Assessment of the Occurrence and Effects of Submarine Groundwater Discharge on Coastal Ecosystems of Portugal

Julián Esteban Londoño Londoño

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Supervisors
Ana Catarina Silva
Maria Teresa Condesso de Melo

Examination Committee
Chairperson: Ramiro Joaquim de Jesus Neves
Supervisor: Ana Catarina Silva & Maria Teresa Condesso de Melo
Members of the Committee: João Nuno Palma Nascimento & Michael McClain

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by
Julián Esteban Londoño Londoño

Supervisors
Maria Teresa Condesso de Melo

Mentors
Ana Catarina Silva

Examination committee
Ramiro Joaquim de Jesus Neves
Ana Catarina Silva
João Nuno Palma Nascimento
Michel McClain

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Resumo

A descarga submarina de água subterrânea (SGD) é um processo essencial no funcionamento dos ecossistemas aquáticos costeiros devido ao seu papel significativo no ciclo de nutrientes, balanços geoquímicos de massa e produtividade primária em estuários, costas arenosas e rochosas e lagoas costeiras. No entanto, os padrões de ocorrência, importância e efeitos desta descarga nas comunidades biológicas costeiras permanecem muito pouco conhecidos, particularmente em costas rochosas. Este trabalho teve como objetivo fazer uma identificação e avaliação pioneira da importância das descargas de águas subterrâneas nos ecossistemas costeiros de Portugal. O trabalho teve dois objectivos específicos, desenvolver uma ferramenta simples e rápida para mapear potenciais pontos de descarga de água subterrânea em toda a costa portuguesa e, comparar a estrutura das comunidades de macroinvertebrados de praias rochosas em locais com e sem descarga de água subterrânea. Para o primeiro objetivo, imagens de infravermelho térmico (TIR) do Landsat 8 foram adquiridas, a partir das quais os mapas de temperatura da superfície do mar e anomalias de temperatura foram derivados. Os pontos potenciais de SGD foram identificados com base na premissa de que a descarga de água subterrânea relativamente fria em águas costeiras mais quentes se manifesta na faixa térmica de imagens de satélite adquiridas durante os meses de verão. Para o segundo objetivo, foram analisados os dados disponíveis da comunidade de macroinvertebrados bentónicos em cinco zonas intertidais rochosas divididas em locais de descarga e sem descarga. Os dados biológicos foram recolhidos em dez quadrados replicados de 50x50 cm, distribuídos aleatoriamente em cada local nos níveis médio e superior da zona intertidal. Os resultados obtidos confirmaram a capacidade da teledetecção TIR para a identificação de sítios SGD, sendo que a análise térmica evidenciou uma útil correlação visual-espacial entre a localização de plumas de anomalias térmicas e superfícies potenciométricas de aquíferos costeiros em Portugal. Além disso, mostrou-se que as costas rochosas na costa Sul e Sudoeste de Portugal podem ser consideradas como ecossistemas dependentes das águas subterrâneas até determinado grau, uma vez que a descarga de águas subterrâneas afetou de forma significativa e consistente a estrutura das comunidades biológicas nos locais de estudo. Taxa específico como as algas *Enteromorpha sp.,* o caracol *Melaraphe neritoides* e/ou o líquen *Verrucaria maura* podem ser potencialmente usados como ferramentas bioindicadoras para alterações na quantidade de descarga de água subterrânea e padrões qualitativos, uma vez que são os que mais contribuiram para a diferença entre os locais de descarga e não descarga. Este estudo preenche uma lacuna importante no estado da arte atual ao: *i.* desenvolver uma ferramenta de baixo custo para identificar pontos

SGD em larga escala que pode ser usada como uma macro-abordagem preliminar, *ii.* fornecer o primeiro mapa regional de áreas potenciais de SGD ao longo da costa portuguesa e, *iii.* validar a importância biológica deste fator comumente esquecido na escala local e, para a classificação potencial de zonas costeiras rochosas como ecossistemas dependentes de água subterrânea.

Palavras chave: *Descarga submarina de água subterrânea, detecção remoto infravermelho térmica, zona costeira rochosos, macroinvertebrados bentónicos, litoral português, ecossistemas dependentes de água subterrânea, mapeamento, indicadores biológicos.*

Abstract

Submarine Groundwater Discharge (SGD) is an essential process in the functioning of coastal aquatic ecosystems due to its significant role in nutrient cycling, geochemical mass balances, and primary productivity in estuaries, sandy shores, reefs, and coastal lagoons. However, the occurrence patterns, importance, and effects of this discharge on the biological communities remain much underexplored, particularly on rocky shores. This work aimed to make a pioneer identification and assessment of the importance of groundwater discharge into coastal ecosystems of Portugal. The work had two specific objectives, to develop a fast and simple tool for mapping potential groundwater discharge points in the entire Portuguese coast and, to compare the structure of the macroinvertebrate communities of rocky shores in locations with and without groundwater discharge. For the 1st objective, Landsat 8 thermal infrared (TIR) scenes were acquired from which sea surface temperature and temperature anomalies maps were derived. Potential SGD spots were identified based on the premise that relatively cool groundwater discharging to warmer coastal waters manifests in the thermal band of satellite imagery acquired during the summer months. For the 2nd objective, we analyzed the available data of benthic macroinvertebrate community in five rocky intertidal zones divided into discharge and no-discharge sites. The biological data was collected with ten replicated 50x50 cm quadrates randomly deployed in each site at the mid and uppershore levels. The results confirmed the capacity of TIR remote sensing for identifying SGD sites, whereby the thermal analysis highlighted a useful visual-spatial correlation between the location of thermal anomalies plumes and potentiometric surfaces of coastal aquifers in Portugal. Furthermore, we showed that rocky shores in the South and Southwest coast of Portugal can be considered as groundwater-dependent ecosystems to some degree as groundwater discharge significantly and consistently affected the biological communities' structure in the study sites. Specific taxa such as the algae *Enteromorpha sp.* the snail *Melaraphe neritoides*, and/or the lichen *Verrucaria maura* can potentially be used as bioindication tools for shifts in groundwater discharge quantity and qualitative patterns since they contribute the most to the difference between the discharge and no-discharge sites. Hence, this study fills an important gap in the current state of the art by: *i.* developing a cost-efficient tool for identifying SGD points at large scales which can be used as a preliminary macro-approach, *ii.* providing the very first regional map of potential SGD areas along the Portuguese coast and, *iii.* validating the biological importance of this commonly overlooked factor at the local scale to the potential classification of rocky shores as groundwater dependent ecosystems.

Keywords: Submarine groundwater discharge, Thermal Infrared remote sensing, Rocky shores, Benthic macroinvertebrates, Portuguese coastline, groundwater-dependent ecosystems, mapping, biological indicators.

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CHAPTER 1 – GENERAL INTRODUCTION

1.1. Thesis structure and work context

This thesis is organized in four chapters with the following structure:

Chapter 1 – General Introduction where the work context, specific objectives and expected outcomes are highlighted.

Chapter 2 – Research chapter with the objective of identifies potential SGD spots through the application of a thermal infrared satellite imagery analysis, using Portuguese coastline as a case study.

Chapter 3 – Research chapter with the objective of assess the potential response of intertidal rocky shore communities to the influence of groundwater in south and southwest Portugal.

Chapter 4 – General Conclusion

Each research chapter is structured in a paper format, under the formatting guidance of the Hydrogeology Journal of the International Association of Hydrogeologists.

This thesis project represents a natural continuation of a previous work developed by CERIS-IST research group which developed a tool for mapping groundwater dependent terrestrial ecosystems (Ribeiro et al., 2015). Therein there was a focus on terrestrial ecosystems but preliminary evidence indicated that coastal aquatic ecosystems could also be influenced by groundwater discharges. This preceding work was the motivation for Chapter 2 of the current thesis.

Chapter 3 is also a continuation of previous work that assessed the biodiversity levels of the rocky shores on the South West Portuguese coastline (unpublished work, 2018). Sampling sites included locations with and without groundwater discharge and hence, the existing biological database on macroinvertebrates was used here to evaluate the currently unknown importance of the groundwater discharge in the structure of the biological communities of rocky shores.

Together, these two research chapters contribute to fill in the currently very limited capacity and knowledge on the mapping of groundwater dependent coastal habitats and on its effects on coastal rocky shores communities.

1.2. Research objectives

General Goal

This research work aims to present a pioneer identification and assessment of the importance of submarine groundwater discharge into coastal ecosystems of Portugal.

Specific Objectives

A. To develop a tool for preliminary identification at large scales (kms) of groundwater discharge points into coastal zones in Portugal using thermal remote sensing and hydrogeological variables.

B. To assess the potential response of intertidal rocky shore communities to the influence of groundwater discharge.

Expected Outcomes

- Develop the 1st map of potential groundwater discharge sites in coastal areas of Portugal

- Fill an important gap in literature by assessing the importance of groundwater discharge on sedimentary and rocky intertidal key coastal ecosystems.

- Identify for the first-time key responsive taxa that could serve as bioindicators for monitoring protocols of environmental governing bodies to achieve biodiversity sustainability of the important rocky shores’ habitats.

1.3. State of the Art – Literature Review

1.3.1. Coastal Aquifers and Sustainability Challenges

Coastal aquifers are groundwater systems that cross land-ocean boundaries (USGS, 2020), constituting systems where the interface fresh water - salt water is in a fragile balance. These systems provide freshwater to more than one billion people who live along the coast and interact with coastal hazards and coastal ecosystems alike (Ferguson & Gleeson, 2012).

Usually, in coastal conditions the aquifer is open toward the sea and fresh waters float on salt water of marine origin; hence, the over-exploitation of the aquifers creates a progressive salinization of groundwater due to seawater intrusion (MED-EUWI WG ON GROUNDWATER, 2007). Coastal karstic aquifers are more sensitive to this phenomenon than porous or fractured ones, however, each type of aquifer need particular care in their management that can be realized only by knowing exactly how they function.

The characteristics of groundwater in coastal regions vary both spatially and temporally. Furthermore, the groundwater systems are normally so complex as they are influenced by many factors in a particular site. Rainfall, landform, soil, lithology, seawater intrusion and other anthropogenic activity are some of the factors determining the groundwater conditions in coastal regions (Manikandan et al., 2012)

In the twenty-first century, projected climate change and human population growth will dramatically affect coastal aquifers. For example, saltwater intrusion exacerbated by groundwater extraction and rising sea levels will degrade the quality and quantity of freshwater available in coastal aquifers. Watershed activities such as agriculture, industry, and urbanization will also affect groundwater resources (Ferguson & Gleeson, 2012)

These same factors also contribute to changes in the rate and quality of groundwater being discharged into the coastal areas. This coastal and submarine groundwater discharge process is nearly ubiquitous on all types of coastlines and delivers water and associated constituents to nearshore ecosystems, including estuaries and wetlands, coral reefs, rocky shorelines, and the continental shelves (USGS, 2020).

Pressures over groundwater resources in the Mediterranean region have increased dramatically during the last decades due mainly to an increase in irrigated agriculture, tourism and industry (Rachid et al., 2021) Thus, many groundwater resources are at risk of being exhausted through over-pumping. With withdrawal exceeding the internally renewable water resources, the resulting groundwater scarcity is rapidly becoming a major concern in most countries of the Mediterranean.

The pressures on natural groundwater resources are higher in the summer period, when natural supply is minimal, while water demands are maximum (irrigation, tourism) (Stigter et al., 2014; da Costa et al., 2020; Rachid et al., 2021).

In the south of Portugal, characterized by a warm Mediterranean climate, water is a scarce and fragile resource, unequally distributed in space and time and widely exploited (Almeida et al., 2000). From the hydrogeological point of view this sedimentary basin is mainly composed of Tertiary karstified limestones and Quaternary alluvial deposits, which represent the main water bearing formations in the Algarve coastal belt (Carreira et al., 2014). Although aquifer potential is high, the large demands from irrigated agriculture and tourism threaten the sustainability of the resource and the associated ecosystems. Decreased aquifer recharge and more frequent periods of drought are predicted for this area (Stigter et al., 2014). In the Central Algarve, stream flow is highly ephemeral, except when located over the large karstified carbonate rock aquifers where it is highly influenced by base flow in effluent reaches. Important and sensitive surface/ groundwater ecotones exist at the location of the springs, many of them classified as protected areas (Stigter et al., 2014). Along the southern coast, intensive exploitation of existing aquifers, plus the extensive agricultural development and tourism, may result in problems of exhaustion and quality degradation of local/regional groundwater systems (Carreira et al., 2014).

1.3.2. Surface and Groundwater Interaction in Coastal Areas

1.3.2.1. Groundwater Discharge in Coastal Zones

Water flowing through the terrestrial landscape ultimately delivers fresh water and dissolved solutes to the coastal ocean (William C Burnett et al., 2003). It generally occurs as a slow diffuse flow but can be found as large point sources in certain terrain, such as karst. In addition to typically low flow rates, groundwater discharge is temporally and spatially variable, complicating efforts to characterize site-specific flow regimes (Mulligan & Charette, 2009).

Historically, such inputs were considered insignificant compared to riverine flow. However, recent work has shown that groundwater flow through coastal sediments and subsequent discharge to the coastal ocean can have a significant impact on coastal water quality and geochemical cycles by transporting heat, nutrients, contaminants, and dissolved ions (Sawyer et al., 2013), and it is therefore a process that must be better understood (Mulligan & Charette, 2009). Likewise, freshwater discharges from coastal aquifers have significant impact on the structure of biological communities in submarine coastal environments, contributing to enhance the transfer of energy from the lower levels of the trophic web to upper levels (Encarnação et al., 2013).

Submarine Groundwater Discharge – SGD (Figure 1) is ubiquitous in sandy, muddy and rocky shorelines and represents a combination of fresh and saline groundwater interacting with coastal surface waters (Burnett et al., 2003). Fresh SGD is driven by a positive terrestrial hydraulic gradient and emerges from shallow or deep aquifers intersecting the shoreline carrying natural and anthropogenic nutrients from land. Saline SGD (sometimes also referred to as seawater circulation in sediments) is defined as the advection of saline groundwater through intertidal zone sediments and/or across the coastal seafloor, and/or advective porewater exchange on scales larger than one meter. Saline groundwater also mixes with fresh SGD owing to the interactions of tides and waves, density-driven flow and dispersion processes, with the resulting brackish SGD transporting both land-derived and marine-derived nutrients (Santos et al., 2021).

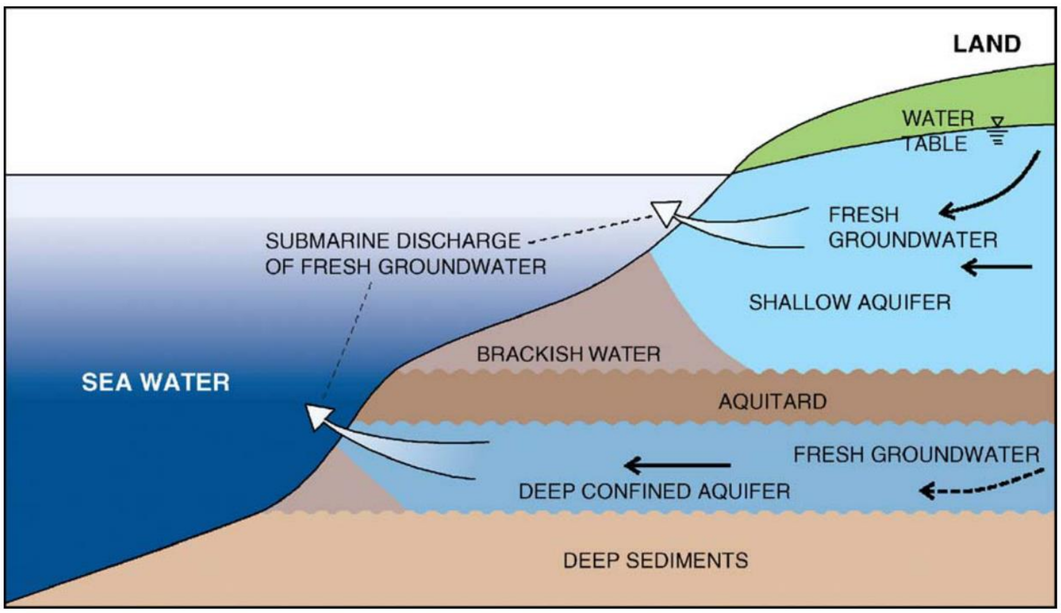


Figure 1. Schematic depiction (no scale) of processes associated with SGD. Arrows indicate fluid movement. Source: Burnett et al. (2006)

Fresh and saline SGD pathways vary between sandy, muddy and rocky coastlines, owing to the unique hydrogeological characteristics of coastal aquifers. Sandy coasts generally consist of highly permeable sediments that effectively connect aquifers to the coastal ocean. A typical unconfined surficial sandy aquifer stores fresh groundwater from upland regions, discharging to the sea within or below the intertidal zone (Robinson et al., 2006). In contrast, muddy coasts dominated by mangroves and saltmarshes are characterized by lower permeability sediments that facilitate saline SGD once the secondary permeability has been enhanced by burrows, root structures or buried vegetation (Xin et al., 2009 in Santos et al., 2021). Rocky coasts contain fractures and/or conduits that allow direct fresh SGD flows to the sea with no or minor biogeochemical transformations (Santos et al., 2021)

Topography and geomorphology can also influence SGD, but the effects remain largely unquantified. For example, the regional topography of the coastal zone dictates the slope of the water table and the inland hydraulic gradient in coastal unconfined aquifers, which, in turn, influences fresh SGD. Nearshore morphological features, such as beach slope breaks, tidal creeks and heterogeneous stratigraphy, affect seawater circulation in beaches and saline SGD.

1.3.2.2. Identifying Submarine Groundwater Discharge

A number of qualitative and quantitative techniques have been developed to sample submarine groundwater discharge, with each method sampling a particular spatial and temporal scale. Because of limitations with each sampling method, several techniques should be used at any particular site. Most attempts to quantify different drivers of SGD tend to focus on a separation between fresh SGD driven by terrestrial hydraulic gradients vs. saline SGD driven by multiple marine forces (Poggi et al., 2019).

Earlier investigations relied on salinity observations of water collected from seepage meters to assess the relative contribution of fresh SGD to total SGD (Michael et al., 2003; Santos et al., 2009 cited in Poggi et al., 2019), as well as a comparison between Darcy's Law derived fresh SGD vs. total SGD derived from seepage meters (Taniguchi & Iwakawa, 2004 cited in Poggi et al., 2019) or geochemical tracers (Mulligan and Charette, 2006 cited in Poggi et al., 2019).

More recent investigations have relied on a comparison of salt balance approaches (fresh SGD) vs. geochemical tracers (total SGD). For example, salinity and flow observations were used to infer fresh SGD, while a radium isotope mass balance was used to estimate tidally-driven saline SGD in Australian estuaries (Sadat-Noori et al., 2016, Sadat-Noori et al., 2017). The different half-lives of radium isotopes have been used to broadly separate SGD from porewater exchange (Tamborski et al., 2018).

Next are described the most common methodologies used for SGD identification studies.

- *Infrared Thermography*

Infrared imaging has been used to identify the location and spatial variability of SGD by exploiting the temperature difference between surface water and groundwater at certain times of the year (Mulligan & Charette, 2009). On large spatial scales (km-scale), readily available space borne remote sensing thermal infrared sensing data can be used to identify large SGD inflows sustaining persistent temperature plumes (Wilson & Rocha, 2012; Sass et al., 2014; Tamborski et al., 2015; Samani et al., 2021).

Identification of SGD using TIR remote sensing is possible in areas where there is significant thermal contrast between the receiving surface-water body and the discharging pore fluid (Kelly et al., 2013). Indeed, remote sensing-based methods are not only useful in understanding SGD patterns in coastal environments, but also help in determining geological heterogeneity at a relatively high spatial resolution and over large areas. Importantly, satellite TIR remote sensing has been found to be an effective tool for detecting SGD (Samani et al., 2021). Furthermore, the potential of TIR remote sensing has been explored in various regions around the world (Kelly et al., 2013). For example, Wilson & Rocha (2012) used Landsat Enhanced Thematic Mapper (ETM+) thermal infrared (TIR) imagery in a regional scale to assessment the submarine groundwater discharge flux to the south and west the coastal waters in Ireland. Also, Tamborski et al. (2015), performed airborne thermal infrared overflights to investigate SGD along the north shore of Long Island, New York (Figure 2). More recently, Samani et al. (2021) used Landsat 8 thermal sensor data to identify potential sites of SGD at a regional scale in the Northern Persian Gulf. Similarly, Jou-Claus et al. (2021) demonstrated the significant usefulness of the thermal infrared imagery as an exploratory tool for identifying SGD springs in karstic coastal aquifers in the Mediterranean Sea basin during different seasons and under diverse meteorological conditions.

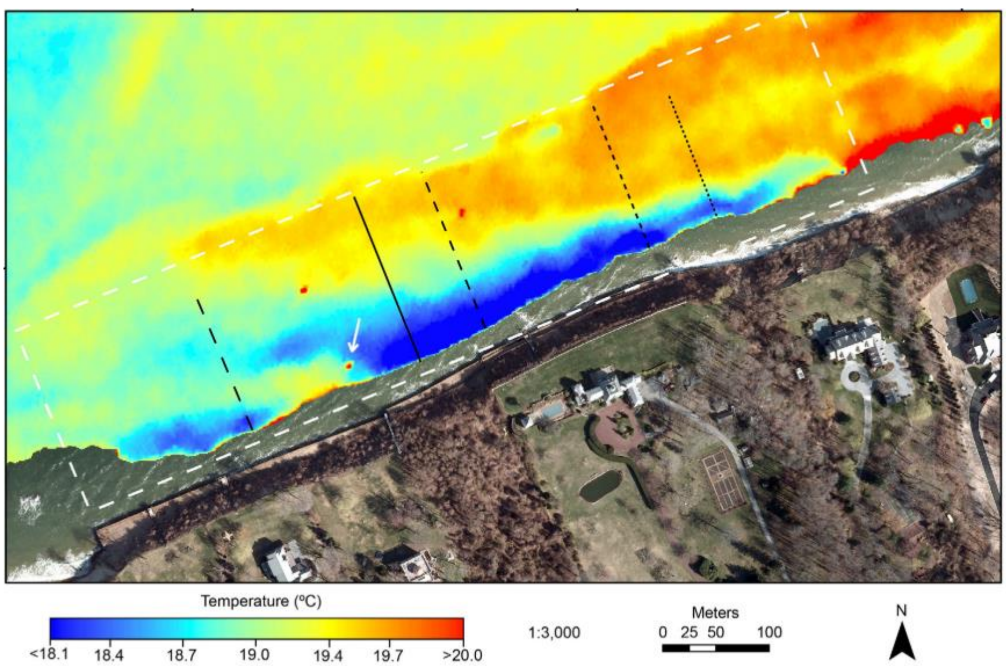


Figure 2. Example of an Airborne Thermal infrared (TIR) remote sensing map of Eastern Short Beach within Smithtown Bay, Long Island, New York.
Source: Tamborski et al. (2015)

- *Geophysical Surveys*

The geophysical tools applied in SGD studies are based on temperature and salinity variations. They can discriminate between freshwater and saline components of SGD (e.g. Tamborski et al., 2015). Particularly applicable to point sources of freshwater SGD, e.g., karstic or volcanic origin, where considerable spatial contrasts in these parameters exist, these approaches provide a "map," but do not allow for a quantification of SGD fluxes without combining with other methods (Poggi et al., 2019).

