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Characterizing groundwater salinity patterns in a coastal sand aquifer at Magilligan, Northern Ireland, using geophysical and geotechnical methods

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Abstract
Tidal forcing influences groundwater flow and salt distribution in shallow coastal aquifers, with the interaction between sea level variations and geology proving fundamental for assessing the risk of seawater intrusion (SI). Constraining the relative importance of each is often confounded by the influences of groundwater abstraction and geological heterogeneity, with understanding of the latter often restricted by sampling point availability and poor spatial resolution. This paper describes the application of geophysical and geotechnical methods to better characterize groundwater salinity patterns in a tidally dominated ~20 m thick sequence of beach sand, unaffected by groundwater abstraction. Electrical resistivity tomography (ERT) revealed the deposit to consist of an upper wedge of low resistivity (<3 Ωm), reaching over 8 m thick in the vicinity of the low water mark, overlying a higher resistivity unit. Cone penetrometer testing (CPT), and associated high-resolution hydraulic profiling tool system (HPT), coupled with water quality sampling, revealed the wedge to reflect an intertidal recirculation cell (IRC), which restricts freshwater discharge from a relatively homogeneous sand unit to a zone of seepage within the IRC. The application of CPT and HPT techniques underscored the value of geotechnical methods in distinguishing between geological and water quality contributions to geophysical responses. Survey results have permitted a clear characterization of the groundwater flow regime in a coastal aquifer with an IRC, highlighting the benefit of combining geophysical and geotechnical methods to better characterize shallow SI mechanisms and groundwater flow in coastal hydrogeological environments.

Keywords Seawater intrusion · Coastal aquifer · Intertidal recirculation cell · Cone penetration test · Electrical resistivity tomography

Introduction
Seawater intrusion (SI) into coastal aquifers arises naturally from density differences between seawater and fresh groundwater. However, this process can be exacerbated by human activity. Coastal aquifers act as the primary source of drinking water for more than one billion people around the world, with many units experiencing high abstraction pressures (Small and Nicholls 2003; Shi and Jiao 2014). This, coupled with ancillary factors such as reduced recharge due to urbanization, frequently gives rise to induced SI and the loss of valuable groundwater supplies (Werner and Simmons 2009; Águila et al. 2019; Olarinoye et al. 2020). Assessing the risk of seawater ingress into aquifers, and preventing its entry into potable water supplies, poses a widespread challenge to hydrogeologists and water resources engineers across the world.

Despite its prevalence and ongoing research efforts to better characterize it, significant knowledge gaps remain in current understanding of SI, particularly at field scale. These include an inadequate knowledge of the influence of subsurface conditions on groundwater flow and the absence of an appropriate rubric to distinguish between saltwater migration and aquifer heterogeneity (Weinstein et al. 2007; Werner et al. 2013; Kreyns et al. 2020). The application of effective characterization strategies in coastal aquifers thus
makes up a crucial component in improving current understanding of SI (Custodio 2010).

Traditional studies of SI have focused on the investigation of the deep saline wedges in which salt water can underlie freshwater in both confined and unconfined aquifers (Cooper 1959; Kohout 1960). Under these circumstances, when fresh groundwater, flowing through coastal deposits, comes into contact with denser salt water, it flows over the deeper saltwater wedge before discharging to the ocean (Robinson et al. 2009). On the other hand, other studies have noted that marine forces can result in seawater entering the upper parts of an unconfined aquifer, leading to the development of an upper saline recirculation cell beneath the intertidal zone, known as the Intertidal Recirculation Cell (IRC) (Boufadel 2000; Robinson et al. 2006). Aquifers with an IRC have typically been investigated through laboratory tests and modelling (Xin et al. 2010; Kuan et al. 2012; Vithanage et al. 2012; Bakhtyar et al. 2013; Han et al. 2018; Yu et al. 2019), or by combining limited field investigations with numerical models (Lebbe 1999; Vandenbohede and Lebbe 2005; Robinson et al. 2007; Abarca et al. 2013; Heiss and Michael 2014; Zhang et al. 2017). More detailed characterization of groundwater salinity patterns based entirely on field measurements in real coastal aquifers with an IRC prove less common (Urish and McKenna 2004; Henderson et al. 2010; Buquet et al. 2016; Comte et al. 2017). Study findings have revealed that the variety of hydrogeological conditions and tidal regimes around the world results in complex and diverse patterns that require more comprehensive characterization to allow SI processes to be better understood (Carrera et al. 2010; Azizi et al. 2019). Moreover, findings are frequently complicated by abstraction, which alters natural groundwater-flow regimes (Sahoo and Jha 2017; Radulovic et al. 2020), while limited numbers of sampling points give rise to further ambiguity (Nilsson et al. 2007).

Geophysical methods display considerable promise for better characterizing SI since the movement of seawater into aquifers causes an increase in the electrical conductivity (EC) of groundwater. This contrast has allowed electrochemical methods, such as electrical resistivity tomography (ERT) to image the subsurface in coastal environments (Martínez et al. 2009; Dimova et al. 2012; Hermans et al. 2012; Rey et al. 2013; McInnis et al. 2013; Ronczka et al. 2015; Goebel et al. 2017; Costall et al. 2018). Nonetheless, it is not always possible to use geophysical data to clearly distinguish intervals containing salt water from geological features, such as low resistivity marine clays (Szalai et al. 2009; Michael et al. 2016). Chemical analyses of groundwater, when combined with geophysical methods, can reduce these uncertainties (Sherif et al. 2006; Cimino et al. 2008; Kura et al. 2014; Eissa et al. 2016; Kazakis et al. 2016; Waska et al. 2019). Nevertheless, hydrogeochemical analyses normally require the presence of boreholes which, if they are not properly designed, may not accurately reflect the natural phenomenon since, among other things, the flow within the well could be large enough to compromise the integrity of water samples (Shalev et al. 2009).

The benefits of geophysical methods increase considerably when combined with direct investigation methods. Although boreholes often prove the favored method of providing corroborating information, difficulties with sample recovery can often limit the resolution of the geological data collected (Misstear et al. 2007). By contrast, geotechnical methods such as direct push technologies can provide valuable high-resolution profiles that facilitate the creation of three-dimensional models of the subsurface when combined with the results of surface geophysical surveys (Olayanju et al. 2017). More specifically in-situ geotechnical testing, including cone penetration tests (CPT) and use of hydraulic profiling tool (HPT) systems, provide accurate information on stratigraphy and relevant soil physical properties, which can also be used to calibrate the geophysical data and improve the site characterization (Dezert et al. 2019). These combined geophysical and geotechnical approaches are commonly employed in civil engineering projects. However, integrated application of geophysical techniques with geotechnical methods, proves less common in SI investigations (Pauw et al. 2017).

This paper presents the combined application of geophysical and geotechnical techniques (ERT, CPT and HPT), coupled with water quality sampling, to better characterize the groundwater-flow regime and the salinity patterns of an unconfined coastal sand aquifer affected by tidal processes. The test site at Magilligan (Northern Ireland) occurs on the beach between the tidal Atlantic Ocean and a landward sand dune complex. Critically, the site is unaffected by anthropogenic activities such as groundwater abstraction, thus permitting more confident interpretation of hydrogeological conditions operating under passive gradient conditions, including the occurrence of an IRC and how this affects groundwater flow. ERT profiles generated across the site provided one of the clearest assessments to date of salinity distribution in a coastal aquifer with an IRC. Complementary application of in-situ geotechnical methods provided a detailed picture of the textural homogeneity/heterogeneity of the aquifer, while groundwater samples defined spatial variations in groundwater salinity. Investigation results highlight the value of combining these methods for characterizing the geometry of the IRC, while also demonstrating the benefits of characterizing aquifer heterogeneity and defining the configuration of groundwater discharge zones within the intertidal zone.
Site description

The Magilligan Test Site (Magilligan) occurs in northwest Northern Ireland (United Kingdom) (Fig. 1) and forms part of one of the largest coastal dune systems on the island of Ireland, measuring 7.5 km × 1.5 km. The area evolved as a result of late Pleistocene and Holocene sea level changes, coupled to a declining offshore sediment supply (Carter et al. 1982). The focal area of investigation at Magilligan occurs within the intertidal zone of Benone Strand (Fig. 1). This is a mildly sloping (~0.02) sandy beach with an intertidal zone up to 150 m wide at spring tide. Tides are semi-diurnal with a mean range of 1.72 and 0.65 m during spring and neap tides, respectively. Carter (1975) reported the materials making up the beach to consist of medium- to fine-grained sands, with 90% quartz and 8% calcium carbonate (shell debris), along with subordinate heavy minerals, mainly magnetite, epidote and biotite. Hydraulic conductivity of the sands in the study area ranges from between 5 and 25 m/d decreasing with depth due to an increase in soil compaction (Águila et al. 2020).

Magilligan experiences a temperate oceanic climate in which the mean annual temperature and precipitation are 9.6 °C and 1094 mm, respectively. Rainfall occurs throughout the year, although the spring and early summer months tend to be slightly drier. Annual average groundwater recharge for the site was estimated to be around 400 mm, while groundwater pHs ranges from 7.5 to 8 (Robins and Wilson 2017). The sand deposits make up an unconfined aquifer which receives direct rainfall recharge over the full areal extent of the dune system, and which discharges directly to the sea. Chemically, the fresh groundwater within the sand is reported to be dominated by Ca-HCO₃, reflecting the presence of shell debris.

