



Time-lapse resistivity imaging and self-potential monitoring of experimentally induced saline intrusion in coastal aquifer sands

Jesús F. Águila^{a,*}, Thomas S.L. Rowan^b, Mark C. McDonnell^a, Raymond Flynn^a, Shane Donohue^c, Matthew D. Jackson^d, Adrian P. Butler^b, Gerard A. Hamill^a, Eric M. Benner^a, Georgios Etsias^a

^a School of Natural and Built Environment, Queen's University Belfast, Belfast, Northern Ireland, United Kingdom

^b Department of Civil and Environmental Engineering, Imperial College London, United Kingdom

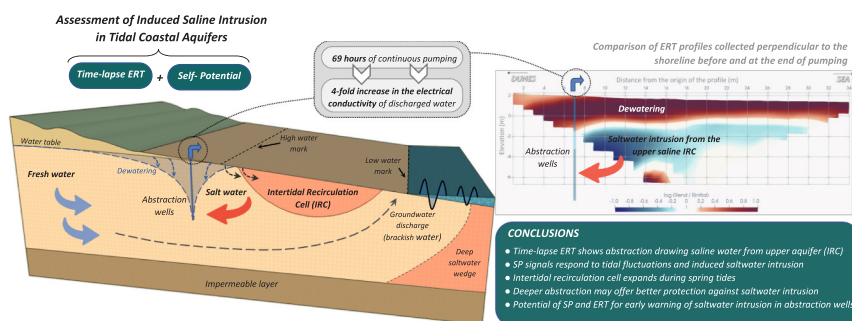
^c School of Civil Engineering, University College Dublin, Dublin, Ireland

^d Department of Earth Science and Engineering, Imperial College London, United Kingdom

HIGHLIGHTS

- Saltwater intrusion from abstraction in coastal aquifer mapped by time-lapse ERT
- Self-Potential signals respond to tidal fluctuations and induced saltwater intrusion
- Intertidal recirculation cell expands during spring tides
- Deeper abstraction may offer better protection against saltwater intrusion
- Potential of SP and ERT for early warning of saltwater intrusion in abstraction wells

GRAPHICAL ABSTRACT



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ABSTRACT

Excessive groundwater abstraction in coastal areas exacerbates saltwater intrusion (SWI), a widespread global issue. Characterization of mechanisms delivering saltwater to wells can assist in developing suitable SWI mitigation strategies for reducing the risk of groundwater degradation. This paper presents findings from hydro-geological monitoring, time-lapse electrical resistivity tomography (ERT) and self-potential (SP) measurements to investigate SWI under natural and artificially perturbed conditions in a quasi-homogeneous pristine coastal sand aquifer, affected by large tidal ranges (>2 m). Time-lapse ERT surveys conducted under undisturbed conditions identified an upper saline recirculation cell (IRC) beneath the intertidal zone, arising due to seawater infiltrating into an underlying ~20 m thick sand sequence containing fresher groundwater, with resistivity variations noted between spring and neap tides. Measurements taken during a 69-h constant-rate pumping test, discharging at 10.2 L/s, revealed that pumping drew saline water from the IRC towards abstraction wells. This resulted in saltwater contributions to discharge increasing from 1.4 to 4.1 %, consistent with the decrease in resistivity detected in ERT profiles between 3 m and 7 m below surface. Over the same period, SP signals fell by between 20 and 30 mV with greater declines occurring at locations nearer to the high-water mark. Monitoring data suggest that these changes in SP are primarily due to saline water intrusion from the IRC, rather than

* Corresponding author.

E-mail address: jesus.fdz.aguila@hotmail.com (J.F. Águila).

pressure changes resulting from pumping. Research findings provide further evidence that SP monitoring could act as a key geophysical early warning parameter for SWI, while ERT data further highlight the potential for monitoring SWI in shallow coastal aquifers. This study also demonstrates that optimal groundwater abstraction strategies in tidal-influenced coastal aquifers can be achieved by targeting deeper zones.

1. Introduction

Projected growth in the world's population over the next 50 years will occur disproportionately in coastal areas, placing further pressure on already stressed groundwater resources (Neumann et al., 2015). With projected sea level rises due to climate change, and the global growth in water consumption projected to increase at a rate of about 1 % per year (WWAP, 2018), this issue is expected to become more pressing over the next decades (Bouderbala, 2019; Amanambu et al., 2020; Atawneh et al., 2021; Richardson et al., 2024). Anthropogenic activities, such as excessive groundwater abstraction and reduction of groundwater recharge due to urbanization of coastal areas, can accentuate saltwater intrusion (SWI) processes, which naturally arise from density contrasts between fresh and salt water (Águila et al., 2019; Mehdizadeh et al., 2019; Olarinoye et al., 2020). This phenomenon highlights the critical need to not only address current overexploitation of coastal aquifers but also for an improved understanding of the pathways through which seawater permeates the subsurface, thereby informing more effective management strategies (Hussain et al., 2019; Basack et al., 2022).

As a result of its higher density, salt water typically underlies fresh water. This causes the classical or deep salt water wedge observed in both confined and unconfined aquifers and the focus of many SWI investigations (e.g. Cooper, 1959; Kohout, 1960; Schincariol and Schwartz, 1990; Zhang et al., 2002; Goswami and Clement, 2007; Kerrou and Renard, 2009; Lu et al., 2013; Etsias et al., 2020, 2021a, 2021b, 2021c). Under these circumstances, fresh water from coastal deposits discharge to the sea by flowing over the deeper salt water wedge, while simultaneous mixing processes caused by diffusion and dispersion take place (Smith, 2004; Abarca et al., 2007; Tur-Piedra et al., 2024). This contrasts with groundwater salinity patterns in unconfined aquifers in some tidal areas, where an upper saline recirculation cell can develop beneath the intertidal zone. This is widely referred to as the Intertidal Recirculation Cell (IRC) or Upper Saline Plume (USP), and is generated by the infiltration of seawater (Robinson et al., 2007a). The fundamental processes underpinning SWI in aquifers with an IRC have been understood for some time, based on findings from laboratory tests and modeling (Xin et al., 2010; Kuan 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; Abarca et al., 2013; Heiss and Michael, 2014; Zhang et al., 2017). However, comprehensive field studies, where the drivers leading to SWI have been confidently demonstrated in natural deposits, remain scarce in the literature (Urish and McKenna, 2004; Henderson et al., 2010; Buquet et al., 2016; Águila et al., 2022; McDonnell et al., 2023). Moreover, uncontrolled groundwater abstraction complicates responses observed, making definitive attribution of responses to particular wells challenging. Conversely studies of SWI in pristine groundwater bodies, otherwise unaffected by groundwater abstraction prove rare (Custodio, 2009; Ferguson and Gleeson, 2012).

Assessment of temporal variations in groundwater salinity in natural deposits has been limited by restricted access to the subsurface, via observation wells. This gives rise to uncertainties concerning underpinning mechanisms, leading to observed variations in water quality (Nilsson et al., 2007), while these are further complicated by abstractions, which alter natural groundwater flow regimes (Sahoo and Jha, 2017; Radulovic et al., 2020). By contrast, geophysical methods display considerable scope to more comprehensively characterize subsurface conditions in space and time, through the measurement of contrasts in physical properties of soil/rock and pore fluid (Reynolds, 2011).

Consequently, the resistivity contrast between fresh and salt water has led to the wide use of geophysical methods such as the electrical resistivity tomography (ERT) technique in SWI investigations (Martínez et al., 2009; Dimova et al., 2012; Hermans et al., 2012; Kazakis et al., 2016; Goebel et al., 2017; Balwant et al., 2021; Niculescu and Andrei, 2021; Águila et al., 2022; Obakhume, 2022; McDonnell et al., 2023). The value of this approach improves significantly when combined with detailed characterization of soil heterogeneities, from intrusive investigation, to facilitate calibration of geophysical data, thus making it possible to more confidently distinguish intervals containing changes in salinity within geological features (Szalai et al., 2009; Michael et al., 2016; González-Quirós and Comte, 2020).

The benefits of geophysical techniques may be further extended through time-lapse ERT to facilitate detection of temporal variations in electrical properties of the subsurface. Leroux and Dahlin (2006) carried out time-lapse resistivity investigations for imaging saltwater transport in glaciofluvial deposits, while De Carlo et al. (2020) applied time-lapse ERT to determine the impact of using brackish wastewater for irrigation. This approach has also been successfully applied to assess SWI in coastal aquifers. Franco et al. (2009) applied the time-lapse ERT to monitor saltwater intrusion dynamics, highlighting the value of this technique to evaluate multi-scale contaminant variations at different time scales. Ronczka et al. (2015) investigated model resolution properties when monitoring saltwater intrusion in a shallow aquifer by using single time step and time lapse inversion of ERT data. McDonnell et al. (2023) demonstrated the potential of time-lapse ERT to monitor pumping-induced SWI in coastal aquifers. Moreover, the time-lapse ERT method was combined with other techniques, with the aim of improving the characterization of coastal environments. For instance, Inim et al. (2020) further demonstrated the value of time-lapse ERT combined with vertical electrical soundings (VES) to identify the spatial and temporal changes of salinity patterns in coastal aquifers. Similarly, Palacios et al. (2020) showed that the combined use of CHERT (cross-hole ERT) and surface ERT improves model resolution for imaging the SWI and monitoring its dynamics through time-lapse acquisitions. Moreover, Folch et al. (2020) combined fiber optic distributed temperature sensing, cross-hole ERT and time-lapse induction logging to evaluate temporal variations of a coastal aquifer at different spatial scales. Despite the aforementioned research, Costall et al. (2018) highlighted the scarcity of publications of time-lapse ERT for monitoring SWI dynamics, emphasizing the need to advance this field to facilitate accurate reconstruction of coastal hydrogeology and, in particular, the seawater interface in time and space for electrical resistivity imaging, especially beneath the intertidal zone (rarely captured by ERT surveys).

Another geophysical technique, which has been applied in coastal environments and has demonstrated potential as a predictor of SWI in groundwater boreholes, is the self-potential or spontaneous potential (SP) method (Graham et al., 2018; MacAllister et al., 2018). Self-potential voltages arise from subsurface pressure and concentration gradients (Jackson et al., 2012). These gradients can cause ion separation, which gives rise to an electrical potential and a flow of electrons in order to maintain electrical neutrality. The potentials, typically in the millivolt range, can be detected and logged in the field. Contributors to the total signal typically subdivide into electro-kinetic potentials (V_{EK}), due to differential flow velocities, and exclusion-diffusion potentials (V_{ED}), due to ion concentration gradients with different mobilities. MacAllister et al. (2016) installed a downhole array of SP electrodes on the south coast of England to monitor the temporal behavior of SP signals in a coastal chalk aquifer. A later study revealed that a consistent

vertical electrical potential gradient exists within a coastal groundwater borehole that had previously been affected by SWI, whereas this gradient was absent in boreholes further inland (Graham et al., 2018). MacAllister et al. (2016) also investigated dynamic SP responses and concluded that these responses were primarily driven by ocean tides. They further found that the movement of saline water, occurring some distance away from the monitoring boreholes, generated a distinct SP signal in advance of saline breakthrough at the borehole. Supported by simulations of geoelectrical responses to the movement of saline water by Graham et al. (2018), this suggested that SP could be a useful tool for the proactive management of abstraction and saline intrusion in coastal aquifers (MacAllister et al., 2018). However, and as highlighted in prior research, distinguishing relative contributions to SP signals remains challenging, in part due to the complicating effects of geological heterogeneity (Graham et al., 2018). Demonstrating the broad applicability of SP as a predictor of SWI requires further investigations at additional sites, with different hydrogeological conditions, ideally under more homogeneous conditions.