The electrical conductivity (and resistivity) of coastal sediments is a function of the soil porosity (or pore water fraction) and of the salinity (and temperature) of the interstitial water. In SGD studies, spatial variations of pore water salinity close to the fresh-salt interface are significantly greater than those of porosity. Geoelectric instrumentation consist of an array of multiple electrodes (minimum four), either directly inserted into the ground, deployed on the sediment surface, or, in some cases, towed behind a boat (Lashkaripour & Nakhaei, 2009; Supper et al., 2011; Poggi et al., 2019). The geometry of the electrode array determines the volume of sediment over which conductivity/resistivity will be averaged (Poggi et al., 2019).

Geoelectric mapping (Figure 3) helps to improve SGD field studies by, for example, informing a more representative placement of seepage meters where preferential flow paths persist (Kroeger et al., 2007). It allows upscaling of point measurements to beach-scale fluxes, and repeated measurements along the same transects document the temporal variability of the fresh-salt interface and of fresh groundwater and seawater recirculation fluxes. They can also be used for the establishment of a sub-surface salt balance model from which SGD fluxes can be calculated (Poggi et al., 2019).

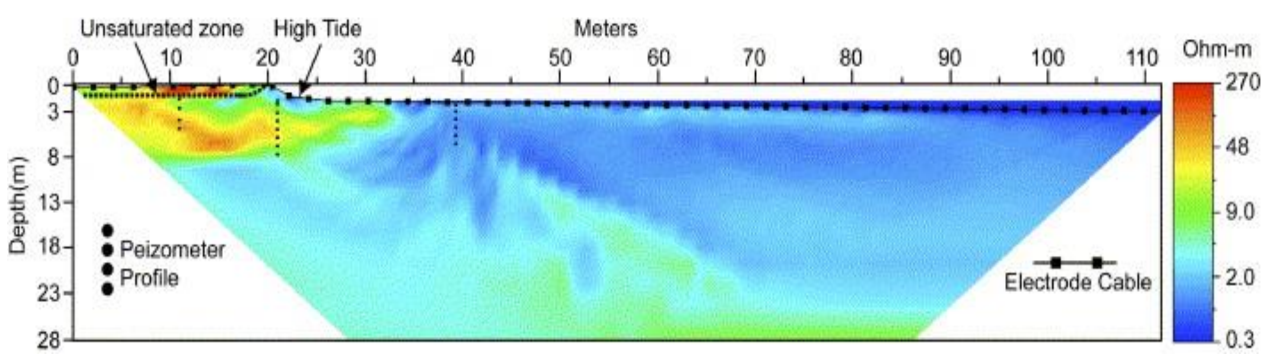


Figure 3. Example of a Stationary resistivity profile in a shore-perpendicular transect in the Tampa Bay, Florida. Source: Kroeger et al. (2007)

- *Hydrological Approaches*

There are two hydrologic approaches to estimating SGD, the mass balance method and Darcy's law calculation. Both methods are typically applied to estimating fresh groundwater discharge, although Darcy's law can be used to estimate saline flow into and out of the seafloor.

On one hand, the mass balance approach to estimating SGD requires ascertaining all inputs and outputs of water flow, except SGD, through the groundwater basin. Assuming a steady-state condition over a specified time frame, the groundwater discharge rate is calculated as the difference between all inputs and all outputs. Implementing this approach can be quite simple or can result in complex field campaigns, but the quality of the data obviously affect the level of uncertainty. Even with extensive field sampling, water budgets are seldom known with certainty and so should be used with that in mind. Furthermore, if the spatial and temporal variability of SGD is needed for a particular study, the mass balance approach is not appropriate (Mulligan & Charette, 2009). The water budget equation for the estimation of fresh SGD (Burnett et al., 2006) is as follows:

$$P = E_T + D_S + D_G + d_S \tag{1}$$

where P is precipitation/rainfall, E_T is evapotranspiration, D_S is surface discharge, D_G is fresh groundwater discharge, and d_S is the change in water storage assumed to be insignificant (Burnett et al., 2006). The modified equation as proposed by Kroeger et al. (2007) for calculating SGD is as follows:

$$D_G = P - E_T - D_S \tag{2}$$

On the other hand, to apply Darcy's Law (Equation (3)), one must measure the soil permeability and hydraulic head at several locations (at least two) at the field site. Data must also be gathered to determine the cross-sectional flow area. The field data are then used with Darcy's law to calculate a groundwater flow rate into the coastal ocean as follows:

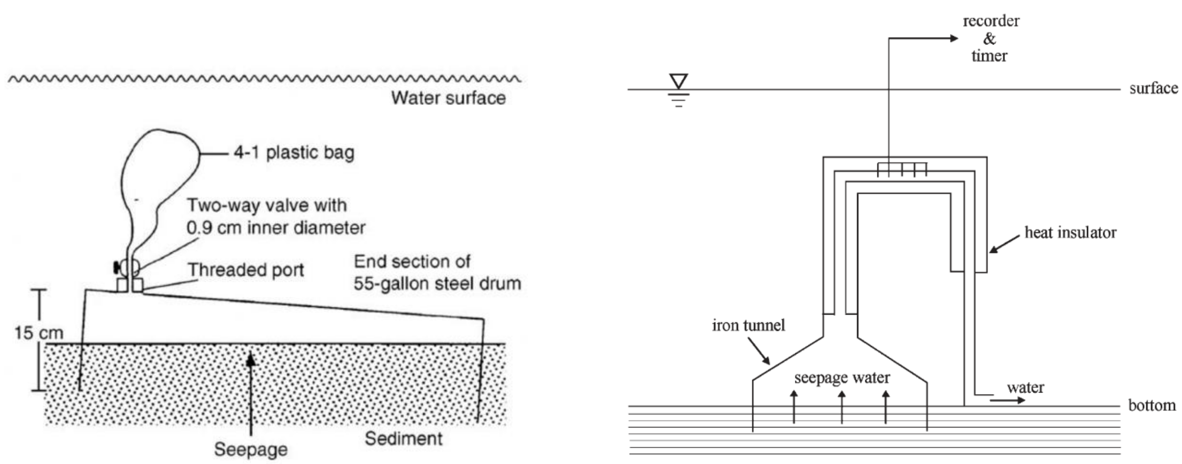
$$Q = -K \times A \times i \tag{3}$$

Where Q is amount of fresh groundwater discharge (m^3 day^{-1}), K is aquifer hydraulic conductivity (m day^{-1}), i is the hydraulic gradient in the aquifer (m m^{-1}), and A is aquifer cross-sectional area

The main disadvantages of this approach include the fact that permeability is highly heterogeneous, often ranging over several orders of magnitude, and so an "average" value to use with Darcy's law is seldom, if ever, well known. Furthermore, hydraulic head measurements require invasive, typically expensive, well installations. Finally, hydraulic head is a point measurement and capturing the spatial variability therefore requires installing many wells. The primary advantage of this approach is that it is well established and easy to implement: head measurements are easy to collect once wells are installed and the flux calculations are simple (Mulligan & Charette, 2009).

- *Direct measurements: Seepage meters*

Submarine groundwater discharge can be measured directly with seepage meters (Figure 4). The simple manual seepage meters (Figure 4a) has a valve on top through which water can flow; a plastic bag pre-filled with a known volume of water is attached to the valve so that inflow to or outflow from the sediments can be determined. After a set length of time, the bag is removed and the volume of water in the bag is measured. The change in water volume over the sampling period is then used to determine the average flow rate of fluid across the water-sediment boundary over the length of the sampling period. These meters are very simple to operate, but they are manually intensive and are sensitive to wave disturbance and currents. Furthermore, they only sample a small flow area and so many meters are needed to characterize the spatial variability seen at most sites. Recently, several other technologies have been applied toward developing automated seep meters. These meters can be left in place for days and often weeks and will measure seepage without the manual intervention needed using traditional seepage meters (Mulligan & Charette, 2009). The "Taniguchi-type (heat-pulse type)" (Figure 4b) automated seepage meter is based on the travel time of a heat pulse down a narrow tube. The device uses a string of thermistors in a column positioned above an inverted funnel covering a known area of sediment.



(a) ***(b)***

Figure 4. Sketches of a a) simple "Lee-type" manual seepage meter, and b) Taniguchi-type (heat pulse) automated seepage meter.
Source: Burnett et al. (2006)

- *Natural Tracers*

The chemical tracer approach to quantifying SGD has an advantage over seepage meters in that it provides an integrated flux over a wide range of spatial scales from estuaries to continental shelves. In applying geochemical tracing techniques, several criteria must be assessed or defined, including boundary conditions (i.e., area, volume), water and constituent sources and sinks, residence times of the surface water body, and concentrations of the tracer. Sources may include ocean water, river water, groundwater, precipitation, in situ production, horizontal water column transport, sediment resuspension, or sediment diffusion. Sinks may include in situ decay or consumption, horizontal water column transport, horizontal or vertical eddy diffusivity, and atmospheric evasion. Through simple mass balances or box models, as shown in Figure 5, incorporating both sediment advection and water column transport, the geochemical approach can be quite useful in assessing SGD (Burnett et al., 2006).

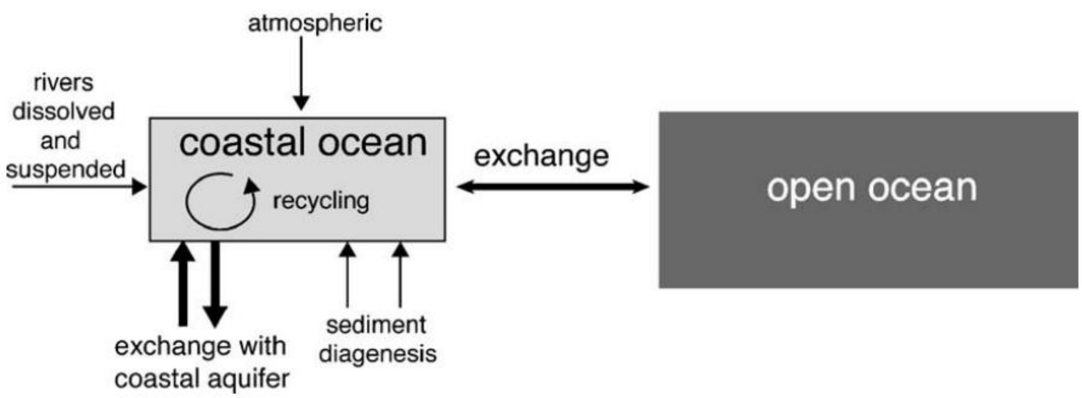


Figure 5. Box model showing how isotopes can be used to investigate exchange different compartments
Source: Burnett et al. (2006)

The principle of using a chemical tracer is simple, find an element or isotope that is highly enriched (or depleted) in groundwater relative to other sources of water, like rivers or rainfall, to the system under study. If SGD is occurring, then the flux of this element via groundwater will lead to enrichment in the coastal zone that is well above background levels in the open ocean. A simple mass balance/box model for the system under study can be performed, where all sources of the tracer other than groundwater are subtracted from the total inventory of the chemical. The residual inventory, or “excess”, is then divided by the concentration of the tracer in the discharging groundwater to calculate the groundwater flow rate (Mulligan & Charette, 2009).

Over the last decade, numerous studies worldwide have successfully applied radon and radium isotopes to quantify SGD fluxes over a range of different time-scales, as well as to estimate the magnitude of SGD and determine its relative importance in chemical budgets of coastal waters.

However, the behavior of radium and radon in coastal aquifers is complex, and also laboratory experiments of radioisotopes are expensive and difficult to carry out in developing countries (Samani et al., 2021).

Each of the above-described methods present advantages and disadvantages, the most salient being: Satellite Infrared Thermography is useful and efficient for regional assessment but might not recognize local signals of the temperature gradient. Finer resolution images obtained via airborne thermal infrared overflights or unmanned aerial vehicles, help to identify local effects of SGD, but increase the cost significantly. On the other hand, Geophysical Surveys helps to improve SGD field studies by providing more accurate information of the subsoil, but their scope is limited in horizontal and vertical extension. Hydrological approaches and direct measurement are among the most effective methods because they capture the actual behavior of the variables of interest, however, those methods are time consuming and require a long period of data collection. Natural tracer, on the contrary, are highly efficient to determine SGD fluxes through the monitoring of the chemical composition of the different water bodies, nonetheless, it is an expensive technique which limits its implementation in regional scale studies.

1.3.2.3. Coastal Groundwater Dependent Ecosystems

Groundwater Dependent Ecosystems are defined as "ecosystems that require access to ground-water on a permanent or intermittent basis to meet all or some of their water requirement so as to maintain their communities of plants and animals, ecological processes and ecosystem services" (Richardson et al., 2011)

Just as terrestrial and aquatic ecosystems have a surface water requirement to maintain their structure and function, GDEs also have an ecological water requirement. The presence of groundwater drives the evolution, persistence and resilience of GDEs, and the state of these ecosystems is dependent on at least two aspects of the groundwater, including (Brown et al., 2007)): *i)* physical characteristics, such as the quantity, location, timing, frequency and duration of groundwater delivery (or supply), and *ii)* chemical characteristics, such as water quality (especially salinity and nutrient concentrations) and temperature. Changes in any one of these variables can initiate changes in the structure and function of a GDE (Richardson et al., 2011)

As ecotones that connects riverine, marine, and subsurface environments, estuaries and sandy and rocky shores play an important role in regulating the fate of water and solutes in coastal areas. They are also subject, and so far, unknown to us, to the influence of groundwater coastal discharges which may impart so dependency level to their ecological functioning. Ecologically, the functioning of these systems is differentiated and their structure may affect the species diversity and abundance in several systems, therefore, it determines the functioning of the ecosystems and the environmental services it provides.

- *Sandy Shores*

A sandy shore constitutes a dynamic environment and an unstable substrate. It is characterized by a sandy profile from the point where wave action reaches the sediment bed, through a wave-dominated subaqueous zone and a wind and wave dominated beach, up to the dune belt where aeolian processes dominate. This is also known as the active zone, which differs per location and depends on the time frame considered (McLachlan & Brown, 2006).

The shore dynamics, driven by tides, waves and wind greatly influence the occurrence of species (Janssen & Mulder, 2005). This yields a characteristic biodiversity and unique habitat gradients. On the beach, diversity increases from the high water to the low water line, then decreases again lower in the surf zone, to pick up strongly – in mass as well as diversity – further seaward. Organisms living here are adapted to this dynamic environment and reflect the complex ecomorphological interactions (McLachlan & Brown, 2006).

Due to the usually high nutrient concentrations, coastal waters and sandy shores have a high primary production and are therefore important as breeding grounds, resting areas and nurseries for a variety animal species. They also provide multiple benefits to society such as recreational opportunities, groundwater reserves for drinking water and coastal protection (McLachlan & Brown, 2006).

- *Rocky Shores*

A rocky shore is an intertidal area of seacoasts where solid rock predominates, still it is considered as a part of marine ecosystem. This zone is at the confluence of marine and land; subject to cover or exposure to air at different point of time in a day due to the cyclical tidal action. Rocky shores are biologically rich environments, and are a useful 'natural laboratory' for studying intertidal ecology and other biological processes. Therefore, the ecology of animals and plants on intertidal rocky shores has been a topic of interest for decades in many parts of the world (Satyam & Thiruchitrambalam, 2018).

Rocky shores are biologically rich in terms of the number and variety of species they support. This high species diversity is attributable to the existence of a large number of ecological niches. Several studies have accounted the detailed structure of flora and fauna of intertidal rocky shore

(Colman, 1933; Fischer-Piette, 1936 cited in Satyam & Thiruchitrambalam, 2018). Organisms that live in this area experience daily fluctuations in their environment. For this reason, they must be able to tolerate extreme changes in temperature, salinity, moisture and wave action to survive. As a result, the sharp physical gradient and spatially clustered community has made the rocky intertidal zone as an ideal place to study the role of physical and biological factors in determining the abundance and distribution of organisms (Satyam & Thiruchitrambalam, 2018).

In recent times, these rock shore habitats are under increasing threat as a consequence of anthropogenic activity such as increasing population, tourism, trampling and sea food gathering activities and climate change. Further, many of these areas are still unexplored and the influence of groundwater discharge modification is yet unexplained. It is expected that changes in both quality and quantity of groundwater reaching the rocky shores from coastal aquifer may affect the presence and richness of the biodiversity associated to these environments.

1.3.3. Biodiversity as Indicator in Coastal Ecosystems

To apply an ecosystem-based approach is considered one of the most important requirements for sustainable environmental management and was defined as 'a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way' (United Nations Convention on Biological Biodiversity, 1993).

Indicators, broadly defined are a scientific response to the governmental need for reliable and accurate information on a system's conditions (Van Hoey et al., 2010). The first aim of these indicators is to distinguish between a healthy and degraded water system with sufficient precision to identify the critical border between the need for 'action' and 'no action' to improve the ecological condition. Biological elements and supporting physico-chemical parameters, along with the concentration of pollutants are selected to assess the health of the ecosystem. These ecosystem attributes are important since they provide information about the functioning and status of the ecosystem (Van Hoey et al., 2010).

Groundwater dependent ecosystems are systems where there is a large exchange of biological and non-biological materials with neighboring systems. These exchanges include water, salts, nutrients, sediments, and organisms (Day & Yánez, 1982). Understanding ecosystem attributes, such as food web dynamics, species diversity, and the distribution of life histories can help to assess the structural and functional characteristics of the ecosystem.

Ecological and microbiological exploration of groundwater over the past two decades has identified a diverse range of organisms inhabiting groundwater systems, collectively called stygofauna (Glanville et al., 2016). These are valued as a biodiversity resource, as indicators of groundwater ecosystem health, and potential providers of ecosystem goods and services. The integrated functioning of the GDEs implies the existence of delicate equilibrium physical and biological processes. This ecological role of groundwater suggests that GDEs will react to changes in any element with variable magnitude (Brkić et al., 2019).

Assuming that changes in quality and/or quantity of groundwater will potentially result in changes in the ecological configuration of the interconnected systems, it becomes important to understand how benthic estuarine species respond in the present day to the groundwater-estuarine interaction (Silva et al., 2012). Invertebrate communities of transitional waters (freshwater-saltwater ecotone) are highly influenced by freshwater discharge, showing marked seasonal variation mainly related to salinity fluctuation (Chainho et al., 2006). The evaluation of shifts in the species presence on an ecosystem is a valid strategy for environmental monitoring (Van Hoey et al., 2010), because the life cycle of organisms integrates alterations on the environmental characteristics in a relatively wide period of time. This approach overcomes the limitations of an evaluation of the environmental condition singly based on physical-chemical parameters, which does not considers the consequences of environmental alterations on the ecosystem (Silva et al., 2012).

Biological indicators can be defined as the presence or abundance of some taxa which may be considered to represent biodiversity of a large assemblage, of species living in a particular habitat or the presence or abundance of other taxa (MacNally and Fleishman, 2002 in Silva et al., 2012). They are expected to be useful in identifying areas that warrant special protection and specific conservation measures, and are based on the presence of specific taxonomic groups. Within an aquatic ecosystem, the benthic fauna is often used as indicator of environmental changes and considered to be the most adequate descriptor of estuarine habitats because organisms are mostly sedentary and thus, reliable local indicators over time of environmental conditions (Warwick, 1993 in Silva et al., 2012).

1.3.4. Monitoring of Coastal Groundwater Dependent Ecosystems

Due to their complexity, the development of management strategies adapted to coastal GDEs is particularly complex because it requires a strong transdisciplinary approach. The improvement of GDEs' management inevitably involves an increasing knowledge of their hydrogeological and ecological condition and processes (Foster et al., 2016).

The current increasing anthropogenic pressures and predicted climate change effects threaten not only the subterranean aquatic ecosystems, but also groundwater-dependent coastal terrestrial and aquatic vegetation, and reduce the value of the resource for human use (Nevill et al., 2010).

Substantial aquifer exploitation threatens wetlands, lagoons, and estuaries that constitute groundwater-dependent ecosystems and, in coastal areas it can lead to seawater intrusion, an aggravating problem worldwide, including the Mediterranean countries. Climate change may particularly aggravate this problem in the Mediterranean region (Giorgi, 2006), due to the combined effect of rising sea levels and reduced recharge of aquifers associated with the expected decrease in precipitation and average temperature increase (Stigter et al., 2014).

Although the existence of local specificities shows the importance of establishing adaptive case-by-case water management strategies, water resource management simultaneously requires the definition of appropriate management scale which makes it possible to manage the hydro-system as a whole, taking into account the complexity of interactions between water bodies but also between humans and their environment (Erostate et al., 2020). In that sense, the consideration of biological indicators and the evaluation of shifts in the species presence on coastal ecosystems has emerged as a valid strategy to complement the characterization of the ecological status of transitional ecosystems.

To overcome the lack of knowledge about GDEs, advances to establish practical guides have been done. These “GDE practical guides” can in theory assist state agencies in the identification and management of GDEs for water management plans (Erostate et al., 2020). They offer a range of methods for determining ecosystem reliance to groundwater and help water managers conducting the necessary technical investigations and monitoring protocols to define ecological water requirements for GDEs.

In practice, these guides must conduct the search of data keys to understand all types of systems but recognizing that each GDE is an individual case, having specific characteristics and behavior that require special analysis when delineating management strategies. The identification of appropriate study tools requires significant scientific support and the evaluation and monitoring of the relevance of the tools used is yet another debate. There are still gaps that need to be fill in the process of understanding and managing groundwater dependent ecosystems.

All water resources in the coastal areas should be managed collectively and strategically, in order to maximize use efficiency, reduce water use conflicts and avoid overexploitation. In the global context of unprecedented anthropogenic pressures, hydro-food crises and climate change, the consideration given to coastal GDEs represents a key issue for the socioeconomic and environmentally sustainable development of many coastal Mediterranean areas. Integrated water management strategies that consider environmental needs on an equal footing with socio-economic constraints within the coastal hydro-system need to be improved (Erostate et al., 2020).