Materials and methods

Cone penetration test (CPT)

CPT is a common in situ testing method for determining geotechnical properties of soils and delineating soil stratigraphy (Lunne et al. 1997). It is ideally suited for well sorted, shallow and loosely consolidated sediments. Seven CPT soundings were performed to refusal (maximum depth of

![Fig. 1 Location of the study area with the position of the CPT and HPT soundings, groundwater samples and traces of the ERT profiles including electrode location. Red triangles show the start of ERT profiles, while red squares indicate their end. Satellite photograph source: ESRI, Digital Globe](image-url)
22.64 m below the ground surface (BGS)) within the intertidal zone of Benone Strand using a 14-ton track-mounted CPT rig during the last week of February 2019. The locations of the seven CPT soundings were chosen to align with the traces of ERT profiles, thus facilitating more confident interpretation of geophysical data and the development of a more comprehensive model of subsurface conditions (Fig. 1, T1-T7). An instrumented cone, with a cross-sectional area of 15 cm², was pushed into the ground at a controlled penetration rate of 20 mm/s ± 10%. Soil samples were not collected in the seven CPT soundings. The cone resistance \( q_c \), sleeve friction \( f_s \) and porewater pressure \( u_2 \) were measured every 10 mm of penetration. \( q_c \) is the total force acting on the cone divided by the projected area of the cone, while the \( f_s \) is the total frictional force acting on the friction sleeve divided by its surface area. The friction ratio \( R_f \) was estimated from the \( q_c \) and \( f_s \) values according to (Lunne et al. 1997):

\[
R_f(\%) = \frac{f_s}{q_c} \times 100. \tag{1}
\]

Porewater pressure was measured with a filter in the \( u_2 \) shoulder position (just behind the cone). The net pore pressure was normalized with respect to the cone resistance obtaining the pore pressure ratio \( B_q \) which is defined as (Senneset et al. 1989):

\[
B_q = \frac{u_2 - u_0}{q_i - \sigma_{vo}}, \tag{2}
\]

where \( u_0 \) is the equilibrium pore pressure, \( q_i \) is the cone resistance corrected for unequal end area effects and \( \sigma_{vo} \) is the total overburden stress.

Changes in \( R_f \) typically represents changes in grain size and sediment texture, while \( q_c \) is indicative of soil density and consistency (Lunne et al. 1997). Generally, high \( q_c \) (> 8 MPa), low \( R_f \) (< 2%) and generate low excess pore water pressure are considered representative of coarse-grained sandy sediment, whereas fine-grained silty and clayey deposits tend to have lower \( q_c \) (< 4 MPa), high \( R_f \) (> 2%) and high excess pore water pressure values (Zhang et al. 2018). For clean sands \( B_q \approx 0 \), while in soft to firm intact clays, \( B_q \approx 0.6 \pm 0.2 \) (Cai et al. 2011). The geotechnical parameters previously described, as well as their value ranges associated with the sediment type, were used to characterize the coastal aquifer at Magilligan.

**Hydraulic profiling tool (HPT) system**

The hydraulic profiling tool (HPT) system supplements CPT measurement and consists of a direct push apparatus designed to evaluate the hydraulic behavior of unconsolidated materials. As the HPT probe is pushed into the subsurface at a rate of 2 cm/s, a down-hole transducer measures the pressure required to inject a low flow of water (HPT flow) into the ground medium. A low pressure response usually indicates a relatively large grain size and the ability of the soil to easily transmit water, while changes in the ratio between HPT flow and pressure suggest variation in soil permeability (McCall et al. 2014). In addition, the HPT probe is equipped with an EC measurement array providing logs of bulk formation electrical conductivity (solids and pore water). This array is strategically placed to ensure that the injection of water from the HPT probe did not affect the EC measurements. The bulk EC is typically influenced by different factors such as grain size, mineralogy and the presence of dissolved ions. The joint analysis of the three parameters measured by the HPT system (pressure, flow rate and EC) helps with the definition of the spatial variation of hydrogeological properties, formation lithology and porewater chemistry. For instance, if variations in EC but not in pressure are detected in the HPT soundings, this usually suggests changes in groundwater salinity without lithological variations.

Seven HPT tests were conducted at Magilligan within 0.5 m of the CPT sounding locations (Fig. 1) using the same 14-ton rig. Geotechnical campaigns (CPT and HPT) were conducted during the last week of February 2019 in the same physical site conditions. The HPT system was tested and calibrated using differential pressure sensors; deviations from the expected values were found to be less than 10%. Measurements focused on the upper part of the aquifer, where tides were suspected to induce the development of an IRC based on preliminary ERT profiles conducted in the area. Consequently, the maximum depths reached in the seven HPT soundings ranged from between 8 m (T1) to 13.5 m (T3) BGS. The three factors directly measured in the seven HPT soundings were pressure response, injection flow rate and bulk formation electrical conductivity (inverse of resistivity). Hydrostatic and atmospheric pressures were subtracted from the total HPT pressure to obtain the pressure required to inject water into the medium (corrected HPT pressure). 54 dissipation tests were performed at various intervals to determine the local piezometric pressure, while the bulk EC was determined using a dipole array. HPT data were processed and analyzed using the Geoprobe® Direct Acquisition software.

**Electrical resistivity tomography (ERT)**

ERT is a geophysical technique for imaging the subsurface using electrical resistivity measurements, which are often taken at the surface (Reynolds 2011). The method involves the introduction of an electrical current through two electrodes and measuring the electrical potential decrease using two other electrodes aligned to create pre-defined arrays. Two different arrays were used at Magilligan when acquiring the ERT profiles: dipole–dipole and Wenner–Schlumberger.
Measurements using both configurations were compared to ensure the reliability of the measurements. Similar results were obtained using both arrays, with the dipole–dipole array being the one selected to present the results here due to its slight advantage in better mapping vertical variations in salinity.

Five ERT profiles were performed parallel to the shoreline (P1–P5) and one perpendicular to the shoreline (P6) (Fig. 1). The ERT profiles parallel to the shoreline were generated from December 2018 to March 2019 during the winter period, although some of them (profiles P3 and P5) were repeated in summer time (June 2019) to verify that the seasonal variation did not cause significant changes in the resistivity models. All the parallel ERT profiles were carried out using 48 electrodes spaced by 5 m with the goal of detecting the base of the sand. Profile P6 was generated on 16 May 2019 during low spring tide using 48 electrodes spaced by 3 m. The total length of each ERT profile parallel to the coastline is 235 m while profile P6 has a length of 141 m. The contact resistance of the electrodes with the ground was checked before data acquisition, with steps taken to ensure the smallest resistance values possible. Contact resistance values of less than 1 kΩ were achieved in profiles P2, P3, P4 and P5, while slightly higher values (<4 kΩ) were returned in some electrodes of profiles P1 and P6 placed in slightly drier sand. All 2D ERT tomographic profiles were acquired using a 10-channel SYSCAL Pro Switch 72 resistivity meter (Iris Instruments).

The inverse modelling software RES2DINV (Loke 2006) was used to determine the true resistivity distribution from the field-measured apparent resistivities. L1 norm or blocky method was used for inverting the ERT data because it is more suitable in areas with strong resistivity contrasts (Loke et al. 2003). Visualisation and analysis of the ERT data was carried out using ParaView software (Ayachit 2015). The RMS error for the whole set of profiles was 4.8%, demonstrating the reliability of the ERT data measured in this research.

**Groundwater sampling**

Groundwater samples were collected on Benone Strand at regular intervals along a transect which extended from the high water mark to the low water mark (Fig. 1) to analyze the salinity variations in the upper part of the aquifer, verify the consistency of ERT data and provide information on the transformation of measured geophysical properties into hydrogeological parameters using petrophysical relationships (a key step in quantitative hydrogeophysical interpretations) (Lesmes and Friedman 2005; González-Quirós and Comte 2020). Small holes were manually excavated to the water table to allow collection of 60 mL water samples. The field campaign was conducted on 16 May 2019, the same day the ERT profile P6 was acquired. The groundwater samples were collected at low tide when the beach width was greater than 140 m. Thus, a larger number of samples could be collected for comparison with the ERT profile. The groundwater samples were analyzed for EC using a calibrated YSI Professional Plus Multiparameter quality meter. The YSI meter was recalibrated before each analysis. Groundwater salinities were determined from the EC data by applying the algorithms proposed by APHA (1995). Resulting EC data allowed calculation of bulk electrical resistivity \(\rho_e\) by factoring the electrical resistivity of groundwater \(\rho_g\) using Archie’s law (Archie 1942):

\[
\rho_e = a \rho_g \phi^{-m},
\]

where \(a\) is a parameter related to the tortuosity, \(\phi\) is the porosity and \(m\) is the cementation factor. \(a\) and \(m\) are constants, usually determined experimentally. For unconsolidated sediments such as sands, values of \(a = 1\) and \(m = 1.3\) are typically used (Archie 1942). The porosity of the sands was determined equal to 0.35 in laboratory using the volumetric saturation method (Rosas et al. 2014) from samples collected on the beach. However, given the difficulties of taking samples without disturbing the loosely packed grains and the lack of sand samples at depth (Román-Sierra et al. 2014), estimates were also calculated assuming porosity values of 0.25 (coarse sand) up to 0.45 (fine sands) (Freeze and Cherry 1979).

