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PREFACE

Preface: Advances in understanding offshore freshened groundwater

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Introduction

Offshore fresh or freshened groundwater (OFG) is defined as low-salinity water stored within sediment pore spaces and rock fractures beneath the seafloor, with total dissolved solids (TDS) concentrations lower than those of seawater (Post et al. 2013; Micallef et al. 2021). While submarine groundwater discharge (SGD) has been exploited since antiquity (Moosdorf and Oehler 2017; Luijendijk et al. 2020), the context of these SGDs and especially how they relate to the aquifer system as a whole has, until recently, largely been unexplored. It is only very recently that new scientific research has started to produce widespread evidence suggesting that significant freshwater reserves may exist beneath most continental margins (Kohout 1964; Hathaway et al. 1979). These aquifer systems are distributed worldwide (Post et al. 2013), and this recognition has brought increased scientific focus on OFG.

While "OFG" is the most commonly used term, it encompasses slightly varying nomenclature used by authors through time, such as "offshore low-salinity groundwater" (Post et al. 2013), "offshore fresh or low salinity (paleo) water" (Edmunds and Milne 2001; Cohen et al. 2010; Paleologos et al. 2018) and "submarine fresh or low-salinity groundwater" (Bakken et al. 2012).

The purpose of this special issue is to provide a snapshot of the current research efforts on OFG and to discuss future avenues of investigation, with contributions that have a wide geographical spread (Fig. 1). The essay by **Bertoni et al.** provides a global perspective on the challenges associated with OFG and discusses future avenues and open questions for research, including critical issues on the potential use of OFG as a future freshwater resource in water-scarce coastal or insular regions. Further specific reported contributions focus on descriptions of worldwide examples of OFG, including regional exploration studies providing insights on the formation and evolution of OFG over time, present-day OFG potential, and practical water resources management issues, entailing a broad range of research methods, including field observations, experimental analyses and numerical modelling.

OFG research has developed and expanded from initial work to study and methodically record near-coast, submarine freshwater discharge. Research in this field has shown that freshwater discharge can reach several kilometres off the coast, with peaks of over 15 km offshore recorded for karst/fractured aquifers (e.g. Schuler et al. 2020), prompting the search for farther reaching freshwater. In a contribution to this special issue, the profile of an eminent hydrogeologist by **Pistre et al.** describes how the seminal work of Michel Bakalowicz improved the understanding of coastal karst aquifers and their link with submarine springs in the Mediterranean Sea. Geoscientists now explore OFG in deeper, porous, and often confined aquifers, as research expands to submarine siliciclastic reservoirs that can extend hundreds

