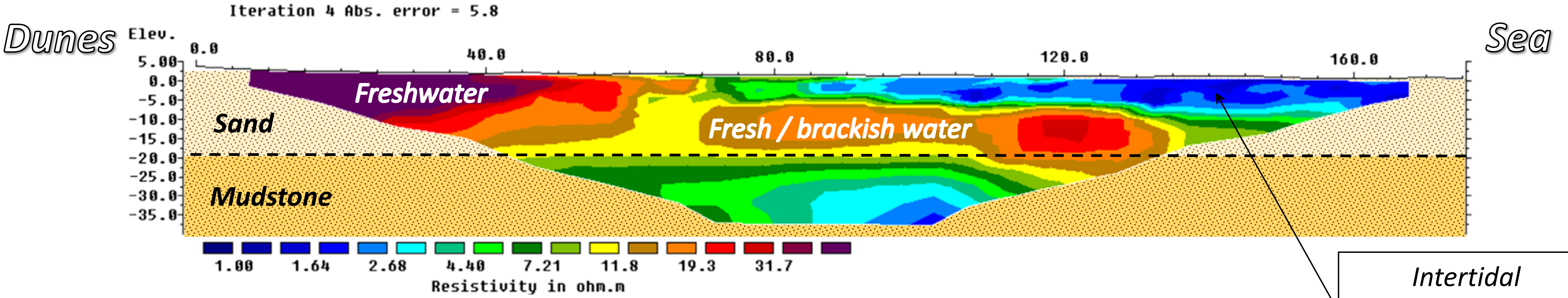


Intertidal Recirculation Cell (saltwater)

Slight differences in the resistivities measured with the two arrays in the mudstones

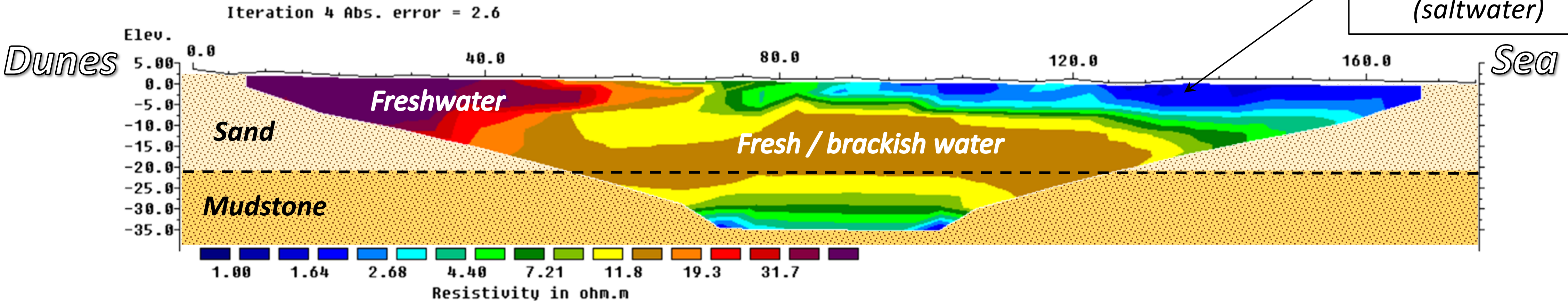
Electrical Resistivity Tomography

- ERT 2 (diagonal to the coastline). Electrode spacing = 5 m. Total length = 175 m
  - ✓ Dipole-Dipole array



Intertidal Recirculation Cell (saltwater)

