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

Julián Esteban Londoño Londoño

Thesis to obtain the Master of Science Degree in

Environmental Engineering

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

September 2021

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

Master of Science Thesis
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

This thesis is submitted in partial fulfilment of the requirements for the academic degree of
Master of Science in Water Science and Engineering
UNESCO-IHE Institute for Water Education, Delft, the Netherlands
Master of Science in Environmental Engineering
Instituto Superior Técnico, Universidade de Lisboa, Portugal
Master of Science in Hydro Science and Engineering
Technische Universität Dresden, Germany

MSc research host institution
IST, Lisboa, Portugal

September 2021

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.

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.

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).

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 recognition of both the significance of groundwater discharge in influencing the intertidal rocky macroinvertebrates communities, and the challenges of locating potentially groundwater-dependent coastal ecosystems, this study aimed, on the one hand, to identify potential SGD spots through the application of a thermal infrared satellite imagery analysis, using Portuguese coastline as a case-study, and on the other hand to verify 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 ratifying the usefulness of the thermal infrared imagery as an exploratory tool for identifying SGD sites, and validating the biological importance of this commonly overlooked local factor and contribute to the potential classification of rocky shores as groundwater dependent ecosystems.

2. METHODOLOGY

2.1. Thermal Infrared Imagery Analysis

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. As shown in Figure 1, 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.

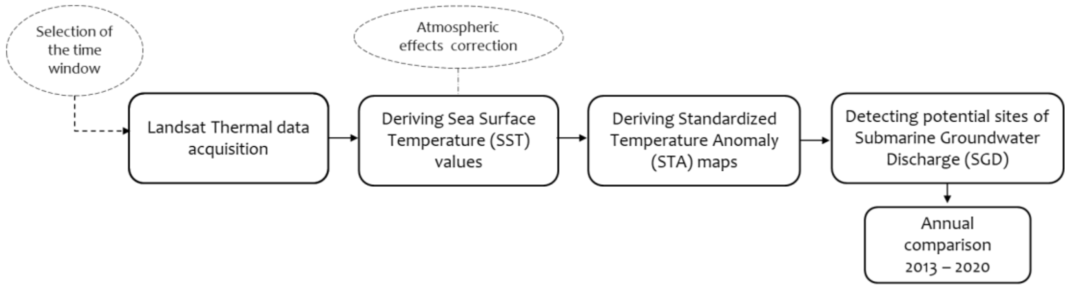

Figure 1. Methodological flow chart: selection, processing and analysis of the Thermal Infrared Landsat 8 images.

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 (1) (Samani et al., 2021):

$$L_{\lambda TOA} = M_L Q_{CAL} + A_L \tag{1}$$

Where $L_{\lambda TOA}$ is TOA spectral radiance (Watts $m^{-2}\cdot sr^{-1}\cdot \mu m^{-1}$), 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 (2)) 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.

$$L_{\lambda T} = \frac{L_{\lambda TOA} - L_{\lambda UP}}{\tau \epsilon} - \frac{1-\epsilon}{\epsilon}(L_{\lambda DOWN}) \tag{2}$$

Where $L_{\lambda T}$ is the radiance of a blackbody target of kinetic temperature T ($Wm^{-2}\ sr^{-1}\ \mu m^{-1}$), 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 (1). 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 1.

Table 1. 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 (3)

$$T_{SS} = {K_2}\Big/{\ln\left(\frac{K_1}{L_{\lambda T}} + 1\right)} \tag{3}$$

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.

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 (4).

$$TA = T_p - T_a \tag{4}$$

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 (5)), where, σ is the standard deviation of SST values.

$$STA = \frac{TA}{\sigma} \tag{5}$$

2.1. Biological Response to Groundwater Discharge

2.2.1. Study Sites Description

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.

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).

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.

2.2.2. Biological Sampling and Data Analysis

For all shores 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. 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.