CHAPTER 2 – DEVELOPMENT OF A THERMAL-BASED METHODOLOGY FOR IDENTIFYING COASTAL ZONES WITH POTENTIAL GROUNDWATER DISCHARGE DEPENDENCE

2.1. Introduction

Groundwater discharge is a key factor for hydrological and ecological studies in coastal areas due to the significant role it can play in processes such as nutrient cycling, geochemical mass balances, and primary productivity in coastal ecosystems (Sawyer et al., 2013; Amato et al., 2016; Santos et al., 2021). These ecosystems are called groundwater dependent (GDEs) when this resource is needed to secure the ecosystem services, functioning and community structure (Richardson et al., 2011). Therein, the presence of groundwater drives the evolution, persistence and resilience of GDEs, which state is dependent on at least two aspects of the groundwater according to Brown et al. (2007), including: *i)* physical characteristics, such as the quantity, location, timing, frequency and duration of groundwater delivery (or supply), and *ii)* chemical characteristics, such as water quality (especially salinity and nutrient concentrations) and temperature.

There is a vast body of literature on the importance of groundwater discharge as a source of solutes and nutrients for various coastal and marine environments and their ecosystem services. Capone & Bautista (1985) presented the first substantial evidence of the effect of nitrate-enriched groundwater discharge through coastal sediments into the Great South Bay, New York. Similarly, Bowen et al. (2007) established that groundwater-borne nutrient loads had increased the nitrogen content of receiving estuaries on the northeast coast of the United States, hence influencing the phytoplankton and macroalgal production and biomass. More recently, Rodellas et al. (2018) found that inputs from karstic springs represent the principal source of freshwater to some coastal lagoons, contributing to maintain them under non-hypersaline conditions for most of the year. In the same way, Fujita et al. (2019) revealed that nutrients supplied via submarine groundwater were potentially important for primary production in the coastal sea areas of Japan. Likewise, Starke et al. (2020) demonstrated that elevated nutrient concentrations transmitted by submarine springs caused a bottom-up control resulting in a higher abundance of fish in a coastal lagoon of Tahiti, French Polynesia. Overall, it is hence possible to conclude that groundwater discharge has important implications in coastal zones' biological functioning, plankton dynamics, sedimentary geochemistry, microbial ecology, and environmental toxicology. Hence, in coastal zones management, it is fundamental to recognize the importance of the linkage in the coastal boundary area that originates from groundwater discharge.

The general movement of groundwater to the coast is typically termed as submarine groundwater discharge (SGD). This process has received several definitions, depending on whether it merely takes into account freshwater discharge or also includes re-circulated water seepage (Taniguchi et al., 2002). The most widely accepted definition is presented in Burnett et al. (2006) corresponding to "any flow of water out across the sea floor". Whether SGD includes a large component of freshwater or not, also referred to as coastal groundwater discharge (CGD), depends on the local hydrogeological conditions, i.e., aquifer lithology, aquifer type and hydraulic gradients, as well as the groundwater balance and how it is affected by human activities (Hugman, Stigter, Monteiro, et al., 2015).

According to Luijendijk et al. (2020), the total flux of groundwater to the ocean can be divided into three distinct fluxes: fresh groundwater, near-shore terrestrial groundwater discharge, and recirculated seawater. However, the methodology developed in this study does not focus on the separation of the different fluxes of SGD, rather defines SGD without regard to its composition (e.g., salinity), its origin, or the mechanism(s) driving the flow. Therefore, it will always be referred to as Submarine Groundwater Discharge, indistinctly.

Earlier investigations relied on salinity observations of water collected from seepage meters to assess the relative contribution of fresh SGD to total SGD (Michael et al., 2003; Santos et al., 2009 cited in Poggi et al., 2019), as well as a comparison between Darcy's Law derived fresh SGD vs. total SGD derived from seepage meters (Taniguchi & Iwakawa, 2004 cited in Poggi et al., 2019). Over the last decade, numerous studies worldwide have successfully applied isotopes to quantify SGD fluxes over a range of different time-scales, estimate the magnitude of SGD and determine its relative importance in chemical budgets of coastal waters (Burnett et al., 2008, Devries et al., 2014). However, this method can be costly and time consuming. Other methods for mapping SGD such as ground electrical resistivity surveys are only suited for use over small areas (~100m^2) (Stieglitz et al., 2008). Hence, alternative methods for studying the SGD at local to regional scales are required.

Frequently, thermal infrared (TIR) remote sensing techniques are employed to evaluate SGD. Wilson & Rocha (2012) set the foundation for the use of freely available Landsat Enhanced Thematic Mapper (ETM+) thermal infrared (TIR) imagery in a regional scale assessment of submarine groundwater discharge to coastal waters in Ireland. Also, Tamborski et al. (2015), combined airborne thermal infrared overflights with shoreline radionuclide surveys to investigate

SGD along the north shore of Long Island, New York. More recently, Samani et al. (2021) used Landsat 8 thermal sensor data to identify potential sites of SGD at a regional scale in the Northern Persian Gulf. Similarly, Jou-Claus et al. (2021) demonstrated the significant usefulness of the thermal infrared imagery as an exploratory tool for identifying SGD springs in karstic coastal aquifers in the Mediterranean Sea basin during different seasons and under diverse meteorological conditions.

In Portugal, SGD has been investigated with more detail in the Algarve region, where there are several well-studied coastal aquifer systems and important associated aquatic coastal ecosystems (sandy shores, estuaries, and coastal lagoons). Relevant information on the distinguishment of SGD components and the mechanisms of their dispersion throughout the Ria Formosa Lagoon (Faro, Portugal) were provided by Rocha et al. (2016), who assessed land–ocean connectivity combining radon measurements and stable isotope hydrology. In the area of the Albufeira-Ribeira de Quarteira aquifer system, SGD was investigated within the scope of a multidisciplinary research project FREEZE (PTDC/MAR/102030/2008) which aimed to identify and characterize the effects of the hydrological/hydrogeological conditions on associated ecosystems (Encarnação et al., 2013 ;Fernandez et al., 2015; Hugman, Stigter, & Monteiro, 2015; Hugman, Stigter, Monteiro, et al., 2015). Additionally, Silva et al. (2012) showed the estuarine faunal community to significantly respond to a gradient dependent on groundwater input, under a predicted climatic scenario of reduction in groundwater discharge into the estuary.

Nevertheless, the occurrence of groundwater discharge and its effects on rocky shores are less commonly reported in the literature. Intertidal rocky shores are one of the most heterogeneous coastal environments (Piló et al., 2018) and biologically rich in terms of the number and variety of species they support (Satyam & Thiruchitrambalam, 2018). However, they are under increasing threats as a consequence of anthropogenic activity such as increasing population, tourism, trampling and sea food gathering activities and climate change (Mieszkowska, 2016). In southwest Europe, many of these areas are still unexplored in terms of SGD influence, and the threat of groundwater discharge modification is yet unexplained. For instance, in Portugal the effect of groundwater discharge on subtidal macrofaunal assemblages was only focused on mobile sediment (Encarnação et al., 2015), whilst the single study on rocky shores (Piló et al., 2018) evaluated the impacts of groundwater discharges on a rocky intertidal community of South Portugal. Together, their results suggest that changes in both quality and quantity of freshwater reaching the rocky shores from coastal aquifers may affect the presence and richness of the biodiversity associated to these environments.

In recognition of both the significance of groundwater discharge as a potential source of nutrients and/or pollutants, and the challenges of locating potentially groundwater-dependent coastal ecosystems, this study aimed to identify potential SGD spots through the application of a thermal infrared satellite imagery analysis, using Portuguese coastline as a case-study.

2.2. Methods

2.2.1 Rationale and methodological framework

This work is based on the premise that the relatively cool groundwater discharging to warmer coastal waters manifests in the thermal band of Landsat TIR imagery acquired during the summer months. Other studies have used this rationale to assess submarine groundwater discharge (SGD) as temperature gradients between discharging groundwater and the surface water body. For instance, Wilson & Rocha (2012) mapped temperature anomalies in the south and west coasts of Ireland, highlighting the suitability of the approach for a regional scale survey. More recently Samani et al. (2021) used Landsat 8 thermal sensor data to identify potential sites of SGD at a regional scale in the Northern Persian Gulf. Similarly, (Jou-Claus et al., 2021) used Landsat 8 imagery as an exploratory tool for identifying SGD in karstic coastal aquifers in the Mediterranean Sea basin.

Although fine spatial resolution airborne, ground-based thermal imaging systems, and handheld thermal sensors are effective methods to identify groundwater discharge into surface water bodies, these solutions tend to be extremely costly and unsuitable for application to very large areas, especially if continued monitoring of groundwater discharges is desired. Hence, thermal infrared images acquired by the thermal infrared sensor (TIRS) carried on the Landsat-8 satellite with a spatial resolution of 100 m were used.

As shown in Figure 6, Landsat 8 Thermal Infrared scenes were acquired for a regional analysis to detect potential groundwater discharge spots all over the coastal waters of continental Portugal. Sea surface temperature and temperature anomalies maps were derived from the Landsat scenes, after processing the images and applying atmospheric correction parameters. An annual contrast from 2013 to 2020 was done to check for consistency of the discharge patterns. The methodological details of these steps are described next.

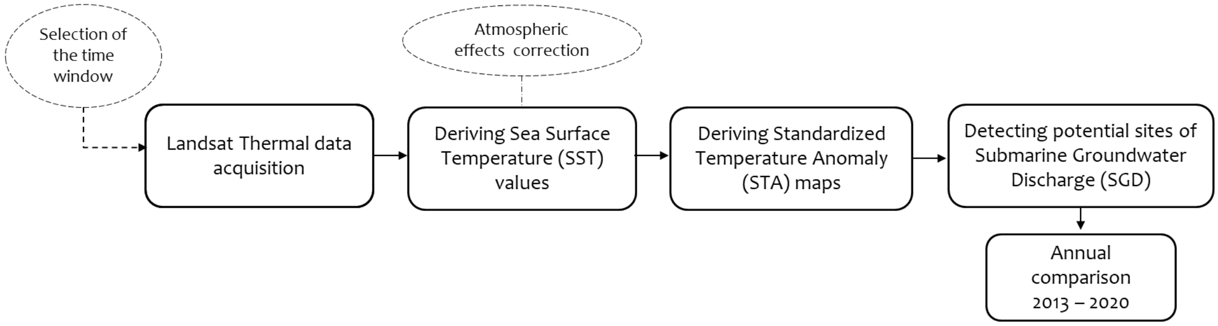


Figure 6. Methodological flow chart for the selection, acquisition, processing and analysis of the Thermal Infrared Landsat 8 images.

2.2.1 Landsat Thermal Data Acquisition

A comparison of sea surface temperature acquired from the Portuguese Institute for Sea and Atmosphere (IPMA for its acronym in Portuguese) and groundwater temperature from a selection of near-coast wells in the monitoring network of the National Water Resources Information System (SNIRH), revealed that the maximum temperature differences occur through the summer and winter months (Figure 7). Also, the general cloud cover in satellite imagery during the winter months is considerably disadvantageous for the thermal infrared analysis. Consequently for this study, the summer time window was selected to acquire the Landsat 8 scenes.

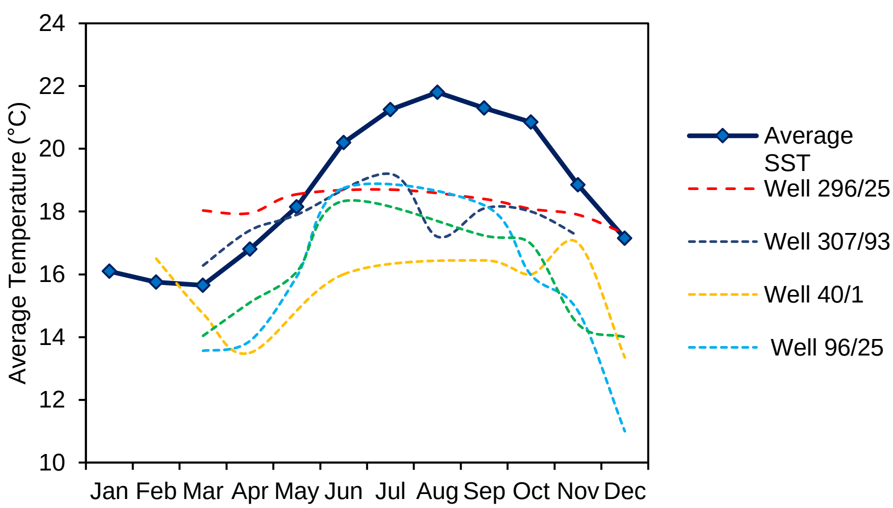


Figure 7. Comparison of groundwater average temperature values in several wells and SST measures from IPMA.

Five sub-regions were defined to cover the Portuguese coast and images were obtained for the late summer months (July, August, and September) with a low percentage of cloud cover (<10%). The sub-regions were designed North, North West, Center, South West and South, with location details provided in Table 1, covering the dashed area presented in the map.

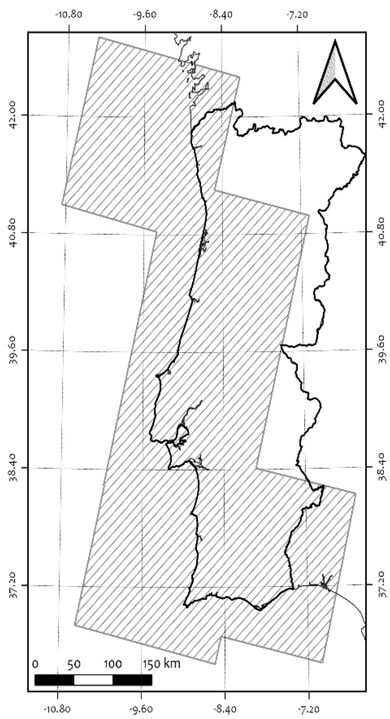


Table 1. Landsat 8 scenes acquired for regional analysis in the coastline of Portugal (map) and data acquisition details.

Coverage area	Path	Row	Center Latitude	Center Longitude
South	203	34	37.4745	-7.7507
South West	204	34	37.4747	-9.2899
Center	204	33	38.9045	-8.8684
North West	204	32	40.3326	-8.4204
North	205	31	41.7596	-9.5063

2.2.2 Thermal Infrared Image Processing

As an initial step, pixel digital numbers (DNs) of the Landsat TIR band 10 were converted to top-of-atmosphere (TOA) spectral radiance using Equation (4) (Samani et al., 2021):

$$L_{\lambda TOA} = M_L Q_{CAL} + A_L \tag{4}$$

Where $L_{\lambda TOA}$ is TOA spectral radiance (Watts m^{-2}·sr^{-1}·µm^{-1}), M_L is rescaling factor (3.342 × 10^{-4} for Landsat-8 band 10), Q_{CAL} is DN values, and A_L is rescaling factor (0.1 for Landsat-8 band 10)

The atmospheric correction was applied to prevent changes due to atmospheric effects being interpreted as changes in the water body. The TOA values were corrected for atmospheric effects (Equation (5)) to determine surface water radiance using parameters derived from the NASA's online atmospheric correction tool (http://atmcorr.gsfc.nasa.gov/), and consequently to derive scene at-surface kinetic sea temperature values.

$$L_{\lambda T} = \frac{L_{\lambda TOA} - L_{\lambda UP}}{\tau \epsilon} - \frac{1-\epsilon}{\epsilon}(L_{\lambda DOWN}) \tag{5}$$

Where $L_{\lambda T}$ is the radiance of a blackbody target of kinetic temperature T (Wm^{-2} sr^{-1} µm^{-1}), τ is the atmospheric transmission (unitless), and ϵ is emissivity of water (ranges from 0.98 to 0.99). $L_{\lambda TOA}$ is calculated from Equation (4). In this study, a constant emissivity of 0.989 was used as suggested in the literature (Wilson & Rocha, 2012). $L_{\lambda UP}$ and $L_{\lambda DOWN}$ are upwelling (atmospheric path radiance) and downwelling (sky radiance), respectively, obtained from the NASA's online atmospheric correction tool as presented in Table 2.

Table 2. Atmospheric correction parameters used for the study sub-regions: Upwelling and downwelling radiances, atmospheric transmission.

Scene date	Coverage area	Path	Row	Time	Upwelling W $m^{-2}sr^{-1}\mu m^{-1}$	Downwelling W $m^{-2}sr^{-1}\mu m^{-1}$	Transmission %
2020-08-19	South	203	34	11:09:03	1.09	1.85	0.88
2020-08-10	Southwest	204	34	11:15:09	1.66	2.69	0.80
2020-07-25	Center	204	33	11:14:42	1.60	2.63	0.81
2020-07-25	Northwest	204	32	11:14:18	1.53	2.52	0.82
2020-07-16	North	205	31	11:20:03	1.59	2.61	0.81

Finally, surface water radiance values were converted into temperature using the Equation (6)

$$T_{SS} = {K_2}\Big/{\ln\left(\frac{K_1}{L_{\lambda T}} + 1\right)} \tag{6}$$

where, T_{SS} is the sea surface temperature (SST) in Kelvin, and K_1 and K_2 are band-specific thermal conversion constants obtained from the available metadata, $K_1 = 774.8853$ and $K_2 = 1321.0789$ for Landsat 8.

2.2.3 Assessment of Thermal Anomalies

Heat has been considered as a groundwater tracer for over a century and remote sensing-based methods for SGD detection are appropriate where temperature gradients form between discharging groundwater and the surface water bodies (Anderson, 2005). Hence, this analysis is based on the hypothesis that in winter months the SGD will be warmer than the receiving surface-waters but in summer SGD will be cooler than surface-waters (Wilson & Rocha, 2012; Tamborski et al., 2015; Samani et al., 2021)

To determine the geographical location of potential sites of SGD, a set of temperature anomaly (TA) and standardized temperature anomaly (STA) maps was generated from each of the Sea Surface Temperature (SST) layers produced from the remotely sensed imagery. Temperature anomaly has been defined as the difference between the SST value of each pixel and the average SST value estimated for the coastal water body Equation (7).

$$TA = T_p - T_a \tag{7}$$

where, TA is temperature anomaly (Kelvin), T_p denotes the temperature value specific to each pixel in the scene (Kelvin), and T_a is the average temperature value for the scene (Kelvin). STA (dimensionless) can be calculated using the following equation (Equation (8)), where, σ is the standard deviation of SST values.

$$STA = \frac{TA}{\sigma} \tag{8}$$

2.3. Results

2.3.1. Temperature and Thermal Anomaly Mapping

2.3.1.1. Standardized Temperature Anomalies

Figure 8 presents the map of negative values of the Standardized Temperature Anomaly (STA) for the coastal area of Portugal. Therein, only the negative standardized anomalies are shown meaning that the surface temperature in those pixels is lower than the average of the scene. Considering the initial hypothesis that the relatively cool groundwater discharging to warmer coastal waters manifests in the thermal imagery, these anomalies would represent potential discharge of groundwater into the ocean during the summer months of 2020. These cold-water plumes can be further interpreted to delineate the location and extent of submarine groundwater discharge (SDG).

Figure 9 presents more detailed results for each of the five regions delineated in this project with the average potentiometric surface of the hydrological year 2019-2020. The figure shows the flow direction of groundwater, allowing the comparison between the potential groundwater discharge inferred from the sea surface temperature anomalies and the actual trends of flow in the coastal aquifers. The analysis of the map allowed the identification of potential discharge areas in all the studied subregions, with higher significance in the South, Northwest and North region (Figure 9). The results show predominance of diffuse SGD in most of the scenes, except for the image of the central region (Figure 9c) where less-clear plume shapes are visible due to the presence of clouds which limit the analysis.

In the South region (Figure 9a), the visible potential SGD sites can be associated to the presence of coastal aquifers like the Covões system in the left corner near Sagres and Vila do Bispo. Similarly, the Almádena-Odeáxere, Mexilhoeira Grande – Portimão, and Ferragudo-Albufeira aquifer systems can be associated to the plume observed in the Barlovento algarvio. Furthermore, the aquifer systems of São João da Venda-Quelfes and Luz-Tavira might be the source of the cold-water plume observed in the Sotavento algarvio. In this region, it is noticeable the presence of several springs nearby the coastline matching the presence of thermal plumes, which coincides with the premise of these sites being potential places of groundwater discharge into coastal waters.