  - ✓ Wenner-Schlumberger array



Electrical Resistivity Tomography

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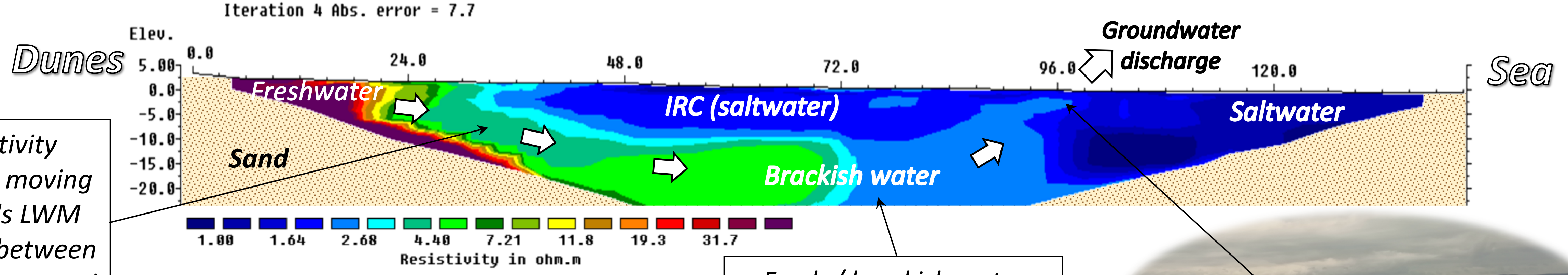
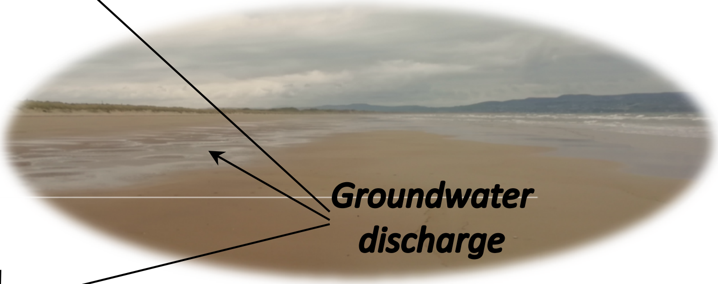
- ERT 3 (perpendicular to the coastline). Electrode spacing = 3 m. Total length = 141 m
  - ✓ Dipole-Dipole array

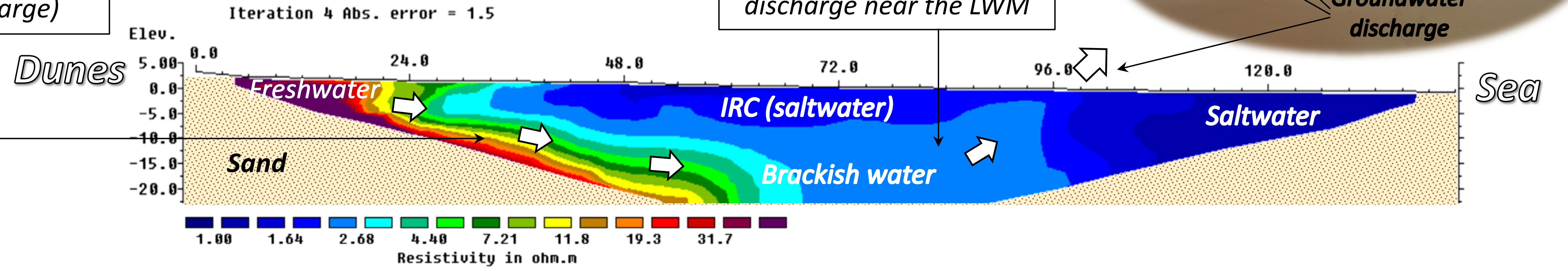


Resistivity declines moving towards LWM (mixing between saline water and the freshwater discharge)

