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ESSAY

Offshore fresh (or freshened) groundwater: Research achievements and future perspectives

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Abstract

Offshore fresh or freshened groundwater (OFG) is an important but under-represented component of coastal hydrogeological and climate systems. Recent advances in geophysical imaging, offshore drilling, numerical modelling, and machine learning have improved understanding of OFG distribution, dynamics, and connectivity with onshore aquifers. Remaining challenges include volumetric quantification, recharge history, ecological implications, and governance. OFG may complement coastal water-resource portfolios, but sustainable utilisation requires integrated management, environmental safeguards, and updated legal frameworks at national and international levels.

Keywords Groundwater and society · Groundwater exploration · Transboundary aquifers · Offshore fresh and freshened groundwater · Geophysical methods

Introduction

Offshore fresh (or freshened) groundwater, i.e. OFG (Post et al. 2013; Micallef et al. 2021), is an important and overlooked component of hydrological and climate frameworks, and its quantification can help refine water-availability forecasts and support adaptation strategies in vulnerable coastal regions. The extent of OFG (Fig. 1), often reaching several kilometres beyond the coastline, indicates long-term storage of freshwater and variable connectivity with coastal aquifers (Arévalo-Martínez et al. 2023). These connections influence groundwater resilience to sea-level rise and salinisation, yet remain poorly constrained in current models. The question of whether the OFG component of the global water cycle should be considered in future climate-change models

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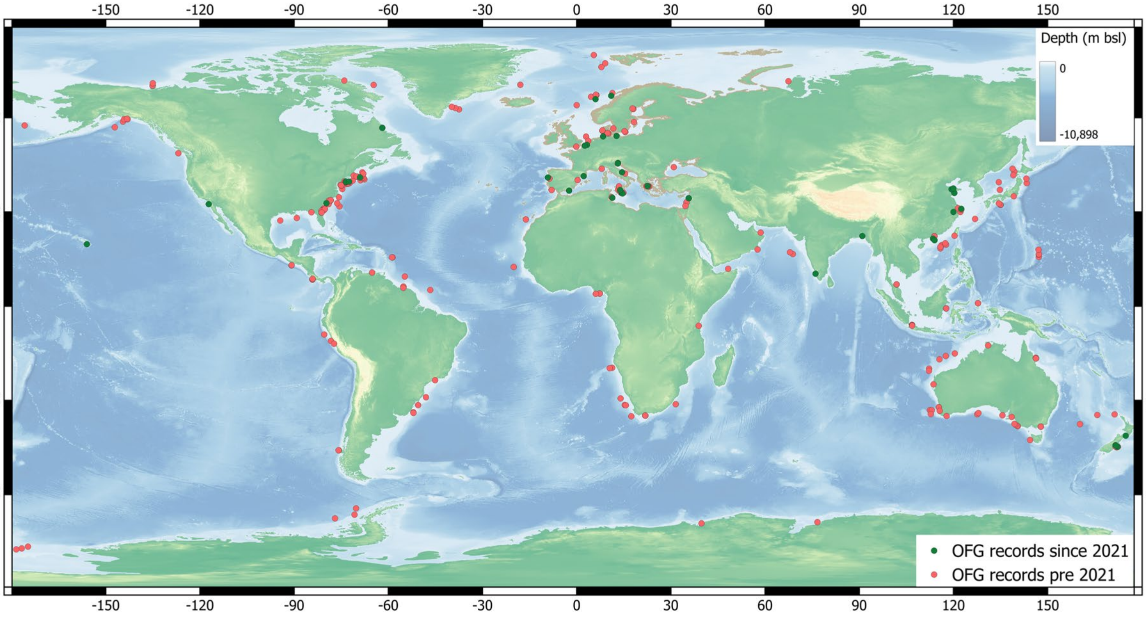

Fig. 1 Updated global map of OFG occurrences. Databases from: Post et al. (2013), Micallef et al. (2021), Giustiniani et al. (2025). Note the location of OFG studies that are part of this special issue (SI): Chiacchieri et al. (2025); Corradin et al. (2025); Horozal et al. (2025); Li et al. (2025); Lin et al. (2025); Rahman et al. (2025); Sola et al. (2025)

(e.g. Waliser et al. 2007; Roberts et al. 2018), together with the implications for projections of coastal hydrology, and the quantification of the associated feedback. Groundwater resilience to sea-level rise, droughts, and salinisation yet remain poorly constrained in current models.

