A SYSTEMATIC REVIEW OF GEOPHYSICS APPLIED IN SEAWATER INTRUSION RESEARCH

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ABSTRACT

Coastal aquifers are critical to the socioeconomic development of coastal areas. One of the most common effects in the coastal profile is the advance of saltwater intrusion, sometimes due to natural factors and sometimes highlighted by anthropogenic actions. Seawater intrusion is a highly studied problem for the control, conservation, and management of aquifers. One of the most pressing challenges in marine coastal reality is managing the effects of saltwater intrusion, and geophysics is one of the most applied techniques. This work aims to analyse geophysics' applications in saline intrusion study cases through bibliometrics and a systematic review of the knowledge of techniques for the study, control and sustainable management of coastal aquifers. The method focuses on searching for scientific publications in the Scopus database using the descriptors 'saltwater intrusion' and 'geophysics' and their synonyms. The publications are classified using the VOSviewer and Bibliometrix software, recognising their evolution and scientific trends. The results reflect 564 publications in Scopus, various methods where the measurement of water levels in nearby wells predominates, geoelectric applications, geoelectric cuts, 3D models, physical-mathematical analysis models such as numerical models and water quality measurements applying isotopic methods. The researcher's experience reveals the integration and synergy in techniques and methods used to ensure the effective management of this phenomenon. Seawater intrusion can be natural, but above all, it stands out due to processes of excessive exploitation of groundwater, which, in many cases, is an irreversible situation. Therefore, the management of a coastal aquifer is vital to its sustainability.

Keywords: groundwater management, salt wedge, conductivity, scientometric, geoelectrical, groundwater flow models.

1 INTRODUCTION

Groundwater resources are the main sources of water supply for humans and the natural environment in coastal aquifers [1]. Groundwater accounts for 30% of the world's freshwater [2]. This resource supports the water demands of dense coastal populations and productive coastal ecosystems [3]. Over the last decades, increasing population demand and resource overexploitation have limited access to water in many parts of the world, where 70% of groundwater exploitation occurs in coastal areas [4]. Over-extraction of aquifers affects groundwater quality and water flow patterns, creating regions vulnerable to anthropogenic pollution (industrial or domestic wastewater leaks, pollution from agricultural activities) and salinisation from seawater intrusion (SWI) (sea level rise, rainfall recharge variations, and projected impacts of climate change) [5]. SWI, also called saltwater intrusion, is one of the main reasons behind groundwater pollution [6]. This phenomenon occurs when saltwater from the sea mixes with freshwater from aquifers, especially in coastal areas where aquifers are close to the sea [7]. Factors such as water table, tides, droughts, surface and groundwater withdrawals for drinking water and irrigation, hydrological connectivity (tidal gates, dams, agricultural diversions, ditches, roadside canals) and climate change contribute significantly to this problem in variables of space, time, frequency and duration [8]. Groundwater with a

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SDP240521

salinity content greater than 2% is considered undrinkable [9]. The usual SWI detection methods are total dissolved solids (TDS) concentrations, which are significantly increased by the presence of solutes from seawater, such as chloride and sodium [10].

SWI has been studied using hydrochemical analysis, isotopes, hydrological models and geophysical techniques to determine the sources and effects causing groundwater salinisation [11]. Geophysical methods allow visualisation of the distribution and depth of salt intrusion [12]. Among the most well-known techniques are Vertical Electrical Soundings (VES), Electrical Resistivity Tomography (ERT), Airborne Electromagnetics (AEM), Frequency Domain Electromagnetic Method (FDEM) and a combination of electrical resistivity with induced polarisation (IP) signatures [13].

Although the environmental problem of SWI is common and well-studied in coastal areas, due to the complexity of the process, the correct way to determine mitigation measures has yet to be determined. Bibliometric techniques allow the identification of scientific advances and mappings through the use of specialised software such as VOSviewer and Bibliometrix [14], co-occurrence factors and scientific production by country [15], [16]. Meanwhile, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) allow a critical evaluation of documents of interest to report gaps, solutions or standard methodologies regarding the lines of research [17]. This work raises the following research question: What geophysical methods are used as monitoring techniques in SWI worldwide?

Considering the importance of determining mitigation and monitoring methods for the SWI process that affects all coastal aquifers, this research aims to analyse the applications of geophysical methods in SWI case studies through bibliographic analysis and systematic review for the knowledge of control techniques and sustainable management in coastal aquifers.