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. RESULTS

3.1. Thermal Infrared Imagery Analysis

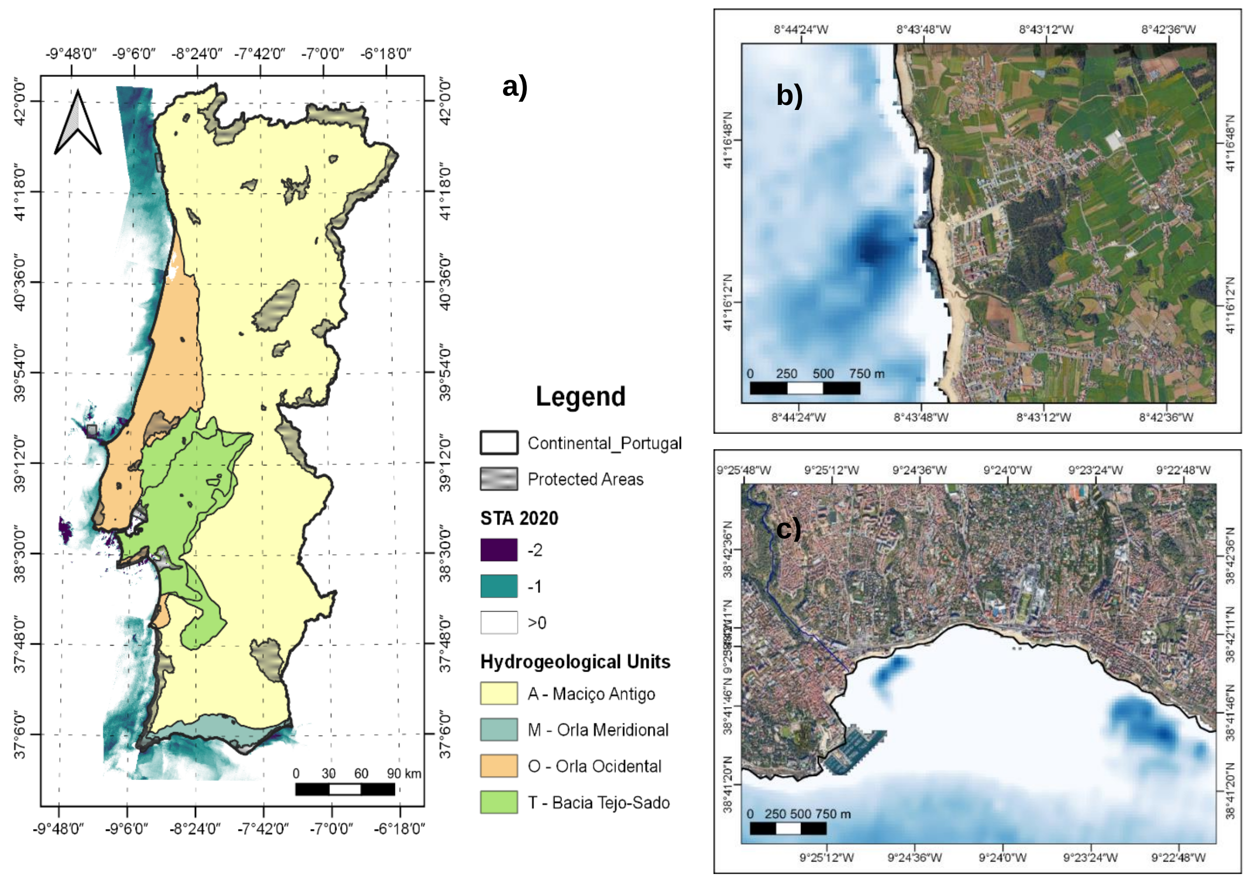

Figure 2. a) Negative Standardized Temperature Anomalies (STA) in the coastal zone of Portugal. Negative STA indicate colder water assumed to potentially be groundwater discharge; b) Standardized Temperature Anomaly maps and potential SGD sites in Praia de Labruge; and c) Baía de Cascais and Sao Joao de Estoril

Figure 2a 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 2b-c presents, in a closer view, the negative standardized temperature anomalies from where some examples of the potential SGD can be detected.

3.2. Groundwater effect on biological communities

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 2), 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 2. 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				

The PCO analysis for the samples in the study sites Azenhas do Mar (AZM) and Porto das Barcas (PB) in the Southwest coast of Portugal showed that the community structure varied strongly with the discharge factor (Figure 3). 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.

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. 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.

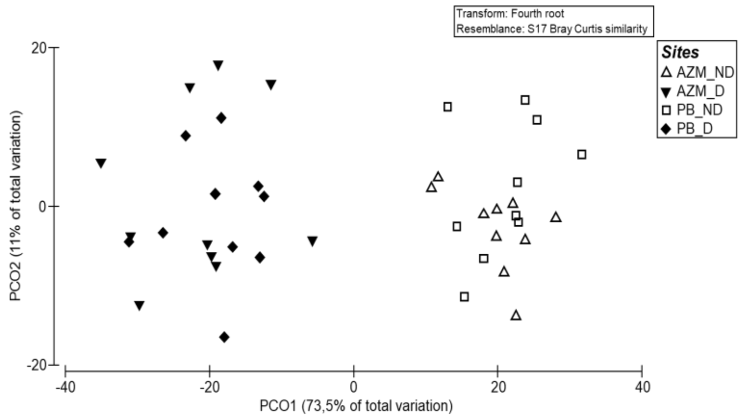

Figure 3. PCO (Principal Coordinates analysis) plot based on Bray-Curtis resemblance matrix of the macroinvertebrate communities comparing Discharge and Non-Discharge zones in the Southwest Coast study sites

On the other hand, 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 4). 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. 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.