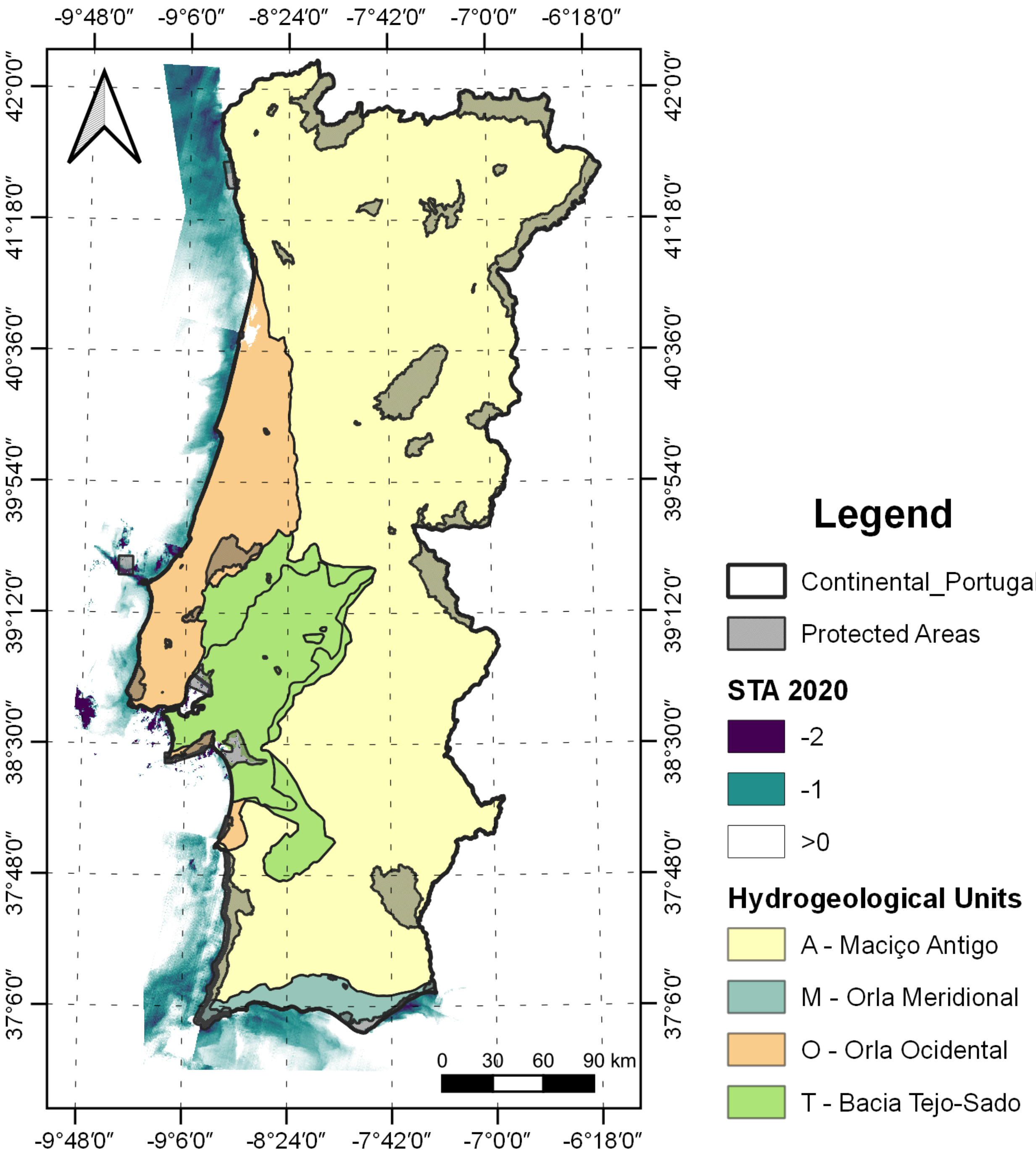
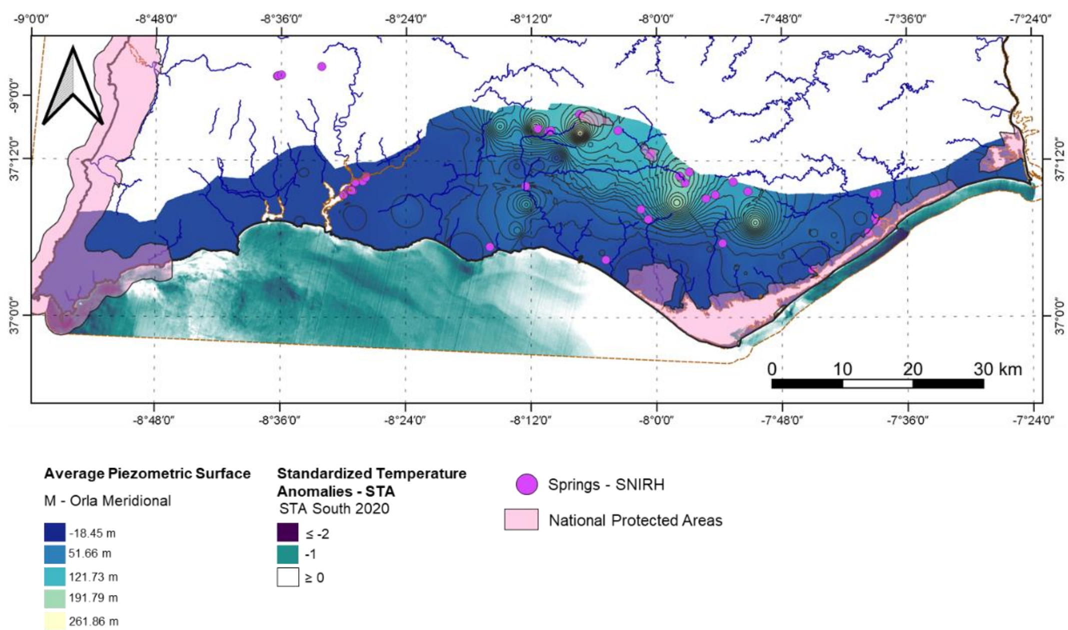


Figure 8. Negative Standardized Temperature Anomalies (STA) in the coastal zone of Portugal. Negative STA indicate colder water assumed to potentially be groundwater discharge.

Similarly for the Northwest region (Figure 9d), Vieira de Leiria-Marinha Grande, Leirosa-Monte Real, and Aveiro systems are probably the most relevant contributors to the plumes detected in those scenes.

In the Southwest and North regions (Figure 9b and Figure 9e respectively), no specific aquifers are recognizable with the hydrogeological unit corresponding to Maciço Antigo. Despite the low hydrogeological potential with which this unit is labelled (Almeida et al., 2000), the groundwater resources stores in those systems are of high importance for the disperse public supply of many municipalities as well as for activities like agriculture. In turn, it remarks the need for further exploration of a correlation of these results with potentiometric level information and the existence of springs, to be able of understand the dynamic of the water movement in these rocky shores and its role in the sustainability of the coastal ecosystems.

a



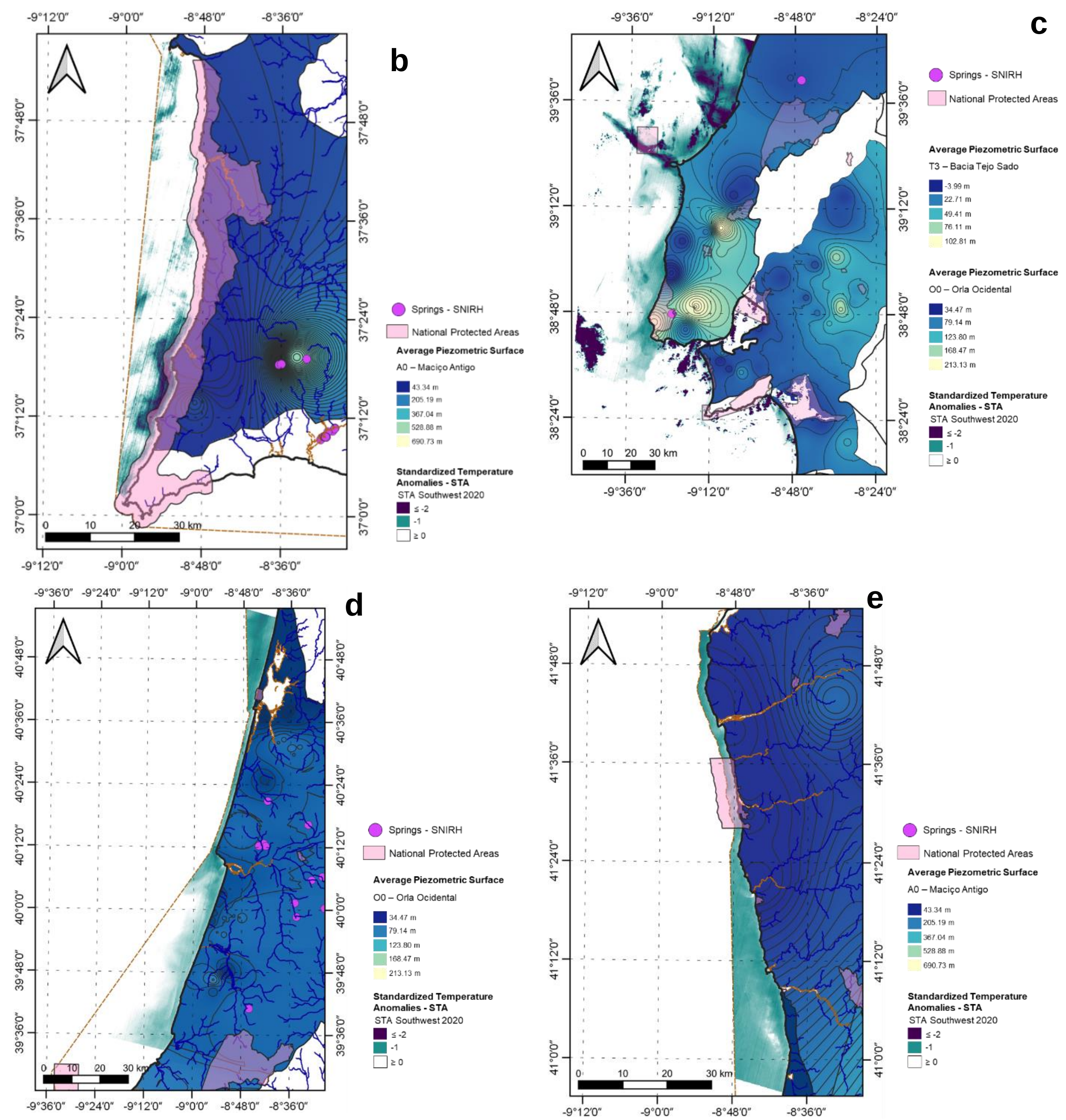


Figure 9. Standardized Temperature Anomaly and Potentiometric Surface for the a) South, b) Southwest, c) Center, d) Northwest, and e) North subregions.

2.3.1.2. Annual Temperature Anomalies

To evaluate consistency of the thermal plumes the same processing described in section 0 was done with images from 2013 to 2020 for all the five regions of interest defined in this project. Sea Surface Temperature (SST) was derived and corrected with upwelling and downwelling radiances coefficients and atmospheric transmission; then, temperature anomalies (TA) were calculated and standardized (STA). Figures 10 to 14 illustrate the annual TA for each region of analysis indicating both colder (blue) and warmer (red) plumes in the summer months of each year.

In the South region (Figure 10), corresponding to the Orla Meridional hydrogeological unit, it is possible to observe consistency in the presence of colder water in the left side, near the cities of Sagres, Lagos, and Albufeira. There was an exception for 2015 when the anomaly map showed warmer water between Lagos and Faro. In the same sense, there is consistent warmer water around Faro, where the coastal lagoon of Ria Formosa exhibits warmer temperature associated to shallow waters and sand banks.

Interestingly, the area located to the right of the map, near Tavira, is consistently a positive anomaly, except for the years 2015 and 2020 when the anomaly map is strongly negative. As discussed before, the presence of inventoried springs in this area validates the idea of groundwater discharging into the coastal water, however, due to the positive anomaly that the region exhibits in most of the maps, the hypothesis requires on-field validation.

In the Southwest region (Figure 11), the temperature anomaly maps show the variability of those potential thermal plumes, whereby most of them exhibit low consistency throughout the years. Additionally, only small areas of potential SGD sites are identified which is associated to the lower capacity of the aquifer to transmit water, and/or the highly hydrodynamic character of this coast that dissipates the effect of SGD. Diffuse patters of cold water can be observed near Sines, Vila Nova de Milfontes, and Carrapateira. The image corresponding to the summer of 2019 seems particularly colder than the rest of the analyzed thermal images, which cannot be interpreted as an effect of groundwater discharge but more likely related to the presence of currents or any other atmospheric-oceanic phenomena.

Visually inspecting the temperature anomalies map of the central region (Figure 12) it is possible to observe the estuaries of the Tagus and Sado rivers in red colors, which indicates that the water temperature of this transitional systems is warmer than the average coastal water in the scene. The thermal imagery approach seems to expose a limitation to determine potential groundwater discharge into these systems, due to the apparently high difference of temperature between the estuary and the coastal waters. Hence, a more local analysis will be useful to unmask the effect of thermal difference between the ocean and the estuary. Furthermore, other techniques such as tracers and chemical analysis would complement and better assess the potential contribution of groundwater to the estuaries. Since the interest of this study is a regional assessment, we did not explore the details of thermal anomalies in the estuaries.

The northern part of the scene, between Cabo da Roca and Nazaré, shows consistent negative temperature anomalies, with some clear plumes that can be associated to the discharge of the costal aquifers in the hydrogeological unit of Orla Occidental. Nonetheless, these results needs to be carefully interpreted to avoid an overestimation of the potential SGD.

This area is known for its usually cold water. During the summer, predominant trade winds from the north cause wind-driven and persistent upwelling along the coast of the Iberian Peninsula. Cooler water from depths of 100-300 m is upwelled (Smyth et al., 2001). These events usually begin around and are particularly intense off of Cape Finisterre and Cabo da Roca, often forming filaments that can reach as far as 100 km westward and their velocities, tracked by thermal features in satellite images, can reach up to 0.28 m s^{-1} (Smyth et al., 2001).

Additionally, the contrast of the pixels in coastal water with warmer water pixels of the estuaries may mask the relative gradient between SGD sites and the surrounding waters. Finer-scale and complementary analysis of isotopes, and hydrogeochemical mass balances can contribute to a better understanding of the effect of groundwater discharge in this zone.

In the Northwest region, the temperature analysis of the coastal water polygon shows a similar behavior in all the images (Figure 13). In this region, there is a visible diffuse potential groundwater discharge along the coastline. The predominant negative anomaly of the map and the presence of highly productive coastal aquifers suggest that the groundwater discharge in this region is an important contribution to coastal waters. In the coastal lagoon of Aveiro the situation is quite like the one described for the coastal lagoon of Ria Formosa in the south region near the city of Faro. Here the anomalies are mainly positive due to the shallow water and the presence of sand banks that register higher temperature.

Finally, the temperature anomalies for the north part of the country are presented in Figure 14. Consistent negative anomalies are observed in the northern part of the region near the city Viana do Castelo, where the influence of the river Minho needs to be considered as well. While the southern part of the region, the temperature anomaly is normally positive with a remarkable influence of the river Douro in the city of Porto. Similarly with the Southwest region described before, no coastal aquifer systems are identified in this region, but the Maciço Antigo, a low productivity unit that is mainly compose by hard rocks, hence the groundwater contribution to coastal areas is expected to be low.

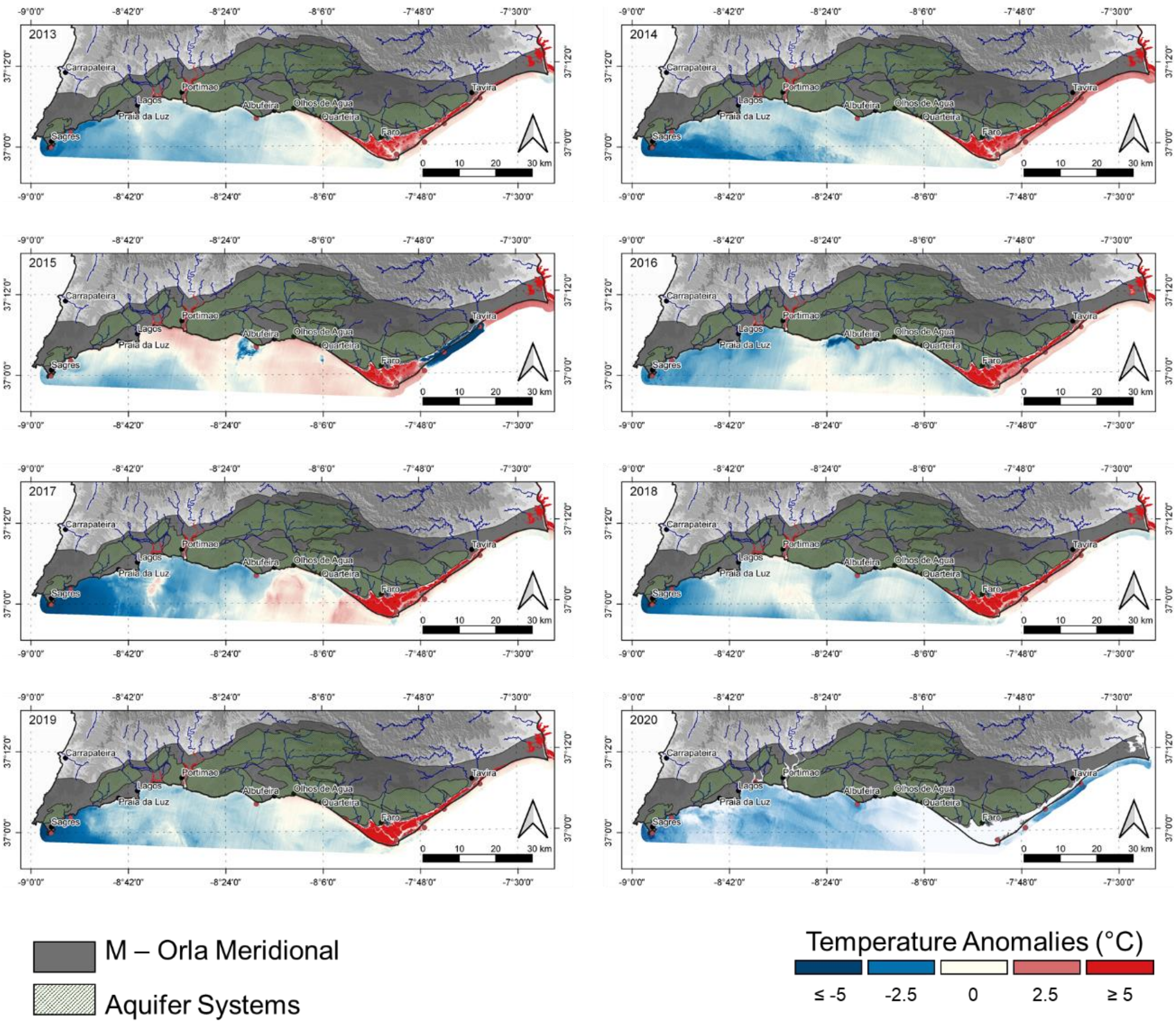


Figure 10. Annual Comparison of Temperature Anomalies in the South region in the summer months between 2013-2020.

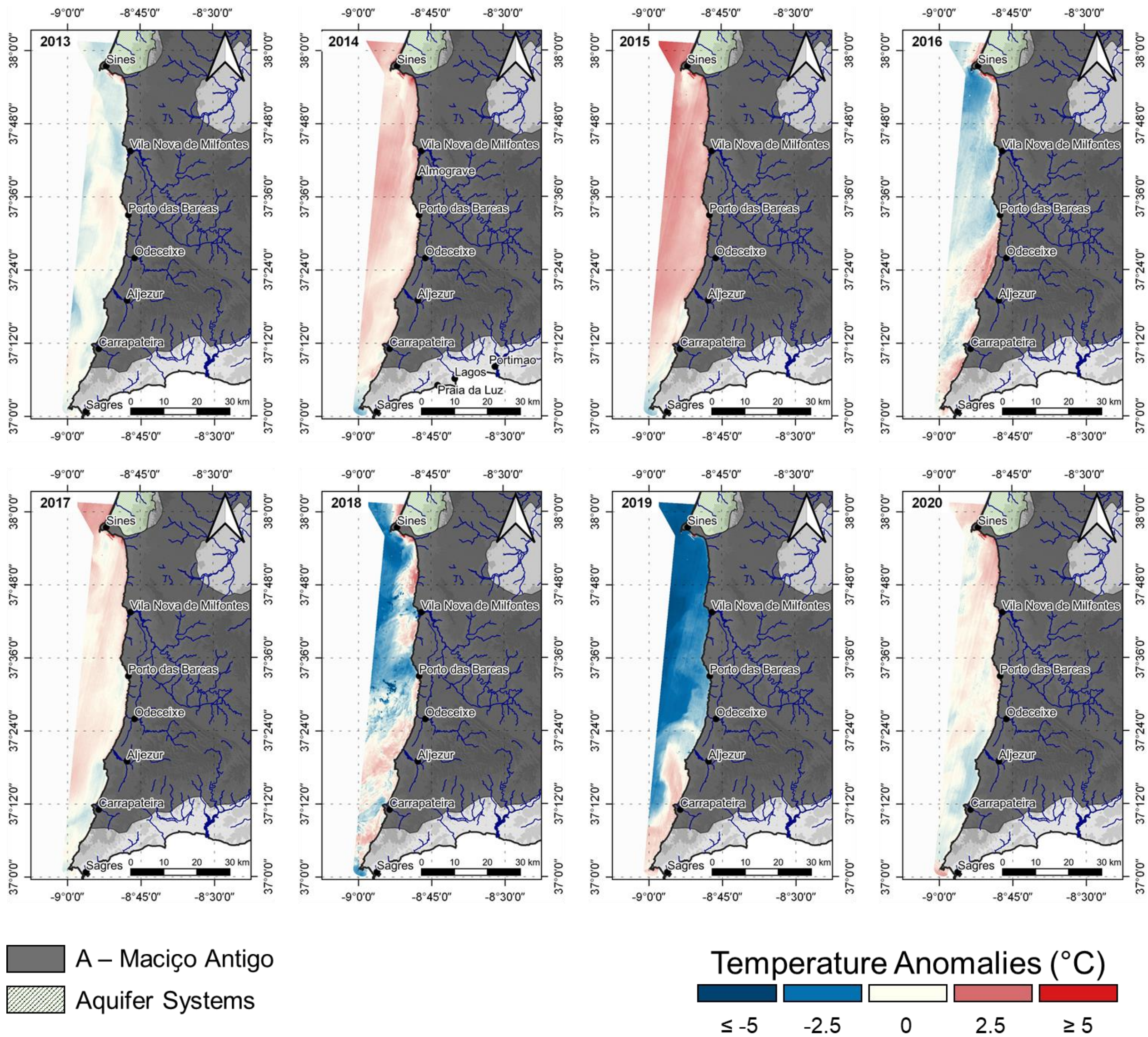


Figure 11. Annual Comparison of Temperature Anomalies in the Southwest region in the summer months between 2013-2020