The combination of time-lapse electrical resistivity and self-potential methods has been demonstrated for several applications, including groundwater flow monitoring (Bai et al., 2021), characterization of old mine sites (Srivastava et al., 2020), locating and monitoring piping

sinkholes (Cardarelli et al., 2013), and mapping of zones affected by anaerobic degradation (Fernandez et al., 2019). However, to the best of the authors' knowledge, the combined use of both techniques for monitoring saltwater intrusion dynamics has not yet been explored.

This paper presents the findings of an investigation, employing time-lapse electrical resistivity tomography and self-potential methods, to monitor the response of experimentally induced saline intrusion during a pumping test. Investigations were conducted in a pristine coastal sand aquifer, in which tidal activity has resulted in the establishment of a saline recirculation cell, beneath the intertidal zone. Selection of a relatively homogeneous coastal sand deposit, unaffected by anthropogenic activities, facilitates interpretation of field-scale (10–100 m) investigations into the ability of time-lapse geophysics to characterize dynamics of saltwater intrusion into coastal groundwater systems experiencing tidal fluctuations, without the need to factor out the complicating influence of high levels of geological heterogeneity. At the same time, application of SP monitoring permitted the utility of the method to be further evaluated as a means of predicting imminent saltwater intrusion into coastal water supplies. This study represents the first time that time-lapse ERT and self-potential methods have been combined to monitor the saline intrusion in tidal unconfined aquifers, induced through pumping tests, on coastal aquifers.

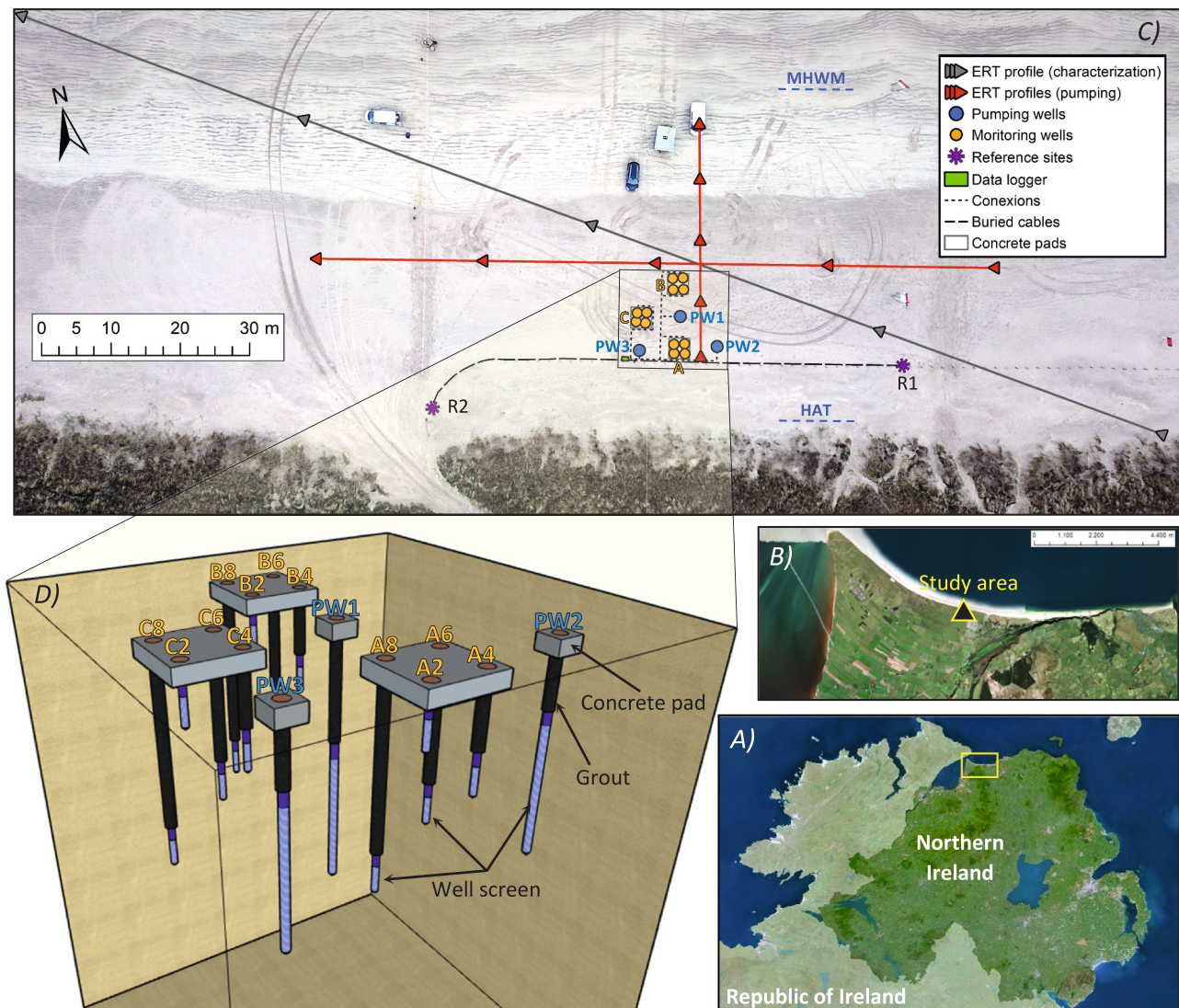


Fig. 1. Map of the study area location (A and B); positions of monitoring and pumping wells, ERT profile traces, SP reference electrodes R1 and R2, and tide markers: Mean High Water Mark (MHWM) and Highest Astronomical Tide (HAT) (C); 3D diagram showing design and layout of the wells (D).

2. Site description and instrumentation

The Magilligan Test Site (Magilligan) consists of an array of pumping boreholes and nests of observation wells installed in a beach sand complex at a horizontal distance around 30 m from the mean high water mark on Benone Strand, County Derry, Northern Ireland (Fig. 1). A belt of coastal sand dunes, immediately to the south of the site, forms part of a hydrogeological continuum that extends approximately 7 km to the west and 1.5 km to the south (Robins and Wilson, 2017). Previous geophysical and geotechnical investigations in the study area indicated that the sequence of approximately 20 m of Holocene sands underlay Magilligan that rested directly on Lr. Jurassic mudstones (Águila et al., 2022). The sand is dominated by quartz (> 90 %), although local concentrations of calcium carbonate (shell debris) and heavy minerals such as magnetite, epidote and biotite occur (Carter, 1975). Sand hydraulic conductivity ranges between 5 and 25 m/d, decreasing with depth,

while the underlying mudstone has values that are four orders of magnitude lower. Other hydrogeological parameters of the coastal aquifer include specific yield (S_y) values between 0.1 and 0.11, specific storage (S_s) values ranging from $3 \cdot 10^{-4} \text{ m}^{-1}$ to $3.5 \cdot 10^{-4} \text{ m}^{-1}$, and an effective porosity (n_e) of 0.28. The hydraulic gradient in the study area is approximately 0.006, leading to estimated groundwater velocities of 0.1–0.3 m/d. Further details on the characterization of the aquifer parameters can be found in Águila et al. (2023). Groundwater head patterns reflect recharge arising from high year-round (between 225 and 250 rain days (rainfall > 0.2 mm)) precipitation of approximately 1100 mm/year (Walsh, 2012). Annual average actual evapotranspiration of approximately 550 mm occurs predominantly between April and October (Werner et al., 2016). Water level data from both Magilligan and the adjacent dunes reveal no influence from external pumping, which is consistent with the absence of records for significant abstractions (> 100 m^3/day).

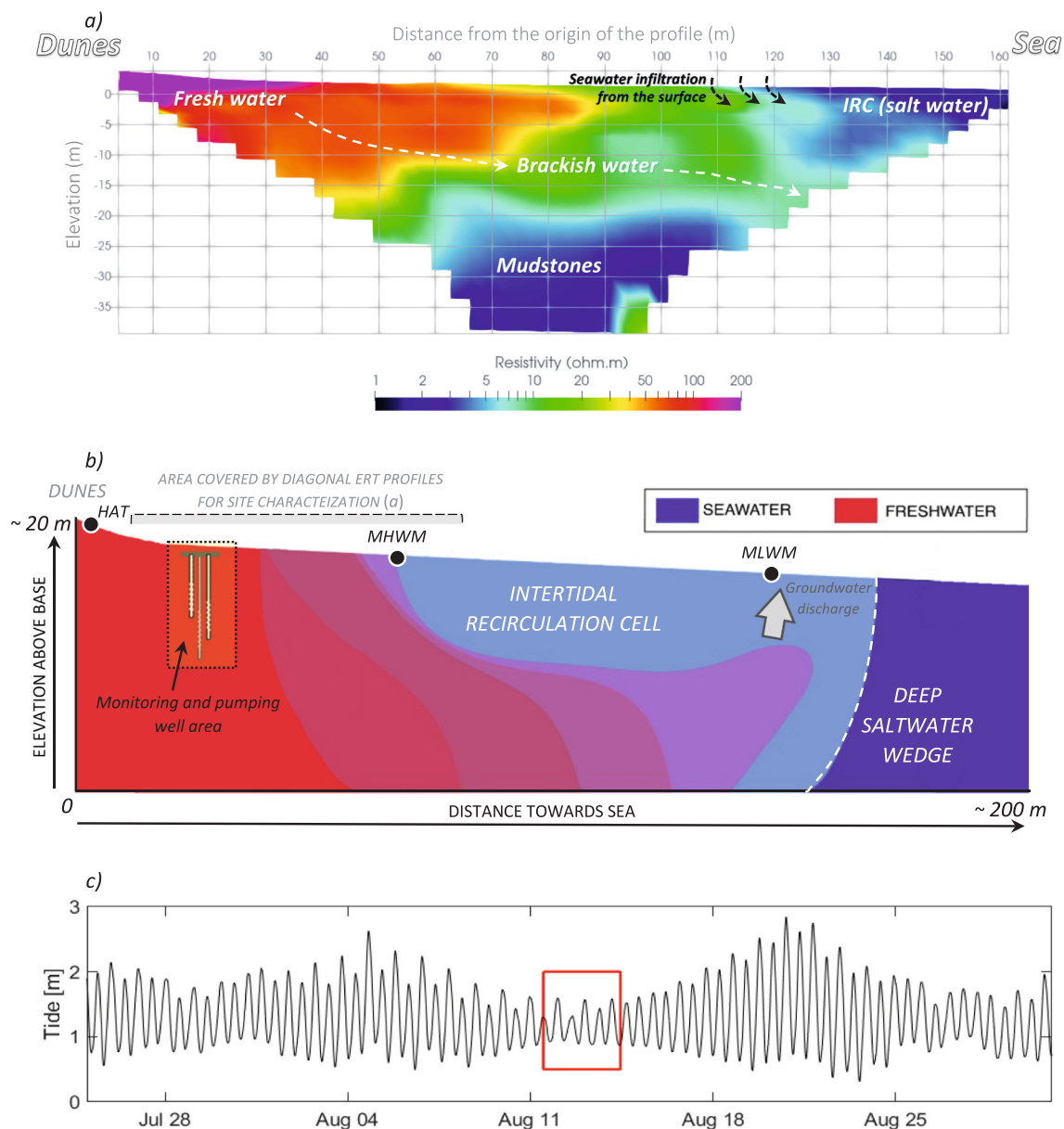


Fig. 2. ERT profile diagonal to the shoreline for the site characterization collected on 2nd July 2019 (a); cross-sectional view of the conceptual model of the spatial distribution of resistivities in the shallowest 20 m of the sand aquifer (Águila et al., 2022) (HAT: Highest Astronomical Tide, MHWM: Mean High Water Mark, MLWM: Mean Low Water Mark) (b); and tidal heights at Portrush (Northern Ireland) from 25th July to 31st August 2020, with the pumping test timeframe highlighted in Red (c).