2 MATERIALS AND METHOD

This article consists of a statistical analysis of publications registered in Scopus from 1966 to 2024 on the study of SWI using different geophysical techniques (Fig. 1). The methodological sequence was divided into three study phases, from a generalised analysis of the topic to a focused analysis through a review of case studies. Bibliometric analyses combined with reviews using the PRISMA statement allow for a more objective review.

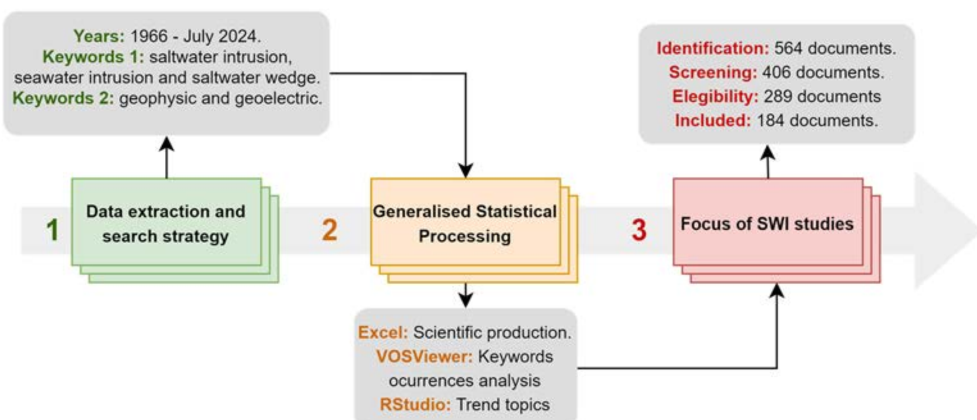

Figure 1: Methodological design of the systematic review with a generalised analysis and a focus on case studies.

2.1 Search strategy and data extraction

Publications were downloaded from the Scopus database from 1966 to July 2024, and 564 documents were collected. The search equation included two keywords in the titles, abstracts, and keywords: aquifer salinisation*"))) AND ((TITLE-ABS-KEY ("geophysic*") OR TITLE-ABS-KEY ("geoelectric*") OR TITLE-ABS-KEY ("geo electric*") OR TITLE-ABS-KEY ("geo-electric*") OR TITLE-ABS-KEY ("TDEM*") OR TITLE-ABS-KEY ("ERT*") OR TITLE-ABS-KEY ("Geophysical log*"))). As part of the keywords, synonyms were considered to encompass combinations of the subject, focusing on the SWI in coastal areas and the main geophysical exploration methods used. The data were downloaded from Microsoft Excel. The CSV format was cleaned, eliminating five documents that did not have information, such as the author, DOI, or title.

2.2 Generalised statistical processing

With the database clean and Excel, a graph of scientific production was generated, comparing it with citations over time. In the VOSviewer software, a graph of the co-occurrence of keywords with a frequency of five was obtained, in which graphs related to the dominant keywords, the variation of these keywords over time, and the geographical distribution of the publications were obtained.

2.3 SWI study approach

With generalised analysis, it was possible to focus on publications on SWI by geophysical techniques and concentrating on reviewing case studies. The clean Scopus search equation was used as the identification criterion in the PRISMA method, and 564 documents were obtained until July 2024. For the identification criterion, documents with less than one citation were excluded, resulting in 406 documents. The screening criteria selected documents published in the last two decades, defining 378 publications. 289 documents were determined by searching the title for the suffixes ‘salt’, ‘sea’, and ‘geo’. The fourth inclusion criterion, 184 case studies, methodologies, and geophysical tools used for monitoring and studying the SWI were considered.

3 RESULTS

3.1 Scientific production

Fig. 2 shows the scientific production during the period 1966–2024. The accumulated bars show two behaviours regarding the number of documents (1966–2003 and 2004–2024), while the linear series shows the number of citations per year. From 1966 to 2003, a low scientific production is observed around the SWI problem, with an annual average of four documents. The second period, corresponding to the last 20 years, presents a higher scientific yearly production, with 2020 being the highest production year (46 documents). Production growth shows that this field of study is not obsolete and follows Price’s law of exponential growth with a correlation coefficient of R^2 = 0.8065, indicating a high degree of variability. The frequency of citations reached a maximum of 1,100 in 2010. The topics with the highest frequency of citations in 2010 focus on studies of the behaviour and structure of saline flow in estuaries [18] and three-dimensional and historical modelling of wells [19]. Regarding the