**Results**

**CPT data**

Figure 2 (and Figure S1 in the electronic supplementary information) presents \(q_c, f_d, R_p, u_2\) and \(B_q\) logs measured in the seven CPT soundings. The data were projected on a vertical profile along a south-north transect for clear visualization. The cone resistance values measured in the T1 sounding in the shallowest 2 m of the aquifer increase with depth, reaching 21 MPa. \(q_c\) ranges from between 8 and 27 MPa from 2 to 14 m BGS, while it increases to 32 MPa at 15.5 m BGS. Instead, \(q_c\) decreases with depth from 17.7 m BGS, reaching 1.35 MPa at 19.8 m BGS. The trend of the \(q_c\) logs measured in the other six soundings down to a depth of 20 m BGS is similar to that determined in the T1 sounding. At greater depths, however, \(q_c\) values show less variability in the T5, T6 and T7 soundings than in those closer to the dunes (T1, T2, T3 and T4). The \(f_d\) logs show similar patterns to the \(q_c\) logs, increasing from 1 to 300 kPa in the shallowest 15 m of the aquifer, and then decreasing by more than 200 kPa at a depth of 20 m BGS. The friction ratio increases from 0.4% near the surface to 0.8% at 20 m depth in all...
the CPT soundings. Significant variations in the measured values of $R_f$ occur at depths greater than 20 m BGS, where the friction ratios are typically in the 2–4% range. The $u_2$ values measured in the shallowest 20 m of the aquifer also increase slightly with depth, although such an increase is not manifested in the normalized porewater pressure logs, where $B_q$ is close to 0. From a depth of around 20 m BGS, $B_q$ usually ranges from 0.2 to 0.4.

Therefore, profiles generated for the first 20 m BGS in all the CPT soundings display a friction ratio less than
1% with the cone resistance reaching maximum values of 30 MPa and \( B_q \) values close to 0. These high values of \( q_c \) and low \( R_f \) are typical for sands. The abrupt changes detected in the CPT data at approximately 20 m BGS are indicative of an area with deposits of finer grain size. Findings are consistent with existing Quaternary geological (McCann 1988) and bedrock geological maps and indicated that the 20 m thick sand aquifer rests directly on Lower Jurassic (Lias) mudstones. Hydraulic conductivity in the mudstones was estimated at around \( 10^{-2} \text{–} 10^{-3} \text{ m/d} \) from CPT data using the Soil Behavior Type Index (SBT) (Robertson 2010), i.e., it is four orders of magnitude lower than that of sands (Águila et al. 2020). Maximum pore-water pressure values measured in sands reached around 200 kPa; these were lower than those measured in mudstones where values of 1500 kPa were reached.

The consistent behavior displayed in the seven CPT soundings in the sand aquifer suggests high levels of homogeneity. Table 1 lists the maximum, minimum, mean, median, standard deviation (\( \sigma \)) and coefficient of variation (\( COV \)) of parameters measured/derived for each CPT sounding in the sand aquifer. The mean values of each parameter calculated from the data collected in each CPT sounding proved similar. For instance, the \( q_c \) means calculated in the seven soundings range from between 18.55 and 19.8 MPa, while in the case of the \( R_f \) they range from between 0.59 and 0.63%. In both cases, the differences between the mean values are less than 6%. Furthermore, the maximum standard deviations of \( q_c \) and \( R_f \) calculated in the seven CPT soundings are 5.5 MPa and 0.17%, respectively. The \( COV \) for \( q_c \) and \( R_f \) calculated from the data collected in each CPT sounding ranged between...
0.23 and 0.3. The \( u_z \) means range from between 85 and 98 kPa, while the hydraulic conductivity means estimated from CPT data range from between 18.5 and 27.4 m/d. The uniformity and homogeneity of the sand aquifer was also evidenced through the SBT charts generated by Robertson et al. (1986) to predict sediment types from CPT data by plotting \( q_t \) against \( R_f \) and \( B_q \). Figure 3 (and Figs. S2 and S3) show the data from the seven CPT soundings on SBT charts, with CPT data grouped by depths to provide a view of the sand’s stratigraphy and heterogeneity. CPT data generated by the most landward sounding (T1) shows that all the data taken down to a depth of 19.5 m BGS are within a zone corresponding to sands, with data taken at greater depths corresponding to zones between sand to silty sand (Zone VIII) and clays (Zone III). The same trend applies for the most seaward sounding (T7) although the threshold depth is now slightly less (17.2 m). Remaining SBT charts exhibit broadly similar behavior, with threshold depths occurring between 17.2 and 19.5 m BGS. Taking into account the topography of the beach, it can be deduced that the base of the sand aquifer has a slope of less than 1%.

**Fig. 3** Soil Behaviour Type charts (Robertson et al. 1986) plotted from the data obtained in the CPT soundings T1 (top) and T7 (bottom). Responses in the uppermost 17–19 m suggest sand deposits, while deeper units are finer grained.
HPT data

Figure 4 shows the pressure and the ratio between the flow rate and corrected pressure in the HPT soundings T3 and T6. Pressure values of 115 kPa were measured near the surface in both soundings, increasing with depth to 460 kPa at 12–13 m BGS. The piezometric pressure increases from 110 to 240 kPa, so the corrected pressure ranges from between 5 and 220 kPa in the seven HPT soundings. Nevertheless, the ratio between flow and pressure decreases from over 40 to 2 mL/min·kPa in the shallowest 2 m of the aquifer, approximately. Minor variations in this ratio were detected at depths greater than 2 m BGS, with a mean of around 4–5 mL/min·kPa. Thus, HPT data suggest greater permeability in upper layers of the aquifer, while the absence of additional abrupt variations rules out lithological changes in the rest of the aquifer in the seven HPT soundings. In addition, all 54 dissipation tests performed on Benone Strand at different depths had dissipation times of 120 s or less (see Fig. S4 for dissipation test performed at a depth of 5.9 m BGS in the sounding T6), in line with rates anticipated for granular materials (McCall and Christy 2020).

When performing the dissipation tests, the stabilized pressures (absolute hydrostatic pressures) were determined at different depths in the aquifer. Knowing the value of this parameter, along with the atmospheric pressure and the depth of the dissipation tests, made it possible to calculate the piezometric/hydraulic heads at these depths (McCall 2011). Piezometric head is a specific measurement of liquid pressure above a vertical datum, usually measured as a liquid surface elevation and expressed in units of length. The piezometric heads estimated from the dissipation tests conducted at Magilligan were interpolated in a vertical plane perpendicular to the coastline (see Fig. 5), from which the direction of groundwater flow can be deduced (groundwater flows from regions of higher hydraulic head to regions of lower hydraulic head). Piezometric heads vary between 0.25 and 2 mAOD in the first thirteen meters of the aquifer, indicating that groundwater flows seaward from the dunes. Piezometric heads increase about 1 m from the surface of the sand aquifer to a depth of 13 m BGS, suggesting a consistent upward flow component across the survey area. However, the contour lines of the piezometric heads are steeper and closer to each other between the T6 and T7 soundings, so the
upward flow component proves highest in this area, indicating that groundwater discharges to the surface in the vicinity of the low tide mark (Fig. 5). Figure 5 also presents the bulk EC measured in the seven HPT soundings. The bulk EC represents the ability of the soil (soil and pore water) to conduct electric current.

Due to the high level of homogeneity of the aquifer under investigation deduced from the CPT data, the EC values measured using the HPT system mainly reflect the groundwater salinity patterns. Electrical conductivity increases with increasing pore water salinity. The highest EC values were measured at the top of the sands, where values higher than 4000 μS/cm were measured to a depth of 1.5 m BGS in the most landward HPT sounding (T1). The thickness of this interval increases with proximity to the sea, reaching a depth of 6 m BGS in the soundings T2 and T3, while high EC values (8000 μS/cm) were measured to a depth of 12 m BGS in sounding T4. Beyond 40 m seaward from the dunes, the depth at which high EC values were measured exceeded 13 m BGS (i.e., the maximum depth of soundings T5, T6 and T7). The highest bulk EC values in the intertidal zone were measured near the surface in soundings T5 and T6 (14,000 μS/cm). By contrast, despite the proximity of the sounding T7 to the sea, the measured EC here proved relatively low and uniform (5000 ± 1000 μS/cm).
ERT data

Based on the literature, subsurface regions affected by saline intrusion have been reported with resistivity values of between 0.1 and 10 Ωm (Kouzana et al. 2010; Senthilkumar et al. 2019; Niculescu and Andrei 2021). However, there is no single criterion to define the resistivity limit indicative of the presence of salt water. Some authors defined this limit at 3 Ωm (Silliman et al. 2010), while others raised it to 5 Ωm (McInnis et al. 2013). The criteria used here for the interpretation of ERT profiles was the same as that proposed by Kura et al. (2014) in lower resistivity formations, i.e., intervals with resistivity values between 0.1 and 5 Ωm were considered to contain salt water, between 5 and 10 Ωm are considered transition zones (containing brackish water), while intervals with resistivity values greater than 10 Ωm were considered unaffected by SI. All ERT profiles collected at Magilligan detected a basal low resistivity interval (<5 Ωm), interpreted as the base of the aquifer (about a depth of 20 m BGS). Figure 6 presents the results of the analysis of the five ERT profiles performed parallel to the shoreline (including resistivity sections at elevations of −5 m, −10 m and −15 m in each profile), along with a comparison between EC measured in the seven HPT soundings.