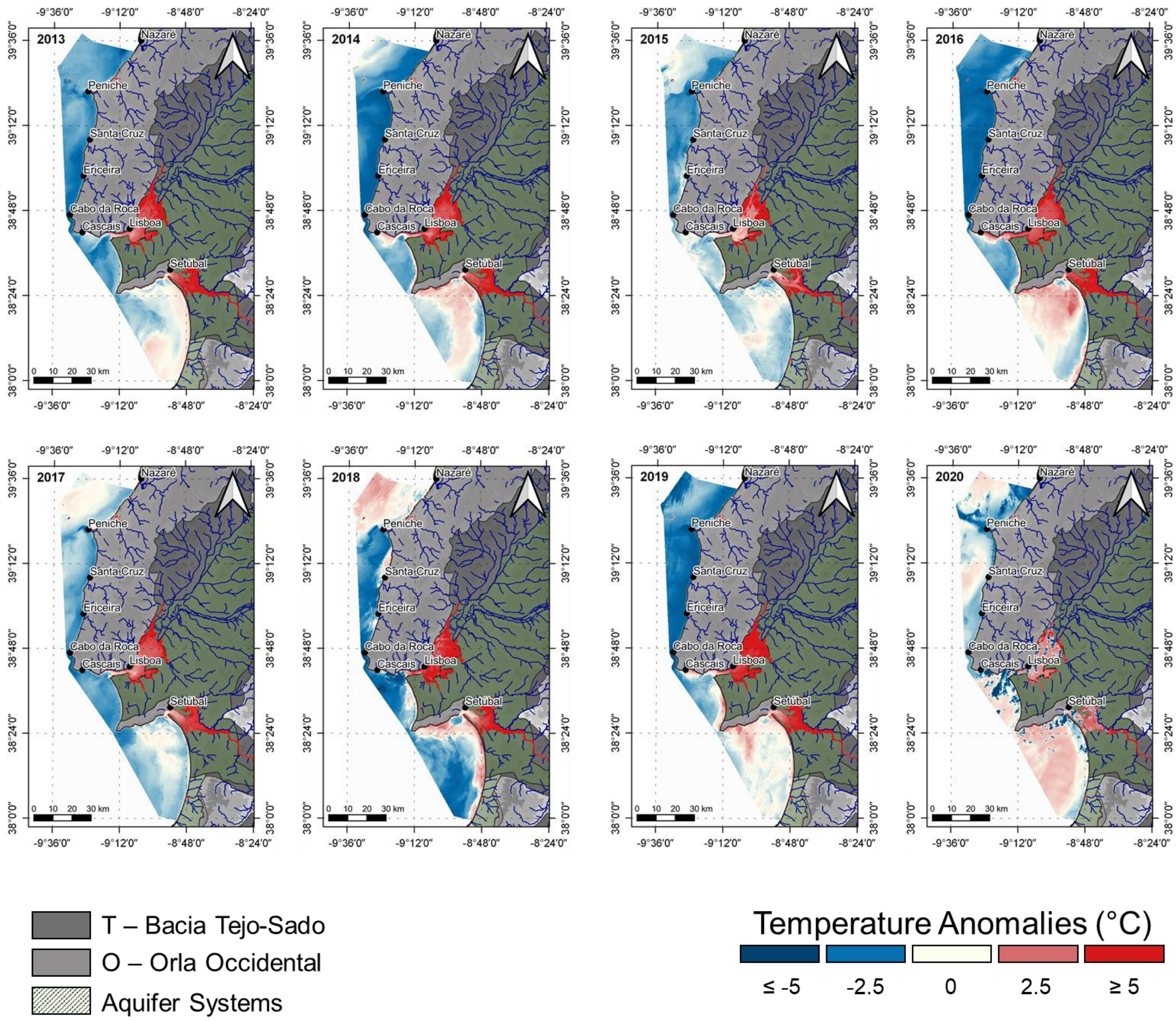


Figure 12. Annual Comparison of Temperature Anomalies in the Center region in the summer months between 2013-2020

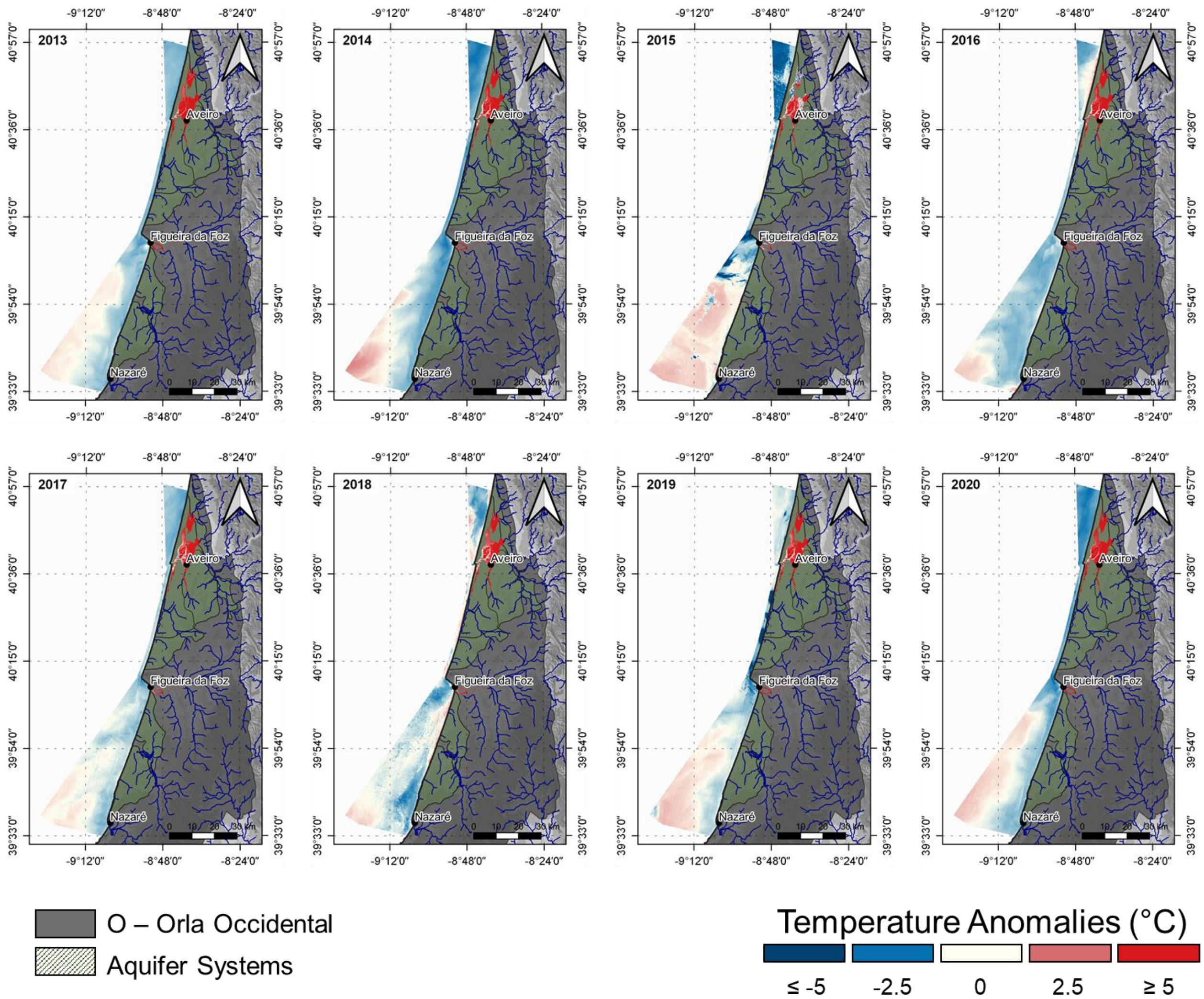


Figure 13. Annual Comparison of Temperature Anomalies in the Northwest region in the summer months between 2013-2020

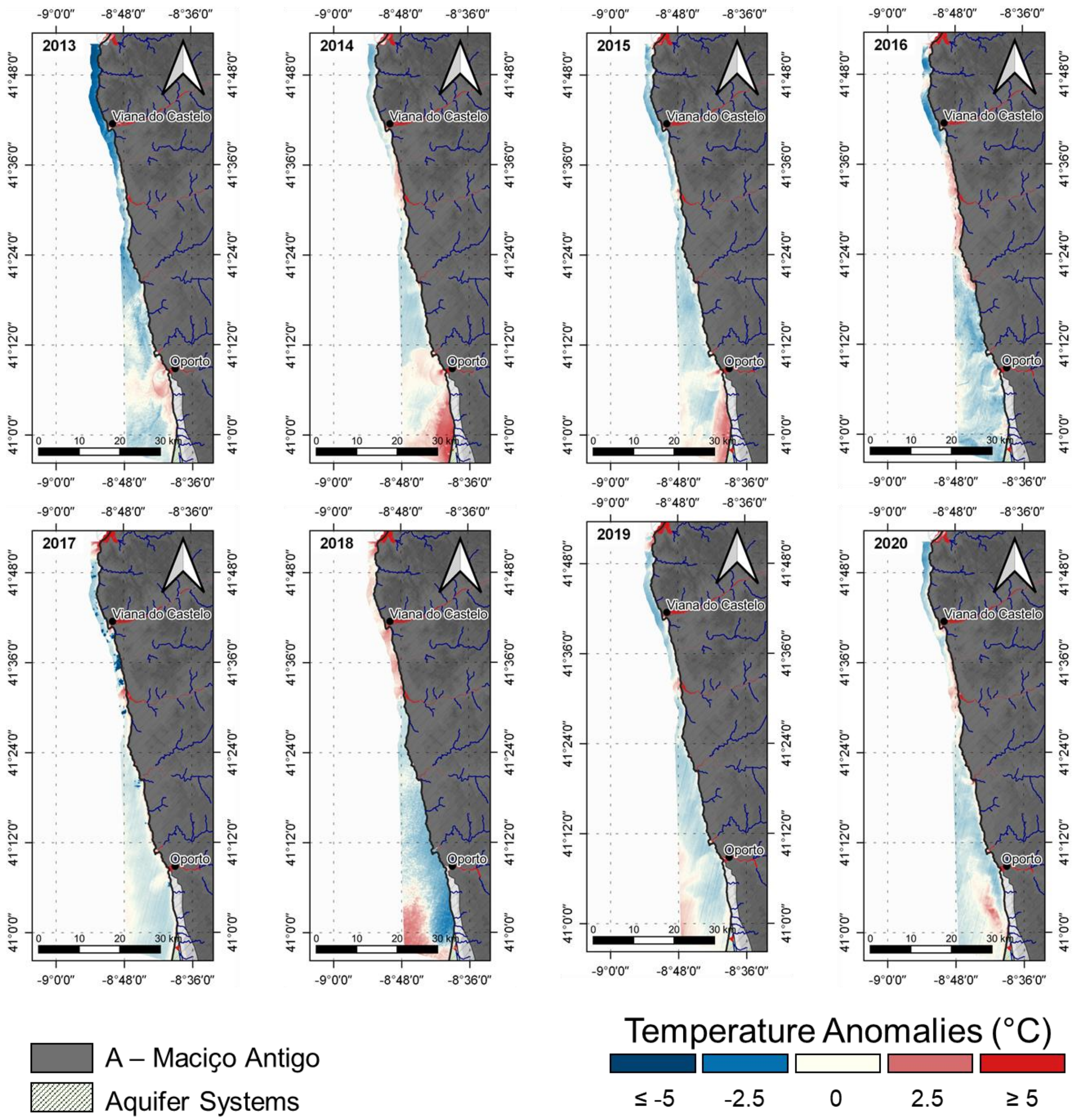


Figure 14. Annual Comparison of Temperature Anomalies in the North region in the summer months between 2013-2020

2.3.2. Identification of Potential Groundwater Discharge Sites

Given the previous results, a visual inspection of temperature anomalies allowed the identification of cold-water anomalies under the premise it represents potential SDG spots. Figure 15 shows the location of 25 identified potential SGD spots. Table 3 includes information about the hydrogeological unit and the dominant lithology of those sites. Important to highlight the potential SDG sites identified in south and southwest coasts overlap with national protected areas, which gives an initial though about the importance of the water and solutes flux for these environments.

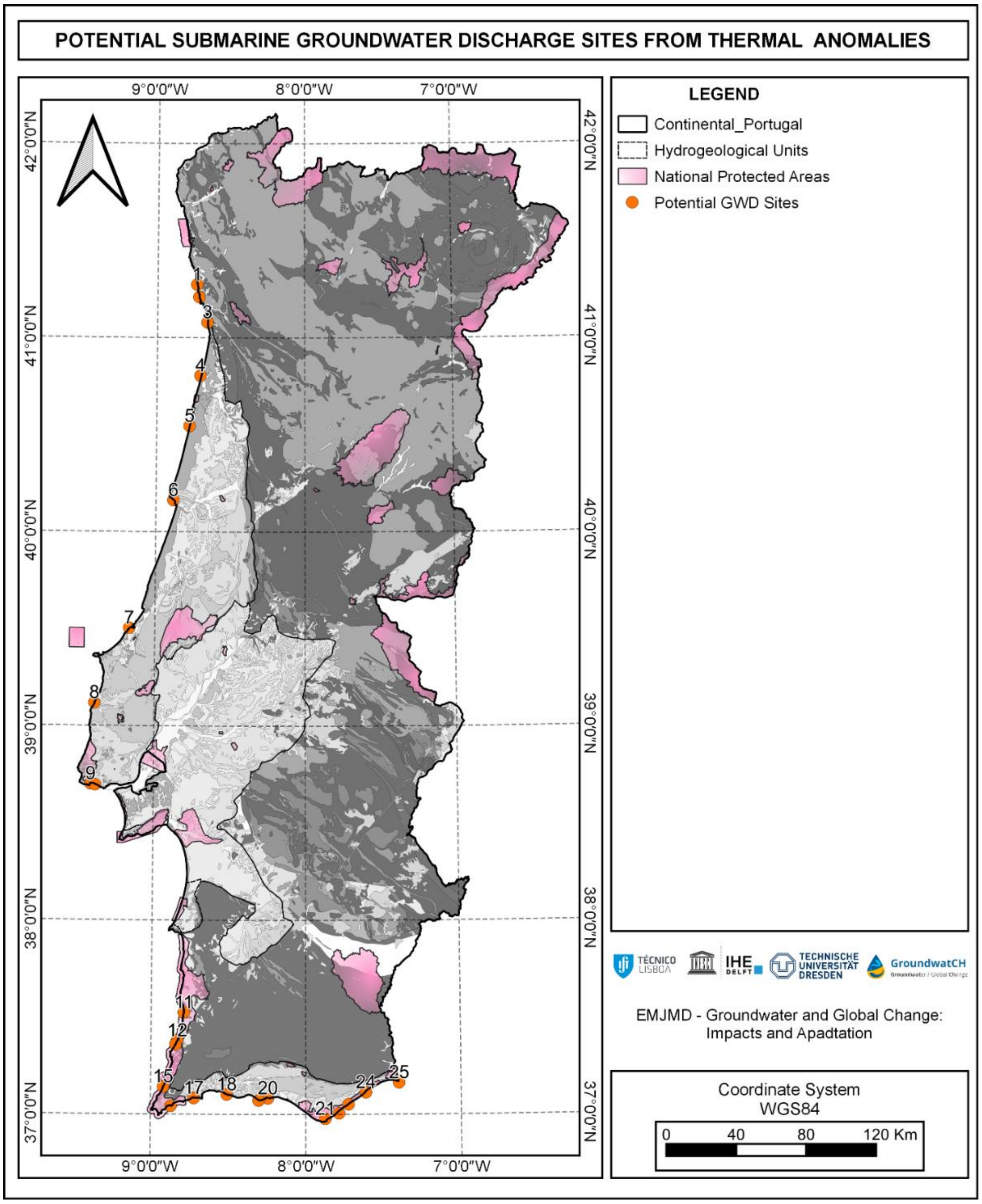


Figure 15. Location of potential sites of groundwater discharge in the Portuguese coastline based on visual inspection of temperature anomalies.

Table 3. Description of the cold-water anomalies and potential sites of groundwater discharge

ID	Name	Latitude	Longitude	Hydrogeological Unit	Lithology
1	Praia de Labruge	41.27360	-8.73318	Maciço Antigo	Granites and related rocks
2	Praia do Aterro	41.20936	-8.71803	Maciço Antigo	Sand and gravels
3	Praia de Francelos	41.07932	-8.66160	Orla Ocidental	Dunes and eolian sand
4	Quintas do Norte	40.80460	-8.70720	Orla Ocidental	Dunes and eolian sand
5	Praia da Duna Alta	40.54517	-8.77860	Orla Ocidental	Dunes and eolian sand
6	Redondos	40.16267	-8.88326	Orla Ocidental	Conglomerates, sandstones, limestones, dolomitic limestones, loamy limestones, marls
7	Salir do Porto	39.50304	-9.17079	Orla Ocidental	Conglomerates, sandstones, limestones, dolomitic limestones, loamy limestones, marls
8	Praia Azul	39.11729	-9.39564	Orla Ocidental	Conglomerates, sandstones, limestones, dolomitic limestones, loamy limestones, marls
9	Baia de Cascais	38.69938	-9.41320	Orla Ocidental	Sandstones, Conglomerates, limestones, dolomitic limestones, loamy limestones, marls
10	Sao Joao de Estoril	38.69500	-9.38345	Orla Ocidental	Sandstones, Conglomerates, limestones, dolomitic limestones, loamy limestones, marls
11	Zambujeira do Mar	37.52343	-8.78933	Maciço Antigo	Clayey shales and schists, greywackes, sandstones
12	Praia de Vale dos Homes	37.37861	-8.83011	Maciço Antigo	Clayey shales and schists, greywackes, sandstones
13	Praia de Carriagem	37.37050	-8.83593	Maciço Antigo	Clayey shales and schists, greywackes, sandstones
14	Praia de Amoreira	37.35930	-8.84234	Maciço Antigo	Alluvium
15	Praia do Mirouco	37.14162	-8.91981	Maciço Antigo	Clayey shales and schists, greywackes, sandstones
16	Zavial	37.04208	-8.87103	Orla Meridional	Sedimentary Formation Conglomerados, arenitos, Calcários
17	Praia da Luz	37.08306	-8.72242	Orla Meridional	Sandstones, Conglomerates, limestones, dolomitic limestones, loamy limestones, marls
18	Ferragudo	37.10202	-8.50998	Orla Meridional	Sandstones, more or less marly limestone, sand, gravel, clay
19	Evaristo	37.07112	-8.30435	Orla Meridional	Sandstones, more or less marly limestone, sand, gravel, clay
20	Albufeira	37.08242	-8.24468	Orla Meridional	Sandstones, more or less marly limestone, sand, gravel, clay

ID	Name	Latitude	Longitude	Hydrogeological Unit	Lithology
21	Ilha do Faron Ria Formosa	36.97688	-7.87467	Orla Meridional	Alluvium
22	Armona	37.00560	-7.78606	Orla Meridional	Alluvium
23	Fuseta	37.05151	-7.72536	Orla Meridional	Alluvium
24	Tavira	37.11274	-7.61348	Orla Meridional	Alluvium, Dunes and eolian sand
25	Santo Antonio	37.16320	-7.39936	Orla Meridional	Alluvium, Dunes and eolian sand

Figure 16 presents, in a closer view, the negative standardized temperature anomalies from where some examples of the potential SGD described in Table 3 can be detected.

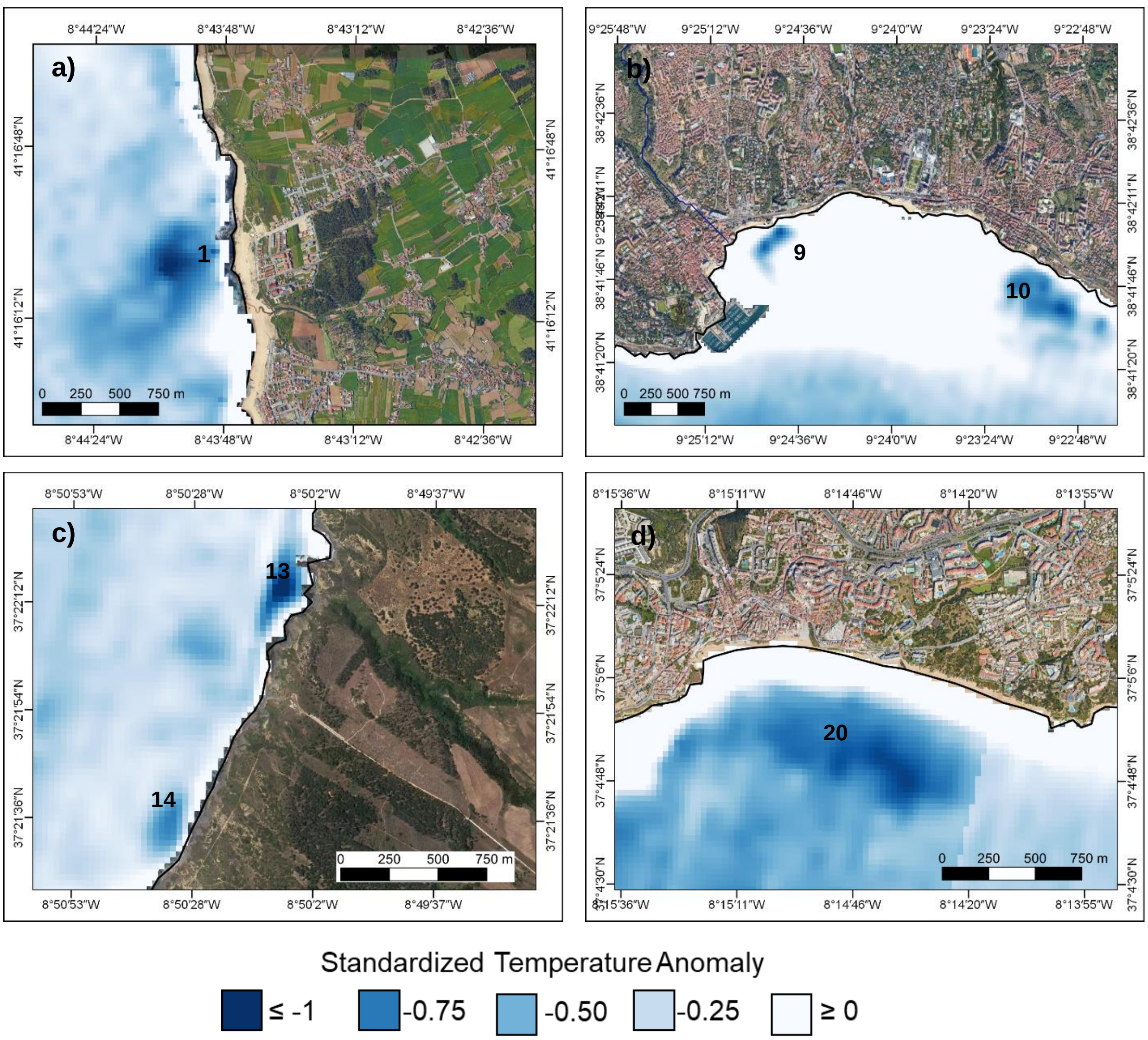


Figure 16. Standardized Temperature Anomaly maps and potential SGD sites in a) Praia de Labruge (1) in the North, b) Baía de Cascais (9) and Sao Joao de Estoril (10) in the Center region, c) Praia de Carriagem (13) and Praia de Amoreira (14) in the Southwest coast, and d) Albufeira (20) in the South coast of Portugal

2.3.3. Piezometric Analysis

As traditionally done, one of the simplest ways of detecting groundwater discharge is by the analysis of the piezometric surfaces of the aquifers. In this case, information from the National Information System of Water Resources (SNIRH for its name in Portuguese) was used to interpolate over the hydrogeological units. Additionally, a field campaign was carried out to identify potential locally important coastal springs, with special focus on the southwest region where the rocky shores of main interest in this study were located. Table 4 and Figure 17 present the location of the identified springs.