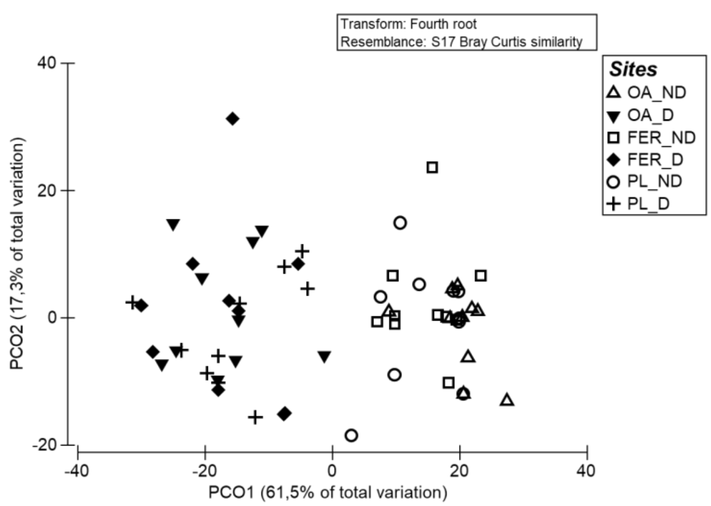

Figure 4. PCO (Principal Coordinates analysis) plot based on Bray-Curtis resemblance matrix of the macroinvertebrate communities comparing Discharge and Non-Discharge zones in the South Coast study sites.

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. 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). 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.

Our study also 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.

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.

5. CONCLUSIONS

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.

6. REFERENCES

Almeida, C., Mendonça, J., Jesus, M., & Gomes, A. (2000). Sistemas aquíferos de Portugal continental. *Instituto Da Água, Lisbon, Portugal*. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Sistemas+aquíferos+de+Portugal+continental#0

Amato, D. W., Bishop, J. M., Glenn, C. R., Dulai, H., & Smith, C. M. (2016). Impact of submarine groundwater discharge on marine water quality and reef biota of Maui. *PLoS ONE*, *11*(11), 1–28. https://doi.org/10.1371/journal.pone.0165825

Anderson, M. J., Gorley, R. N., & Clarke, K. R. (2008). *PERMANOVA + for PRIMER: Guide to Software and Statistical Methods.* PRIMER-E, Plymouth.

Boaventura, D., Ré, P., Cancela da Fonseca, L., & Hawkins, S. J. (2002). Intertidal Rocky Shore Communities of the Continental Portuguese Coast: Analysis of Distribution Patterns. *Marine Ecology*, *23*(1), 69–90.

Brown, J., Wyers, A., Aldous, A., & Bach, L. (2007). Groundwater and Biodiversity conservation: A methods guide for integrating groundwater needs of ecosystems and species into conservation plans in the Pacific Northwest. *The Nature Conservancy*, *December*, 1–176.

Burnett, W. C., Aggarwal, P. K., Aureli, A., Bokuniewicz, H., Cable, J. E., Charette, M. A., Kontar, E., Krupa, S., Kulkarni, K. M., Loveless, A., Moore, W. S., Oberdorfer, J. A., Oliveira, J., Ozyurt, N., Povinec, P., Privitera, A. M. G., Rajar, R., Ramessur, R. T., Scholten, J., … Turner, J. V. (2006). Quantifying submarine groundwater discharge in the coastal zone via multiple methods. *Science of the Total Environment*, *367*(2–3), 498–543. https://doi.org/10.1016/j.scitotenv.2006.05.009

Cave, R. R., & Henry, T. (2011). Intertidal and submarine groundwater discharge on the west coast of Ireland. *Estuarine, Coastal and Shelf Science*, *92*(3), 415–423. https://doi.org/10.1016/j.ecss.2011.01.019

Clarke, K. R., & Gorley, R. N. (2015). *PRIMER v7: User Manual/Tutorial* (p. 300). PRIMER-E. Plymouth.