The resistivity values determined on profile P1 (the most landward profile) vary between 3 and 102 Ωm. Although this profile was measured close to the high water mark, the resulting tomography suggests a zone of low resistivity (between 4 and 8 Ωm) to occur near the surface caused by tidal variations (area delimited in profile P1 from the surface to the horizontal dashed white line). Up to a depth of 14–15 m BGS, there is an area with resistivity greater than 10 Ωm, reaching maximum values (>100 Ωm) at around 8–12 m depth. Resistivities decrease from a depth of 15 m BGS to the bottom of the aquifer. The analysis performed through horizontal sections confirmed that resistivity values determined at 7 m depth (elevation of −5 m) range from between 57 and 102 Ωm along the P1 profile, but are always larger than those determined at 12 m depth (elevation of −10 m). In turn, resistivities identified at an elevation of −15 m (17 m deep), ranging from 6 and 19 Ωm, are lower than those detected at an elevation of −10 m throughout the profile P1. The maximum resistivity values determined for profile P2 proved to be less than 23 Ωm and differ considerably from the 102 Ωm measured in the P1 profile, located 18 m further inland than P2. Moreover, contrary to profile P1, resistivities in profile P2 increase with depth (see resistivity sections performed at elevations of −5 m, −10 m and −15 m in Fig. 6a). Resistivities of between 2 and 4 Ωm were determined along P2 in the shallowest 6 m of the aquifer (see the area delimited in profile P3 from the surface to the horizontal dashed white line). From this depth, the resistivity gradually increased reaching values of 23 Ωm at the base of the aquifer (containing freshwater). Values determined for profile P3 vary between 1 and 14 Ωm, with resistivities of between 2 and 3 Ωm occur from the top of the aquifer to a depth of 8 m BGS. As in profile P2, the resistivities along P3 also increase with depth reaching maximum values of 14 Ωm at the base of the sand aquifer. Nevertheless, there are slight variations in resistivity values determined at similar depths along profile P3. Resistivities at -14 m depth (elevation of −15 m) range from between 8 and 13.5 Ωm, while they range from between 4 and 8.5 Ωm at −9 m depth (elevation of −10 m) along P3. The values determined for profiles P4 and P5 (closest to the sea) suggest unit resistivities range from between 1 and 5 Ωm, so both profiles are clearly affected by salt water. However, as with the other ERT profiles, lower values were determined for the upper part of the aquifer. Resistivities of less than 2.5 Ωm were determined for the shallowest 8 m and 10 m of profiles P4 and P5, respectively (areas delimited from the surface to the horizontal dashed white lines in both profiles). From these depths, the resistivities slightly increase to 4 Ωm at the base of the aquifer in both profiles. Resistivity values calculated at the same depth along the profile P4 showed greater fluctuations than those determined along P5 (see resistivity sections in Fig. 6a).

Figure 6b presents a comparison between electrical conductivities estimated from the parallel ERT profiles and those measured in the seven HPT soundings. The resistivity values determined in the ERT profiles at the locations of the HPT soundings were converted to EC values for comparison purposes. The trends of the bulk EC determined with ERT and HPT methods are similar. However, differences between the two approaches seem to increase with depth, possibly reflecting the loss of resolution using surface geophysics. Furthermore, this comparison reflects that changes in EC are defined in greater detail by the HPT system than through the ERT method. Thus, HPT data show high EC values at a depth of between 0.7 and 1.7 m BGS in the T1 sounding, reaching a maximum value of 4180 μS/cm at a depth of 1.2 m BGS. Instead, a constant value of EC equal to 1860 μS/cm was determined in the shallowest 2.5 m of the aquifer through ERT data collected close to the T1 sounding. Higher EC values were measured with the HPT system than with the ERT method in the shallowest 2.7 m and 2.1 m of the aquifer in soundings T2 and T3, respectively. From these depths, EC values determined using the ERT method were higher than those measured through the HPT system, especially between depths of 6 and 9 m BGS where no high EC values were recorded in both HPT soundings. In contrast, the opposite occurs in the T4 sounding at depths greater than 8 m where higher EC values were measured with the HPT system than with the ERT method. In soundings T5, T6 and T7, EC values determined using the HPT system and the ERT technique show a higher degree of similarity, except for
(a) Distribution of resistivity along the profiles P1 to P5:
- Low resistivity area caused by tides (IRC) at Elev. = -5 m, Elev. = -10 m, and Elev. = 15 m.

(b) EC (µS/cm) and Depth (m) graphs for profiles T1 to T7:
- HPT system and ERT comparison.
depths between 9 and 12 m BGS in the T5 sounding where a partial blockage of the HPT port prevented the acquisition of reliable EC data.

The resistivities determined at various depths in the ERT profiles parallel to the shoreline were interpolated to create resistivity planes at depths of 2 m and 10 m BGS to provide a snapshot of the tide’s influence on aquifer salinity patterns (Fig. 7). Resistivity values at 2 m depth range from between 1 and 8 Ωm, while the maximum resistivity value increases to 74 Ωm at 10 m depth BGS. In addition, resistivities determined at a depth of 2 m BGS always proved lower than those measured at a depth of 10 m BGS. Resistivities gradually decrease moving from the dunes towards the sea at both depths. However, survey data suggest that resistivity values determined near the landward dunes at 10 m depth BGS are more than nine times larger than those determined at a depth of 2 m BGS. In addition, there is a difference of about 30 m between the distances from the trace of profile P1 to areas with resistivities less than 2.25 Ωm at both depths. The consistency in resistivity values from the dunes to the sea in both resistivity planes suggests that the coastal aquifer under investigation is composed of relatively homogeneous sand. Nevertheless, natural deposits are not perfectly homogeneous so slight variations in resistivity values were detected in north–south direction at both depths. For instance, resistivity values less than 2.25 Ωm were determined in some areas at a depth of 10 m BGS at 45 m from the P1 profile seaward, while these values were not reached in other areas of the intertidal zone (see Fig. 7).

Figure 8a presents profile P6 generated perpendicular to the shoreline. The results proved consistent with the resistivities determined in the profiles parallel to the shoreline. Resistivities less than 3 Ωm were determined for the upper part of the aquifer beneath the intertidal zone. The thickness of this lower resistivity interval gradually increases approaching the low tide mark, reaching a thickness of greater than 8 m. Overall, resistivity increases below this interval, but declines towards the low tide mark. Resistivity values less than 5 Ωm were determined near the surface from 27 m from the origin of the profile P6, while these values were not detected at the base of the aquifer until 67 m from the origin of the profile. Similar differences (40 m) were found between the distances from the origin of the profile where resistivities lower than 3 Ωm were determined in the surface layers and the base of the aquifer (see the 3 Ωm and 5 Ωm resistivity isolines in Fig. 8a). Moreover, an increase in resistivity was detected close to the surface in the vicinity of the mean low water mark (at 90 m from the landward dunes), where discharge of groundwater can be seen with the naked eye during low tide at spring tides (see photograph in Fig. 8a). Very low resistivity values (around 1 Ωm) were detected from 100 m from the origin of the profile, suggesting that this area could correspond to the classical or deep saltwater wedge formed by density differences between fresh water and salt water.

**Groundwater samples**

Figure 8b summarizes the findings of the water quality survey, showing the salinity of the water samples and comparing the bulk electrical resistivity measured from groundwater samples and ERT profiles at several distances from the origin of profile P6. Moreover, Figure S5 in the electronic supplementary information presents the electrical conductivity of water samples collected at several distances from the origin of the ERT profile P6. Although a more comprehensive chemical analysis of the water samples would allow the concentrations of the major ions to be known, it is common practice to measure the electrical conductivity of groundwater during field campaigns when investigating saline intrusion (Urish and McKenna 2004; Robinson et al. 2007; Weinstein et al. 2007; Heiss and Michael 2014; Sylus and Ramesh 2015). The bulk electrical resistivity was calculated from EC of the water samples by applying Eq. (3). Resistivity values at 10 m from the origin of profile P6 were determined to be greater than 35 Ωm. The salinity of the water sample collected in this area was 0.7 ppm, very close to the salinity of fresh water, which is usually equal to or less than 0.5 ppm. Groundwater salinity in the upper part of the aquifer increases to 4.86 ppm at 26 m from the origin of the P6 profile. However, the greatest increases in salinity along the beach transect occurred from this distance up to 50 m from the origin of the P6 profile, where water salinity increased seaward at a rate of approximately 1.2 ppm/m perpendicular to the shoreline. Between 50 and 90 m from the origin of profile P6, the salinity of the water samples ranged from 23 to 32 ppm, while the ρ w values were calculated to range between 1 and 2 Ωm in the upper part of the aquifer. The salinity of groundwater sampled at 115 m from the origin of profile P6 was 35 ppm, the typical value for seawater salinity.