Using a Digital Elevation Model (DEM), profiles of the topography and the piezometric level were built for some of the identified coastal springs. Figure 18 contains the obtained profiles showing that the presence of those springs is explained by the discharge of groundwater. Profiles A-A', B-B', and C-C' are located in the south coast of Portugal, while the three additional profiles correspond to springs in the Southwest region.

Table 4. Location of coastal springs identified in situ during fieldwork in the South and Southwest coast of Portugal

	Name	Latitude	Longitude
1	Almograve	37.65083	-8.80253
2	Alteirinhos	37.51851	-8.78819
3	Carvalhal	37.50016	-8.79107
4	Ferragudo	37.10452	-8.51325
5	Foz do Almograve	37.65772	-8.80002
6	Foz do Barranco do Cavaleiro	37.60297	-8.81520
7	Lapa de Pombas	37.63606	-8.80846
8	Porto das Barcas	37.55092	-8.79188
9	Machados	37.49146	-8.79405
10	Nascedios A	37.68144	-8.79515
11	Olhos d'Agua	37.08953	-8.18867
12	Praia da Amalia	37.48142	-8.79476
13	Praia da Luz	37.08550	-8.72883
14	Ribeira da Azenha	37.46322	-8.79685
15	Zambujeira	37.52250	-8.78655

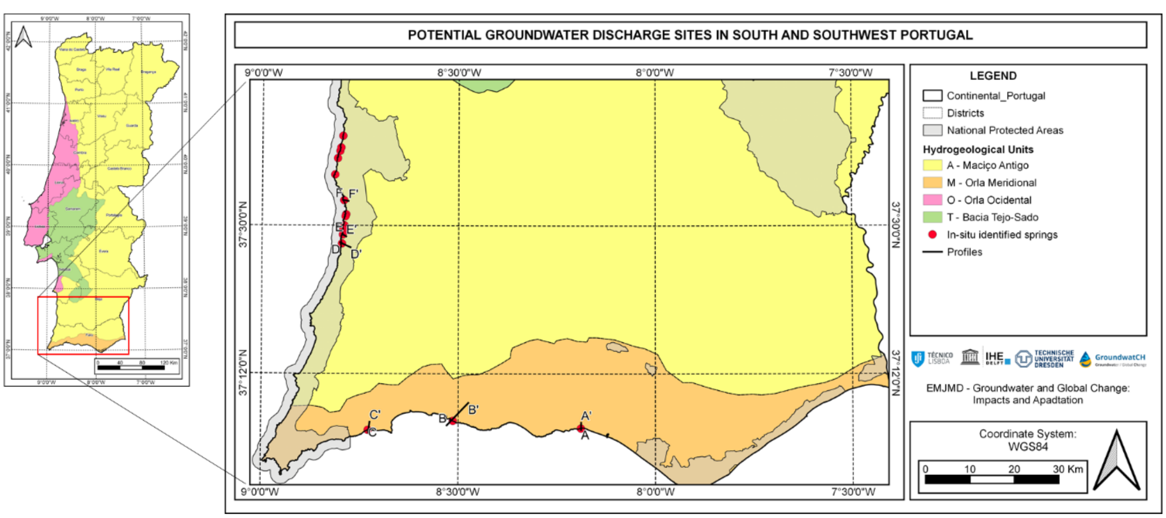


Figure 17. Potential Groundwater Discharge Springs identified in situ in South and Southwest Portugal

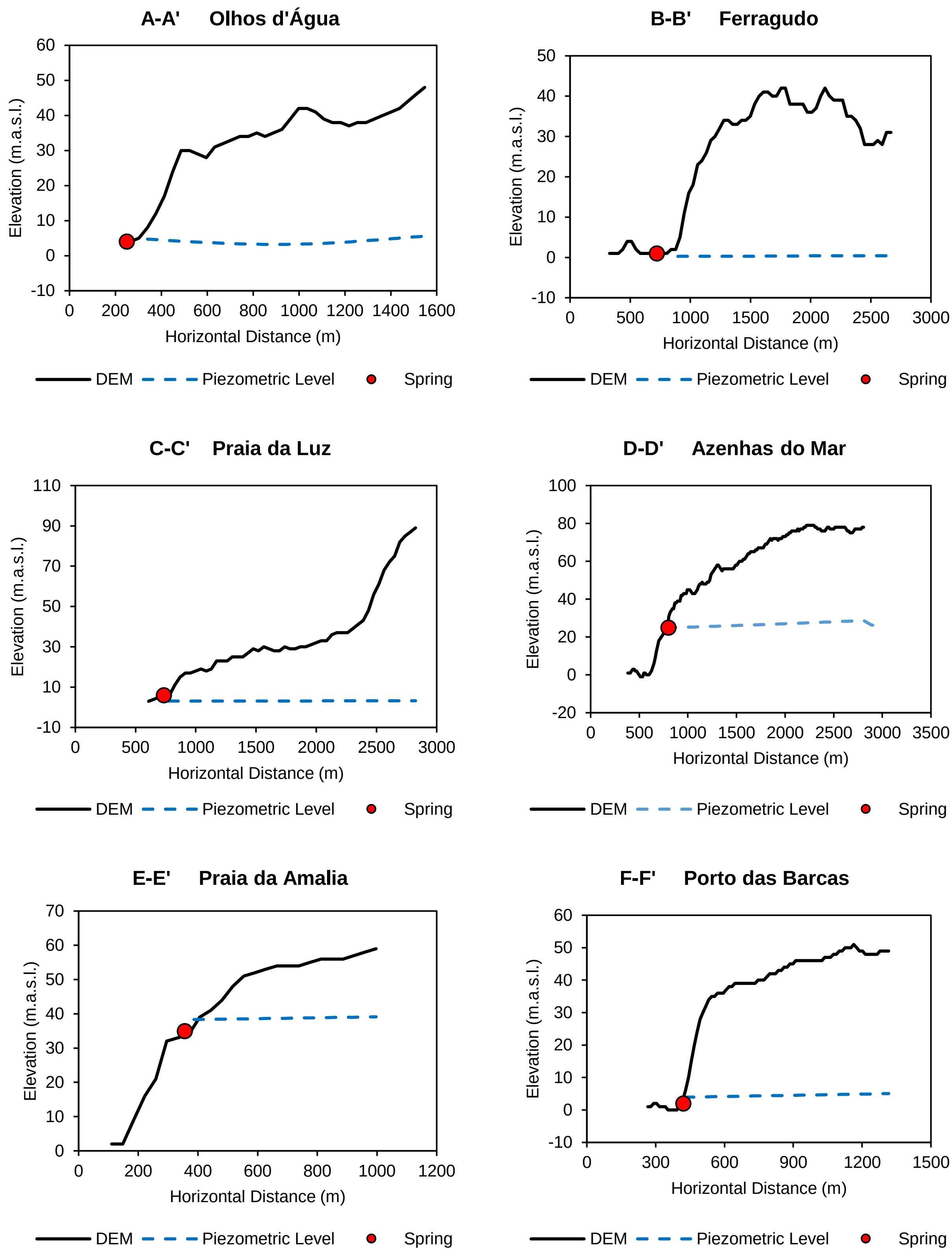


Figure 18. Coastal springs profiles based on the comparison of the Digital Elevation Model (DEM) and the average piezometric surface of the hydrological units.

2.4. Discussion

The relevance of Landsat 8 TIR imagery to recognize Submarine Groundwater Discharge SGD sites has been effectively applied in previous studies (Wilson & Rocha, 2012; Wilson & Rocha, 2016; Samani et al., 2021; Jou-Claus et al., 2021). Here, we also confirmed the capacity of thermal remote sensing for identifying SGD sites, based on the premise that relatively cool groundwater discharging to warmer coastal waters manifests in the thermal band of satellite imagery acquired during the summer months.

The thermal analysis highlighted a useful visual spatial correlation between the location of thermal anomalies plumes and potentiometric surfaces of coastal aquifers in Portugal. It cannot be assumed that the thermal signatures observed are exclusively due to the presence of groundwater as sources of freshwater to coastal nearshore waters also include surface runoff. Local validation would be required but it was beyond the capacity of this project. Nonetheless, the location of the on-field identified springs in the southwest and south rocky shores confirmed the existence of SGD since some of them actually matched the visual spatial correlations. Concomitantly, it cannot be assumed that all groundwater seepage points from coastal aquifers can be detected via remote sensing techniques as buoyancy will strongly influence the capacity of the thermal sensor to detect the surface signature (Wilson & Rocha, 2012).

Environmental and marine conditions cause seawater mixing with the discharging groundwater, affecting the thermal contrast between the groundwater plume and seawater (Jou-Claus et al., 2021). This represents a limitation for the identification of SGD with a thermal-based approach. However, there is few literature discussing the implications of these conditions to the effectiveness of thermal infrared remote sensing techniques to spot potential SGD sites. Jou-Claus et al. (2021) discuss the main environmental and marine condition that can affect SGD identification. On one hand, the action of wind, which can mix the first millimeters of the sea surface water, limiting the identification of SGD springs as it weakens the temperature gradient. On the other hand, marine hydrodynamic conditions such as tides, coastal currents and fetch generate seawater movement and mix groundwater with seawater, causing a thermal contrast attenuation. Similarly, the presence of a pycnocline can result in less vertical mixing of the water column.

Nonetheless, in subtropical areas with cold winters and hot summers, such as the Mediterranean Sea, coastal waters often develop a pycnocline during the summer months, as high temperatures increase the evaporation of seawater, generating an increase in salinity and therefore water density. This effect causes cold, fresh groundwater to flow over salty and dense seawater, generating a visible SGD layer on the sea surface (Jou-Claus et al., 2021).

It is worth remarking that the successful application of thermal imagery to identify sources of SGD is also constrained by the spatial resolution of the remote sensing system employed (Wilson & Rocha, 2012). The usually coarser spatial resolution of satellite data is not successful resolve small localized features that are common for SGD (Kelly et al., 2013) specially in highly hydrodynamic shores when the thermal effect of SGD is dissipated (C. E. Robinson et al., 2018). Nonetheless, the results presented in this study are very promising for regional-scale assessments, and suggest that the acquisition of higher resolution imagery obtained through airborne surveys would likely serve to elucidate finer-scale patterns of SGD and by doing so, highlighting numerous and significant inputs of groundwater discharge on a local scale.

Since particular site conditions may also provide clues to the occurrence of SGD, the presence of coastal springs identified in situ reassures that topography and geomorphology can also influence SGD, as described in Samani et al. (2021) and Santos et al. (2021). However, these effects remain largely unquantified, hence it offers an opportunity for further research on the correlation of the regional topography of the coastal zone as it determines the slope of the water table and the inland hydraulic gradient in coastal unconfined aquifers, which, in turn, governs fresh SGD. Additionally, the identification of unconsolidated coastal ponds and bluffs, which may maintain a high hydraulic head near shore, may be other indicators (Burnett et al., 2006).

The high spatial variability of SGD fluxes results on locally important fluxes in specific areas (Luijendijk et al., 2020). The supply of solutes to coastal waters through SGD directly impact the productivity of coastal ecosystems (Johannes, 1980; Erostate et al., 2020; Lecher & Mackey, 2018). SGD can also supply dissolved contaminants to the coastal ocean derived from anthropogenic sources (e.g., agriculture, industrial, mining activities, domestic wastewaters) (e.g., Alorda-Kleinglass et al., 2021; Rodellas et al., 2015), which can endanger the coastal ecosystems and the well-being of local population living around them. In this regard, societies living around SGD-influenced zones may benefit or be harmed by the services and goods provided by the ecosystems influenced by SGD (Alorda-Kleinglass et al., 2021). Outstandingly, we showed that some of the identified potential SGD sites are located in national protected areas. The cases in the southwest coast of Portugal corresponds to the Southwest Alentejo and Vicentine Coast Natural Park, a world’s heritage site. In the south, some of the sites overlap with the coastal lagoon Ria Formosa, a RAMSAR site. Hence, this first approach to the identification of potential SGD spots along the Portuguese coast, calls the attention to continue exploring the effects of SGD on the receiving systems, especially in those that coincide with areas of high interest due to the provision of environmental services.

Previous studies evaluating the ecological impacts of SGD faced several limitations, mostly associated with the difficulty in locating SGD areas, evaluating the spatial extent of SGD-impacted areas and identifying SGD impacts on local biological communities (Amato et al., 2016; Piló et al., 2018; Lecher & Mackey, 2018; Starke et al., 2020). Here, we provide a cost-effective solution to address those limitations since satellite TIR imagery has the great advantage of being free of charge (Landsat), easily accessible, globally available, multi-temporal and covering a regional scale instantaneously. Furthermore, this study offers a pioneer regional identification of potential SGD spots along the coast of continental Portugal. It constitutes a useful management tool as it guides the future exploration of the dependency of local coastal ecosystems on groundwater discharge.

Further investigation must be carried out to determine the conditions of those local areas and their environmental state. We suggest that the environmental authorities and coastal water managers focus their efforts on deepening the knowledge of some of the here identified SGD spots, namely, the ones that overlap with protected areas or are near important coastal ecosystems. A combination of these results and those obtained by Ribeiro et al. (2015) regarding terrestrial groundwater-dependent ecosystems, will guide a more efficient implementation of integrated water resources policies.

Different methods are suggested to continue the investigation of potential SGD sites. Finer resolution thermal images obtained along the hydrological year using unmanned aerial vehicles will facilitate the identification of local dynamics of SGD in the prioritized spots, and overcome the limitation of the high percentage of cloud cover during the winter and spring months. Additionally, A quantitative combination of the relevant hydrological parameters can serve as a proxy for the SGD conditions not directly measured. Monitoring of water temperature and salinity together with the use of seepage meters, radioactive isotope tracers (Garcia-Solsona et al., 2010; Wilson & Rocha, 2012), electrical resistivity tomography (Fu et al., 2020), and correlation with multiple geo-environmental variables (Samani et al., 2021), is suggested to quantify the SGD and its potential effect in the receiving ecosystems.

CHAPTER 3: ASSESSMENT OF THE RESPONSE OF INTERTIDAL ROCKY SHORE COMMUNITIES TO THE INFLUENCE OF GROUNDWATER DISCHARGE

3.1. Introduction

The groundwater discharge into coastal ecosystems such as estuaries, lagoons, sandy and rocky tidal zones has been shown to be a key factor influencing their biological communities (Félix et al., 2015; Encarnação et al., 2015; Shapouri et al., 2016; Piló et al., 2018; Rodellas et al., 2018). This freshwater input is important for setting ecotones by influencing parameters like salinity, sediment type or organic matter and even as a pollutant source (Capone & Bautista, 1985; Nevill et al., 2010; Lewandowski et al., 2020), making aquatic coastal ecosystems potentially groundwater dependent (GDEs). The GDE definition considered in this study states that are “ecosystems that require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirement so as to maintain their communities of plants and animals, ecological processes and ecosystem services” (Richardson et al., 2011).

The potential importance of groundwater discharge into coastal ecosystems is greatly intensified in coastal Mediterranean regions where groundwater availability for discharge is hampered by diminished recharge rates, overexploitation of the resource, and climate change effects (Stigter et al., 2014; da Costa et al., 2020; Rachid et al., 2021). The groundwater availability becomes then a critical factor which may threaten the sustainability of coastal groundwater-dependent ecosystems and their associated ecosystem services (Erostate et al., 2020).

Groundwater availability has been influenced negatively worldwide during the last decades by the increased use of groundwater for human consumption and irrigation, resulting in a reduction in groundwater levels (Konikow & Kendy, 2005). The effects of over abstraction of groundwater are escalating from local problematics to become an increasingly regional issue (Bartolino & Cunningham, 2003), especially in arid and semiarid areas where groundwater is the main source of freshwater (Stigter et al., 2014; Erostate et al., 2020). In addition, the predicted climate change patterns will exacerbate these problems in many parts of the world due to decreasing rainfall and increasing evapotranspiration, which will reduce the recharge and cause a groundwater level decline (Kløve et al., 2013; Stigter et al., 2014).

Although aquatic systems are generally viewed as resilient and able to maintain a healthy and self-sustaining condition despite large year-to-year variation in hydrologic and temperature conditions (Poff et al., 2002), alterations to the timing, quality, quantity, and distribution of groundwater by natural or anthropogenic means can potentially alter both the form and function of the groundwater dependent ecosystems (Murray et al., 2003; Foster et al., 2003 in Lagomasino et al., 2015). Hence, the ecological consequences of global change in coastal ecosystems will largely depend on the rate and magnitude of change in critical environmental drivers such as temperature, sea level rise, precipitation, runoff, and groundwater discharge.

However, and although recognized as essential, the hydraulic, chemical, and ecological characterization of connections between coastal surface and groundwater bodies in Mediterranean regions still has room for development (Erostate et al., 2020). The improvement of GDEs' management inevitably involves an increasing knowledge of their hydrogeological and ecological condition and biodynamic processes (Casanova et al., 2016). This information is most often unavailable and gaps at the intersection of groundwater hydrology and ecology do not facilitate the study of GDEs (Tomlinson, 2011).

Numerous methodologies have been developed to improve the understanding of coastal GDEs, with most effort on the physical-chemical characterization of these environments. The monitoring of groundwater levels and the establishment of piezometric maps are often the first steps to highlight the groundwater dependence of coastal ecosystems (Sena & Condesso De Melo, 2012). Commonly, the approaches used to assess surface/groundwater interaction vary from temperature, geochemical and isotopic tracers (Sánchez-Martos et al., 2014), to numerical modeling (De Pascalis et al., 2012).

Nonetheless, the effects of groundwater on coastal GDEs' biodiversity and ecosystem dynamics have been much less explored. Benthic communities are subject to various physical and chemical gradients that can affect their growth and physiology, and groundwater discharge is one factor that contributes to these environmental gradients in coastal waters (Lecher & Mackey, 2018). Invertebrate communities of transitional waters (freshwater-saltwater ecotone) are highly influenced by freshwater discharge, showing marked seasonal variation mainly related to salinity fluctuations (Chainho et al., 2006 in Silva et al., 2012). The identification of such sensitive communities together with associated environmental conditions make it possible and effective to predict and detect impacts from variations on groundwater discharge. From these communities, it is then possible to identify specific biological indicator taxa, allowing in turn the determination of the groundwater dependent ecosystem status (Brkić et al., 2019).

Rocky shores are amongst the most biodiversity rich coastal aquatic ecosystems (Satyam &

Thiruchitrambalam, 2018), yet are under increasing threat due to anthropogenic activities such as increasing population, tourism, trampling and seafood gathering activities, and climate change and sea-level rise effects (Mieszkowska, 2016). Furthermore, and due to their physical adjacency to groundwater discharge points in cliffs, springs and runoffs, are highly exposed to groundwater influence, discharged from coastal aquifers. The main motivation of this work is the blatant lack of information on the importance and effects of this discharge on the shores' biological communities, and the unknown classification of rocky shores as GDEs. Most available work has focused on submarine coastal communities (e.g. Bussmann et al., 1999; Johannes, 1980; Encarnação et al., 2013) and on loose sediment sandy shore and mud tidal flats (Dale & Miller, 2007; Migné et al., 2011; Ouisse et al., 2011; Cave & Henry, 2011).

The current gaps in knowledge on the *i.* importance of groundwater discharge in influencing the intertidal rocky macroinvertebrates communities and *ii.* the habitat potential groundwater dependence will be addressed in this study through verification of the hypothesis that biological communities are different (e.g., abundance and/or diversity) in sites within shores where there is groundwater discharge to those where no freshwater influence is perceived.

Hence, the present work represents a pioneer assessment of the potential response of intertidal rocky shore communities to the influence of groundwater in southwest Europe. It will fill an important gap in the current state of the art by validating the biological importance of this commonly overlooked local factor and contribute to the potential classification of rocky shores as groundwater dependent ecosystems.

3.2. Methods

3.2.1. Study Sites Characterization

Two study regions were selected, the Southwest Portuguese Coast and the Barlovento Algarvio, the western part of the Algarve region in south Portugal. Therein, five rocky shores (including sandy shores with rocky platforms) were selected, *Azenhas do Mar* and *Porto das Barcas* in the Southwest, and *Olhos d'Água*, *Ferragudo*, and *Praia da Luz* in the South.

These locations were chosen because there were available existing biological databases from previous projects. However, it is important to highlight that those databases have not been previously analyzed for the hypothesis examined in the current study. Moreover, the location where de data were collected coincide with potential regional SGD sites identified in Chapter 2. Locally it was observed that groundwater discharges in springs in all the selected study sites

These locations are currently under several statutes and diplomas for protection and management of its natural assets. In 1988, the Southwest Coast was classified as Protected Landscape Area and in 1997 promoted to National Park – Southwest Alentejo and Vicentine Coast Natural Park (SAVCNP). Major threats to these Mediterranean regions include the increase and transformation of agricultural practices, growing touristic pressure and the presence of invasive species.

3.2.1.1. Geological Framework

The South Portuguese Zone (Figure 19) constitutes the southernmost segment of the Variscan Iberian Massif. The northern boundary of the South Portuguese Zone with the Ossa–Morena Zone is defined by the Beja Acebuches Ophiolite, whereas to the south the contact is an angular unconformity with the Mesozoic sedimentary rocks of the Algarve Basin. The South Portuguese Zone is divided into four domains (Oliveira 1990; Ribeiro et al., 1990 cited in Rodrigues & Jorge, 2015), which are, from NE to SW, the Pulo do Lobo Suture Zone, the Pyrite Belt, the Baixo Alentejo Flysch Group and the SW Portugal Domain.

The Pulo do Lobo Formation consists of highly deformed phyllites and quartzites with intercalations of amphibolites with mid-ocean ridge basalt affinity in the lower parts of the sequence. The Iberian Pyrite Belt succession consists of phyllites and quartzites of the Phyllite Quartzite Group overlain by volcanic and sedimentary rocks of the Volcano-Sedimentary Complex. The Baixo Alentejo Flysch Group comprises three formations characterized as beds of greywacke interbedded with shales, siltstones, conglomerates and rare mudflows. The SW Portugal Domain succession comprises Late Devonian quartzites and shales of the Tercenas Formation followed by a mud-dominated carbonate platform sequence of the Carrapateira Group (Rodrigues et al., 2015).

On the other hand, The Algarve Basin (Figure 20) is an important Mesozoic depocenter in southern Portugal and mainly comprises Jurassic and Lower Cretaceous limestones. The dominant lithofacies are shallow limestones and cycles of pelagic marls and limestones. The Lower Cretaceous is represented by a mixed clastic and carbonate succession, deposited in nearshore and terrestrial settings (Borges et al., 2011).