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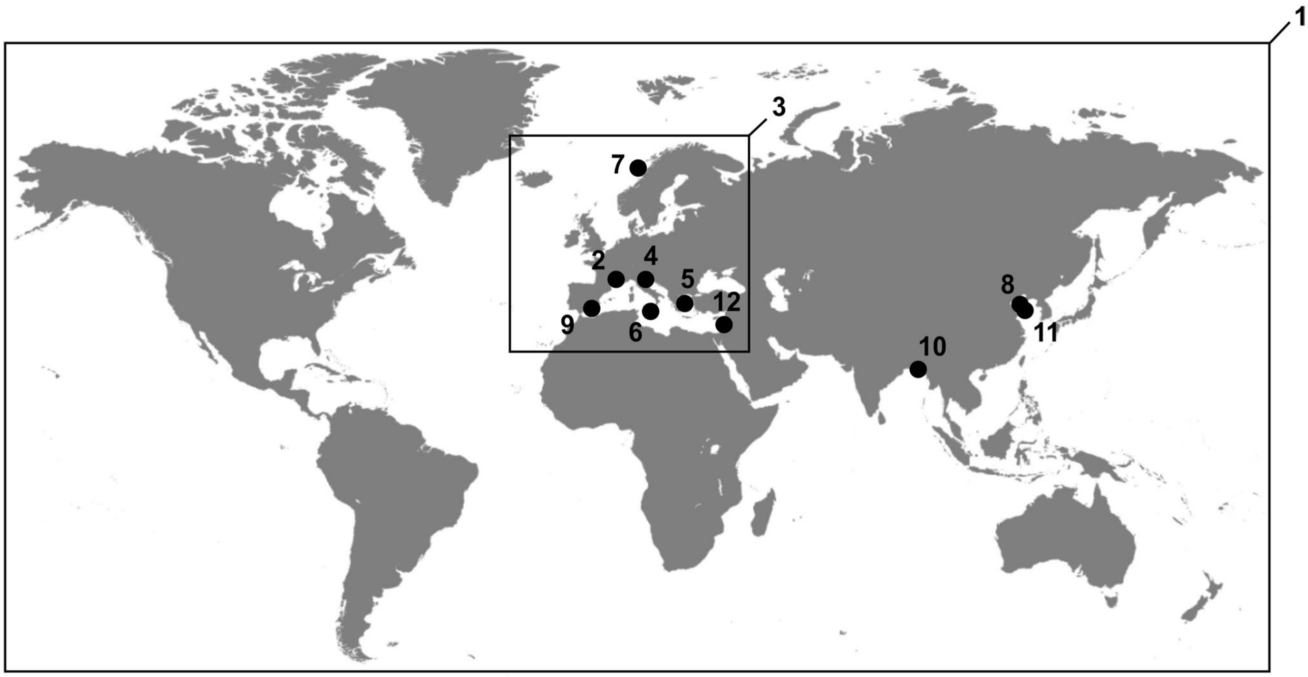

Fig. 1 Geographical location of the articles included in this special issue. 1. Bertoni et al.; 2. Pistre et al.; 3. Giustiniani et al.; 4. Corradin et al.; 5. Horozal et al.; 6. Chiacchieri et al.; 7. Ten Hietbrink et al.; 8. Lin et al.; 9. Sola et al.; 10. Rahman et al.; 11. Li et al.; 12. Stein et al.

of kilometres offshore, and hundreds of metres below the seabed.

The study of OFG requires the integration of interdisciplinary data, scattered across a range of government ministries and industry sources, as a dedicated and centralised hydrogeological offshore database does not currently exist. Building such an integrated database of geological, geophysical and geochemical datasets is fundamental for further studies to take place and to better characterise the heterogeneous aquifer systems and the physiochemical properties of their pore fluids. Micallef et al. (2021) initiated the development of a database compiling available literature and data on OFG. Building on this initial effort, a significantly expanded database has been compiled, which is presented in the technical note by **Giustiniani et al.** This database integrates extensive geological and geophysical datasets which are critical for quantitative assessments of the freshwater resources potential, with a focus on the European and neighbouring regions.

OFG exploration case studies

The three articles in this theme provide examples of OFG siliciclastic and karstic aquifers and the volumes of freshened groundwater they can host, illustrating that OFG can be present in a variety of geological settings.

Corradin et al. addresses the extent of the Venetian-Friulian Plain (northeastern Italy) aquifers into the offshore Northern Adriatic Shelf. They used 3D digital geological and stratigraphic modelling, constrained by onshore hydrogeological data, offshore seismic reflection data, and long-distance well ties to legacy oil and gas wells, allowing for a new conceptualisation as a complex layered artesian aquifer system in Middle to Late Pleistocene alluvial and marine sediments. The geometry of the offshore aquifer and aquitards shows significant lateral and vertical facies variability, driven by Quaternary glacio-eustatic fluctuations. Their findings confirm that the Northern Adriatic Shelf has significant potential to host widespread OFG aquifers.