Figure 8c presents the correlation between the bulk electrical resistivity values estimated from EC of the groundwater samples and those determined from the ERT profile P6. Data obtained from both approaches show a linear correlation with a coefficient of determination (R^2) equal to 0.994. However, the resistivity values determined directly from the
ERT profile were in most cases slightly larger than those estimated from the water samples by applying Archie's law. The average of percentage errors (mean percentage error, MPE) between the values of bulk electrical resistivities obtained from both method was 23.6%. The most significant differences were found near the dunes. The resistivity value estimated from the EC of the water sample collected 10 m from the origin of the profile P6 was 48 Ωm, while that determined from the ERT profile was equal to 38 Ωm. Nevertheless, such differences decreased seaward. The root mean square error (RMSE) and mean absolute error (MAE) of the data collected by the ERT technique and groundwater sampling between 34 and 115 m from the origin of the P6 profile were equal to 0.593 and 0.471, respectively. Taking into account the different measurement scales in both methods and the approximations considered when applying Archie's law, the agreement between the ρ<sub>r</sub> values estimated from ERT methods and groundwater samples is strong. This comparison confirms that the resistivities measured with ERT methods in the upper part of the aquifer are accurate and the applicability of the Archie's law in homogeneous clean sand aquifers.

**Discussion**

Geophysical investigations of coastal deposits typically assume that porewater salinity primarily controls the bulk electrical conductivity (Jiao and Post 2019). However, this assumption can lead to misinterpretation, given the potential impact of geological heterogeneity on subsurface resistivity. González-Quirós and Comte (2020) demonstrated
that large errors could be introduced when defining SI using resistivity models if aquifer heterogeneity has not been characterized. At Magilligan, preliminary ERT profiles suggested significant resistivity changes in the intertidal zone and low basal resistivity values at a depth of 20 m BGS that could be attributed either to changes in lithology or areas with high salinity (arising from a classical SI wedge). The integration of geophysical and geotechnical techniques, along with groundwater sampling, helped reduce these uncertainties, proving the effectiveness of this combined approach in SI investigations.

The CPT technique assisted in the quantification of geological heterogeneities and in the definition of the geometry of the aquifer under investigation. The aforementioned uncertainties when interpreting preliminary ERT profiles were clarified after incorporating CPT data into the analysis. Significant variations in the values of all CPT parameters \( q_c, f_s, R_f, u_2 \) and \( B_q \) were detected at a depth of 20 m BGS (Figs. 2 and S1), especially in the friction ratio and water pressure with increases of 400%. Thus, the seven CPT soundings proved the existence of a geological boundary at this depth. Moreover, estimates of hydraulic conductivity

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**Fig. 8** ERT profile perpendicular to the shoreline (P6) (a); comparison of the bulk electrical resistivity measured from water samples and ERT profiles (yellow and blue bars) and salinity of water samples (red circles) at several distances from the origin of profile P6 (orange circles in a) (b); and correlation between the resistivity values obtained from the two methods (c). Error bars show the resistivity computed from Archie’s law using porosities values of 0.25 and 0.45 (sands). The photograph shows the groundwater discharge zone in the vicinity of the mean low water mark during a spring low tide.
made from CPT data (SBT index) (Águila et al. 2020) indicated that the sand rests directly on an almost impermeable unit, thus defining the sand deposit’s base and permitting investigations to focus on the uppermost 20 m. The representation of $q_u$, $R_f$, and $B_q$ on Soil Behavior Type charts by grouping the data by depths (Figs. 3, S2 and S3) also provided a view of the soil stratigraphy and heterogeneity. Low levels of variation observed in the CPT data reflected the textural homogeneity of the sand unit. The means estimated from the CPT data collected in each sounding proved similar (e.g., differences less than 6% for $q_u$ or $R_f$), while standard deviations were small and constant (see Table 1). The coefficient of variation for $q_u$ and $R_f$ ranged between 0.23 and 0.3, which according to the categorizations proposed by Harr (1987) and Paikowsky (2004) is considered as a site of low/medium variability. Furthermore, the homogeneity of the sand deposit is more evident when considering that $COV$ of inherent variability of $q_u$ in sands typically ranges between 0.2 and 0.6 (Uzielli et al. 2007). Data collected using the geotechnical HPT method corroborated this finding; logs of pressure required to inject water into the medium did not show significant variations in the seven HPT soundings, suggesting comparable grain size in all deposits tested (Fig. 4). Similarly, bulk conductivity data and dissipation times suggest that the sands are also compositionally homogeneous. Therefore, the application of geotechnical techniques in coastal aquifers proved useful to remove much of the ambiguity associated with distinguishing between geological and water quality contributions to geophysical measurements (widely used in SI investigations). In addition, the HPT method, along with the associated dissipation tests, makes it possible to define the groundwater-flow regime in three dimensions (see Fig. 5).

As significant ground heterogeneities were not detected in the sand aquifer, resistivity changes determined using geophysical techniques could be more confidently attributed to porewater salinity variations. Consequently, and to the best knowledge of the authors, one of the clearest representations to date of the effect of tides on saline intrusion in a real-world coastal aquifer was determined via ERT (Fig. 8). Figure 9 shows a 3D view of the six ERT profiles and the refined conceptual model of the spatial distribution of resistivities in the coastal sand aquifer. Unlike aquifers with a classical SI wedge, lower resistivity values were found in the upper layers of the aquifer, showing a wide mixing zone with significant salinity variations in the intertidal zone. Marine forces cause salt water to infiltrate from the surface, creating the emergence of an upper saline IRC beneath the intertidal zone. The resistivities of the IRC range between 1 and 3 $\Omega$m, while its thickness increases when moving towards the sea, reaching depths greater than 8 m. The fresh water, derived from groundwater recharge flows, continues to flow below the IRC to discharge in the vicinity of the low tide mark. The resistivity increases below the IRC, but declines moving towards the low water mark (from more than 100 $\Omega$m to around 3 $\Omega$m). These findings reflect a mixing zone between saline water and the freshwater discharge caused by the higher density of salt/brackish water. The mixing zone separating pure fresh water from pure salt water extends more than 60 m into the intertidal zone below the IRC. The site conceptual model suggests that the IRC has not fully formed near the high water mark, while fresh water has not yet been restricted between the IRC and the base of the aquifer. This, together with the density variations, may be the reason why resistivity slightly decreases at the base of the aquifer from the high water mark landward (ERT profile P1 in Fig. 6). The comparison of resistivity values in horizontal sections at elevations of $-5$ m, $-10$ m and $-15$ m in each ERT profile parallel to the shoreline (Fig. 6) confirmed that resistivity decreases with depth in the profile P1 whose trace is close to the high water mark, while resistivity increases with depth in the rest of the ERT profiles located in the intertidal zone. This demonstrates that tides control the coastal groundwater dynamics in shallow aquifers causing saltwater to infiltrate from the surface in the intertidal zone leading to the emergence of an upper saline IRC and a decrease of water salinity with depth. In contrast, the distribution of water salinity in the aquifer near the high tide mark (profile P1), where saltwater infiltration from the surface no longer occurs and the IRC is not fully developed, is not controlled by tides. In this area of the aquifer, salinity increases with depth due to the contrast in density between fresh and salt water, in a similar way to what occurs in aquifers with a classical SI wedge.

No clear quantitative correlations between geotechnical data and inverted resistivity extracted from ERT profiles were found at Magilligan, which is in line with previous investigations carried out by authors such as Cosenza et al. (2006). Nonetheless, data quantitatively demonstrated consistency between geotechnical and geophysical approaches and the usefulness of their joint application to improve the characterization of underground systems. The data collected at Magilligan from geotechnical methods contributed in the refinement of the conceptual model, in the definition of the groundwater-flow regime and in the interpretation of the ERT profiles. The analysis of the hydraulic heads from HPT data indicated that groundwater flows seaward from the dunes with an upward component of groundwater flow from depth, leading to discharge in the vicinity of the mean low water mark; this is consistent with the increase in resistivity observed in the ERT profile P6 at 80–90 m away from the origin of the profile (Fig. 8). Moreover, the incorporation of an EC measurement facility in the HPT probe helps to increase the reliability of the ERT profiles by comparing measurements taken at different scales using different techniques. Previous research works, such as those
carried out by Fischer et al. (2016) and Obrocki (2019), have already highlighted that the combined use of HPT and ERT techniques contributes to increase reliability in determining EC patterns in aquifer characterization. The HPT technique offers a higher resolution of the EC in specific locations, while the ERT method allows to know the distribution of the EC in three dimensions in larger areas. The trends of the bulk EC measured with both methods at Magilligan proved similar despite the scale effect in the measurements (scale of centimeters in the HPT system and several meters in the ERT profiles) (Fig. 6). Both the HPT data and the ERT data show that the IRC begins to form around the high water mark (trace of the ERT profile P1 and HPT sounding T1), although its thickness in that area is less than 2 m according to the HPT technique. By contrast, ERT data suggest that high EC values reach 2.5 m in depth close to the high water mark due to the lower spatial resolution of this method. Both approaches show that the thickness of the IRC increases seaward, although differences between the EC measured with the ERT and HPT techniques seem to increase with depth.
reflecting the loss of resolution using surface geophysics. The relatively low and uniform EC measured near the low water mark using the HPT method (T7 sounding in Fig. 5) are consistent with the resistivity changes detected in ERT profiles in this area, affected by the discharge of fresh/brackish water from the base of the aquifer.