Fresh / brackish water flow below the IRC and discharge near the LWM



  - ✓ Wenner-Schlumberger array



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Groundwater sampling

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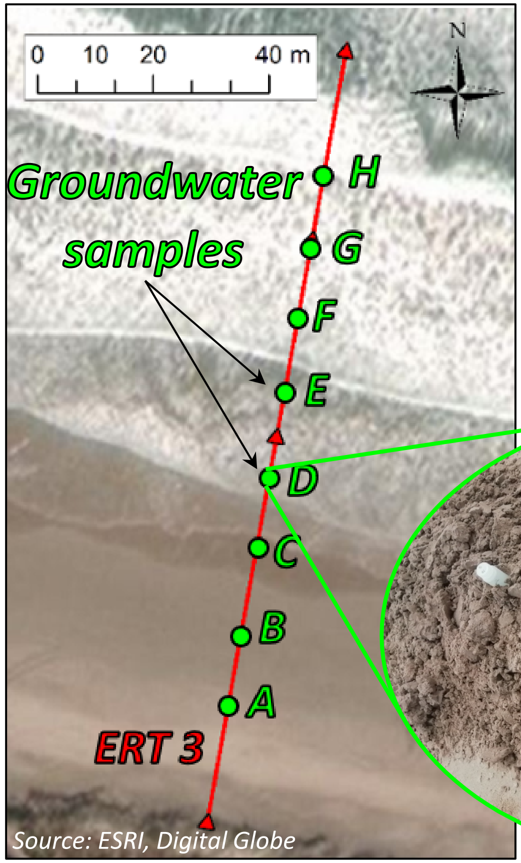
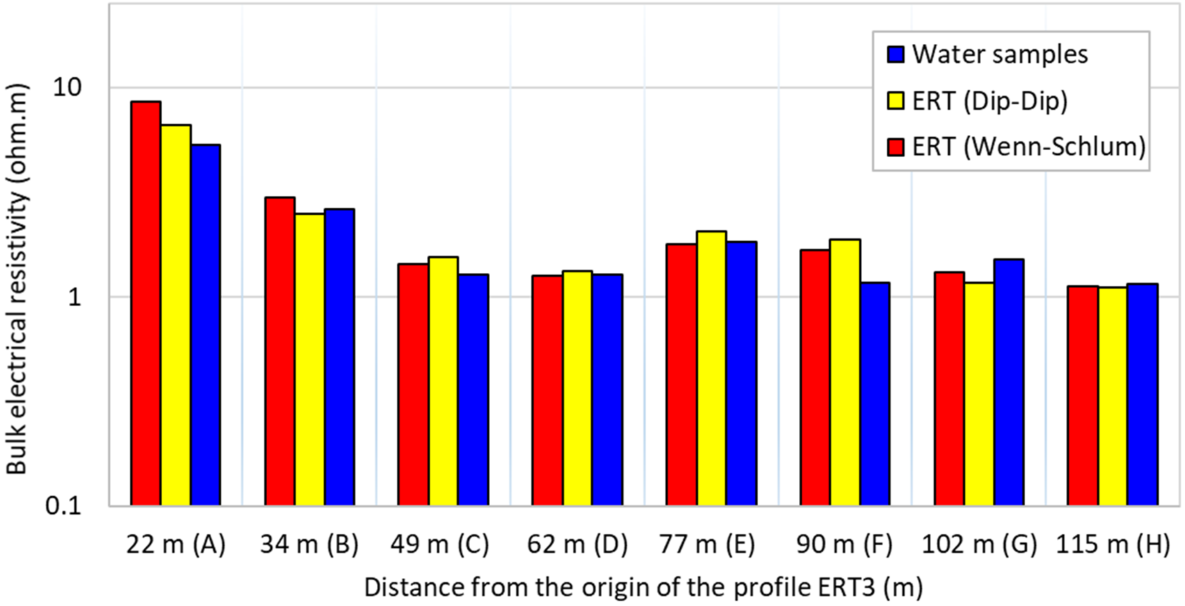
- Groundwater samples were collected in the IRC from the HWM to the LWM
- The electrical conductivities (EC) of the water samples were measured and compared with the resistivities obtained in the ERT profiles using Archie's law (Archie, 1942):