OFG can also have a significant and dynamic correlation with seafloor geomorphology, primarily through sediment destabilisation and associated fluid discharge processes (Hoffmann et al. 2023; Micallef et al. 2023; Saadatkhah et al. 2023). It influences marine ecology by facilitating biogeochemical fluxes from land to sea through submarine groundwater discharge (SGD, Taniguchi et al. 2002), a process that provides substantial fluxes of nutrients and carbon to coastal waters at levels comparable to major rivers (Moore 2010; Santos et al. 2008).

Understanding these environmental interactions is critical not only from an Earth system science perspective, but also for assessing OFG's viability and sustainability as a freshwater resource for drought-affected and water-stressed coastal regions (Bakken et al. 2012; UN-Water 2020). A fundamental consideration in this assessment is whether OFG systems contain fossil groundwater, emplaced during past sea-level lowstands and effectively non-renewable, or are actively recharged by present-day SGD. Consequently, in parallel with scientific efforts to identify and quantify OFG resources, attention has increasingly turned to their economic feasibility (Bakken et al. 2012) and associated legal frameworks (Martin-Nagle 2020), as well as the potential impacts of OFG abstraction on onshore groundwater resources (Yu and Michael 2019). Beyond assessing utilization feasibility and direct impacts, these early evaluations offer a unique opportunity to establish foundational principles for the prospective development, management, and protection of this currently untapped resource, while also accounting for potential wider social and environmental impacts.

Nevertheless, comprehensive regional assessments of OFG remain uncommon, as they require either time-consuming, resource-intensive sub-seafloor data acquisition techniques or advanced integrated onshore-offshore 3D modelling. Lack of data leads to challenges in parameter selection in the models, which rarely include the required spatial complexity and the representation of long-term paleoenvironmental and paleoclimatic conditions. Recently, improvements in remote sensing technologies, subsea and subseafloor data acquisition tools and numerical methods have provided means to advance OFG investigations and shed light on the occurrence and extent of OFG. Emerging acquisition techniques now allow more efficient and cost-effective subsurface data collection. Simultaneously, the integration of multidisciplinary datasets and the adoption of advanced analytical approaches are substantially expanding our capacity to identify and characterize complex OFG systems. In this essay, we evaluate the current understanding of OFG in view of recent research, by highlighting unresolved questions and methodological challenges, and outlining emerging data acquisition and modelling methods, and research opportunities.

Timeline of OFG research

Although occurrences of deep, low-salinity or fresh groundwater within offshore sedimentary sequences have been noted earlier in unpublished oil & gas (O&G) well reports (Ruden 2007), the phenomenon only acquired scientific awareness following a drilling campaign along the U.S. continental margin (Kohout 1964; Hathaway et al. 1979). Terminology has varied considerably since its discovery (Table S1 of the electronic supplementary material (ESM)).

As interest in the subject expanded, the need for a unified and unambiguous term became apparent, leading to the adoption of the term OFG as “offshore fresh groundwater” (Post et al. 2013; Knight et al. 2018) or “offshore freshened groundwater” (Micallef et al. 2021). However, referring to these systems as “offshore” introduces an implicit spatial separation from onshore groundwater systems that does not necessarily exist from a hydrogeological perspective. In many settings, so-called offshore aquifers are directly connected to their onshore counterparts, forming a single groundwater system. Additionally, the use of the descriptor ‘freshened’ is often debated, as while it simply refers to salinity lower than ambient seawater (Micallef et al. 2021), for other authors the term suggests that groundwater was originally saline and it had been later diluted, in contrast with the widely accepted emplacement mechanisms of OFG as meteoric freshwater recharged during sea level lowstands.