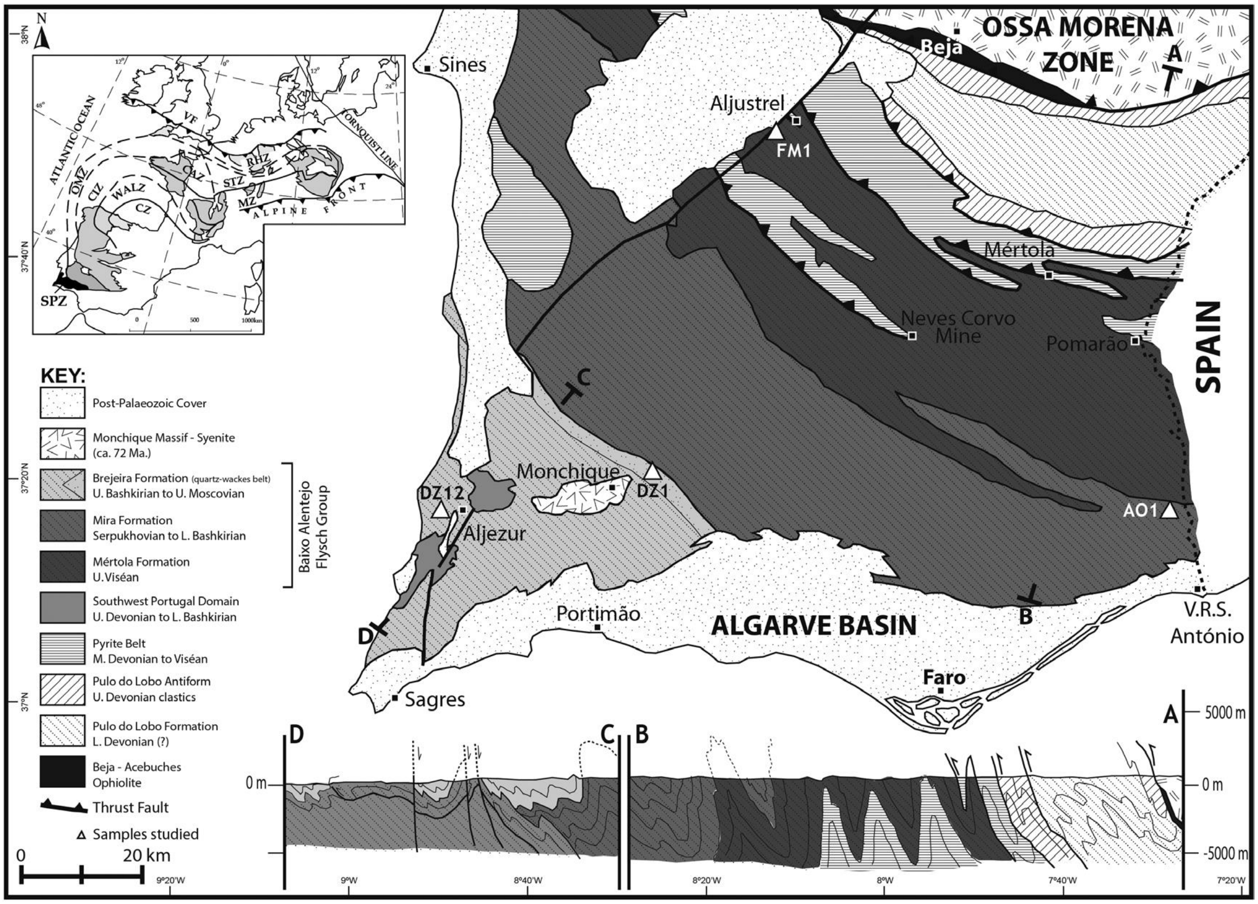


Figure 19. Geological map of the South Portuguese Zone
Source: Rodrigues & Jorge (2015)

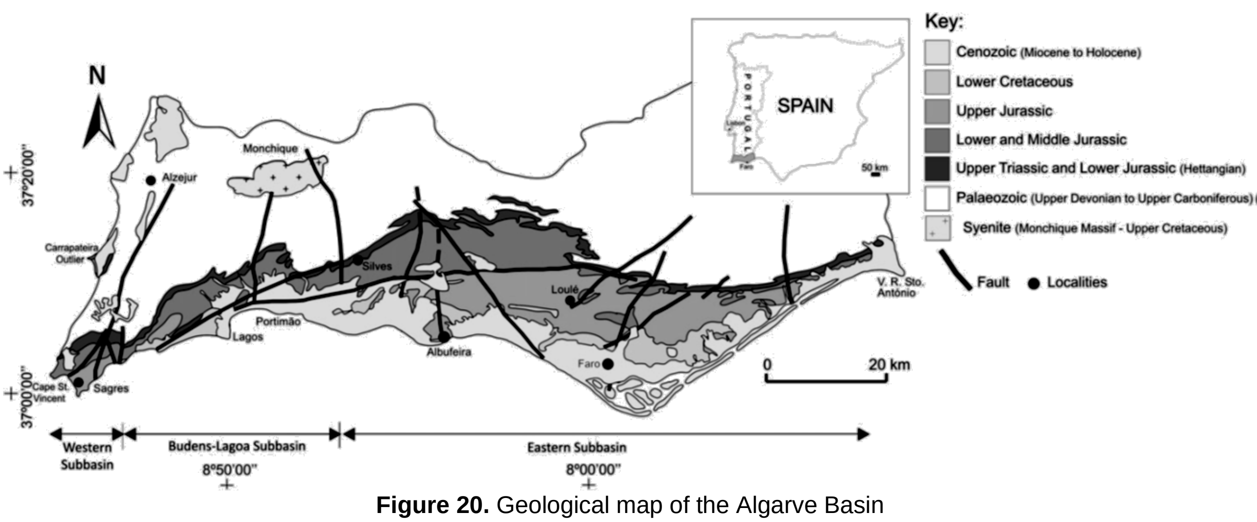


Figure 20. Geological map of the Algarve Basin
Source: Borges et al. (2011)

3.2.1.2. Hydrological Framework

The Mediterranean Climate, which is associated with a trend of high average temperature, long, hot summers without rain, and moderate winter, with low values of atmospheric precipitation, corresponds to the real conditions found in the studied regions. The analysis of the climatic component shows that this is a critical zone classified as dry and semi-arid according to the Aridity Index (Figure 21). The high temperatures recorded during the long summer have been a significant aspect of the climate, as well as precipitation rates that are among the lowest in Europe, mainly distributed over the winter period, and being practically null throughout the summer. Most rivers and water lines have runoff only during the rainy season, being dry during the summer, with the exception of some deeper areas, with springs, which maintain water throughout the year (Guerra et al., 2019).

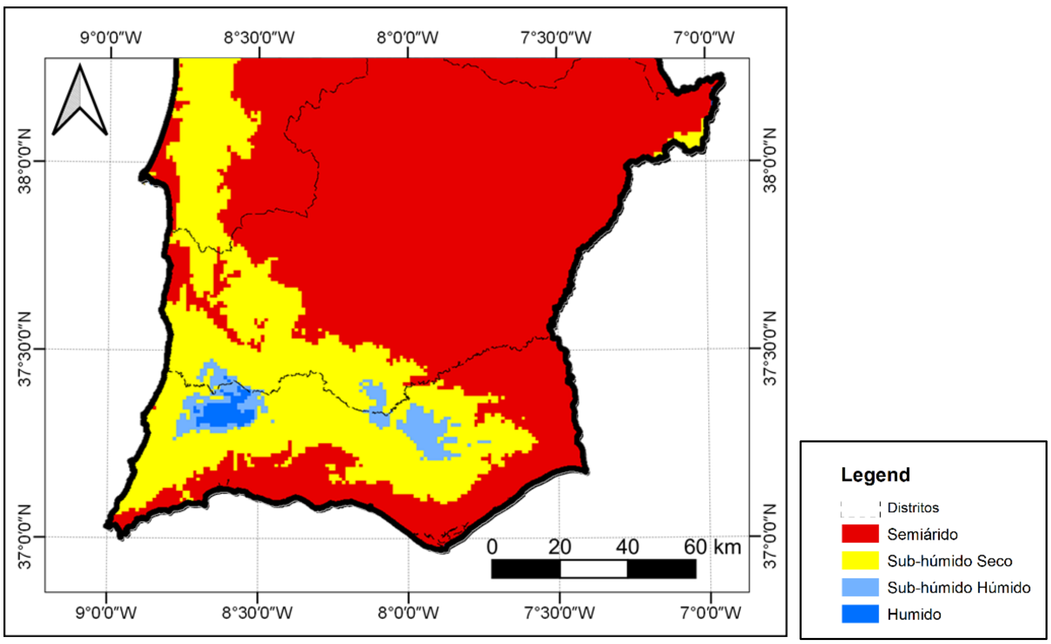


Figure 21. Aridity Index 1980 – 2010 for the Southern part of Portugal
Source: Cartografia de Apoio ao PDR 2020 Instituto da Conservaçao da Natureza e das Florestas

3.2.1.3. Hydrogeological Framework

The southwest coast of Portugal corresponds to the hydrogeological unit named Maciço Antigo which is the geological unit that occupies the greatest extent in Portugal, consisting essentially of eruptive and metasedimentary rocks. The lithologies corresponding to those types of rocks are usually designated by hydrogeologists as crystalline rocks or hard rocks, or even as fractured or fissured rocks. In general terms, they can be considered as materials with little hydrogeological aptitude, poor in groundwater resources. However, despite the scarcity of groundwater resources, they play an important role, both in supplying the population and in agriculture. In fact, in addition to thousands of small private catchments, most municipalities have a large number of underground water supplies for supply (Almeida et al., 2000). This unit is dived into three main zones: Central Iberian, Ossa-Morena, and South-Portuguese. This last one is of interest to this work. The South-Portuguese zone is the poorest in groundwater resources, basically made up of schist and greywacke, affected by low-grade metamorphisms, and there is also a strip where massive metavulcanites and sulfide deposits emerge (Almeida et al., 2000).

On the other hand, the south region studied here (Algarve), corresponds to the hydrogeological unit named Orla Meridional, a highly productive region and very well-studied set of aquifers (e.g. Monteiro & Costa, 2004; Stigter et al., 2006; Stigter et al., 2010; Da Costa, 2011; Stigter et al., 2014; Hugman et al., 2017; Neves et al., 2020). The Orla Meridional is made up of sedimentary lands of Mesozoic and Cenozoic age, resting on a Hercynian base made up of carbonic age schist and greywacke. The aquifer systems in this area develop mostly within the Miocene and Jurassic lithologies, occasionally separated by low permeability Cretaceous formations. Dolomites and occasionally limestones, karstified to a certain degree and depth, make up the Jurassic formations, reaching up to 700 m thickness. Groundwater abstraction for public supply from these systems saw a steady increase from the 1950s until the 1990s, when dams were built to fulfill the supply (José Paulo Monteiro & Costa, 2004).

The general trend of the groundwater flow is oriented towards the coast (Almeida et al., 2000) as shown in the piezometric surfaces available on the National Water Resources Information System – SNIRH website (https://snirh.apambiente.pt). The shift towards surface water irrigation in early 2000's, led to a sharp rise of the water table (Monteiro et al., 2007; Stigter et al., 2006). The increased discharge led to the reactivation of several springs, forming local discharge points of the aquifers. In the summer months, water flow from the aquifers has been greatly reduced by the lack of refilling and also by greater demand for human consumption (Monteiro et al., 2007) nonetheless, some springs remain flowing as was confirmed during a short field campaign in the summer of 2021.

Although much less studied, the hydrogeological unit of the Maciço Antigo in the South Portuguese Zone presents flow direction towards the south (Algarve Basin), and southwest coast (SNIRH: https://snirh.apambiente.pt). The field campaign discussed in chapter one also allowed us to verify the existence of springs along the southwest coast.

3.2.2. Biological Sampling

For all shores and based on previous works, visualization and local information, discharge locations were identified in the shore rocky section. Then, each rocky section was divided into two sites, one immediately adjacent to groundwater discharge site and another at least 20m apart and where no discharge was apparent/possible.

On each site, the macroinvertebrate community was visually assessed and counted (either as abundance or percentage cover for algae and similar frond-like organisms) in ten replicated 50x50 cm quadrates, a standard technique in biological studies on these habitat types (Boaventura et al., 2002). Quadrates were randomly deployed in each site at the mid and uppershore levels, closest to the discharge points. Sampling was made in February-March 2018, after the potential maximum peak of discharge of the 2017 wet season. All organisms were possible to identify *in situ* and care was taken to return to original spots when dislodgment was necessary for identification.

3.2.3. Data analysis

All biological data statistical tests were made with the software PRIMER-E (Clarke & Gorley, 2015) and using the Bray-Curtis similarity matrix. The null hypothesis of groundwater discharge having no effect on the biological communities was tested by comparing the taxa abundance of sites with discharge with that of no discharge, using the multivariate PERMANOVA technique (Anderson et al., 2008). This hypothesis was tested for both studied regions, including shores as replicates within regions. The experimental design had only one fixed factor, “discharge”, with two levels, “discharge” and “no discharge”. A P-value of 0.05 was used for results interpretation. Data was pre-treated with fourth-root to secure homogeneity of variances.

The ordination technique Principal Component Ordination (PCO) was used to visually explore and spatially represent differences in the macroinvertebrate presence across sites. The replicated quadrates are individually positioned in the graph, whereby the closest each replicate is to each other, the more similar they are in terms of macroinvertebrate community abundance and composition. The similarity percentages – species composition (SIMPER) technique identifies the contribution of each taxa (%) to the dissimilarity between each two groups, discharge versus no discharge locations in the case of the present study. It is calculated from the Bray-Curtis dissimilarity matrix, and the last two columns show the contributions for each taxa in descendant order, in a accumulative format. This technique was used here to identify the taxa most contributing for differences between discharge and no discharge locations. Histograms were used to visually represent the average abundance of the taxa identified by the SIMPER technique.

3.3. Results

The PERMANOVA analysis rejected the null hypothesis consistently for all the Southwest and South study sites, proving that the macroinvertebrate community significantly responded to groundwater discharge (Table 5), differing between discharge and non-discharge zones. The Southwest and South study sites specific biological response patterns are examined in the next two subsections.

Table 5. PERMANOVA analysis of the macroinvertebrate communities for factor discharge in the two regions where the study sites were located. N=10; p-value=0.05. Significant values and italicized.

Region	Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Southwest	Discharge	3	16602	5534.1	24.762	***0.0001***	9944
	Res	36	8045.9	223.5			
	Total	39	24648				
South	Discharge	5	16960	3392.1	13.26	***0.0001***	9927
	Res	54	13814	255.81			
	Total	59	30774				

3.3.1. Groundwater effect on biological communities of the Southwest Coast Study Sites

The PCO analysis for the samples in the study sites Azenhas do Mar (AZM) and Porto das Barcas (PB) showed that the community structure varied strongly with the discharge factor (Figure 22). Two clearly differentiated groups are recognized as response of the discharge (D) and non-discharge (ND) zones. Approximately, 84.5% of the variation is explained by this factor. The macroinvertebrate community was very similar between shores for each discharge zone type.

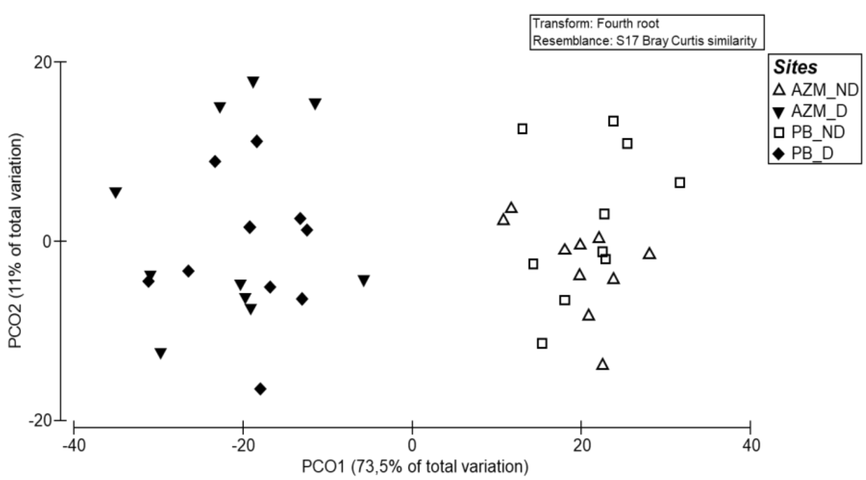


Figure 22. PCO (Principal Coordinates analysis) plot based on Bray-Curtis resemblance matrix of the macroinvertebrate communities comparing Discharge and Non-Discharge zones in the Southwest Coast study sites

3.3.1.1. Abundance of Species

Figure 23 shows the average abundance of the sampled species in both study sites. It can be observed that the algae *Enteromorpha sp.* and the limpet *Patella vulgata* were more abundant in discharge zones, together with a higher percentage of bare rock. In contrast, the lichen *Verrucaria maura*, the *Chthamalus sp.* barnacle and several gastropod taxa (limpets and snails) were more abundant in no-discharge zones.

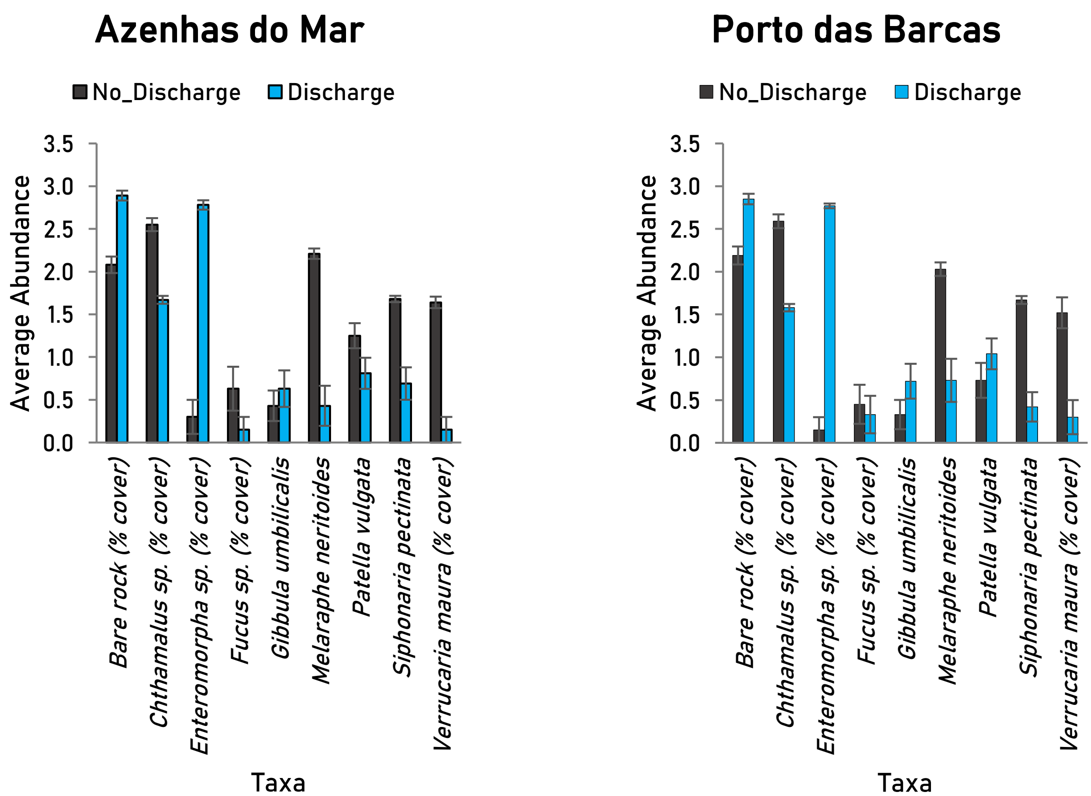


Figure 23. Average abundance (±S.E.) of taxa in Discharge and No-Discharge zones in a) Azenhas do Mar and b) Porto das Barcas study sites in the Southwest coast of Portugal.

3.3.1.2. Identification of key responsive taxa

The algae *Enteromorpha sp.*, the snail *Melaraphe neritoides*, and the lichen *Verrucaria maura* contributed the most to the differences in the biological communities' structure by discharge factor in both study sites (Table 6 and Figure 24). Cumulatively, these taxa contributed approximately 51% for the differences between sampling zones in the study site Azenhas do Mar, and approximately 47% for the differences in the study site of Porto das Barcas.

Table 6. Relative and Cumulative Contribution of macroinvertebrate taxa to the dissimilarity of the samples in the Southwest study sites

Azenhas do Mar			Porto das Barcas		
Taxa	Contrib%	Cum.%	Taxa	Contrib%	Cum.%
Enteromorpha sp. (% cover)	21.7	21.7	*Enteromorpha sp.* (% cover)	23.5	23.5
Melaraphe neritoides	15.7	37.4	*Melaraphe neritoides*	11.9	35.4
Verrucaria maura (% cover)	13.3	50.7	*Verrucaria maura* (% cover)	11.5	46.9
Siphonaria pectinata	8.9	59.6	*Siphonaria pectinata*	11.3	58.1
Chthamalus sp. (% cover)	7.8	67.4	*Chthamalus sp.* (% cover)	8.9	67.1
Bare rock (% cover)	7.2	74.6	Bare rock (% cover)	6.1	73.2
Patella vulgata	5.6	80.2	*Gibbula umbilicalis*	6.1	79.3
Fucus sp. (% cover)	5.5	85.7	*Patella vulgata*	6.1	85.4
Gibbula umbilicalis	5.5	91.2	*Fucus sp.* (% cover)	5.3	90.7

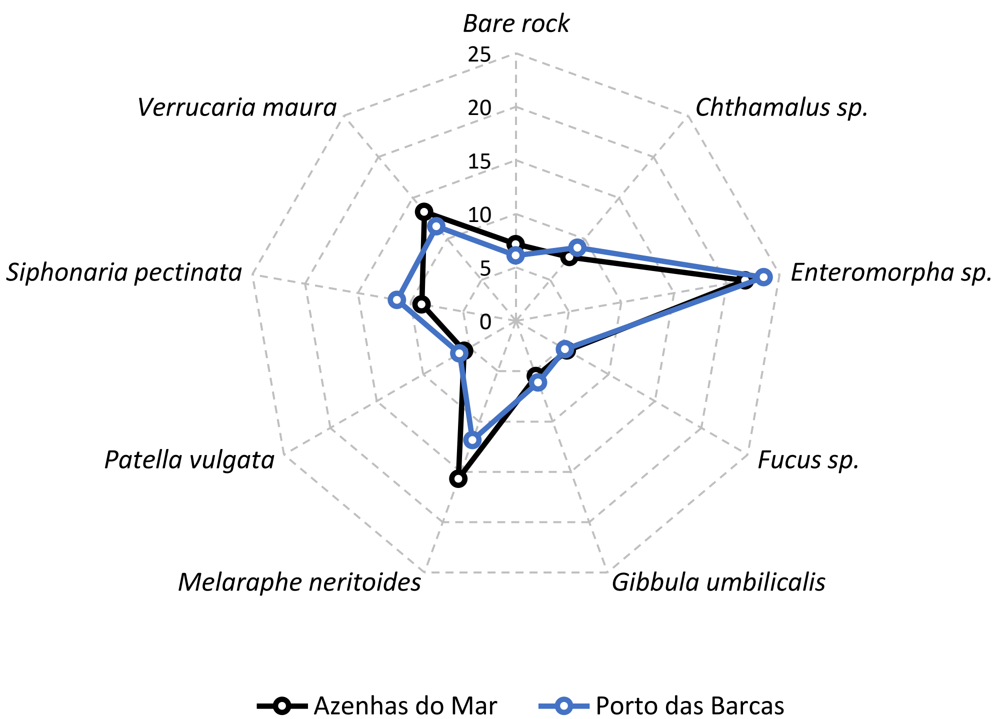


Figure 24. Percentage of contribution of each taxa to the dissimilarity of the samples in the Southwest study sites

3.3.2. Groundwater effect on biological communities of the South Coast Study Sites

The structure of the macroinvertebrate communities was consistently different between the discharge (D) and no-discharge (ND) zones in the South coast study sites Olhos d'Água (OA), Ferragudo (FER), and Praia da Luz (PL). The PCO analysis showed that approximately 79% of the variation is explained by the discharge factor, meaning the samples are clearly affected by the occurrence of freshwater discharge (Figure 25).