Benone Strand has a slope of approximately 2 %, with an intertidal zone of up to 150 m wide at spring tide. Tides are semidiurnal, having an annual mean range of 1.72 m for spring tides and 0.65 m for neap tides, respectively (Fig. 2c). This regular change in sea level gives rise to an upper saline IRC, in which the uppermost parts of the beach sands become intruded by sea water from above, before being partially flushed with freshwater (Águila et al., 2022). Prior to implementing geophysical monitoring, a reconnaissance program was conducted aimed at characterizing subsurface conditions at the field site, including the application of various techniques such as Cone Penetrometer Testing, Hydraulic Profiling Tool system (HPT), ERT, and hydraulic tests. Fig. 2a shows an ERT profile generated diagonally to the shoreline (see Fig. 1 for location), summarizing the findings of the site characterization. The profile was obtained using a Syscal Pro resistivity system with 48 electrodes spaced 3.5 m, employing a dipole-dipole configuration. The ERT profile, obtained using the RES2DINV software (Loke, 2006) for data inversion, forms an angle of approximately 20° with the shoreline. A diagonal ERT profile configuration was selected for site characterization to maximize profile length and depth while adhering to site-specific constraints, including the inaccessibility of adjacent dunes designated as Special Areas of Conservation (SAC) and the need to avoid seawater exposure to the equipment during high tides. Although groundwater primarily flows perpendicular to the shoreline, from the dunes towards the sea, the 2D interpretation of diagonal provides valuable insights into the spatial distribution of resistivity patterns and supports a comprehensive understanding of the salinity dynamics. The Root Mean Square (RMS) error of the characterization ERT profile was 3.96 %. It is important to note that the precision of the ERT models decreases with depth; however, sensitivity analyses of the collected data showed that the results are particularly reliable at the primary depths of interest in this study (the uppermost 15–18 m). The supplementary material includes information on the 66 ERT profiles collected during this research, analyzing inverted models and errors for each profile.

From the information displayed in Fig. 2, combined with previous research on the site under investigation (Águila et al., 2022, 2023), it is confirmed that this is a sand deposit approximately 20 m thick. Significant ground heterogeneities are not present, making it an ideal coastal site for studying fundamental influences on variations in groundwater salinity. Although the quality of resistivity data in ERT profiles typically decreases with depth, the results from the diagonal model are consistent with previous geotechnical investigations at the site (Águila et al., 2022), supporting the reliability of the ERT models. The spatial distribution of resistivities indicates the presence of an IRC, with resistivities ranging between 1 Ω m and 3 Ω m. The IRC begins near the high water mark, approximately 120 m from the origin of the ERT profile (Fig. 2a), where saltwater infiltrates due to tidal action. The thickness of the IRC increases towards the sea, reaching depths >8 m. Freshwater, derived

from groundwater recharge in the dunes, flows inland to the intertidal zone, where it encounters the IRC. This freshwater remains unconstrained between the IRC and the aquifer base. Below the IRC, freshwater mixes with tidal saltwater (with resistivities decreasing from >100 Ω m to <10 Ω m), forming brackish water that discharges near the low tide mark (Fig. 2b). The mixing zone separating pure freshwater from pure saltwater extends >60 m into the intertidal zone below the IRC. In summary, the different techniques employed confirm a conceptual model where tides control the coastal groundwater dynamics in the shallow aquifer of Magilligan; this includes saltwater infiltrating from the surface in the intertidal zone, leading to the emergence of an upper saline IRC and a decrease in water salinity with depth. For more details, see Águila et al. (2022, 2023).

Table 1 provides details of wells installed across the site. The three pumping wells (PW1, PW2 and PW3), along with three clusters, containing four observation wells, were installed south (landwards) of the mean high water mark (HWM) (Fig. 1). The wells were drilled using a percussion rig and constructed with PVC casing and screens, featuring five-millimeter screen slots wrapped in a 300 μ m geotextile for additional filtration. Well depths ranged between 2 and 10 m, with the well screens positioned at the base of the boreholes. Bentonite/Ordinary Portland Cement (OPC) grout was placed between 0.5 and 1 m above the well screens and extended to the ground surface to ensure proper sealing. One of the pumping wells was installed closer to the shoreline to draw saline water, while the other two were located further inland to intercept freshwater contributions from the dune system. All observation wells were capped with a watertight seal and vented to a location around 30 m away from the mean HWM. The beach morphology varies over time due to tidal dynamics and meteorological conditions (Anfuso et al., 2020), so the references to tidal marks included in Fig. 1c should be considered approximate. Solinst Levellogger probes (5 m range), installed in all wells, permitted water level monitoring over the duration of the investigation.

Non-polarizing Silvion Ag/AgCl WE300 potable water electrodes, placed in each of the twelve observation wells, permitted continuous monitoring of SP. In addition, the two reference electrodes (R1 and R2) were encased in bentonite and installed at a depth of approximately 1 m, at locations above the spring high tide mark (see Fig. 1). Electrodes in the WE300 probes were surrounded by 0.05 M KCl gel and a low permeability ceramic disk to ensure stable contact with either the borehole water or beach sand. The probes were connected to a Campbell Scientific CR3000 data logger, using shielded coaxial cable, where the shield is connected to R2, as a communal ground.

3. Material and methods

A constant discharge pumping test was conducted at Magilligan

Table 1
Characteristics of the monitoring and pumping wells installed at the Magilligan test site.

Well ID	Diameter (mm)	Application	Monitoring devices	Screened Depth (metres b.g.s.)	Latitude	Longitude
PW1	150	Pumping	–	5–10	55.169231	–6.884934
PW2	150	Pumping	–	5–8	55.169203	–6.885058
PW3	150	Pumping	–	5–8	55.169226	–6.885051
A2	150	Monitoring	Levellogger + SP probe	1–2	55.169184	–6.885005
A4	100	Monitoring	Levellogger + Barologger + SP probe	3–4	55.169182	–6.885008
A6	100	Monitoring	Levellogger + SP probe	5–6	55.169185	–6.885013
A8	100	Monitoring	Levellogger + SP probe	7–8	55.169187	–6.885017
B2	100	Monitoring	Levellogger + SP probe	1–2	55.169378	–6.884951
B4	100	Monitoring	Levellogger + SP probe	3–4	55.169372	–6.884953
B6	100	Monitoring	Levellogger + SP probe	5–6	55.169374	–6.884964
B8	100	Monitoring	Levellogger + SP probe	7–8	55.169372	–6.884968
C2	100	Monitoring	Levellogger + SP probe	1–2	55.169257	–6.885072
C4	100	Monitoring	Levellogger + SP probe	3–4	55.169251	–6.885071
C6	100	Monitoring	Levellogger + SP probe	5–6	55.169254	–6.885087
C8	100	Monitoring	Levellogger + SP probe	7–8	55.169252	–6.885084

between 11th and 14th of August 2020 with the aim of inducing changes in saltwater intrusion in an aquifer characterized by an upper saline IRC. Changes in groundwater salinity were monitored using ERT and SP probes. The test took place in summer, when reduced freshwater flushing from the dunes was expected due to lower groundwater recharge/reduced hydraulic gradients. To minimize the risk of tidal surge reaching pumping wells, the test was carried out during neap tide.

Geophysical investigations were performed under natural (i.e., unpumped) conditions in the study area with two objectives: to contrast with observations made during the pumping test and to evaluate changes in salinity patterns during spring and neap tides.

3.1. Geophysical investigations under undisturbed conditions

During the previous summer (July 2019), the effect of semi-diurnal tides over a spring-neap cycle on salinity distribution in the intertidal zone at Benone Strand was investigated using time-lapse resistivity imaging. The main objectives of this investigation were to: (1) analyze the changes in salinity patterns during daily tidal cycles, (2) compare resistivity distributions obtained during spring and neap tides, and (3) gather information for planning pumping tests to experimentally induce and monitor saltwater intrusion using geophysical techniques. Ten ERT profiles (48 electrodes spaced at 3.5 m), diagonal to the shoreline (see Fig. 1 for location), were obtained similar to that shown in Fig. 2a. Five ERT profiles were generated on 2nd July 2019 during spring tide at approximately 60-min intervals, while another five profiles were taken on 23rd July 2019 during neap tide (Fig. 3a). To ensure comparability between the profiles acquired during spring and neap tides, the electrodes were positioned in similar locations using a Leica GS08 differential GPS (dGPS).

The inverse modeling software RES2DINV was used to determine the true resistivity distribution from field-measured apparent resistivities. Extensive tests and analyses were conducted on the raw measured data to evaluate their reliability, along with comparisons of different inversion methods and approaches, to enhance the interpretation of the ERT profiles and support the conclusions drawn in this study. Finally, a *L1* norm or blocky method was used for inverting the ERT data, as it is more suitable for dealing with strong resistivity contrasts (Loke et al., 2003). The average RMS error for the whole set of profiles individually inverted was 3.73 %. Visualization and analysis of the ERT data were carried out using ParaView software (Ayachit, 2015). The analysis of these ERT profiles focused on the uppermost 20 m of the subsurface, corresponding to the sand deposit, as these depths are of greater interest and are considered more reliable than the deeper data. The color scale used for resistivity profiles was carefully selected to suit the characteristics of the relatively homogeneous sand deposit and the intertidal zone, effectively distinguishing between saline water (1–3 $\Omega\cdot\text{m}$), brackish water (3–10 $\Omega\cdot\text{m}$), and freshwater (>10 $\Omega\cdot\text{m}$) to aid in the interpretation of salinity distribution patterns.

3.2. Investigations during the pumping test

The pumping test aimed to induce flow from the intertidal zone to evaluate how geophysical (SP and ERT) patterns changed in response to alternations in the natural groundwater flow field. The test was conducted during neap tides to minimize tidal effects on the induced saltwater intrusion. This also ensured greater resilience of the ERT monitoring equipment against unexpected storm surges during the pumping test. Furthermore, previous work had shown that variations in SP signals were also minimized during neap tides.

Continuous constant discharge from the three abstraction wells, pumping at a combined rate of 10.2 L/s, took place over a 69-h period using three Caprari (E4xPD60) submersible pumps. An average of 3.8 L/s was pumped from well PW1 to induce an increase in salinity in the pumping well closest to the HWM. Simultaneous pumping of PW2 and PW3 at an average of 3.2 L/s aimed to enhance drawdown, while

intercepting fresh groundwater flow from the dunes. The pumping rates were calibrated manually, and subsequently monitored using ARAD flow meters installed in the discharge lines of the three pumping wells, the day before starting the test.

Electrical resistivity measurements were taken before and during the pumping test to monitor the migration of saline groundwater during pumping. A Syscal Pro resistivity system with 36 stainless steel electrodes, connected via multicore cables, collected ERT profiles at approximately three-hour intervals along two lines, parallel and perpendicular to the shoreline (see Fig. 1 for location), using the dipole-dipole array configuration. The length of the ERT profiles parallel to the shoreline, crossing immediately north of observation well cluster B, was 105 m, with an electrode spacing of 3 m, while the length of the perpendicular ERT line, located east of well PW1 and clusters A and B, was 35 m with an electrode spacing of 1 m. The dunes adjacent to the beach were not accessible due to their designation as Special Areas of Conservation, which restricted the length of the ERT profile perpendicular to the coastline. A total of 55 ERT profiles were acquired during the pumping test, 28 perpendicular and 27 parallel to the shoreline. The average RMS error of the ERT profiles parallel to the shoreline was 4.72 %. However, the RMS error of the ERT profiles perpendicular to the shoreline was greater (average of 15.07 %) due to higher contact resistances between the electrodes in dry sand near the dunes. The high contact resistance in dry sands is primarily attributed to the low moisture content which hinders the efficient transfer of electrical current between the electrodes and the subsurface (Herring et al., 2023). Despite some measures taken to improve the contact resistance, the ERT models perpendicular to the shoreline still exhibited higher RMS errors compared to the other ERT profiles. However, the results remain valid for the purposes of this study. Detailed information on the errors and adjustments for each ERT profile is available in the supplementary material.