The use of portable sampling handheld meters to measure the EC of groundwater during field campaigns is common in SI investigations, since it is a fast and cost-effective indicator to study salinity variations of groundwater associated with SI processes (Klassen et al. 2014). However, the application of appropriate petrophysical relationships to transform geophysical variables into hydrogeological ones and vice versa requires knowing the degree of heterogeneity of the aquifers (González-Quirós and Comte 2020). The analysis of groundwater samples collected at the top of the aquifer at Magilligan demonstrated that geotechnical investigations contribute to the selection of appropriate petrophysical relationships, thus reducing the errors made when estimating the pore water salinity from geophysical data (Lesmes and Friedman 2005). The comparison between bulk electrical resistivities determined from ERT profiles and those estimated from water samples (Fig. 8b) proved the accuracy of the ERT profiles and the applicability of the Archie’s law in homogeneous clean sand aquifers, although differences of around 20% were found that could be caused by the different measurement scale in both approaches.

Integration of findings from geotechnical and geophysical techniques applied at Magilligan has allowed current understanding of site hydrogeology and SI mechanisms to be refined, highlighting the utility of geotechnical techniques to investigate the SI phenomenon in coastal aquifers, which is in agreement with Pauw et al. (2017). The groundwater salinity patterns characterized at Magilligan showed great similarities with the findings found in previous investigations based on numerical modelling and laboratory tests to assess the impact of tidal processes on groundwater quality in relatively homogeneous coastal aquifers. The numerical models carried out in the study area by Benner et al. (2020) demonstrated the relevance of the tides in the development of the IRC and also confirmed the homogeneity of the aquifer under investigation. Both the areal extent of the IRC detected at Magilligan and the area where the groundwater is discharged are in agreement with the laboratory experimental observations and modelling performed by Kuan et al. (2012) and Bakhtyar et al. (2013) simulating homogeneous aquifers, although salinity increases below the IRC were not detected in these previous studies. Instead, both the thickness of the IRC and the salinity patterns below the IRC measured in the aquifer at Magilligan agree with the groundwater-flow models developed by Evans and Wilson (2016) simulating coastal aquifers with a beach slope of around 0.02 (similar to that of Benone Strand). On the other hand, more significant differences were found when comparing the groundwater salinity patterns defined at Magilligan and those characterized in other real-world coastal aquifers with an IRC. A significant increase in salinity landward at the base of coastal aquifers was reported by Urish and McKenna (2004) and Abarca et al. (2013), but these features were not detected at Magilligan. By contrast, the resistive measurements performed by Lebbe (1999) showed resistivity values in the IRC similar to those measured at Magilligan, although the shape of the IRC was clearly affected by heterogeneities. ERT data presented in Buquet et al. (2016) suggested salinity patterns different from those detected at Magilligan, with the IRC representing a smaller volume of sea water and the salt water spreading in the coastal aquifer at greater depths under the dunes. Over the course of this research conducted at Magilligan, no major changes in the shape of the IRC have been observed during semi-diurnal tides and spring-neap cycles, which differs from that reported by Heiss and Michael (2014) during seasonal water-table fluctuations and spring-neap tidal cycles. Time-lapse resistivity imaging acquired at Magilligan during both spring tide and neap tide confirmed that the resistivity distribution in the sand aquifer remains nearly constant over semi-diurnal tidal cycles and that there are no significant resistivity changes during spring-neap cycles. Nevertheless, further research will be carried out in the future by installing an additional time-lapse geophysical system to study in detail the effect of seasonal fluctuations on the IRC (Franco et al. 2009).

The relatively uniform conditions and the absence of anthropogenic influences on aquifer hydraulics at Magilligan allowed for one of the clearest assessments to date of salinity distribution in a coastal aquifer with an IRC using only field measurements. The significance of such an achievement is reflected in the investigations performed by Goebel et al. (2017) who, after acquiring 40 km of ERT data along the Monterey coast (USA), highlighted the complex salinity patterns which can be detected when investigating SI at field scale. Knowledge of real-world coastal aquifers, which is garnered in situ, is essential to identify the fundamental processes of SI at large scales and to assess the capacities and shortcomings of the numerical models and laboratory tests widely used to study the SI phenomenon (Jørgensen et al. 2012; Greskowiak 2014; Yang et al. 2015; Li et al. 2016; Meyer et al. 2019; Yu and Michael 2019; Etsias et al. 2020, 2021a, b, c; Ketabchi and Jahangir 2021). The combined geophysical and geotechnical approach used at Magilligan to successfully characterize geological heterogeneities and groundwater salinity in a real-world coastal aquifer on a local scale could be applied to other sandy beaches which form coastal dunes. Such deposits are not uncommon, occupying approximately 20% of the world’s coastline (Masselink...
and Kroon 2009). Furthermore, all the techniques used in this investigation have been non-destructive, permitting their application to ecologically sensitive areas along the coast.

Conclusions

Correct interpretation of geophysical data in seawater intrusion investigations requires a good understanding of ground heterogeneities, since subsurface resistivity changes are both controlled by porewater salinity and lithology variations. In this paper, the effectiveness of a combined geotechnical and geophysical approach to characterize coastal areas and assess salinity patterns has been proved. Four different methods (CPT, HPT system, ERT and groundwater sampling) were integrated to study the saline intrusion in an unconfined sand coastal aquifer where tides and waves induce the emergence of an upper saline recirculation cell beneath the intertidal zone. The application of geotechnical methods contributed to removing much of the ambiguity associated with distinguishing between geological and water quality contributions to geophysical measurements, highlighting the homogeneity of the aquifer under study. As a consequence, resistivity variations were attributable to changes in salinity and one of the clearest assessments to date of salinity distribution in a real-world coastal aquifer with an IRC was achieved.

The presence of the tidally driven recirculation cell causes fresh groundwater to flow below the IRC and discharge in the vicinity of the low tide mark. ERT data suggest that resistivities of the IRC range between 1 and 3 Ωm and its thickness increases with proximity to the sea, reaching depths greater than 8 m. Resistivity increases below the IRC, but declines moving towards the low water mark indicating a mixing zone between saline water and the freshwater discharge. These data suggest that the mixing zone separating pure freshwater from pure saltwater spreads more than 60 m in the intertidal zone below the IRC, which differs from field investigations performed by Urish and McKenna (2004) and Abarca et al. (2013) who reported a significant increase in salinity landward at the base of the aquifers. By contrast, the salinity patterns identified at Magilligan agree with those simulated numerically by Evans and Wilson (2016), highlighting the relevance of the present investigation based on field measurements in a relatively homogeneous aquifer to verify and assess the value of laboratory/modeling studies and their ability to predict up-scaled responses of the SI phenomenon. The resistivity values determined using the ERT technique were proven accurate and reliable when compared them with values obtained directly with the HPT system and indirectly from groundwater samples by applying Archie’s law. However, the combined interpretation of the ERT profiles and HPT data contributed to improve the understanding of site hydrogeology and salinity distribution. The upward component of groundwater flow from depth derived from HPT data, along with the increase in resistivity determined in ERT profiles in the vicinity of the mean low water mark, allowed to identifying zones of fresh/brackish water discharge penetrating through the IRC.

The present research work demonstrated the usefulness of the combined application of CPT, HPT and ERT techniques, coupled water quality sampling, in the development of robust hydrogeological conceptual models in sandy beach environments (20% of the world’s coast) by assisting in: (1) quantifying geological heterogeneities; (2) mapping groundwater-salinity distribution in three dimensions; (3) removing much of the ambiguity associated with distinguishing between geological and water quality contributions to geophysical measurements; (4) defining the groundwater-flow regime in three dimensions; (5) increasing the reliability of the data collected by comparing measurements taken at different scales using different techniques; and (6) selecting appropriate petrophysical relationships to transform geophysical variables into hydrogeological ones and vice versa.

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Author contributions JFÁ: Conceptualization; JFÁ, MCM: Methodology; JFÁ: Formal analysis; JFÁ, MCM, AR: Investigation; JFÁ: Visualization; JFÁ: Writing—Original Draft: MCM, RF, AR, EMB, GE, SD: Writing—Review & Editing; RF, AR, EMB, GE, SD: Validation; RF, AR, SD: Resources; RF, GAH: Supervision; GAH: Project administration; GAH: Funding acquisition.

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Data availability The data collected and analyzed in this research work are available at https://osf.io/tqamf/?view_only=c50a428c8a414153b6ef31fa80512371.