$$\rho_b = \phi^{-m} \rho_w$$

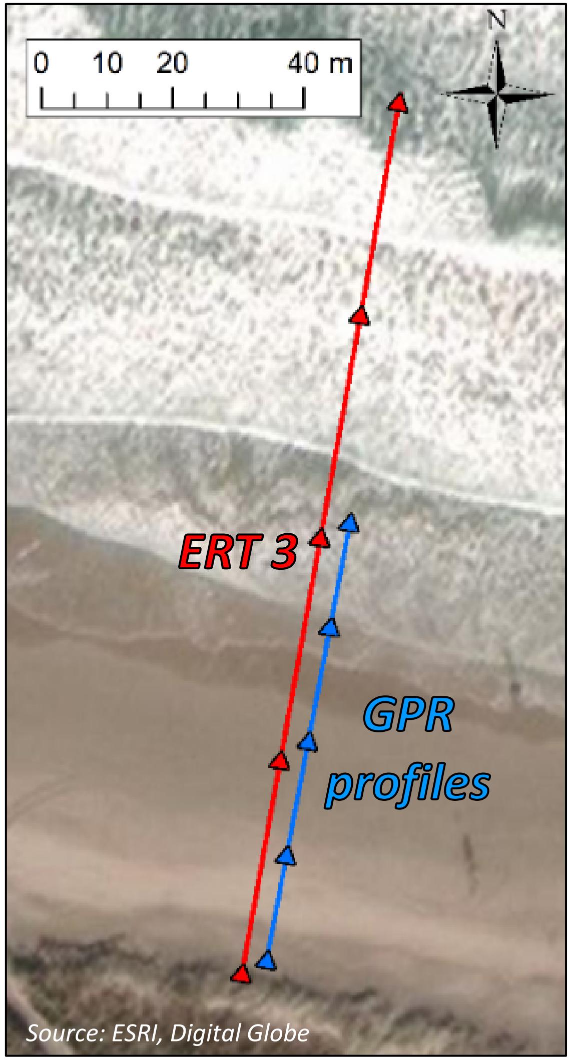
- ρ_b and ρ_w are the bulk and groundwater electrical resistivities, respectively
- ϕ is the porosity (0.27 estimated from the water saturation method)
- m is the cementation component (1.3 for unconsolidated sediments)