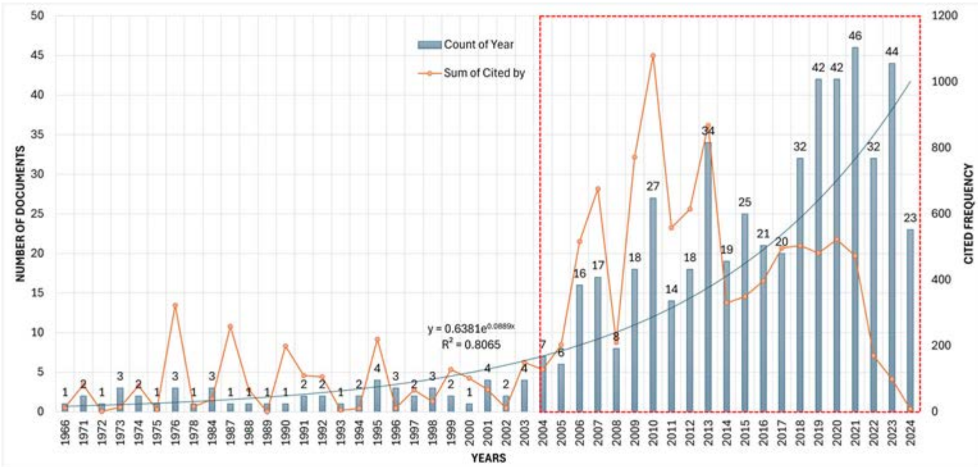

Figure 2: Analysis of production and citations by year for the period 1966–2024.

year of greatest scientific production, the studies focus on the modelling and analysis of the SWI using geochemical techniques [20], geophysical techniques [21] and a combination of both [22].

3.2 Keyword co-occurrence analysis

According to the keyword co-occurrence analysis, it is possible to identify five well-defined clusters corresponding to the research subareas within the geophysical applications in saline intrusion studies (Fig. 3). Cluster one (red nodes) and cluster five (purple nodes) contemplate the characterisation and modelling of hydrogeological systems through geophysical and numerical techniques such as Time Domain Electromagnetics (TEM) [23] and IP [13]. On the other hand, cluster two (green nodes) shows research that integrates geophysical methods and Geographic Information Systems (GIS) in the study of groundwater quality and its relation to saline intrusion [24]. Cluster three (blue nodes) and four (yellow nodes) correspond to research fields related to the application of VES [25] and ERT [26] in the assessment of aquifer contamination.

The mapping of clusters by country shows in Fig. 4 the participation of seven main countries: the United States, Spain, Australia, France, China, the United Kingdom and Greece. Spain, France, Germany and China have high levels of interaction. Meanwhile, the United Arab Emirates shows low scientific collaboration with European and Asian countries. Among the most relevant collaborations for the three countries with the highest scientific production, the following stand out:

- The United States (yellow node) shows extensive collaboration with Asian countries (Taiwan and Japan) on topics such as the Fluvial Acoustic Tomography (FAT) system as an innovative technique to measure salt flow in coastal environments [27] and the use of TEM methods for obtaining SWI images [28].
- In collaboration with China, Spain (orange node) has developed stochastic models for predicting SWI progress [29]. In addition, simulations have been carried out using geophysical and geochemical techniques [30].