Da Costa, L. R. (2011). *Calibração de um modelo de escoamento e simulação de cenários de exploração do sistema aquifero Luz-Tavira - Uma ferramenta para a gestão da agua* (p. 105).

Encarnação, J., Leitão, F., Range, P., Piló, D., Chícharo, M. A., & Chícharo, L. (2013). The influence of submarine groundwater discharges on subtidal meiofauna assemblages in south

Portugal (Algarve). *Estuarine, Coastal and Shelf Science*, *130*, 202–208.

Encarnação, J., Leitão, F., Range, P., Piló, D., Chícharo, M. A., & Chícharo, L. (2015). Local and temporal variations in near-shore macrobenthic communities associated with submarine groundwater discharges. *Marine Ecology*, *36*(4), 926–941. https://doi.org/10.1111/maec.12186

Fernandes, J., Carrara, G., Terrinha, P., Sousa, F., Leitão, F., Loureiro, M., Roque, C., Noiva, J., Boutov, D., Range, P., Dills, A., & Almeida, C. (2015). *Descargas do sistema aquífero Albufeira-Ribeira de Quarteira em meio marinho: métodos e cartografia*.

Flores, F. (2018). *The effects of submarine groundwater discharge on tropical reef benthic community composition, structure, and primary productivity* (p. 110).

Hugman, R., Stigter, T., Costa, L., & Monteiro, J. P. (2017). Numerical modelling assessment of climate-change impacts and mitigation measures on the Querença-Silves coastal aquifer (Algarve, Portugal). *Hydrogeology Journal*, *25*(7), 2105–2121. https://doi.org/10.1007/s10040-017-1594-0

Hugman, R., Stigter, T., & Monteiro, J. P. (2015). Potential Offshore Submarine Groundwater in the Albufeira-Ribeira de Quarteira aquifer system (Algarve, Portugal). In *Geophysical Research Abstracts* (Vol. 17).

Hugman, R., Stigter, T. Y., Monteiro, J. P., Costa, L., & Nunes, L. M. (2015). Modeling the spatial and temporal distribution of coastal groundwater discharge for different water use scenarios under epistemic uncertainty: case study in South Portugal. *Environmental Earth Sciences Volume*, *73*, 2657–2669.

Jou-Claus, S., Folch, A., & Garcia-Orellana, J. (2021). Applicability of Landsat 8 Thermal Infrared Sensor to Identify Submarine Groundwater Discharge Springs in the Mediterranean Sea Basin. *Hydrology and Earth System Sciences Discussions*, 1–29. https://doi.org/10.5194/hess-2020-569

Lagomasino, D., Price, R. M., Herrera-Silveira, J., Miralles-Wilhelm, F., Merediz-Alonso, G., & Gomez-Hernandez, Y. (2015). Connecting Groundwater and Surface Water Sources in Groundwater Dependent Coastal Wetlands and Estuaries: Sian Ka'an Biosphere Reserve, Quintana Roo, Mexico. *Estuaries and Coasts*, *38*, 1744–1763. https://doi.org/10.1007/s12237-014-9892-4

Lecher, A. L., & Mackey, K. R. M. (2018). Synthesizing the Effects of Submarine Groundwater

Discharge on Marine Biota. *Hydrology*, *5*(60). https://doi.org/10.3390/hydrology5040060

Mieszkowska, N. (2016). Intertidal Indicators of Climate and Global Change. In T. M. Letcher (Ed.), *Climate Change* (Second Edi, pp. 213–229). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-444-63524-2.00014-2

Monteiro, J. P., & Costa, M. S. (2004). Dams, Groundwater Modelling and Water Management at the Regional Scale (the Southern Portugal Region – Algarve). *Larhyss Journal*, *3*, 157–169.

Neves, M. C., Nunes, L. M., & Monteiro, J. P. (2020). Evaluation of GRACE data for water resource management in Iberia : a case study of groundwater storage monitoring in the Algarve region. *Journal of Hydrology: Regional Studies*, *32*. https://doi.org/10.1016/j.ejrh.2020.100734

Piló, D., Barbosa, A. B., Teodósio, M. A., Encarnação, J., Leitão, F., Range, P., Krug, L. A., Cruz, J., & Chícharo, L. (2018). Are submarine groundwater discharges affecting the structure and physiological status of rocky intertidal communities? *Marine Environmental Research*, *136*(November 2017), 158–173. https://doi.org/10.1016/j.marenvres.2018.02.013

Ribeiro, L., Nascimento, J., Buxo, A. C., Condesso De Melo, M. T., Silva, A., & Mendes, M. P. (2015). *Metodologia para a identificação de ecossistemas terrestres dependentes das águas subterrâneas (ETDAS) em Portugal*.