Code availability Not applicable.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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References

Abarca E, Karam H, Hemond HF, Harvey CF (2013) Transient groundwater dynamics in a coastal aquifer: the effects of tides, the lunar cycle, and the beach profile. Water Resour Res 49:2473–2488. https://doi.org/10.1002/wrcr.20075

Águila JF, Samper J, Pisani B (2019) Parametric and numerical analysis of the estimation of groundwater recharge from water-table fluctuations in heterogeneous unconfined aquifers. Hydrogeol J 27:1309–1328. https://doi.org/10.1007/s10040-018-1908-x

Águila JF, McDonnell M, Flynn R, Hamill G, Etsias G, Benner E (2020) Comparison of saturated hydraulic conductivity estimated by hydraulic and indirect methods in a coastal sand aquifer at Magilligan (Northern Ireland). Civil Engineering Research in Ireland 2020, 571–576. Cork, Ireland. ISBN 978-0-9573957-4-9

APHA (1995) Standard methods for the examination of water and wastewater, 19th edn. American Public Health Association Inc., New York

Archie GE (1942) The electrical resistivity log as an aid in determining some reservoir characteristics. Trans AIME 146:54–62. https://doi.org/10.2118/942054-g

Ayachit U (2015) The ParaView guide: a parallel visualization application (ParaView 4.3 ed.). Kitware, Incorporated

Azizi F, Vadiati M, Moghaddam AA, Nazemi A, Adamowski J (2019) A hydrogeological-based multi-criteria method for assessing the vulnerability of coastal aquifers to saltwater intrusion. Environ Earth Sci 78:548. https://doi.org/10.1007/s12665-019-8556-x

Bakhtyar R, Brovelli A, Barry DA, Robinson C, Li L (2013) Transport of variable-density solute plumes in beach aquifers in response to oceanic forcing. Adv Water Resour 53:208–224. https://doi.org/10.1016/j.adwres.2012.11.009

Benner EM, McDonnell M, Águila JF, Flynn R, Hamill G, Etsias G (2020) Tidal generation of saltwater recirculation cells on coastal beaches: computational models of Magilligan aquifer. Civil Engineering Research in Ireland 2020, 582–586. Cork, Ireland. ISBN 978-0-9573957-4-9

Boufadel MC (2000) A mechanistic study of nonlinear solute transport in a groundwater-surface water system under steady state and transient hydraulic conditions. Water Resour Res 36(9):2549–2565. https://doi.org/10.1029/2000wr900159

Buquet D, Sirieux C, Anschütz P, Malaurent P, Charbonnier C, Naessens F, Bujan S, Lecroart P (2016) Shape of the shallow aquifer at the fresh water-sea water interface on a high-energy sandy beach. Estuar Coast Shelf Sci 179:79–89. https://doi.org/10.1016/j.ecss.2015.08.019

Cai G, Liu S, Puppala AJ (2011) Comparison of CPT charts for soil classification using PCPT data: example from clay deposits in Jiangsu Province, China. Eng Geol 121(1–2):89–96. https://doi.org/10.1016/j.enggeo.2011.04.016

Carrera J, Hidalgo JJ, Slooten LJ, Vázquez-Suñé E (2010) Computational and conceptual issues in the calibration of seawater intrusion models. Hydrogeol J 18:131–145. https://doi.org/10.1007/s10040-009-0524-1

Carter RWG (1975) Recent changes in the coastal geomorphology of the Magilligan foreland, Co. Londonderry. Royal Irish Acad Chem Sci 75:469–497

Carter RWG, Lowry P, Stone GW (1982) Sub-tidal ebbe-shoal control of shoreline erosion via wave refraction, Magilligan foreland, Northern Ireland. Mar Geol 48:M17–M25. https://doi.org/10.1016/0025-3227(82)90126-8

Cimino A, Cosentino C, Oteni A, Tranchina L (2008) A geophysical and geochemical approach for seawater intrusion assessment in the Acquedolci coastal aquifer (Northern Sicily). Environ Geol 55:1473. https://doi.org/10.1007/s00254-007-1097-8

Comte JC, Wilson C, Ofterdinger U, González-Quirós A (2017) Effect of volcanic dykes on coastal groundwater flow and saltwater intrusion: a field-scale multiphysics approach and parameter evaluation. Water Resour Res 53:2171–2198. https://doi.org/10.1002/2016WR019480

Cooper HH (1959) A hypothesis concerning the dynamic balance of fresh water and salt water in a coastal aquifer. J Geophys Res 64(4):461–467. https://doi.org/10.1029/JZ064i004p00461

Cosenza P, Marmet E, Rejiba F, Cui YJ, Tabbagh A, Charley Y (2006) Correlations between geotechnical and electrical data: a case study at Garchy in France. J Appl Geophy 60:165–178. https://doi.org/10.1016/j.jappgeo.2006.02.003

Costall A, Harris B, Pigois JP (2018) Electrical resistivity imaging and the saline water interface in high-quality coastal aquifers. Surv Geophys 39:753–816. https://doi.org/10.1007/s10712-018-9468-0

Custodio E (2010) Coastal aquifers of Europe: an overview. Hydrogeol J 18:269–280. https://doi.org/10.1007/s10040-009-0496-1

Dezert T, Fargier Y, Lopes SP, Côte P (2019) Geophysical and geotechnical methods for fluvial levee investigation: a review. Eng Geol. https://doi.org/10.1016/j.enggeo.2019.105206

Dimova MT, Swarzenski PW, Dulaiova H, Glenn CR (2012) Utilizing multichannel electrical resistivity methods to examine the dynamics of the fresh water–seawater interface in two Hawaiian groundwater systems. J Geophys Res 117:C02012. https://doi.org/10.1029/2011J C0075 09

Eissa MA, Mahmoud HH, Shouakar-Stash O, El-Shiek A, Parker B (2016) Geophysical and geochemical studies to delineate seawater intrusion in Bagoush area, Northwestern coast, Egypt. J Afr Earth Sci 121:365–381. https://doi.org/10.1016/j.jafrearsci.2016.05.031

Etsias G, Hamill GA, Benner EM, Águila JF, McDonnell MC, Flynn R, Ahmed AA (2020) Optimizing laboratory investigations of saline intrusion by incorporating machine learning techniques. Water 12(11):2996. https://doi.org/10.3390/w12112996

Etsias G, Hamill GA, Águila JF, Benner EM, McDonnell MC, Ahmed AA, Flynn R (2021a) The impact of aquifer stratification on saltwater intrusion characteristics. Comprehensive laboratory and numerical study.Hydrod Process 35(4):e14120. https://doi.org/10.1002/hyp.14120

Etsias G, Hamill GA, Campbell D, Straney R, Benner EM, Águila JF, McDonnell MC, Ahmed AA, Flynn R (2021b) Laboratory and numerical investigation of saline intrusion in fractured coastal aquifers. Adv Water Resour 149:103866. https://doi.org/10.1016/j.adwres.2021.103866

Etsias G, Hamill GA, Thomson C, Kennerley S, Águila JF, Benner EM, McDonnell MC, Ahmed AA, Flynn R (2021c) Laboratory and numerical study of saltwater upconing in fractured coastal aquifers. Water 13(11):2996. https://doi.org/10.3390/w13112996

Evans TB, Wilson AM (2016) Groundwater transport and the freshwater–saltwater interface below sandy beaches. J Hydrol 528:563–573. https://doi.org/10.1016/j.jhydrol.2016.04.014

Fischer P, Wunderlich T, Rabbel W, Vött A, Willershäuser T, Baika K, Rigakou D, Metallinou G (2016) Combined Electrical Resistivity
Tomography (ERT), Direct-Push Electrical Conductivity (DP-EC) logging and coring - a new methodological approach in geoarchaeological research. Archaeol Prospect 23(3):213–228. https://doi.org/10.1002/arp.1542

Franco R, Biella G, Tosi L, Teatini P, Lozej A, Chiozotto B, Giada M, Rizzetto F, Claude C, Mayor A, Bassan V, Gasparetto-Stori G (2009) Monitoring the saltwater intrusion by time lapse electrical resistivity tomography: The Chioggia test site (Venice Lagoon, Italy). J Appl Geophy 69:117–130. https://doi.org/10.1016/j.jappgeo.2009.08.004

Freeze RA, Cherry JA (1979) Groundwater. Prentice Hall, Englewood Cliffs

Goebl M, Pidlisecky A, Knight R (2017) Resistivity imaging reveals complex pattern of saltwater intrusion along Monterey coast. J Hydrol 551:746–755. https://doi.org/10.1016/j.jhydrol.2017.02.037

González-Quirós A, Comte JC (2020) Relative importance of conceptual and computational errors when delineating saltwater intrusion from resistivity inverse models in heterogeneous coastal aquifers. Adv Water Resour. https://doi.org/10.1016/j.adwres.2020.103695

Greskowiak J (2014) Tide-induced salt-fingering flow during subma-

Goebel M, Pidlisecky A, Knight R (2017) Resistivity imaging reveals complex pattern of saltwater intrusion along Monterey coast. J Hydrol 551:746–755. https://doi.org/10.1016/j.jhydrol.2017.02.037

Han Q, Chen D, Guo Y, Hu W (2018) Saltwater-freshwater mixing fluctuation in shallow beach aquifers. Estuar Coast Shelf Sci 200:93–103. https://doi.org/10.1016/j.ecss.2018.03.027

Harr ME. (1987) Reliability-based design in civil engineering. McGraw-Hill, New York

Heiss JW, Michael HA (2014) Saltwater-freshwater mixing dynamics in a sandy beach aquifer afer tidal, spring-neap, and seasonal cycles. Water Resour Res 50:6747–6766. https://doi.org/10.1002/2014WR015574

Henderson RD, Day-Lewis FD, Abarca E, Harvey CF, Karam HN, Liu LB, Lane JW (2010) Marine electrical resistivity imaging of submarine groundwater discharge: sensitivity analysis and application in Waquoit Bay, Massachusetts, USA. Hydrogeol J 18:173–185. https://doi.org/10.1007/s10040-009-0498-z