Similarly, **Horozal et al.** depicts an OFG system stored in an alternation of sediments deposited during glacial and interglacial periods in the Gulf of Corinth (GOC) in Greece, an active continental rift. Interestingly, using a combination of borehole core physical properties, lithostratigraphy, 2D seismic reflection data and 2D hydrogeological modelling, the authors show that OFG's salinity variations occur independently of sediment porosity. Salinity is instead influenced by vertical diffusion of fluids across sediments deposited during multiple glacial-interglacial cycles. A 2D hydrogeological model of salinity changes over the past 800,000 years is proposed, showing that the deep basin's freshened water is a remnant from sea-level lowstands. This freshened groundwater in the gulf sediments is attributed to meteoric recharge during glacial periods, with an estimated total volume of up to 250 km^3 of OFG.

Chiacchieri et al. assesses the potential presence of fresh groundwater in the deep and offshore part of the Ragusa Oligo-Miocene Formation in southern Sicily, which hosts a karstic and fractured carbonate aquifer. The authors analysed an extensive database of deep oil and gas wells, both onshore and offshore, using petrophysical methods combined with hydrogeological data from onshore wells to produce an integrated regional model of the aquifer system. Their results show evidence of OFG extending deeper than previously known, onshore and continuing offshore up to 10 km from the coastline, with a preliminary estimate of approximately 3 km^3 of fresh groundwater preserved at depths between 500 and 1200 m below sea level. The results are of particular importance because the studied region is vulnerable to water scarcity caused by prolonged droughts, which are expected to amplify in the future.

OFG systems evolution through time

The three articles in this theme illustrate the importance of analysing the evolution of OFG systems both in terms of sediments and fluids. Coastal sedimentary aquifer facies depend on sea-level changes, and their depositional environment dictates whether pore water is fresh or saline. After deposition and during burial, the pore water composition continues to evolve in response to diffusion, and advection through migration pathways such as faults and fractures. Thus, the identification of the aquifer only, without considering its hydrological history, is not enough to assert the presence of freshwater in OFG systems.

Ten Hiebrink et al. presents, for the first time, a numerical simulation study showing the spatial and temporal evolution of offshore freshening and active SGD sites linked to subglacial emplacement of freshened groundwater, applied to the Norwegian Continental Margin. The authors demonstrate through groundwater flow modelling that on this margin, low salinity groundwater was predominantly emplaced vertically when the Fennoscandian ice sheet advanced onto the continental shelf, as opposed to lateral fresh groundwater flow from terrestrial recharge. There is a pronounced vertical variability in freshened groundwater because of the different response times of aquifers to glacial loading and unloading; thus, significant portions of this freshened groundwater can persist into subsequent interglacial or even glacial periods.

Lin et al. addresses the evolution of pore brines of the coastal aquitard of Laizhou Bay in China, using hydrogeochemical and isotope analyses of groundwater and sediments. Through the construction of high-precision vertical aquitard brine profiles, the authors established brine evolution processes. The research provides a reference method for studying groundwater quality evolution in low-lying coastal plains with offshore extension to support the sustainable exploitation of fresh groundwater and brine. Pore waters stored in Holocene and Late Pleistocene aquitards are shown to originate from paleo-seawater during the transgression and regression periods.

Trapped fossil waters in coastal aquifers were also investigated by **Sola et al.**, who address the relationship of salinity variation with paleo-coastline evolution in southeastern Spain, using hydrogeochemical depth profiles. Their results suggest that the shallower and fresher waters are associated with recent recharge, while the saline waters are composed of both recent and ancient recharge (up to 11 ka). The existence of fossil waters trapped in coastal aquifers is particularly important for understanding the evolution of the entire onshore–offshore aquifer system, and it is more widespread than previously thought. The findings align with other studies in the Mediterranean, including by **Corradin et al.**, which show that aquifers and aquitards alternate vertically in onshore–offshore sedimentary systems in response to past sea-level oscillations.

OFG and water resources management

The three articles in this theme provide examples of potential OFG utilization and management, and describe sustainability and environmental issues such as groundwater depletion and pollution. They propose methods for OFG monitoring and highlight the need for sustainable water abstraction in both coastal and offshore domains.