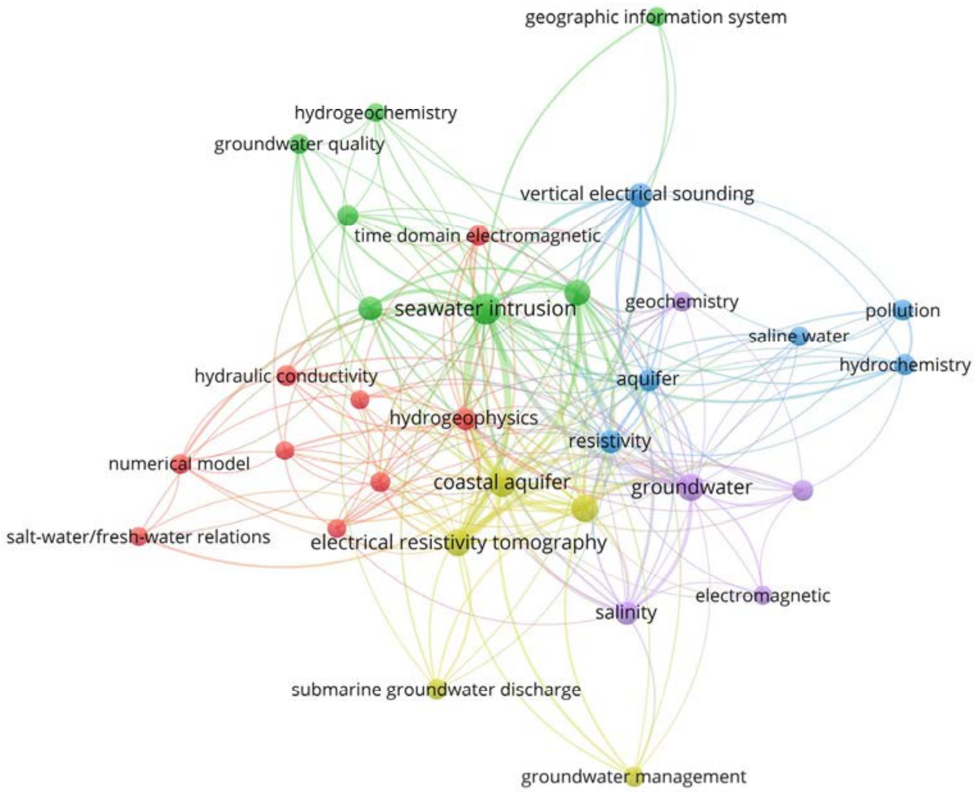

Figure 3: Co-occurrence of keywords with a frequency of five and five study clusters.

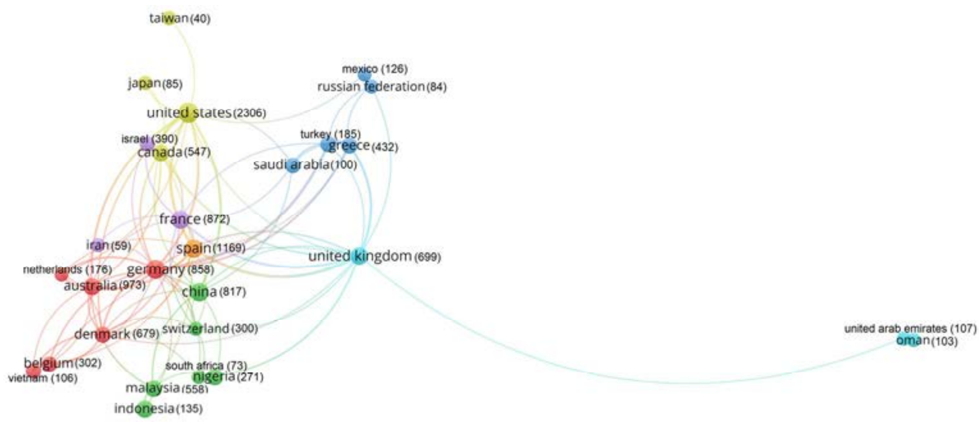

Figure 4: Country clusters with the frequency of scientific publications and the number of citations.

- Australia (red node) presents collaboration with European countries (Denmark, Netherlands, Germany and Belgium). Together, they conducted studies of seawater dynamics using numerical simulation and geophysics, monitoring well analysis [31] and statistical analysis [32].

3.3 Research trends

Fig. 5 shows the trend map from 2000 to 2024, considering a frequency of four times in the research topic. During the period 2006–2022, a pattern of repetition of the word seawater intrusion (201 times), borehole geophysics (six times) and geophysical method (48 times) is observed. During 2020–2022, groundwater management managed aquifer recharge and water resources management is followed, focused on groundwater management, with a frequency of four. In addition, the correlation of occurrence of the words ERT (59), VES (22 times) and electrical resistivity (20 times) with the words aquifer geometry and coastal aquifer is identified during the period 2015–2022.