Hermans T, Vandenbohede A, Lebbe L, Martin R, Kemna A, Beau-

deur H, Schamper C, Burschil T, Roth B, Kirsch R, Auken E (2012) Transboundary geophysical mapping of geological elements and salinity distribution critical for the assessment of future sea water intrusion in response to sea level rise. Hydrol Earth Syst 16:1845–1862. https://doi.org/10.5194/hess-16-1845-2012

Jiao J, Post V (2019) Coastal hydrogeology. Cambridge University Press. https://doi.org/10.1017/9781139334142

Jørgensen F, Scheer W, Thomsen S, Sonnenborg TO, Hinsby K, Wiederhold H, Schamper C, Burschil T, Roth B, Kirsch R, Auken E (2012) Transboundary geophysical mapping of geological elements and salinity distribution critical for the assessment of future sea water intrusion in response to sea level rise. Hydrol Earth Syst 16:1845–1862. https://doi.org/10.5194/hess-16-1845-2012

Kazakis N, Pavlou A, Vargemizis G, Voudouris KS, Soulios G, Pliakas F, Tsokas G (2016) Seawater intrusion mapping using electrical resistivity tomography and hydrochemical data. An application in the coastal area of eastern Thermaikos Gulf, Greece. Sci Total Env 543:373–387. https://doi.org/10.1016/j.scitotenv.2015.11.041

Ketabchi H, Jahangir MS (2021) Influence of aquifer heterogeneity on sea level rise-induced seawater intrusion: a probabilistic approach. J Contam Hydrol. https://doi.org/10.1016/j.jconhyd.2020.103753

Klassen J, Allen DM, Kirste D (2014) Chemical Indicators of Saltwater Intrusion for the Gulf Islands, British Columbia. Department of Earth Science, BC Ministry of Forests, Lands and Natural Resource Operations and BC Ministry of Environment. http://www.sfu.ca/personal/dallen/Chemical%20Indicators%20of%20SWI_Final.pdf. Accessed 5 November 2021.

Kohout F (1960) Cyclic flow of salt water in the Biscayne aquifer of southeastern Florida. J Geophys Res 65(7):2133–2141. https://doi.org/10.1029/JZ065i007p02133

Kouzana L, Benassi R, Ben Mammou A, Sfar Felfoul M (2010) Geo-

Kreyns P, Geng X, Michael HA (2020) The influence of connected heterogeneity on groundwater flow and salinity distributions in coastal volcanic aquifers. J Hydrol. https://doi.org/10.1016/j.jhydrol.2020.124863

Kuan WK, Jin G, Xin P, Robinson C, Gibbes B, Li L (2012) Tidal influence on seawater intrusion in unconfined coastal aquifers. Water Resour Res 48:W02502. https://doi.org/10.1029/2011WR010678

Kura NU, Ramlit MF, Ibrahim S, Sulaiman WNA, Aris AZ (2014) An integrated assessment of seawater intrusion in a small tropical island using geophysical, geochemical, and geostatistical techniques. Environ Sci Pollut Res 21:7047–7064. https://doi.org/10.1007/s11356-014-2598-0

Lebbe L. (1999) Parameter identification in fresh-saltwater flow based on borehole resistivities and freshwater head data. Adv Water Resour 22(8):791–806. https://doi.org/10.1016/S0309-1798(98)00054-2

Lesmes DP, Friedman SP (2005) Relationships between the electrical and hydrogeological properties of rocks and soils. In: Rubin Y, Hubbard SS (eds) Hydrogeophysics. Springer, Dordrecht

Li X, Hu BX, Tong J (2016) Numerical study on tide-driven submarine groundwater discharge and seawater recirculation in heterogeneous aquifers. Stoch Env Res Risk A 30:1741–1755. https://doi.org/10.1007/s00477-015-1200-8

Loke MH, Acworth I, Dahlin T (2003) A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys. Explor Geophys 34(3):182–187. https://doi.org/10.1071/EG03182

Loke MH (2006) RES2DINV ver.3.55, Rapid 2-D resistivity and IP inversion using the least-squares method. Geotomo Software Manual. Penang, Malaysia

Lumme T, Robertson PK, Powell JJM (1997) Cone penetration testing in geotechnical practice. CRC Press

Martínez J, Benavente J, García-Aróstegui JL, Hidalgo MC, Rey J (2009) Contribution of electrical resistivity tomography to the study of detrital aquifers affected by seawater intrusion–extrusion effects: The river Vélez delta (Vélez-Málaga, southern Spain). Geol Eng 108(3–4):161–168. https://doi.org/10.1016/j.geologie.2009.07.004

Masselink G, Koon A (2009) Morphology and morphodynamics of sandy beaches. Coastal Zones and Estuaries. Encyclopedia of Life Support Systems (EOLSS), pp 221–243

McCall W (2011) Application of the Geobrobe® HPT logging system for geo-environmental investigations. Geobrobe® Technical Bulletin No. MK3184. Salina, Kansas: Kejr, Inc

McCall W, Christy TM, Pipp D, Terkelsen M, Christensen A, Weber K, McInnis D, Silliman S, Boukari M, Yalo N, Orou-Pete S, Fertenbaugh C, Sarre K, Fayomi H (2013) Combined application of electrical and geoarchaeological research. Archaeol Prospect 23(3):213–228. https://doi.org/10.1002/arp.1542

McCall W (2011) Application of the Geobrobe® HPT logging system for geo-environmental investigations. Geobrobe® Technical Bulletin No. MK3184. Salina, Kansas: Kejr, Inc

McCall W, Christy TM, Pipp D, Terkelsen M, Christensen A, Weber K, Engelsen P (2014) Field application of the combined membrane-interface probe and hydraulic profiling tool (MiHpt). Groundwa-

McCann N (1988) An assessment of the subsurface geology between Magilligan point and fair head, Northern Ireland. Irish J Earth Sci 9:71–78

McInnis D, Silliman S, Boukari M, Yalo N, Orou-Pete S, Fertenbaugh C, Sarre K, Fayomi H (2013) Combined application of electrical
Characterization and engineering properties of natural soils. Taylor & Francis, London

Vandenbohede A, Lebbe L (2005) Occurrence of salt water above fresh water in dynamic equilibrium in a coastal groundwater flow system near De Panne, Belgium. Hydrogeol J 14:462–472. https://doi.org/10.1007/s10040-005-0446-5

Vithanage M, Engesgaard P, Jensen KH, Illangasekare TH, Obeysekera J (2012) Laboratory investigations of the effects of geologic heterogeneity on groundwater salinization and flush-out times from a tsunami-like event. J Contam Hydrol 136–137:10–24. https://doi.org/10.1016/j.jconhyd.2012.05.001

Waska H, Greskowiak J, Ahrens J, Beck M, Ahmerkamp S, Böning P, Brumsack HJ, Degenhardt J, Ehlert C, Engelen B, Grünenbaum B, Holtappels M, Pahne K, Marchant HK, Massmann G, Meier D, Schnetger B, Schwalfenberg K, Simon H, Vandieken V, Zielinski O, Dittmar T (2019) Spatial and temporal patterns of pore water chemistry in the inter-tidal zone of a high energy beach. Front Mar Sci 6:154. https://doi.org/10.3389/fmars.2019.00154

Weinstein Y, Burnett WC, Swarzenski PW, Shalem Y, Yechieli Y, Herut B (2007) Role of aquifer heterogeneity in fresh groundwater discharge and seawater recycling: an example from the Carmel coast, Israel. J Geophys Res. https://doi.org/10.1029/2007JC004112

Werner AD, Simmons CT (2009) Impact of sea-level rise on sea water intrusion in coastal aquifers. Groundwater 47(2):197–204. https://doi.org/10.1111/j.1745-6584.2008.00535.x

Werner AD, Bakker M, Post VEA, Vandenbohede A, Lu C, Ataie-Ashtiani B, Simmons CT, Barry DA (2013) Seawater intrusion processes, investigation and management: recent advances and future challenges. Adv Water Resour 51:3–26. https://doi.org/10.1016/j.adwatre.2012.03.004

Xin P, Robinson C, Li L, Barry DA, Bakhtyar R (2010) Effects of wave forcing on a subterranean estuary. Water Resour Res 46:W12505. https://doi.org/10.1029/2010WR009632

Yang J, Graf J, Ptak T (2015) Sea level rise and storm surge effects in a coastal heterogeneous aquifer: a 2D modelling study in northern Germany. Grundwasser 20:39–51. https://doi.org/10.1007/s00767-014-0279-z

Yu X, Michael HA (2019) Offshore pumping impacts onshore groundwater resources and land subsidence. Geophys Res Lett 46(5):2553–2562. https://doi.org/10.1029/2019GL081910

Yu X, Xin P, Lu C (2019) Seawater intrusion and retreat in tidally-affected unconfined aquifers: laboratory experiments and numerical simulations. Adv Water Resour 132:103393. https://doi.org/10.1016/j.advwatres.2019.103393

Zhang X, Lin CM, Dalrymple RW, Gao S, Canas DT (2018) Use of the Cone Penetration Testing (CPT) method to interpret late Quaternary tide-dominated successions: a case study from the eastern China coastal plain. Cont Shelf Res 161:49–57. https://doi.org/10.1016/j.csr.2018.03.012

Zhang Y, Li L, Erler DV, Santos S, Lockington D (2017) Effects of beach slope breaks on nearshore groundwater dynamics. Hydrol Process 31(14):2530–2540. https://doi.org/10.1002/hyp.11196

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