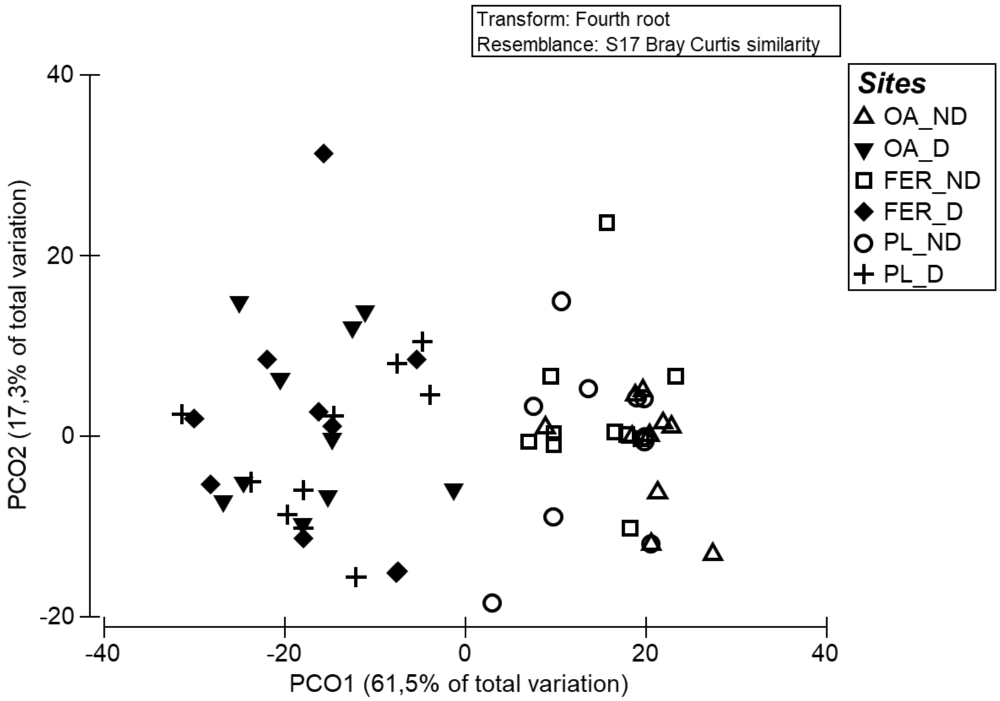


Figure 25. PCO (Principal Coordinates analysis) plot based on Bray-Curtis resemblance matrix of the macroinvertebrate communities comparing Discharge and Non-Discharge zones in the South Coast study sites.

3.3.2.1. Abundance of Species

In these study cases, the algae *Enteromorpha sp.*, the limpet *Patella vulgata*, and the barnacle *Chthamalus sp.* were the most abundant in the discharge zones alongside with a higher percentage of bare rock (Figure 26). In opposition, the taxa *Osilinus lineatus, Melaraphe neritoides*, and *Siphonaria pectinat*a were the less abundant on discharge zones. Conversely, the predominant taxa in the no-discharge zones were the *Chthamalus sp*. and the lichen *Verrucaria maura*.

3.3.2.2. Identification of key responsive taxa

In the South study cases, the average dissimilarity between the discharge and no-discharge sites was mainly explain by the contribution of the algae *Enteromorpha sp.*, the snail *Melaraphe neritoides* and the lichen *Verrucaria maura* (Table 7 and Figure 27). These three taxonomic groups conjunctively explained approximately 44% of the difference in the study site Olhos d'Água, 46% of the dissimilarity in Ferragudo, and 40% of the difference in Praia da Luz. The limpet *Patella vulgata* was the least contributing taxa to the average dissimilarity between the discharge and no-discharge zones in the three study sites.

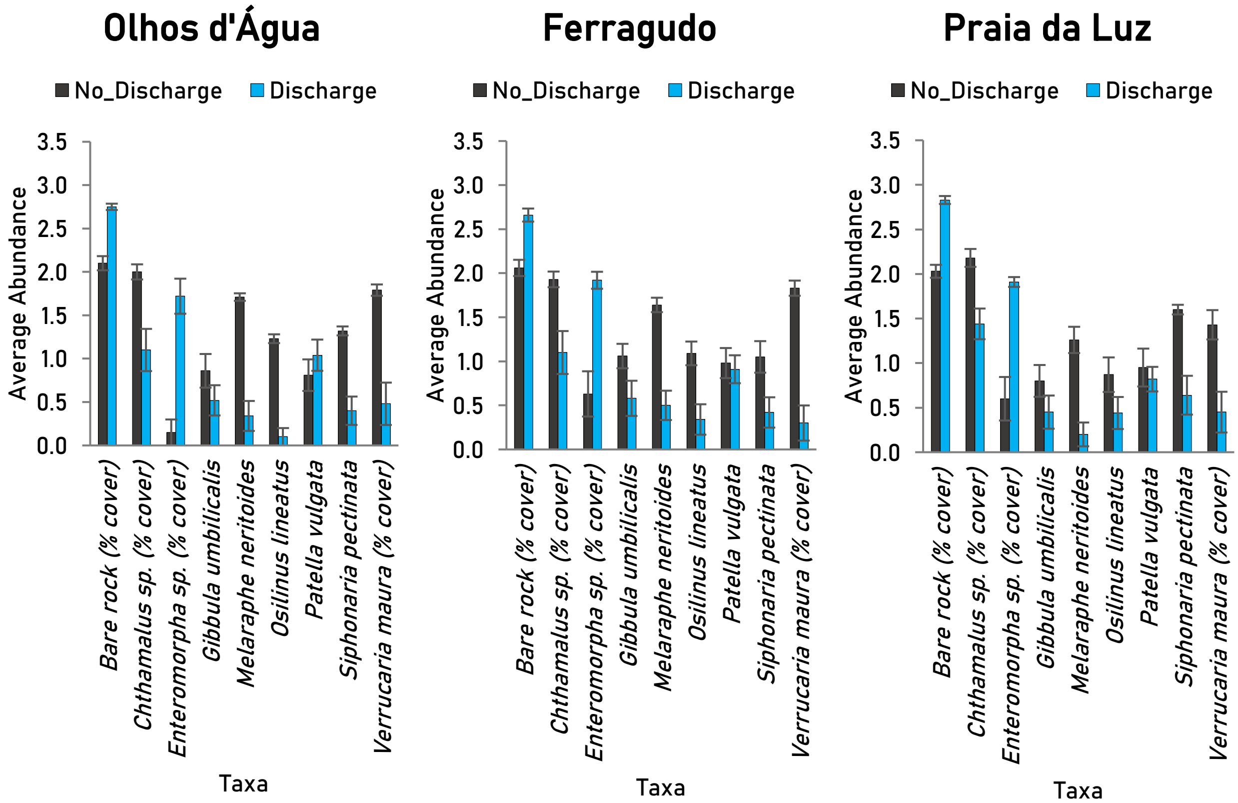


Figure 26. Average abundance (±S.E.) of taxa in Discharge and No-Discharge zones in a) Olhos d'Água b) Ferragudo, and c) Praia da Luz study sites in the South coast of Portugal.

Table 7. Relative and Cumulative Contribution of macroinvertebrate taxa to the dissimilarity of the samples in the South study sites

Olhos d'Água			Ferragudo		
Taxa	**Contrib%**	**Cum.%**	**Taxa**	**Contrib%**	**Cum.%**
Enteromorpha sp. (% cover)	16.6	16.6	*Verrucaria maura* (% cover)	17.2	17.2
Melaraphe neritoides	14.1	30.7	*Enteromorpha sp.* (% cover)	15.1	32.3
Verrucaria maura (% cover)	13.7	44.4	*Melaraphe neritoides*	13.2	45.5
Osilinus lineatus	11.6	56.0	*Chthamalus sp.* (% cover)	9.5	55.1
Siphonaria pectinata	9.5	65.5	*Osilinus lineatus*	9.5	64.6
Chthamalus sp. (% cover)	9.4	74.9	*Siphonaria pectinata*	9.1	73.6
Gibbula umbilicalis	6.7	81.7	*Gibbula umbilicalis*	8.0	81.6
Bare rock (% cover)	6.7	88.4	Bare rock (% cover)	7.1	88.7
Patella vulgata	6.3	94.7	*Patella vulgata*	6.0	94.6

Praia da Luz		
Taxa	**Contrib%**	**Cum.%**
Enteromorpha sp. (% cover)	15.2	15.2
Melaraphe neritoides	12.6	27.7

Praia da Luz		
Taxa	**Contrib%**	**Cum.%**
Verrucaria maura (% cover)	12.6	40.3
Siphonaria pectinata	11.1	51.4
Bare rock (% cover)	9.2	60.5
Chthamalus sp. (% cover)	8.6	69.1
Osilinus lineatus	8.0	77.1
Gibbula umbilicalis	7.5	84.7
Patella vulgata	7.3	92.0

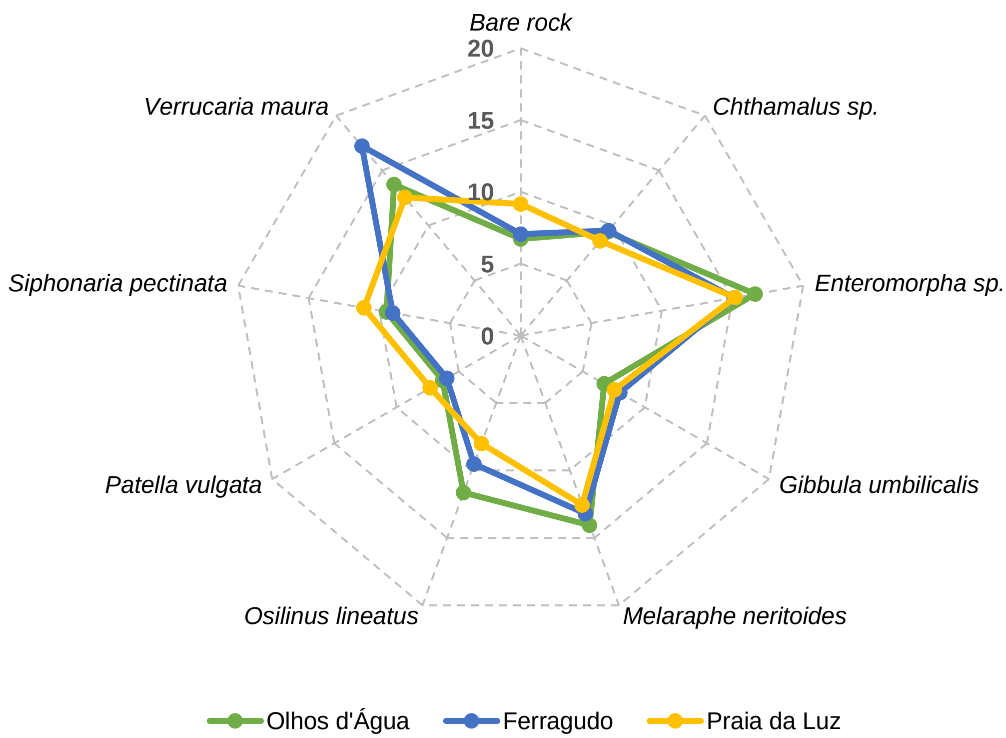


Figure 27. Percentage of contribution of each taxa to the dissimilarity of the samples in the South study sites

3.4. Discussion

Our study showed that rocky shores in the South and Southwest coast of Portugal can be considered as groundwater-dependent ecosystems to some degree as groundwater discharge significantly and consistently affected the biological communities' structure. The consistency of the biological response across all shores and regions signals that albeit this is a local-scale disturbance, it represents an important factor shaping the habitat dynamics in locations elsewhere where groundwater discharges into the rocky intertidal. It also signals that discharge patterns are consistent at least within a wet season as specific slow-growing taxa such as lichens had time to respond to the groundwater influence.

On one hand, these results are in line with previous studies that have also shown similar sensitivity to the influence of groundwater in other type of ecosystems such as sandy shores, estuaries, and reefs. Silva et al. (2012) reported that there was a biological response to a salinity gradient established by groundwater discharge into the Arade river estuarine habitat. Kotwicki et al. (2013), provided evidence that the discharge of groundwater has a clear effect on meiofaunal assemblages in the shallow area of Puck Bay (Baltic Sea), reflected in a significant decline of certain meiofaunal taxa, as well as in altered patterns of temporal distribution and small-scale (vertical) zonation of meiofaunal assemblages. Similarly, Encarnação et al. (2015) investigated the local and temporal variations in near-shore macrobenthic communities associated with submarine groundwater discharges, finding that differences in community structure between locations with and without the influence of groundwater discharge occurred mainly during spring, when the magnitude of groundwater discharge was higher. In similar way, Piló et al., (2018) revealed significant differences at the level of the structure of benthic intertidal community, area coverage, body size and ecophysiological condition of the target epibenthic species between Reference and SGD sites, supporting the hypothesis that morphological and physiological responses of key intertidal mollusk species can be used to detect the effects of the groundwater discharge into coastal ecosystems. Furthermore, Flores (2018) reported that benthic algal and invertebrate community structure was significantly related to spatial and temporal dynamics of the delivery of SGD on two reefs in the Maunalua Bay (Hawaii), which shows that SGD can shape the local species composition, diversity, and richness of biological communities.

On the other hand, this study is the first clearly showing that coastal groundwater discharge can be a key factor shaping intertidal rocky shore macroinvertebrate and algae communities. This may have important cascading associated shifts in their interspecific biotic relationships. In fact, based on the contribution to the differences between the discharge and no-discharge zones, specific taxa such as the algae *Enteromorpha sp.* the snail *Melaraphe neritoides*, and/or the lichen *Verrucaria maura* can potentially be used as a bioindication tools for shifts in groundwater discharge quantity and qualitative patterns. Hence, when these taxa are in high abundance, increased groundwater discharge is more likely. Given that competition for space is a shaping factor in intertidal communities (Dayton, 1971), the fact that the above-mentioned algae and the lichen occupy most space, potentially results in displacement of other species less tolerant to freshwater, altering the competing outcomes. This may have cascading effects in their interdependent prey and predator species, hence altering the habitat biodynamics and food webs, similarly to other coastal marine ecosystems such as seagrass beds (Schanz et al., 2002).

The bioindicator tool is useful in biodiversity monitoring programs in coastal zones and coastal ecosystems, assuming from our study that changes in quality and/or quantity of groundwater will potentially result in changes in the ecological configuration of the interconnected systems. This approach is especially useful for environmental assessments because it overcomes the limitations of evaluating the system merely based on physical-chemical parameters, which does not consider the consequences of environmental alterations on the biological communities. For example, Hwang et al. (2010) associated the high shellfish farming productivity in an enclosed bay to the influence of nearby SGD-driven nutrients and stimulation of primary production. Dean (2008) also described that numerous species of polychaetes have been identified as useful indicator for various types of environmental pollutant (e.g., organic enrichment, pesticides, and heavy metal) in the estuarine environment of the Gulf of Nicoya, Costa Rica. Since the input of those pollutants can be driven by SGD, shifts in polychaetes communities can be as changes in the quantity and/or quality of the SGD.

Furthermore, the consideration of biological communities' response to changes in groundwater discharge contributes to improve the understanding of the climate change effects on coastal aquifers and the associated ecosystems. The current tendencies of global change for Mediterranean regions are increasing temperature and decreasing precipitation and likely decrease of groundwater levels due to a reduction in recharge rates and increasing abstraction to supply anthropogenic demands (Stigter et al., 2014; da Costa et al., 2020; Rachid et al., 2021) . Hence, this results in a lowering of the regional hydraulic gradient which can affect the amount and distribution of the groundwater discharge feeding into coastal ecosystems. Stigter et al.(2012) affirm based on modeling and field observations that although it is known that groundwater input into the freshwater coastal wetlands through springs is only a small component of total groundwater discharge, a reduction in spring discharge into these wetlands is expected until the end of the century. Consequently, the availability of freshwater can directly affect the structure of biological communities in the receiving ecosystems which, in turn, will affect the dynamics and functioning of those essential environmental services they provide. An increase in the diversity of meiofauna, mainly during spring months, when the magnitude of groundwater discharge was higher, has already been documented for the 'Olhos d'Água submarine area (Encarnação et al., 2013).

The effects of SGD will likely vary with the chemical composition of the discharged water and the biological communities present in the areas where it enters (Garcia-Solsona et al., 2010; Flores, 2018; Robinson et al., 2018). Although the solutes associated with SGD vary with many factors including soil characteristics, flow path and length, land use, recharge and discharge rates, and residence time (Flores, 2018), significant impacts to nearshore biota have been observed at locations where SGD was enriched with moderate to high levels of anthropogenic nutrients. In Gamak Bay, Korea, SGD-driven nutrient fluxes were approximately 85–90% and 10–30% of the total input fluxes for dissolved inorganic nitrogen and dissolved inorganic phosphorous, respectively (Hwang et al., 2010). Amato et al. (2016) suggest that fertilizer-derived nitrogen that is delivered to reefs via SGD likely plays a major role in supporting the growth and dominance of macroalgae at both Māʻalaea and Kūʻau Bays (Hawaii). Garcia-Solsona et al. (2010) demonstrated that inorganic nitrogen and silica fluxes alone are substantial enough to promote recurrent phytoplankton blooms observed in the Balearic Island of Menorca. Donis et al. (2017) showed that silicate and phosphate supplied by SGD promoted a seep-site net community production rate that is more than twice as compared to adjacent non seeping sites in sandy sediments of Hel Bight (Poland) in the shallow southern Baltic Sea.

Chemical parameters were not measured in this study due to logistic constraints. However, the anthropogenic pressures (e.g., agriculture, urbanization, tourism) and nutrient concentrations reported for the aquifer systems in the study area (Almeida et al., 2000; Stigter et al., 2006; Fernandes et al., 2015; Rocha et al., 2016; Piló et al., 2018) suggest that the chemical composition of the SGD may have a significant impact on the structure ecophysiological condition of the intertidal biological communities. Further investigation is needed to assess the actual role of SGD physical-chemical composition on coastal ecosystems. Hence, monitoring programs should be implemented to collect information about inorganic nutrients, organic matter, silica, among others. Additionally, it is key that management programs include an assessment of the spatial and temporal variability of the species identified here as potential responders to SGD, and their role in trophic cascades as shifts in the abundance of those species can be also early warnings signals.

This study fills an important gap in knowledge by providing missing information in our understanding of the dynamics of intertidal communities under the influence of coastal groundwater discharge. The study also showcased the importance of considering local-scale disturbance impacts on intertidal macroinvertebrate communities and identified potential sentinel taxa to shifts in groundwater contribution. We suggest future studies should combine natural tracers (Wilson & Rocha, 2012; Lagomasino et al., 2015; Amato et al., 2016), hydrological and physical-chemical monitoring programs (Cave & Henry, 2011; Flores, 2018; Lecher & Mackey, 2018), and other approaches to quantify SGD and understand the role of spatial-temporal heterogeneity from regional to local estimates. Replicated experiments over time (Encarnação et al., 2015; Piló et al., 2018) will also help to assess the evolution of benthic communities, and therefore, it will lead to a better understanding of the potential SGD dependency degree of coastal ecosystems.

CHAPTER 4: GENERAL CONCLUSION

Overall, this study was considered successful in meeting the proposed specific objectives.

First and in light of what we found, thermal remote sensing was considered a suitable and cost-effective tool for the regional identification of potential SGD sites as it recognized relatively cool groundwater discharging to warmer coastal waters during the summer months in Portugal. A visual spatial correspondence between the location of thermal anomalies plumes and the average potentiometric surfaces of coastal aquifers was also observed, hence providing some evidence of tool validation. Hence, this work offers a pioneer management tool, that albeit requires refinement, can effectively support the future identification of key groundwater dependent coastal ecosystems. We suggest future research and tool development to focus on evaluating the temporal variation (in a hydrological year) of the potential SDG sites identified and quantifying the contribution of this fluxes to the local water balance using hydrological, chemical and isotopic techniques.

Secondly, rocky shores in the South and Southwest coast of Portugal can be considered as groundwater-dependent ecosystems to some degree as groundwater discharge significantly and consistently affected the structure of benthic communities. The consistency of the biological response across all shores and regions investigated signals that even though this is a local-scale disturbance, it represents an important factor shaping the habitat dynamics in locations where groundwater discharges into the rocky intertidal. We advocate that future research should focus on replicating the experiment over time and quantifying the SGD chemical and flux patterns, to assess the response of benthic communities to shifts in the magnitude and composition of discharging water.

Thirdly, specific taxa including the algae *Enteromorpha sp.* the snail *Melaraphe neritoides,* and the lichen *Verrucaria maura* can potentially be used as bioindicators for changes in groundwater discharge quantity and quality since they contribute the most to the dissimilarity of the structure between the tested discharge and no-discharge sites. Further investigation on the cascading effect of these taxa must be done to understand the role they play in the sustainment of environmental services associated with rocky shores.

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