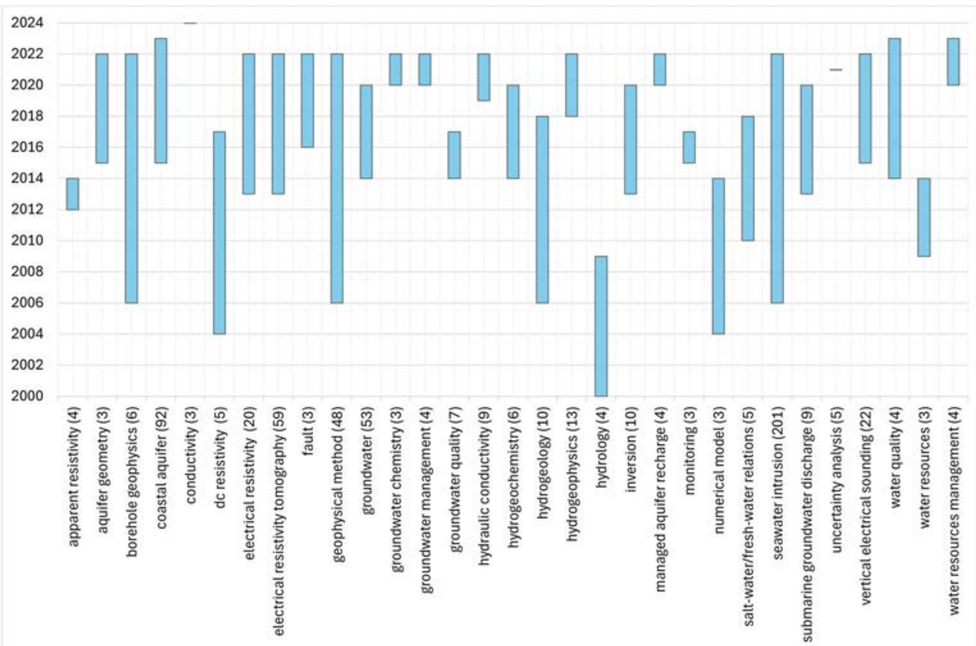

Figure 5: Trend topics with a frequency of four, highlighting the predominant words over time.

3.4 Systematic review on the SWI approach

The systematic review, 184 case studies were analysed (2004–2023), identifying their geographic location, geophysical method used, main results and conclusions (Table 1). The information obtained reveals various geophysical techniques of electrical resistivity, seismic, and TEM applied in different geographic environments. The investigations include advanced

Table 1: Summary of the case studies where geophysical methods were applied for SWI.

Years	Countries	Applied methodology	Main results/conclusions
2004	South Korea, Morocco and Egypt	Geophysical well logs, VES, 1D, 2D and 3D resistivity tests	Geometry characterisation and study of SWI in coastal areas [33]
2005	Palestine	Geochemical and geophysical investigations	Sources of salinity and boron [34] and identification of natural contaminant flows
2006	Kazakhstan	Bathymetry and topography studies	Evaluating interactions between salt/fresh water [35]
2007	Israel and United States	Time-Domain Electromagnetic Method (TDEM) and hydrogeological modelling	Delimitation of the freshwater–saltwater interface and modelling of groundwater discharge [36]
2008	Italy and Malaysia	Geophysical and geochemical approach	Mapping salinity in coastal aquifers [37]
2009	Spain, Germany and United States	ERT, VES and water quality	Study of detrital aquifers affected by SWI and stratigraphic controls [38]
2010	Oman, Egypt, Morocco and Greece	TDEM, numerical simulations and geoelectrical method	SWI Rate Estimation and Recharge Assessment [39]
2011	India, Canada, Vietnam and India	Geophysics, geochemistry and geoelectrical method	Origin and extent of fresh and saline waters, hydrogeological configurations and SWI characterisation [40]
2012	Italy, United Arab Emirates and India	Geoelectrical and geochemical tests	Characterisation and evaluation of the impact of SWI [41]
2013	Spain, India, Malaysia and Cuba	Geoelectrical testing, hydrochemical modelling, TDEM and VES	Complex dynamics of groundwater and saltwater exchange, SWI imaging and mapping [42]
2014	Algeria, Israel, Vietnam, Egypt and Germany	TDEM and 3D geophysical modelling	Detection of saline groundwater bodies and structural models [43]

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Table 1: Continued.