The water pumped from the three pumping wells was discharged diagonally to the shoreline >60 m away from the study area to ensure it did not affect the zone of contribution generated by pumping. A YSI Professional Plus Multiparameter quality meter monitored the quality of water passing through a flow cell, sampling a proportion of the discharge from PW1; water quality parameters included temperature, pH and specific electrical conductance (SEC). Measuring SEC directly in the discharge allowed for more reliable salinity assessment by avoiding the potential biases associated with in-well measurements, such as vertical hydraulic gradients and tidal influences, which can distort EC values in coastal aquifers (Shalev et al., 2009; Levanon et al., 2016). Solinst loggers measured temperature and water level fluctuations during the pumping test in all wells with a frequency of 1 min. Manual measurements of the drawdowns in the wells were taken throughout the pumping test to verify the measurements automatically collected by the loggers. SP data, from the probes in each of the twelve monitoring wells, were also logged automatically at 1 min intervals during the test. When an ERT profile was taken the injected current was detected by the SP electrodes. The electrodes, however, recovered immediately once injection ceased. As a result, 5–12 min of SP data (depending on whether profiles were EW or NS) logged during ERT profiling were discarded.

4. Results

4.1. Data from geophysical investigations under undisturbed conditions

All the preliminary ERT profiles generated at Magilligan showed a general decrease in resistivity from the dunes to the sea (from >40 Ωm to <2 Ωm). Additionally, the salinity distribution in the beach aquifer remained nearly constant over semi-diurnal tidal cycles (ST1 vs. ST5 and NT1 vs. NT5 in Fig. 3a). However, the resistivity fields measured during spring tide and neap tides revealed some differences. Resistivities <10 Ωm were observed at 90 m from the landward origin near the beach surface over spring tide, while similar values were found at around 110

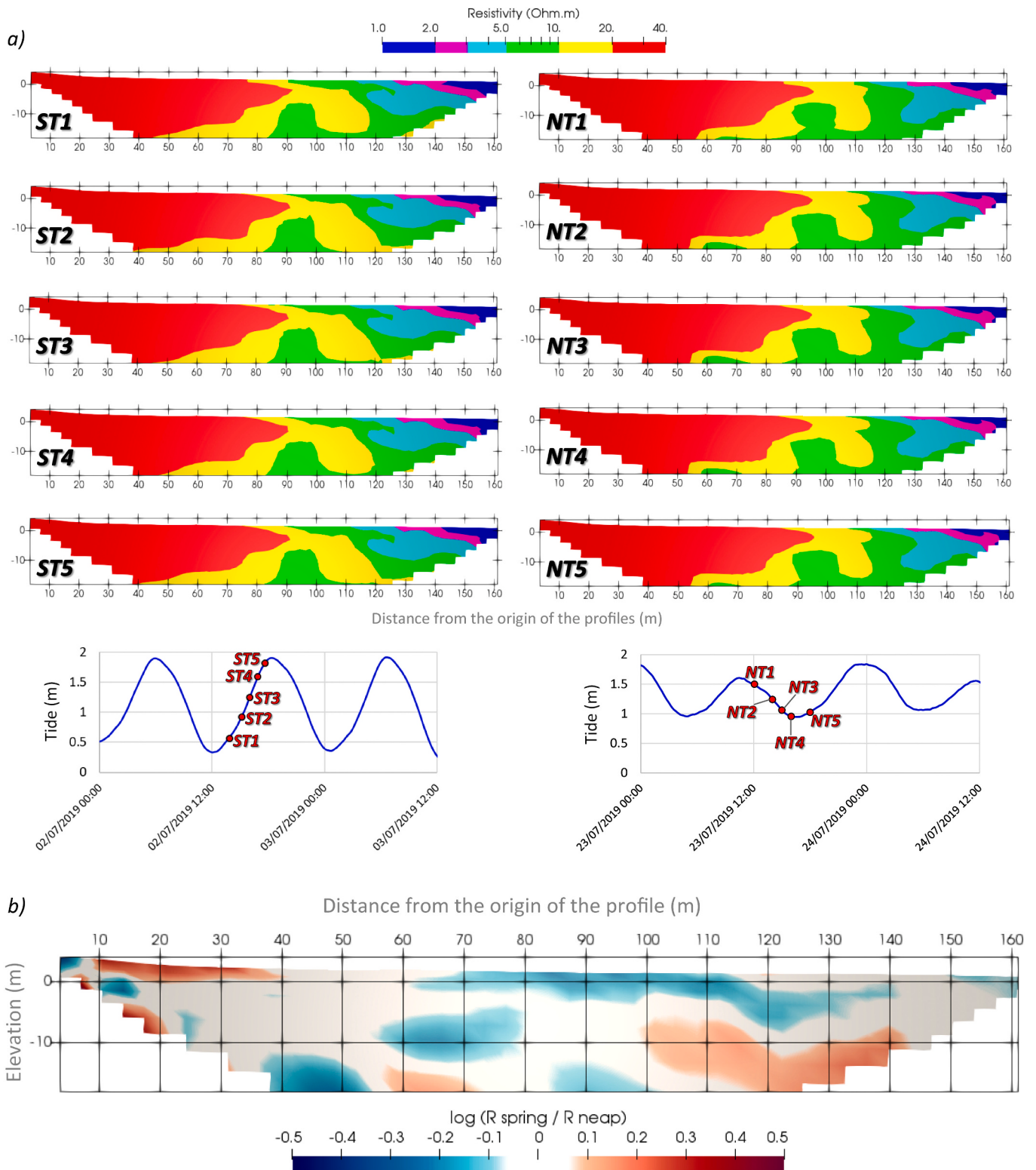


Fig. 3. Sequences of ERT profiles diagonal to the shoreline generated during spring tide (left) and neap tide (right) under undisturbed conditions (a); and ratio of resistivities between ERT profiles generated during spring tide (ST1) and neap tide (NT5) (b). Resistivity fields remain nearly constant over semi-diurnal tidal cycles, but differences are evident between spring and neap tides. During spring tide, resistivities below 10 Ω m occur closer to the beach surface ($\sim$ 90 m from the origin) compared to neap tide ($\sim$ 110 m). Panel b highlights these differences, showing resistivity decreases near the beach surface at 70 m (seaward) during spring tide, extending to almost 10 m depth at 125 m from the origin. Additionally, resistivity increases from 100 m onward to depths >10 m during spring tide.

m from the origin during the neap tide cycle. Fig. 3b illustrates the resistivity comparison between the spring tide (ST1, Fig. 3a) and neap tide (NP5, Fig. 3a). ERT profiles ST1 and NP5 were selected for paired comparison as these were obtained at similar points in the tidal cycle, i. e., during the rising tide, approximately 1 h after low tide. Resistivity decreases near the beach surface at 70 m from the origin of the profile (seaward) during spring tide and extends to almost 10 m depth at 125 m from the origin of the profile. Moreover, resistivity increases from 100 m from the origin of the profiles to depths >10 m during spring tide. The comparison between the two data sets shows strong similarities in the rest of the beach aquifer, although slight increase in the shallow resistivity is observed between 10 m and 35 m from the origin of the profiles, which may be related to a decrease in the minimum water table during spring tide (sea level was almost 0.5 m higher when the ERT profile was acquired during neap tide than during spring tide).

Fig. 4 summarizes the SP signals recorded in the four monitoring wells of Pads A, B & C under undisturbed conditions over an 18-day period prior to the pumping test (the 18-day span covers a full spring-neap cycle and the beginning of the next). Tidal variations caused significant oscillations in the SP signals from the probes installed in the monitoring wells. Analysis of major perturbations in SP observed during surge tide events at the site indicate that changes in SP are in response to saline changes due to the movement of the IRC due to motion of the tide up and down the beach rather than changes in water pressure. This implies that the oscillatory SP response is due to the cyclic movement of the IRC as it is affected by the tide.

4.2. Pumping test

Fig. 5a presents the drawdown, measured in the 4 m, 6 m and 8 m deep monitoring wells during the pumping test. The greatest drawdowns occurred in the observation wells of cluster A, since these experienced the greatest impact from the three pumping wells, which were all located at a distance <5 m. Drawdowns reached up to 2.5 m in monitoring well A8 at the end of pumping, while drawdown decreased with the depth of the observation wells of cluster A, given they are further away from the pumping well screens (covering depths between 3.5 and 10.5 m). This contrasts with drawdowns which decreased with the depth of the observation wells in clusters B and C. The maximum drawdown

reached in clusters C and B were 2.15 m and 1.85 m, respectively. The 2 m deep wells dried out after 310 min (A2), 1015 min (C2) and 1120 min (B2) of pumping, while the maximum drawdowns in the pumping wells were 7.25 m in PW1 and 6 m in PW2 and PW3.

Water quality monitoring results revealed a sustained rise in SEC in pumping well discharge, despite sea level variations linked with tidal cycles (Fig. 5b). Although semi-diurnal tidal cycles caused little variation in resistivity under natural gradient conditions, time evolution of SEC at the discharge from well PW1 suggests influence from tidal variations during the first 1500 min (25 h) of pumping. During this period, more pronounced increases in SEC were observed as the tide rose, while they slowed down during tidal decreases. End member mixing analysis of freshwater, sampled from landward monitoring wells, and sea water suggested an increase in salt water content in discharge of PW1 from 1.4 % sea water to 4.1 % as the test progressed. In addition, pH in the discharge of PW1 also increased during the pumping test, increasing from 7.8 at the beginning of the test to 8.05 just before the end of pumping. The temperature of the groundwater discharge ranged from between 10.8 °C and 11.4 °C.

4.3. Geophysical investigations during the pumping test

Fig. 6 presents resistivity images acquired perpendicular to the shoreline, taken 4 h before pumping and at 5 h, 14.5 h, 34 h and 69 h after the start of pumping. Additionally, Supplementary Video 1 summarizes the resistivity images before, during, and after pumping, integrating the 28 ERT profiles generated perpendicular to the shoreline. Prior to pumping, ERT profiles revealed a consistent pattern of resistivity declining to the north (seawards), aligning with the observations from geophysical investigations under undisturbed conditions. Resistivities of <3 Ωm were determined for the upper layers of the saturated sands at a distance of 20 m from the origin of the ERT profiles seaward (dark blue areas in ERT profiles), while resistivities larger than 40 Ωm were found in the sand deposit near the dunes (pink areas in ERT profiles). After 5 h of pumping (Fig. 6b), a low resistivity plume (more saline) begins to advance from the IRC at the top of the aquifer to the pumping well PW1. The most saline area of the IRC (< 3 Ωm) receded 2 m in the upper part of the aquifer during this time. The low resistivity plume progressively extended towards PW1 as pumping proceeded.