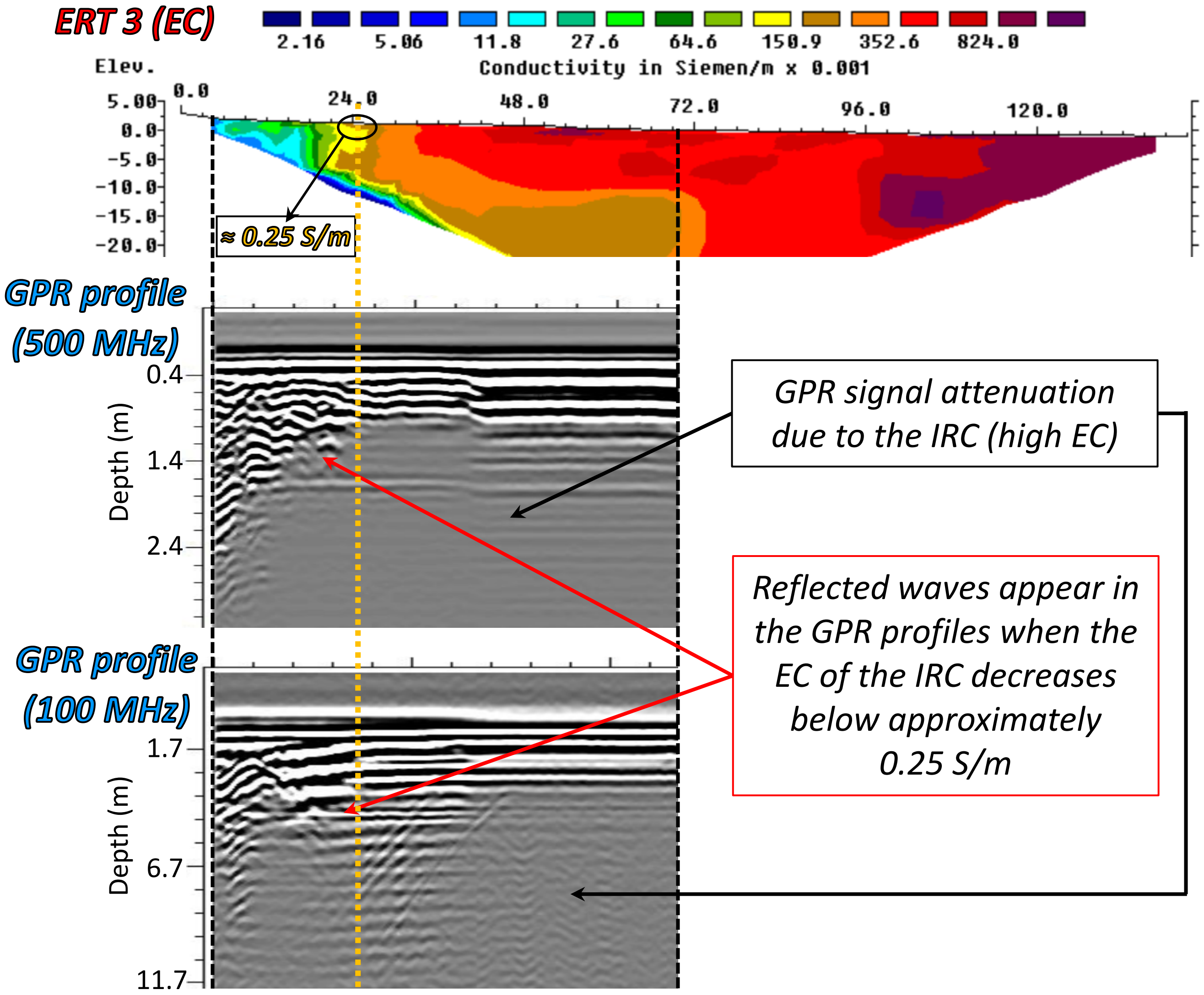
Ground Penetrating Radar

- GPR is a geophysical method that propagates electromagnetic pulses into the ground and receives partially reflected signals
- Penetration depth is strongly dependent on the electrical conductivity of the subsurface. Saline groundwater generally attenuate GPR signals
- A MALÅ ground penetrating radar system operating at several frequencies (50, 100 and 500 MHz) was used to collect 2D GPR profiles at Benone beach from the low tide mark to the high water mark



Ground Penetrating Radar

- The EC of the IRC is high enough to attenuate the GPR signal for all the frequencies used
- Reflected waves appear near the high water mark when the EC of the IRC decreases below 0.25 S/m
  - ✓ This agrees with Wijewardana et al. (2017). They reported that reflected waves disappear when EC > 0.28 S/m
- GPR profiles using higher frequencies (500 MHz) were the most informative to demarcate the interface freshwater-saltwater near the ground surface