Richardson, S., Irvine, E., Froend, R., Boon, P., Barber, S., & Bonneville, B. (2011). Australian groundwater-dependent ecosystems toolbox part 1: assessment framework. In *Waterlines report* (Issue 70).

Rocha, C., Veiga-Pires, C., Scholten, J., Knoeller, K., Gröcke, D. R., Carvalho, L., Anibal, J., & Wilson, J. (2016). Assessing land–ocean connectivity via submarine groundwater discharge (SGD) in the Ria Formosa Lagoon (Portugal): combining radon measurements and stable isotope hydrology. *Hydrology and Earth System Sciences*, *20*(8), 3077–3098. https://doi.org/10.5194/hess-20-3077-2016

Samani, A. N., Farzin, M., Rahmati, O., Feiznia, S., Kazemi, G. A., Foody, G., & Melesse, A. M. (2021). Scrutinizing relationships between submarine groundwater discharge and upstream areas using thermal remote sensing: A case study in the northern Persian gulf. *Remote Sensing*, *13*(3), 1–20. https://doi.org/10.3390/rs13030358

Santos, I. R., Chen, X., Lecher, A. L., Sawyer, A. H., & Moosdorf, N. (2021). Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. *Nature Reviews Earth & Environment*, *0123456789*. https://doi.org/10.1038/s43017-021-00152-0

Satyam, K., & Thiruchitrambalam, G. (2018). Habitat Ecology and Diversity of Rocky Shore Fauna. In *Biodiversity and Climate Change Adaptation in Tropical Islands*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-813064-3/00007-7

Sawyer, A. H., Shi, F., Kirby, J. T., & Michael, H. A. (2013). Dynamic response of surface water-groundwater exchange to currents, tides, and waves in a shallow estuary. *Journal of Geophysical Research: Oceans*, *118*(4), 1749–1758. https://doi.org/10.1002/jgrc.20154

Silva, A. C. F., Tavares, P., Shapouri, M., Stigter, T. Y., Monteiro, J. P., Machado, M., Cancela da Fonseca, L., & Ribeiro, L. (2012). Estuarine biodiversity as an indicator of groundwater discharge. *Estuarine, Coastal and Shelf Science*, *97*, 38–43. https://doi.org/10.1016/j.ecss.2011.11.006

Stigter, T., Monteiro, J. P., Nunes, L. M., Ribeiro, L., & Hugman, R. (2010). Regional spatial-temporal assessment of groundwater exploitation sustainability in the south ofPortugal. *XXXVIII IAH Congress*, *September*, 12–17.

Stigter, T. Y., Nunes, J. P., Pisani, B., Fakir, Y., Hugman, R., Li, Y., Tomé, S., Ribeiro, L., Samper, J., Oliveira, R., Monteiro, J. P., Silva, A., Tavares, P. C. F., Shapouri, M., Cancela Da Fonseca, L., & El Himer, H. (2014). Comparative assessment of climate change and its impacts on three coastal aquifers in the Mediterranean. *Regional Environmental Change*, *14*(Suppl 1), 41–56. https://doi.org/10.1007/s10113-012-0377-3

Stigter, T. Y., Ribeiro, L., & Dill, A. M. M. C. (2006). Evaluation of an intrinsic and a specific vulnerability assessment method in comparison with groundwater salinisation and nitrate contamination levels in two agricultural regions in the south of Portugal. *Hydrogeology Journal*, *14*(1–2), 79–99. https://doi.org/10.1007/s10040-004-0396-3

Taniguchi, M., Burnett, W. C., Cable, J. E., & Turner, J. V. (2002). Investigation of submarine groundwater discharge. *Hydrological Processes*, *16*, 2115–2129. https://doi.org/https://doi.org/10.1002/hyp.1145

Wilson, J., & Rocha, C. (2012). Regional scale assessment of Submarine Groundwater Discharge in Ireland combining medium resolution satellite imagery and geochemical tracing techniques. In *Remote Sensing of Environment* (Vol. 119, pp. 21–34). https://doi.org/10.1016/j.rse.2011.11.018

Wilson, J., & Rocha, C. (2016). A combined remote sensing and multi-tracer approach for localising and assessing groundwater-lake interactions. *International Journal of Applied Earth Observation and Geoinformation*, *44*, 195–204.