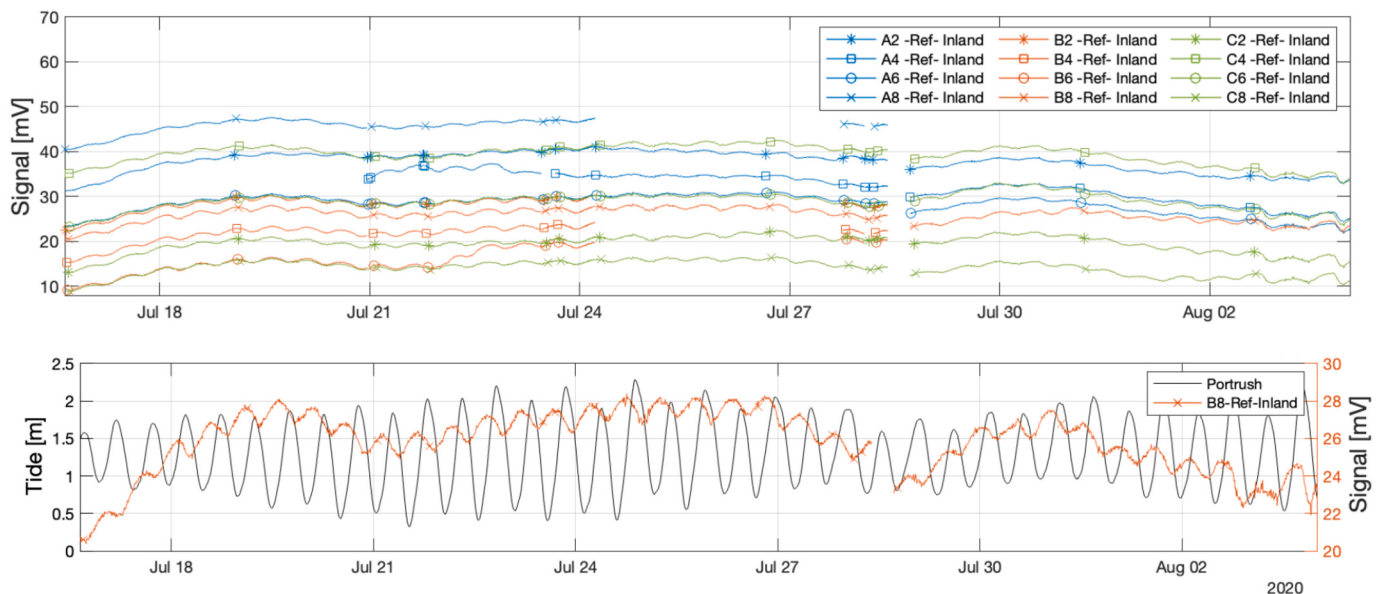


Fig. 4. SP signals from Pads A, B, and C over an eighteen-day period before the pumping test (top) are accompanied by the tide height record at Portrush. The SP signals are all referenced inland and are colored according to the pad (A - blue, B - red, and C - green), with the depths denoted by spaced symbols. The lower (tidal) plot also includes the SP signal from B8-Ref-Inland overlaid to aid in identifying a clear correlation with M2 (principal lunar) tidal signatures as well as possible lower-frequency (spring-neap) tidal signatures. Data gaps are due to pre-pumping experiments and maintenance.

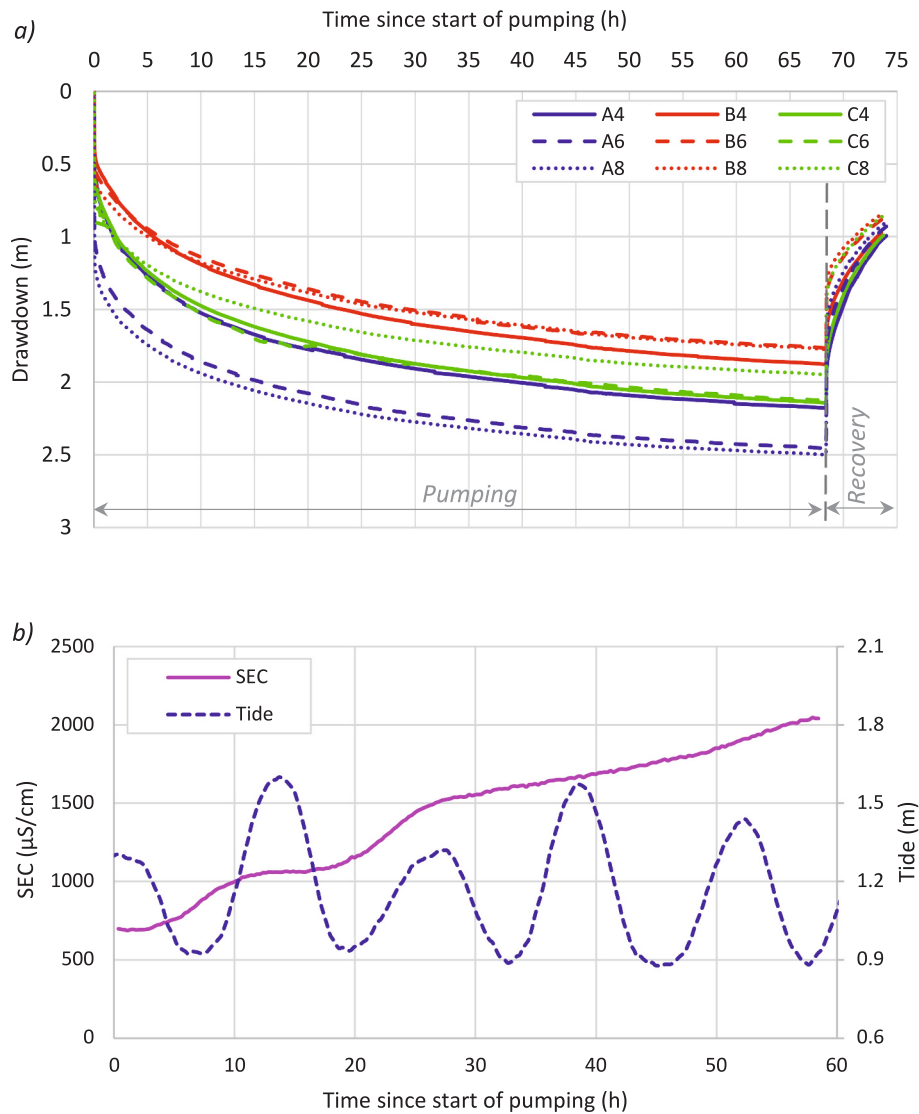


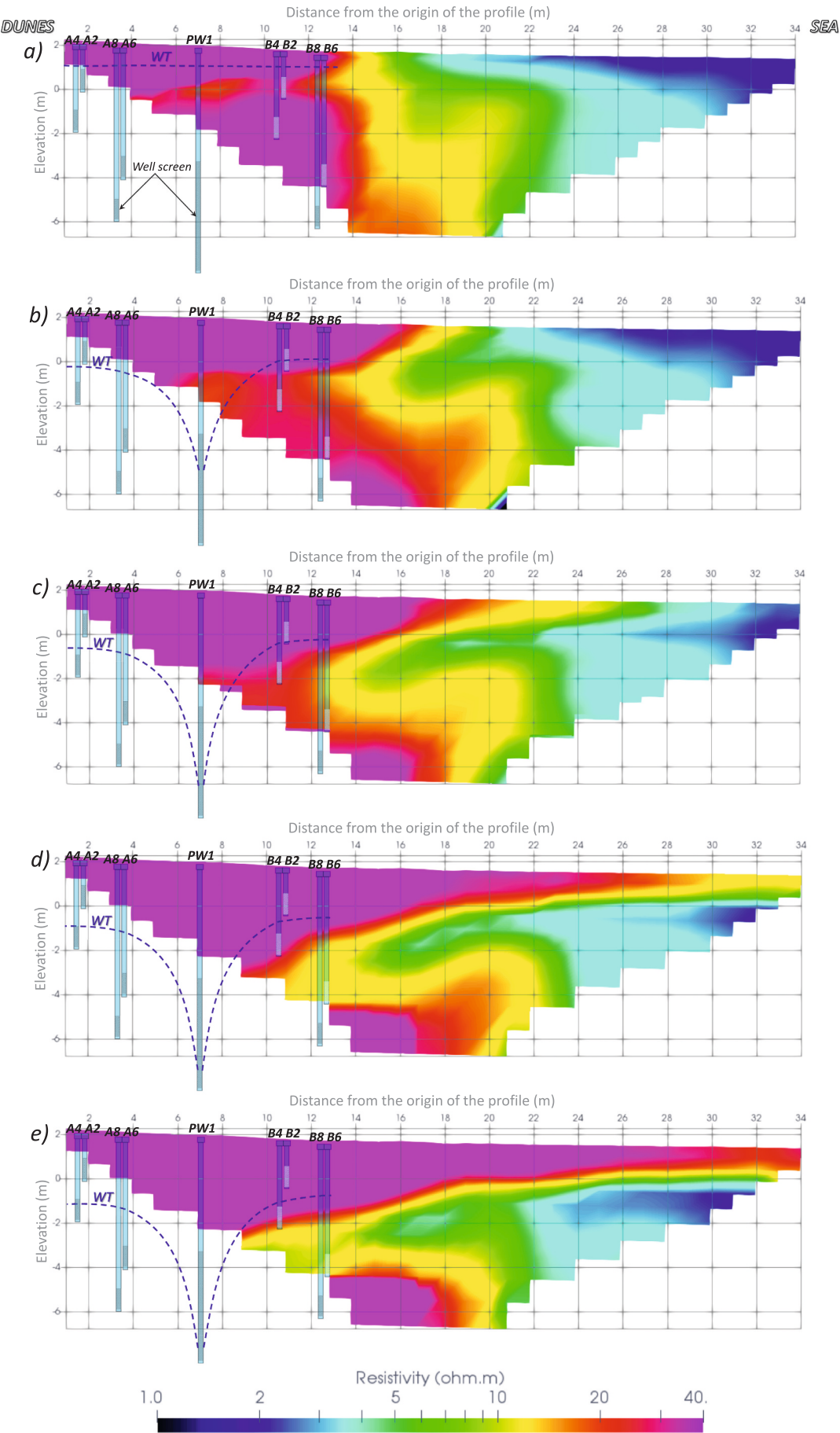
Fig. 5. Time evolution of the drawdowns in the 4, 6 and 8 m deep monitoring wells (a); and tide height and specific electrical conductivity (SEC) measured at the discharge of the PW1 well during the pumping test (b).

After 14 h pumping, the saline plume, with resistivities $<12 \Omega\text{m}$, reached 13 m from the origin of the profile (yellow areas in Fig. 6c), while it crossed the entire domain of the resistivity model 34 h after the start of pumping (Fig. 6d). The resistivity of the saline plume towards well PW1 decreased to values below $10 \Omega\text{m}$ at the end of pumping (green areas in Fig. 6e). On the other hand, the extension of the pink zones in the ERT profiles with resistivities above $40 \Omega\text{m}$, in the upper part of the aquifer, increased as the pumping progressed due to the dewatering of the sands. Comparisons between measured apparent resistivity profiles collected at different times during the pumping test confirm the resistivity variations observed in the inverted models.

Resistivity images generated parallel to the shoreline before, during and after the pumping test, are presented in Fig. 7 and Supplementary Video 2. Previous research focused on the characterization of the aquifer has greatly aided the interpretation of the data obtained from the ERT profiles parallel to the shoreline, confirming that groundwater in the area predominantly flows perpendicular to the shoreline, moving from the dunes towards the sea and crossing the parallel ERT profiles. Before starting the pumping, resistivities of $<10 \Omega\text{m}$ were determined in the upper layers of the sands (in the shallowest 2 m), while an area of greater resistivity, reaching values larger than $20 \Omega\text{m}$ and exceeding 10 m in depth, underlay this upper saline layer (red areas in Fig. 7a). The low-

resistivity zone corresponds to the IRC, formed by seawater inflow from the surface due to tidal action, whereas the deeper high-resistivity zones correspond to the freshwater flow originating from the dunes, confined between the IRC and the aquifer base. Although the reliability of ERT models decreases with depth and the most accurate results from the parallel ERT profiles were identified in the uppermost 13–15 m of the aquifer, a decrease in resistivity is observed at depths close to 20 m, interpreted as the appearance of Lr. Jurassic mudstones (interpretation supported by prior characterization geophysical surveys). The upper low resistivity zone near the pumping wells disappeared after 8.5 h of pumping (Fig. 7b). Instead, resistivity decreased in the vicinity of the pumping well screens as the pumping progressed, reaching values lower than $8 \Omega\text{m}$ at the end of pumping (green areas around the wells in Fig. 7e). In addition, the dewatering of the sand during pumping caused an increase in resistivity in the upper part of the sand deposit. Resistivities $>40 \Omega\text{m}$ were determined near the surface from 50 m to 65 m from the origin of the profile after 24 h of pumping, (pink area in Fig. 7c) while this zone of higher resistivity extended from 32 m to 80 m at the end of the pumping (Fig. 7e).