Ground Penetrating Radar

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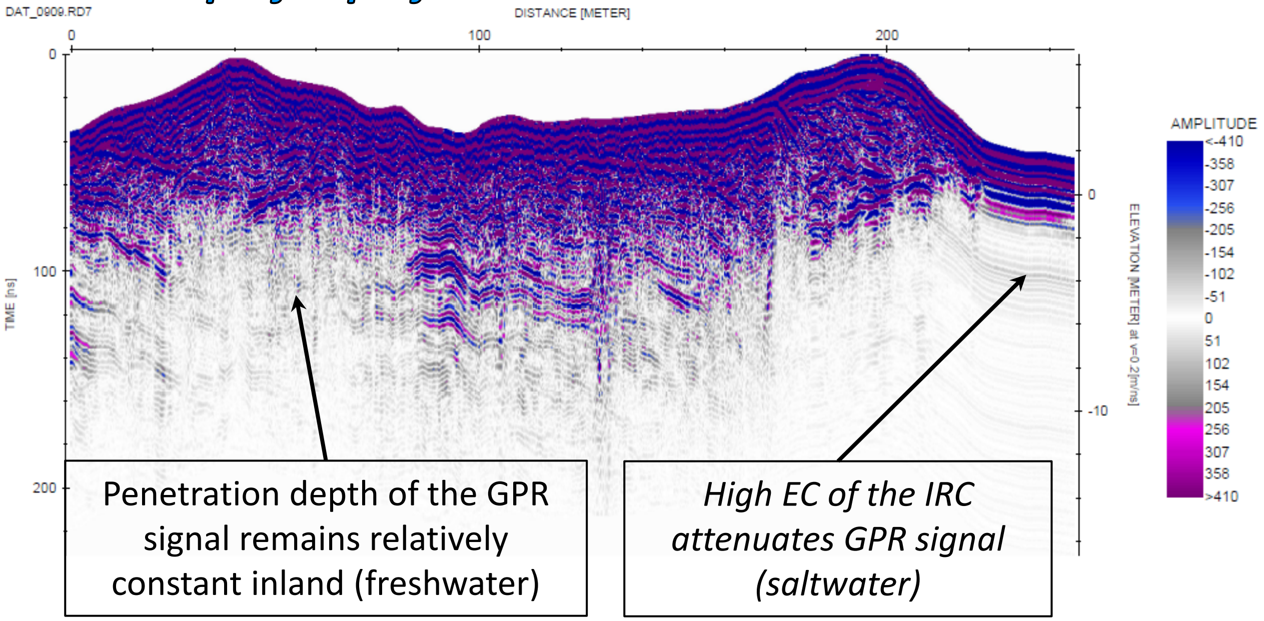
- Additional GPR profiles were performed using MALÅ GX160 HDR (High Dynamic Range) 1 km from the study area where they could be extended beyond the HWM
- High resolution GPR profiles analysed with the ReflexW software (Sandmeier, 2012) confirmed that:
  - ✓ The EC of the IRC is enough to attenuate the GPR signal from the HWM to the sea
  - ✓ Penetration depth of the GPR signal gradually increases moving away from the HWM and remains relatively constant inland

GPR profile performed with MALÅ GX160 HDR



Conclusions

- ERT and GPR techniques were tested to assess salinity in a coastal sand aquifer with a tidally-driven saline recirculation cell (Magilligan, Northern Ireland)
- 2D ERT profiles proved useful for:
  - ✓ Determine the homogeneity of the sands and the aquifer thickness (20 m). These findings were confirmed later through Cone Penetrometer Tests (CPT)
  - ✓ Define the salinity pattern in the intertidal zone:
    - ➢ Ocean forcing drive seawater into the aquifer forming an upper saline recirculation cell (IRC). ERT data suggest that the IRC has a resistivity of approximately 1 Ωm and a thickness of 5-8 m
    - ➢ The presence of the tidally-driven recirculation cell causes fresh groundwater to flow below the IRC ("discharge tube") and discharge in the vicinity of the low water mark
    - ➢ Resistivity increases below the IRC, but declines moving towards the low water mark (possible mixing zone between saline water and the freshwater discharge)
- The combination of several ERT arrays contributed to reduce uncertainties
  - ✓ The Wenner-Schlumberger array was the more suitable choice due to its better vertical resolution than the dipole-dipole array, but the data collection times were also longer

Conclusions

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- Resistivity values measured in the ERT profiles were verified by groundwater sampling taken on the IRC:
  - ✓ The electrical conductivities of the water samples were measured and compared with the resistivities obtained in the ERT profiles using Archie's law. Similar values were obtained in both cases
- GPR profiles were crucially important to demarcate the interfaces between freshwater and saltwater near the ground surface:
  - ✓ GPR signal was attenuated in the intertidal zone due to the high electrical conductivity of the IRC
  - ✓ Reflected waves appeared near the high water mark when the electrical conductivity of the IRC decreases below 0.25 S/m
  - ✓ GPR profiles obtained using higher frequencies (500 MHz) were the most informative
  - ✓ Penetration depth of the GPR signal gradually increased moving away from the HWM and remains relatively constant inland
- This research supports the conclusion that the application of ERT and GPR techniques is effective in delineating seawater intrusion in aquifers where tides create an IRC

Acknowledgement

- This work was funded by EPSRC Standard Research (Grant No. EP/R019258/1) and was carried out in collaboration with the Imperial College London
- The authors would like to thank Desmond Hill for his collaboration during fieldwork

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