Rahman et al. describes an onshore–offshore deltaic groundwater system in Bangladesh, through examination of the groundwater chemistry of 101 wells spread across the coastal mainland and multiple islands located tens of kilometres offshore. Results reveal a relatively uniform hydrogeochemical composition of samples from the deep aquifer described as freshwater and suggesting offshore extension of the mainland aquifer. The authors conclude that the deep freshwater aquifers underlying the delta are more vulnerable to groundwater over-abstraction and potential saline water leakage from overlying brackish aquifers than to climate change-related sea-level rise and lateral saltwater intrusion. This identifies OFG and SGD as potential climate-resilient freshwater resources.

Li et al. illustrates a typical case of depletion and pollution of nearshore freshened groundwater coupled with onshore seawater intrusion in Laizhou Bay, China, caused by extensive nearshore groundwater abstraction. The authors integrated data from onshore and nearshore drilling, geophysical logging geological sampling, isotopic analysis, and long-term hydrological monitoring, describing the multilayered aquifer system as being buried 8–10 m below the seabed within Quaternary sediments extending several kilometres offshore. The findings underscore the urgent need for sustainable groundwater abstraction strategies to preserve coastal ecosystems and groundwater resources, while sustaining the economic activities of coastal areas.

Potential OFG utilization includes the use of brackish groundwater abstracted from shallow marine sediments, as an alternative to seawater desalination which involves chemical and biological treatment of seawater (Bakken et al. 2012). The disposal of brines produced during desalination, whether originating from seawater or OFG is of environmental concern if discharged to the nearshore environment due to high salinity and chemical treatment additives. **Stein et al.** explores re-injection of brines produced from seawater or OFG desalination plants in the saline groundwater portion of coastal aquifers, and its impact on seawater intrusion in onshore coastal aquifers. By using sand tank experiments involving electrical resistivity measurements, and numerical modelling of variable-density flow, they show that simultaneous pumping of saline groundwater and brine injection may be optimised to store brines in saline offshore aquifers without causing landward migration of the saline interface. Modelling further shows that the injected brines would sink to the bottom of the aquifer suggesting this type of disposal may be ecologically beneficial for many places where brine is discharged into the sea.

Conclusions

This special issue provides an overview of occurrence, potential, challenges and opportunities associated with OFG systems worldwide. The case studies capture some of the current efforts in characterising OFG spatial distribution, emplacement mechanisms and the geological and hydrological controls governing emplacement and preservation. OFG occurrences are documented across a broad range of geodynamic settings, including continental rifts, fold-and-thrust belts, and foreland basins, underscoring OFG aquifers structural and stratigraphic variability.

Collectively, these studies highlight the central role of sea-level fluctuations in driving meteoric recharge, aquifer freshening and reservoir development on continental margins. At the same time, they reveal the complex hydrogeological dynamics that regulate submarine fresh groundwater emplacement, control its compartmentalisation and permit its long-term preservation.

They demonstrate that a process-based understanding of offshore groundwater systems is essential for interpreting present-day freshwater distributions, and for constraining future solute fluxes to coastal oceans under scenarios of ongoing sea-level rise. The hydraulic and geochemical connectivity between offshore groundwater and adjacent coastal aquifers is further emphasized, providing quantitative frameworks for resource assessment, monitoring and mitigation of long-term depletion.

Methodologically, the variety of approaches represented, including geological, hydrogeological, groundwater monitoring, numerical modelling, borehole drilling, geophysical surveys, petrophysical methods, and hydrogeochemical analyses, advocates for the integration of interdisciplinary datasets, analyses and collaborations for better understanding and management of OFG. Overall, this special issue advances both conceptual models and applied methodologies, reinforcing the importance of incorporating sustainability principles into the evaluation and management of unconventional water resources.

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Declarations

Conflicts of interest The authors declare that they have no conflicts of interest.

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