Fig. 8a and Fig. 8b summarize the resistivity changes between ERT profiles, collected before the start and at the end of the pumping test, perpendicular and parallel to the shoreline, respectively. In both cases,



(caption on next page)

Fig. 6. ERT profiles perpendicular to the shoreline collected 4 h before pumping (a) and at 5 h (b), 14.5 h (c), 34 h (d) and 69 h (e) after the start of the pumping test. The dashed blue line shows the position of the water table, calculated from the drawdowns measured in the wells closest to the trace of the profile (PW1 and pads A and B). The low-resistivity zone in the upper part of the ERT profiles (dark blue areas in Fig. 6a and b) corresponds to the onset of the upper saline Intertidal Recirculation Cell. As pumping progresses, this zone gradually diminishes, moving downward from the upper aquifer towards the pumping well (PW1), forming a saline front or plume (green and yellow zones).

resistivity decreased during pumping between 3 m and 7 m below surface after inducing seawater intrusion into the coastal aquifer, while resistivities increased in the shallowest 2.5 m of the aquifer due to the dewatering of the saturated sands. Furthermore, an increase in resistivity was observed at depths >8 m, which reflects the partial pumping from deeper and fresher areas of the aquifer.

Fig. 8 also presents the time evolution of resistivity changes, estimated from the ERT profiles in the vicinity of the screens of the observation wells of cluster B, the closest to the shoreline. Resistivities acquired closest to well B2 (Fig. 8c) increased throughout the pumping test, although the rate of increase varied significantly over time. Resistivity increased by about $0.22 \Omega\text{m}/\text{min}$ during the first 17 h of pumping due to the faster drop in the water table, while subsequently the rate of increase reduced to around $0.04 \Omega\text{m}/\text{min}$, due to the slower dewatering process of the saturated sand. A decrease in resistivity of $106 \Omega\text{m}$ occurred close to well B2 following the end of pumping. Variations in resistivity, caused by tides in the vicinity of well B4, proved more evident than near well B2. The resistivity close to B4 decreased by $13 \Omega\text{m}$ during the first 5 h of pumping, but subsequently there was an increase in resistivity of over $55 \Omega\text{m}$. Variations in resistivity at a depth of 4 m below ground were influenced by the tides, revealing a strong correlation, between the tidal peaks and troughs, and the rises and falls in the resistivity values (Fig. 8d). The resistivities decreased by $40 \Omega\text{m}$ during the first 33 h of pumping in the vicinity of well B6, while the resistivity values stabilized from this time with slight variations caused by tides. By contrast, the resistivity changes at 6 m depth reflected the saline intrusion experimentally induced by pumping. Resistivity progressively decreased as salt water flowed landwards from the upper saline layer and remained stable once steady state conditions were reached. Resistivity changes at a depth of 8 m below the ground surface during the pumping test, were less significant than those at shallower depths, with resistivity values ranging between $7.8 \Omega\text{m}$ and $13.2 \Omega\text{m}$. Resistivity values near the well B8 slightly increased during the first 8 h of pumping (Fig. 8f). Later, resistivity values tended to decrease, although they are slightly affected by tides.

The SP signals recorded by the probes installed in the monitoring wells before, during and after the pumping test are shown in Fig. 9. Data have been removed from these plots to avoid effects on the SP signals when ERT measurements were being generated or when the SP probes have been exposed by the drawdown (2 m deep wells). During pumping (highlighted in red in Fig. 9), SP signals fell in all twelve wells by between 20 and 30 mV. However, the largest drop in SP signals, during the pumping test, occurred between 12 h and 40 h after the start of pumping. Once pumping stopped (recovery phase), no significant changes in the SP signals were observed. The implications are that the effects of pumping on the subsurface saline-freshwater interface appear to overwhelm tidal forcing and the associated oscillations (observed in Fig. 4). This results in the observed data pattern of a sustained, smooth drop in SP, which recovers to an oscillating pattern after the pumping test is complete (Fig. 9).

Fig. 10 shows a comparison of the change in SP over the 69 h of pumping in the monitoring wells, grouped by borehole depth and well distance from the dunes towards the sea. The results indicate that depth has little effect on the drop in SP signal. The largest decreases in SP signals were detected in the 2 m deep wells. These, however, were affected by the dewatering of the upper part of the aquifer and the drying of the wells during pumping. The deeper monitoring wells (6 and 8 m deep) closest to the dunes (Pads A and C), with well screens depths similar to those of the pumping wells, showed a slightly greater drop in

SP signal than that recorded in the 4 m deep wells. This suggests that SP responses in wells located within the area most influenced by pumping are dominated by effects in the subsurface arising from pumping. Further support for this is indicated by the lack of tidal oscillations in SP during pumping, as shown in Fig. 9. Excluding the 2 m deep wells, the largest drops in SP signal during pumping were observed in the monitoring wells closest to the sea (B6, B8, and B4). These wells had smaller drawdowns than those observed at the other two pads (see Fig. 5), but were more affected by the saline intrusion induced by pumping, as shown by the sequence of ERT profiles in Fig. 6. This suggests that the observed changes in SP were not solely due to changes in water level but also due to salinity changes caused by pumping. As shown in Fig. 10b, changes in SP signals exhibited some correlation with well location from the dunes when the shallower wells were excluded from the analysis. Although the positions of the interception and abstraction wells pose some limitations, the observed decreases in SP signals were larger with decreasing distance of well location from the sea. This pattern, as demonstrated by the associated ERT profiles, indicates that the saline-freshwater interface is predominantly situated seaward of the boreholes and wells.

5. Discussion

A lack of external human interference from pumping on Magilligan's groundwater regime, coupled with the relatively homogenous nature of the deposits underlying the main test site (Águila et al., 2022), make it an ideal location for experimentally investigating fundamental influences on saline intrusion under undisturbed conditions. Additionally, the absence of significant geological heterogeneity, as demonstrated by geophysical, geotechnical, and hydrogeological investigations in the study area (Águila et al., 2022, 2023), suggests that 3D effects can be discounted in the interpretation of 2D ERT profiles (Hung et al., 2019). Time-lapse resistivity imaging at the site showed a resistivity/salinity distribution in the sand deposit that displayed no significant variation during semi-diurnal tidal cycles (Fig. 3a). Instead, changes in resistivity were found when comparing ERT profiles generated over spring-neap tidal cycles (Fig. 3b). Such behavior, in tidally driven groundwater salinity variations in the coastal aquifer at Magilligan, is consistent with findings from previous research conducted in similar settings through numerical simulation and field studies (Robinson et al., 2007b; Heiss and Michael, 2014). Other studies focused on the effects of tides in coastal aquifers with a classical or deep saltwater wedge located inland (Kim et al., 2006; Swarzenski et al., 2006; Levanon et al., 2016) also demonstrated that the fresh-saltwater interface is influenced by sea tides.

The upper saline IRC, formed by infiltration of seawater from the surface due to the tidal effect and overlying a layer of fresher groundwater, changes in size during spring and neap tides. The extent of the IRC and the mixing zone increase during spring tide due to larger tidal amplitudes. Consequently, the fresh groundwater discharge from the dunes is restricted to a smaller area between the IRC and the bottom of the sand aquifer; this causes an increase in resistivity to depths >10 m during spring tides. Despite the slight variations in the dimensions of the IRC, it persisted beneath the intertidal zone of Benone Strand over the course of this research period; this contrasts with findings reported by Abarca et al. (2013), who suggested that the IRC was not permanent and it can appear and disappear with the lunar cycle.

Beyond the specific case of Magilligan where SWI is strongly influenced by tidal variations, it is important to highlight that, in most cases,

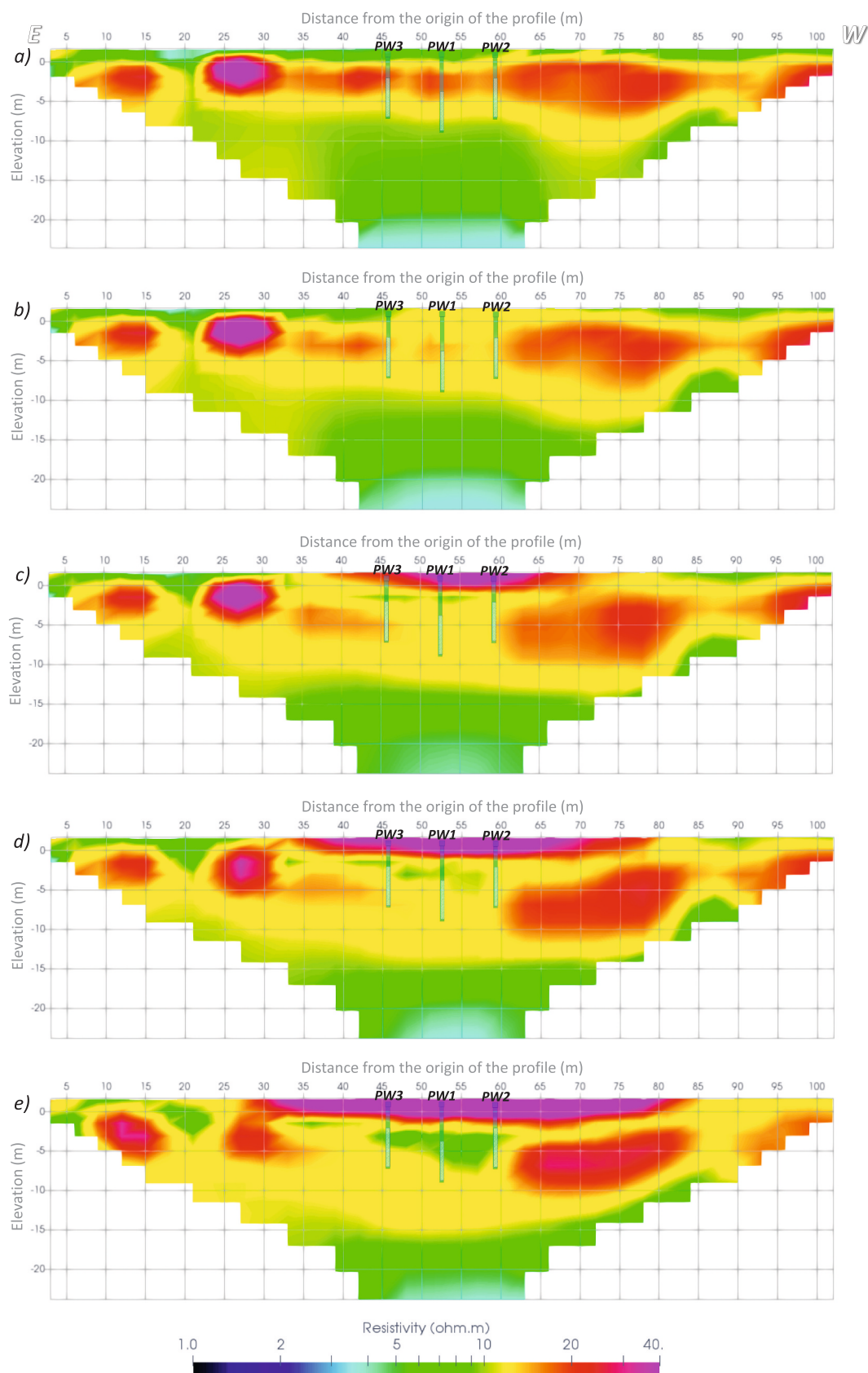


Fig. 7. ERT profiles parallel to the shoreline collected 5 h before pumping (a) and after 8.5 h (b), 24 h (c), 40 h (d) and 67 h (e) from the start of the pumping test.