Years	Countries	Applied methodology	Main results/conclusions
2015	Turkey, China, Italy and Algeria	Numerical modelling, 4D ERT and hydrochemical tests	Assessment, distribution and monitoring of SWI in a coastal urban area [44]
2016	Turkey, China, Italy and Algeria	Geophysical and geochemical studies, ERT, TDEM and VES	Delineation, mapping and monitoring of SWI [45]
2017	Morocco, Türkiye and the Netherlands	Hydrochemical and geoelectrical approaches and TDEM	Identification of saline zones and SWI control in coastal urban cities [46]
2018	Indonesia, India, Iran, Greece and Nigeria	Geoelectrical test, TDEM and Very Low-Frequency Electromagnetic method (VLF-EM)	Quantitative tool for hydrogeology and uncertainty quantification in geophysical inversion [47]
2019	Thailand, Saudi Arabia, India, Romania and Indonesia	VES, ERT and Audio-Telluric-Magnetotelluric (AMT)	SWI factors, patterns and velocity in an aquifer, geological risk distribution and delineation of saltwater–freshwater interfaces [48]
2020	Malaysia, Thailand, Saudi Arabia and Norway	Cross-Hole Electrical Resistivity Tomography (CHERT), borehole and geoelectric methods	Identification and mapping of SWI, groundwater quality management and delineation of contaminated aquifers [49]
2021	Nigeria, Türkiye, Indonesia, China, Vietnam and Africa	Integrated geophysical methods, hydrochemical analysis and AMT	Spatiotemporal variation of SWI, exploitation of the saline stratified coastal aquifer and groundwater quality [50]
2022	Indonesia, Brazil, Nigeria and Vietnam	VES, numerical modelling, remote sensing and GIS	Identification of SWI in coastal areas and characterisation of salinity patterns [51]
2023	Algeria, Jordan, Morocco, China and Egypt	Hydrogeophysics, ERT and TDEM	Characterisation of the hydrogeological system and evaluation of aquifer parameters [52]

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simulations, allowing a better understanding of the development and factors influencing the problem. The results highlight the importance of generating innovative methodologies combined with techniques that maximise resolution and precision in characterisation, evaluation of water resources and sustainable management of coastal water resources.

4 DISCUSSION

SWI is a common problem in coastal aquifers worldwide, mainly due to the excessive exploitation and pumping generated by population demand, tourism, and the agricultural sector. The bibliometric analysis shows the correlation between scientific production and research trends, with the years of excellent productivity in 2004–2024 being those with the highest occurrence of words, such as coastal aquifers and geophysical methods. In addition, from 2015 to 2024, research on SWI has directed studies to propose strategies for managing groundwater and recharge in aquifers as a mitigation measure. In a systematic review of 184 case studies, geophysical techniques were widely used, mainly geoelectrical methods for evaluating, delimitating, and monitoring SWI. Among these classifications, the application of DC resistivity stands out, with 1D, 2D, and 3D techniques; TDEM, ERT, and VES are the most used methods. In addition, the results of the articles of the focused review highlight that the combination of geophysical methods provides a comprehensive evaluation of SWI, emphasising the use of more techniques such as remote sensing, GIS, water quality analysis and hydrogeological analysis that allow innovative assessments for mapping and estimating the rate of contamination in coastal aquifers [48]. This research is aligned with the Sustainable Development Goals (SDG) established by the United Nations (UN), mainly with SDG 6 (targets 6.3 and 6.5), focused on improving water quality and water resources management through the application of geophysical methods that allow the identification of areas of contamination, exploration of new water sources and a technical approach to decision-making in search of the sustainability of the coastal regions. Regarding SDG 11 (target 11.5), knowledge of traditional and current geophysical techniques in the study of SWI strengthens resilience in urban planning of the coastal regions, where one of the main sources of supply comes from aquifers. Finally, SDG 13 (13.1) addresses climate action, highlighting the importance of studies in coastal areas due to contamination by anthropogenic factors, such as the overexploitation of water wells, affecting the quality and availability of groundwater.

5 CONCLUSIONS

SWI is one of the main problems studied in coastal areas because of the overexploitation of aquifers, which affects groundwater quality. The delimitation and monitoring of SWI have been studied by applying and combining different techniques, among which geophysical methods stand out. Scientific research on this subject has shown evidence of growth and interest since 1966 and a notable evolution in the last decade related to climate change that generates seasonal variations in hydrogeological systems. Among the most widely used geophysical methods for studying SWI, traditional geoelectrical methods, such as ERT, VES, and a combination of techniques, with the application of remote sensing, GIS, and hydrochemistry, stand out as the most effective for evaluating, delimiting, and monitoring SWI. The results allow for an integrated approach to scientific research addressing challenges such as climate change in search of sustainability in coastal areas through hydrogeological studies that apply geophysical techniques.

ACKNOWLEDGEMENTS

This work is supported by ESPOL Polytechnic University research project ‘Management and Evaluation of Scientific Research in Earth Sciences, Economy, Administration, and its Links with Society’ with institutional code CIPAT-7-2022.

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