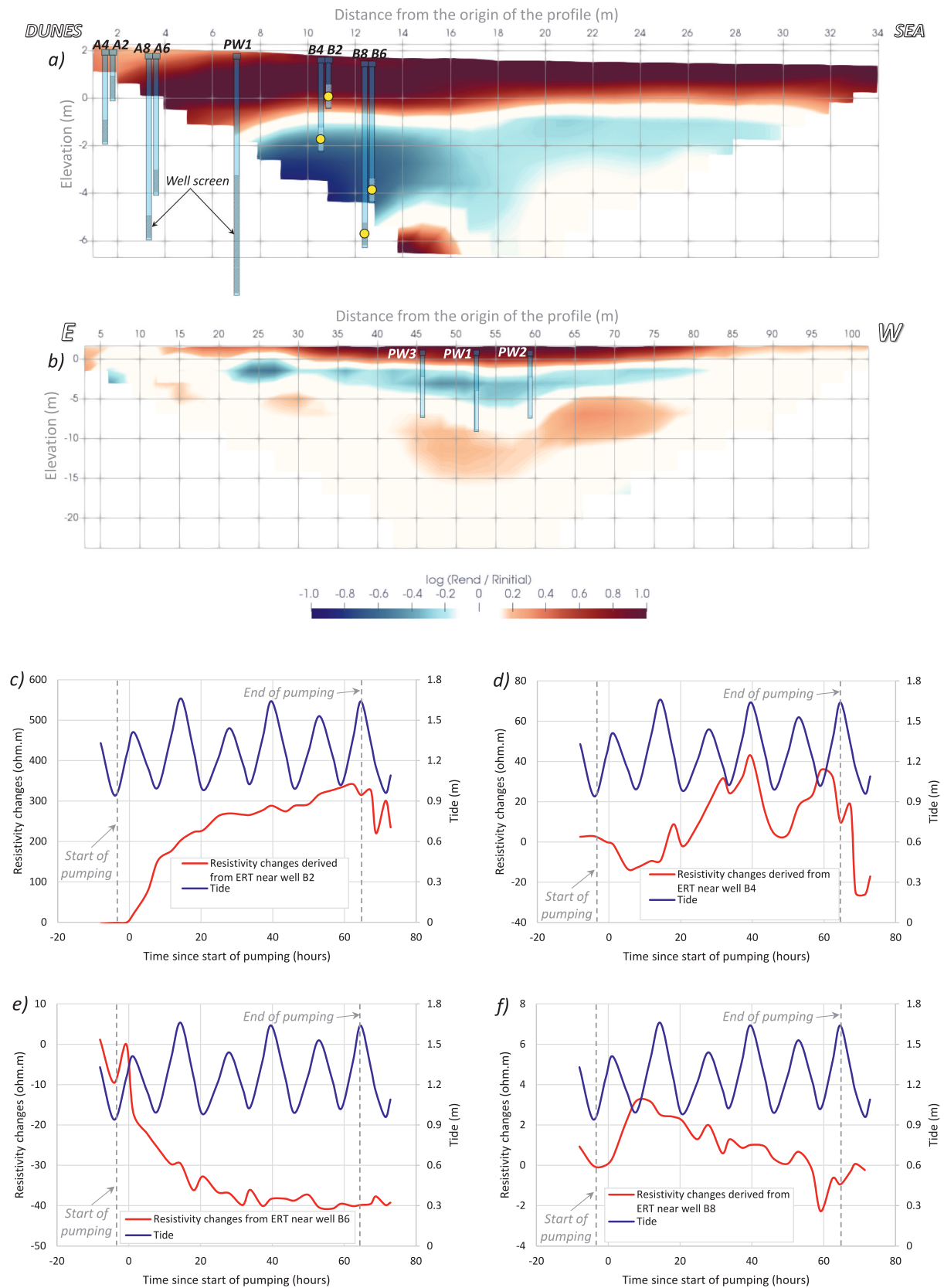


Fig. 8. Resistivity changes between ERT profiles collected before starting pumping and after 69 h of pumping perpendicular (a) and parallel (b) to the shoreline ($R_{end}/R_{initial}$); and time evolution of the tide height and resistivity changes near the screens of wells B2 (c), B4 (d), B6 (e) and B8 (f) projected from the ERT profiles (yellow circles in (a)). Resistivity variations, calculated as the differences between the resistivities at a given time and those just before pumping, for wells B2, B4 and B6 were derived from the ERT profile perpendicular to the shoreline, while those for well B8 were derived from the ERT profile parallel to the shoreline.

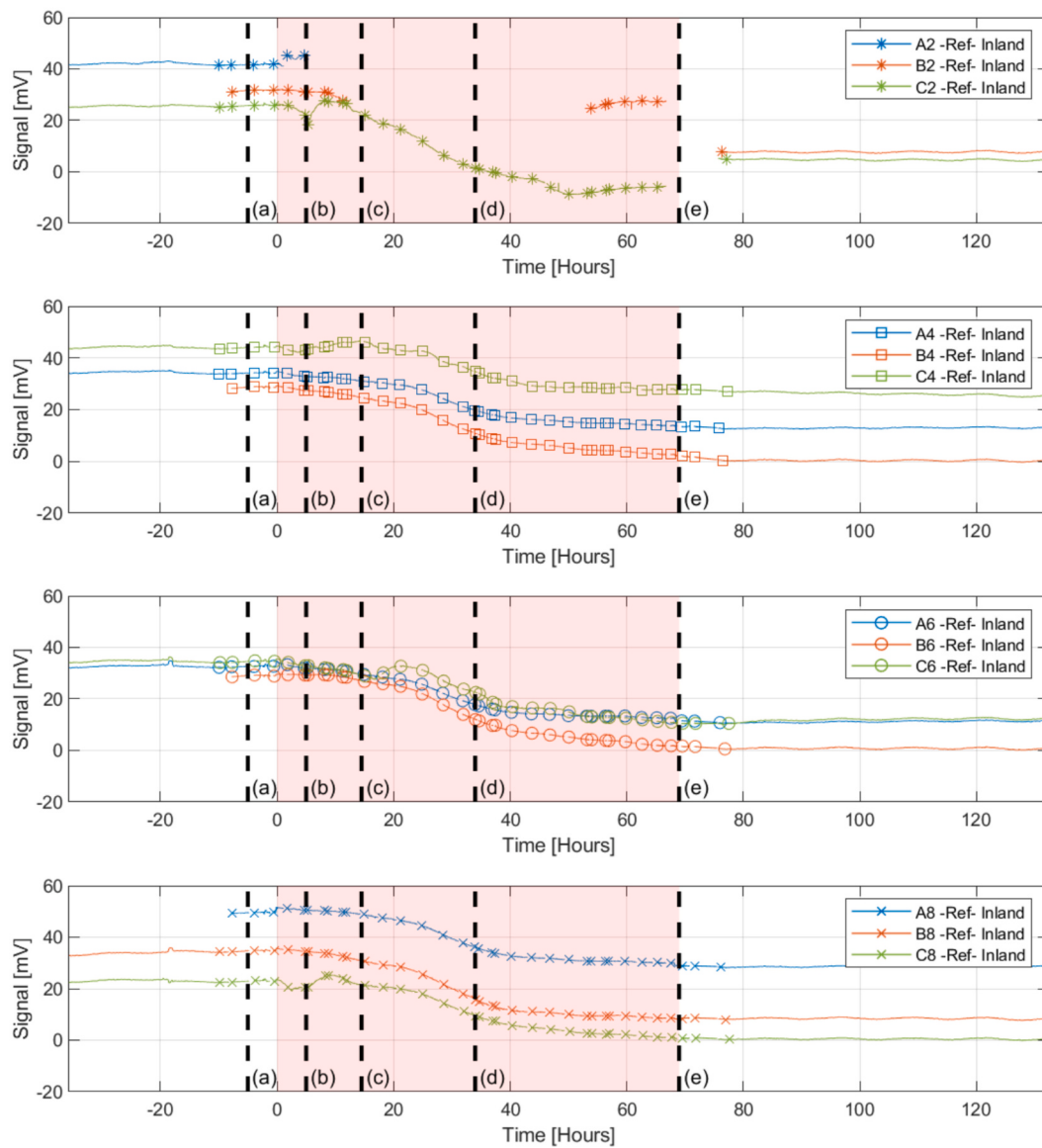


Fig. 9. SP signals from the monitoring wells grouped by depth. The period of pumping is highlighted in red, while the vertical dashed black lines indicate the time when the ERT profiles perpendicular to the shoreline shown in Fig. 6 were generated (a-e). The SP signals are all referenced inland and are colored according to the pad (A - blue, B - red, and C - green), with the depths denoted by spaced symbols.

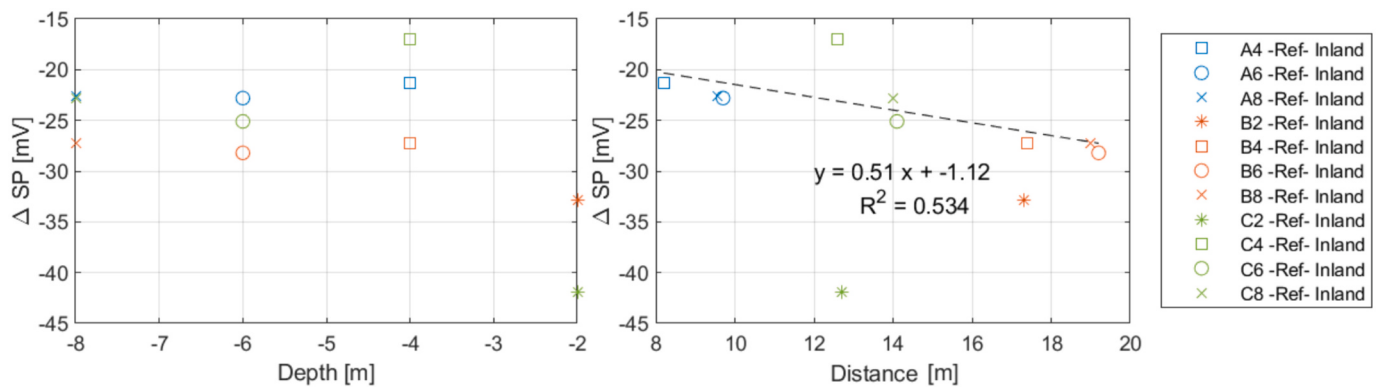


Fig. 10. SP signal change over the 69 h of pumping in the monitoring wells compared to depth (left), and distance from the dunes towards the sea (right). A fitted regression line was used for the deeper wells in the second plot. The SP signals are all referenced inland and are colored according to the pad (A - blue, B - red, and C - green), with the depths denoted by spaced symbols.

SWI occurs in regional coastal aquifers due to density-driven flow, generating a deeper saltwater wedge, or groundwater pumping. However, from a practical standpoint, both the methodology used and the geophysical and hydrogeological tools applied in this study can also be utilized in these more common SWI scenarios, where salinity distribution patterns are typically influenced by multiple factors, including geological heterogeneities, aquifer thickness and geometry, tidal influences, seasonal variations, coastal infrastructure, land use changes, and surface water overtopping. Despite potential complexities arising in regional-scale coastal aquifers, similar monitoring approaches could provide valuable insights into SWI dynamics, allowing for real-time assessment of salinity changes and improved management of groundwater resources.

Geotechnical and hydrogeological measurements of the coastal aquifer at Magilligan confirm the relatively low degree of heterogeneity anticipated for these deposits (Águila et al., 2022). This is further reflected in the near-ideal behavior of the drawdown patterns observed in all monitoring wells during the pumping test (Fig. 5a). These conditions have facilitated clear visualization and monitoring of pumping-induced salinity changes through ERT profiles. To the best of the authors' knowledge, this was the first time that the saline intrusion induced by pumping has been monitored using time-lapse resistivity images in a coastal aquifer with an upper saline IRC, demonstrating that the increase in salinity in pumping wells derives from upper layers of shallow coastal aquifers, with wide tidal variation. Findings of McDonnell et al. (2023) further corroborate this finding by means of four-dimensional electrical resistivity imaging at the same study site, although no comparisons with other geophysical techniques were assessed. The temporal variations observed in the datasets collected during the pumping test suggest that the additional saltwater originated from the upper saline IRC, as evidenced by the sequence of ERT profiles generated perpendicular to the shoreline (Fig. 6). These profiles show low-resistivity zones moving downward from the upper aquifer towards the pumping wells. During pumping, the low-resistivity areas in the upper part of the ERT profiles (associated with the IRC) gradually diminish, while a more saline front becomes apparent closer to the pumping well nearest the shoreline. The decrease in resistivity detected in the ERT profiles is consistent with the increase in SEC measured the discharge water from the PW1 pumping well (the closest to the sea), as monitored using a YSI Professional Plus multiparameter meter (Fig. 5b). Moreover, the findings from resistivity images reflected the dewatering of the upper part of the aquifer, with the observed increase in resistivity in this zone proving consistent with a drop in the water table, as measured from the drawdowns in the observation wells of clusters A and B.

The time-lapse ERT data provided valuable insights into the short-term dynamics of saltwater intrusion and flushing processes in response to tidal fluctuations and pumping activities. The observed changes in resistivity after the cessation of pumping suggest a partial reversibility of the aquifer system, with freshwater gradually displacing the intruded saline water. However, this recovery appears to be incomplete within the timescales of the monitoring period, indicating a delayed response of salinity compared to the rapid recovery of groundwater levels. Similar behavior has been reported in previous studies where reversibility of seawater intrusion in coastal aquifer was assessed through long-term field observation and numerical modeling (Han et al., 2015; Cao and Han, 2024). Processes such as hydrodynamic dispersion and solute trapping contribute to prolonged salinity retention even after the hydraulic gradient returns to pre-pumping conditions. Additionally, differences in resistivity patterns between spring and neap tides highlight the temporal variability of salinity distributions in response to tidal forcing. While no significant variations were observed in daily tidal cycles, seasonal tidal amplitudes influenced the salinity patterns within the coastal aquifer, emphasizing the need for long-term monitoring and the use of variable-density groundwater flow models to fully characterize the reversibility of these processes. The results of this study demonstrate that geophysical methods, such as time-lapse ERT

and SP, can serve as valuable tools for assessing the reversibility of SWI in coastal aquifers and complement conventional hydrogeological data. However, further research, including numerical modeling, is required to quantify the long-term flushing and salinization dynamics under varying hydrological conditions.

Overall, findings demonstrate that the combined use of time-lapse resistivity imaging, along with application of conventional hydrogeological techniques in boreholes, improves the understanding of pumping effects in coastal aquifers. ERT profiles generated parallel to the shoreline at Magilligan showed that the zone of influence after 69 h of pumping exceeded 85 m (see Fig. 8b). Geophysical techniques, such as time-lapse resistivity imaging or SP, offer significant advantages: they are non-invasive, cost-effective, unaffected by artifacts typical of boreholes (e.g., long well screens), and enable real-time monitoring of changes over large areas (Soupios and Kokinou, 2016). However, they also have limitations, including lower resolution compared to conventional well-based techniques, and they often require integration with borehole data for proper calibration and accurate parameter estimation (Linde et al., 2017). As future research lines, comparisons of SEC measurements taken directly in monitoring wells with those measured in the discharged water and derived from ERT profiles could be valuable to further validate the relationship between resistivity changes and salinity patterns in coastal aquifers affected by abstractions, as well as to assess the limitations of the different methods (e.g., biases in in-well measurements, as highlighted by Shalev et al., 2009 and Levanon et al., 2016).

During the pumping test, it was observed how semi-diurnal tidal oscillations significantly affected resistivities measured near the monitoring wells, to a greater extent than under undisturbed conditions. This is likely due to changes in lateral hydraulic gradients resulting from pumping, as Yu et al. (2022) demonstrated after numerically simulating the combined effects of tidal fluctuations and groundwater pumping close to the coast. Conclusions drawn from their variable-density groundwater models also suggested that the presence of the IRC, caused by tidal fluctuations, inhibited seawater intrusion in the lower aquifer. A similar argument is derived from the present research, where it was found that during pumping tests, saline intrusion originated from the IRC in the upper layers of the aquifer rather than from deeper zones characteristic of the classical or deep saltwater wedge. This finding contrasts with the widespread notion that extracting potable water in saline-intruded aquifers should be done from shallow layers, allowing extraction of freshwater above the salinity-affected zone (Hezi et al., 2018; Yu and Michael, 2019).

The current study demonstrates that in tidal-influenced coastal aquifers, an optimal configuration of groundwater abstractions could be carried out from deeper zones, and could even modify the optimal allocation of infiltration galleries and scavenger wells, typically constructed to control pumping-induced saltwater intrusion in coastal aquifers (Castelletti et al., 2012). While this finding applies specifically to the site under investigation, sandy beaches that form coastal dunes similar to Magilligan are not uncommon and are estimated to occupy approximately 20 % of the world's coastline, according to the research by Masselink and Kroon (2009). However, further investigations are required in other locations and under different pumping rates to fully assess the validity and potential of this approach. It is important to note that the effectiveness of deeper groundwater abstractions in mitigating seawater intrusion, as observed in Magilligan, is closely linked to the site-specific conditions, including the relatively high precipitation, the shallow unconfined nature of the aquifer, and the influence of tidal dynamics on the salinity distribution. In coastal aquifers where a classical saltwater wedge extends further inland due to density-driven flow, shallower wells might still be the preferable option to prevent excessive saline water extraction. Therefore, while this study highlights an alternative approach for tidal-influenced sandy coastal aquifers, its applicability to other settings requires further assessment, particularly in regions with differing hydrological and geological conditions.

Although their research did not focus on saltwater intrusion, Bai et al. (2021) demonstrated through experiments that the combined ERT and SP methods can effectively reflect groundwater flow variation and lead to a better understanding of the qualitative relationship between groundwater flow and its geophysical response. At Magilligan however, ERT reveals a stronger correlation between the movement of the saline front and the SP signal, rather than the drawdown achieved in the wells. This indicates that changes in SP are primarily driven by electrochemical responses. Further evidence of this correlation is seen in the recovery phase after the pumping test, when the SP does not return to its previous levels, as the water level rises, but is more consistent with the intruded saline water. Comparing the resistivity variations near the deeper monitoring wells of Pad B (Fig. 8e and Fig. 8f), with changes in the SP signals in all monitoring wells (Fig. 9), it is observed that the more accentuated decrease in SP signals, occurring after 12 h of pumping, coincides with a change in the trend in the resistivities near wells B6 and B8 (more constant and progressive decrease in resistivity due to the saline intrusion). Comparisons between resistivities and SP signal variations would not be representative near the monitoring wells B2 and B4 (Fig. 8c and Fig. 8d), because of the effect of the dewatering of the upper part of the aquifer.

A direct comparison of the ERT profiles generated at different times (Fig. 6), with the variations in the SP signals, also shows how the progressive decrease in SP during the pumping test was due to the progressive advance of the saline plume from the IRC towards the pumping wells. The five ERT profiles perpendicular to the shoreline shown in Fig. 6 are highlighted by dashed lines and labelled accordingly in Fig. 9 with SP data. The progressive drop in SP of around 20–30 mV in all monitoring wells does not coincide with rapid changes in drawdown (and thus velocity) shown in Fig. 5a, instead it appears to be more closely related to the change in groundwater salinity, highlighted in Fig. 6. This suggests that the SP signals in Fig. 9 reflect the V_{ED} response to the movement of the salt wedge and not through the V_{EK} mechanism. These results provide further evidence that SP monitoring could be an important geophysical method for remotely detecting impending SWI approaching monitoring and abstraction wells, and potentially function as an early warning system for saline ingress into groundwater sources (Graham et al., 2018).

6. Summary and conclusions

Time-lapse ERT and self-potential geophysical techniques were applied to a quasi-homogeneous coastal sand aquifer at Magilligan (Northern Ireland) to investigate the phenomenon of saline intrusion under natural and experimentally-induced pumping conditions. Time-lapse ERT survey results, generated under undisturbed conditions, revealed that tidal variations are primarily responsible for spatial variations in groundwater salinity in the aquifer. Additionally, self-potential signals collected from probes installed in monitoring wells above the high water mark also responded to changes in subsurface salinity. An upper saline recirculation cell forms beneath the intertidal zone due to seawater infiltration, driven by tidal forces; this overlies a layer of fresher groundwater. Although the salinity distribution in the Magilligan Sands remained nearly constant over semi-diurnal tidal cycles, significant differences were found when comparing resistivity fields collected during spring and neap tides, with the width of the IRC and mixing zone increasing during the spring tide. This caused fresh groundwater to be restricted to a thinner interval between the IRC and the bottom of the sand deposit.

During a 69-h constant rate pumping test at 10.2 L/s, time-lapse ERT profiles revealed a progressive increase in the resistivity of the shallowest 2.5 m of the aquifer. This arose due to the dewatering of the saturated sands and was consistent with the water table drawdowns measured in the monitoring wells, proving that the combined use of time-lapse resistivity imaging with traditional hydrogeological monitoring techniques in boreholes enhances characterization of pumping

effects in coastal areas. Analysis of the ERT data provided a more accurate determination of the extent of the area affected by pumping-induced drawdowns than from borehole point measurements, exceeding a distance of 85 m at the end of the pumping tests. Over the duration of pumping, end member mixing suggested that the salt water content of discharge water increased from 1.4 % to 4.1 %. This proved consistent with the decrease in resistivity detected in the ERT profiles between 3 m and 7 m below surface. More generally the use of the time-lapse ERT technique proved that saltwater intrusion, induced by abstractions in shallow coastal aquifers with wide tidal ranges, may originate from upper layers, where the saline intertidal recirculation cell is formed. In the case of Magilligan, the presence of salt water near the surface, and its absence at depth, suggests that deeper water supply wells may be better protected from saline intrusion. This contrasts to other studies which have focused on using shallow groundwater for potable supplies (Castelletti et al., 2012; Hezi et al., 2018; Yu and Michael, 2019). However, this finding is highly dependent on the specific hydrogeological conditions of the site, and in coastal aquifers where a classical saltwater wedge extends further inland due to density-driven flow, shallower wells may still be the preferable option to avoid excessive saline water extraction. Further research is needed in different locations and under various pumping scenarios to fully validate this finding. Additionally, numerical modeling could be used to assess the long-term behavior of tidal-influenced coastal aquifers, evaluating the impact of different pumping rates and the reversibility of the seawater intrusion, while supporting the generalization of this study's findings to other coastal settings.

Self-potential signals fell by between 20 and 30 mV during the pumping test in the twelve monitoring wells, with declines greater in magnitude the further seaward the well was. The comparison of SP data with ERT responses and water level variations suggested that the progressive drop in SP during pumping arose primarily due to the saltwater migration from the IRC (V_{ED} response in SP), generating changes in discharge water quality, and rather than due to the V_{EK} mechanism. This study represents the first application of SP monitoring in combination with time-lapse ERT to track salinity changes in a coastal aquifer subjected to experimental pumping, thereby enhancing the understanding of how SP signals respond to the advance of a saline front as captured through ERT imaging. While the results are specific to a tidally dominated coastal aquifer, they highlight the potential for these geophysical methods to be applied in other contexts, including areas where the freshwater-saline water interface is actively moving inland. The findings further evidence that SP monitoring displays significant potential as a key geophysical method for remotely sensing saltwater intrusion in the vicinity of monitoring and abstraction wells, thus functioning as an early warning system for saline ingress into groundwater sources (Graham et al., 2018; MacAllister et al., 2018).

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CRedit authorship contribution statement

Jesús F. Águila: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thomas S.L. Rowan:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Mark C. McDonnell:** Methodology, Investigation, Data curation, Conceptualization. **Raymond Flynn:** Writing – review & editing, Validation, Supervision, Data curation, Conceptualization. **Shane Donohue:** Writing – review & editing, Validation, Methodology, Conceptualization. **Matthew D. Jackson:** Validation, Investigation. **Adrian P. Butler:** Writing – review & editing, Validation, Investigation. **Gerard A. Hamill:** Supervision, Project administration, Funding acquisition, Data curation, Conceptualization. **Eric M. Benner:** Investigation, Data curation. **Georgios Etsias:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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