Recently, in Europe, the COST Action CA21112 (OFF-SOURCE 2024) supported the creation of the first scientific network on OFG. The European Partnership Water-4All funded the RESCUE project (RESCUE 2026) to build knowledge on deep-coastal and offshore low-salinity aquifers in the Northern Adriatic and North Sea. On a global scale, the International Ocean Drilling Programme ($IODP^3$), and the National Science Foundation (NSF), with the European Consortium for Ocean Research Drilling (ECORD) as operator, implemented the first scientific drilling campaign dedicated entirely to OFG, Expedition 501 New England Shelf Hydrogeology ($IODP^3$, 2025), which successfully validated a large OFG system hypothesis off the New England Shelf. Finally, the JPI Oceans launched a Joint Action ‘Offshore Freshened Groundwater’ (JPI Oceans 2025) to explore this untapped potential across European marine basins.

Established and emerging scientific methods

Since the Micallef et al. (2021) comprehensive review on OFG, several methodological advances have substantially expanded OFG investigation capabilities. On the geophysical side, new marine controlled-source electromagnetic (CSEM) hardware and survey concepts, such as the low-cost, surface-towed system and novel onshore–offshore CSEM geometries, have broadened spatial coverage and reduced acquisition costs (Ishizu and Ogawa 2021; Pastoressa et al. 2023). Additionally, trans-dimensional Bayesian inversion of CSEM data now yields probabilistic resistivity and salinity estimates instead of single deterministic models (Faghih et al. 2024).

Increasingly, 3-D hydrogeological models can integrate high-resolution seismic and sequence-stratigraphic analyses, allowing for geologically representative variable-density flow simulations (Thomas et al. 2022; De Biase et al. 2023; Campo et al. 2024). In parallel, multi-borehole porewater and isotope datasets, especially in deltaic and shelf settings, are being tightly coupled to transient paleo-hydrogeological models (Sheng et al. 2023), while 3D and global numerical modelling efforts now explore OFG dynamics, sustainability, and geomorphic impacts under changing sea-level and climate boundary conditions (Yu et al. 2025; Gupta and Micallef 2025; Zamrsky et al. 2022).

Limited offshore drilling, sparse geophysical imaging, and incomplete integration of onshore–offshore hydrogeological data still hinder robust assessments. However, borehole archives and methods from O&G exploration are currently being repurposed to compensate for this deficit and support regional assessments of OFG occurrence (Lipparini et al. 2023). Oil and gas (O&G) borehole data can provide direct evidence of low-salinity groundwater, provided that uncertainty is appropriately quantified and logs are subjected to rigorous petrophysical reinterpretation for hydrogeological purposes (Quiroga et al. 2023). On the other hand, O&G geophysical data such as seismic reflection data can be mostly used to define the presence of suitable reservoirs for OFG (Bertoni et al. 2020).

The use of O&G data remains limited when such datasets have commercial value and are covered by confidentiality agreements, which is commonly the case. Notable exceptions are national open-access repositories maintained by governmental agencies, which publish information derived from regional O&G activities, such as UK, Italy, Norway, Australia and New Zealand’s national data repositories (e.g. NDR n.d.); VIDEPI repository n.d.).

Emerging methods that could also help address the current uncertainties include machine learning (ML), which offers multiple ways to enhance the characterisation of OFG by leveraging advances established in subsurface and groundwater sciences (Pourghasemi et al. 2020). A key application is in the analysis of legacy O&G data, as automated raster digitisation of legacy well logs, geological sections, and maps greatly accelerate the creation of large, standardised databases, reducing the labour-intensive manual work traditionally required (Katole et al. 2025). Additionally, methods including neural networks and unsupervised clustering have demonstrated strong performance in geological mapping (Cracknell and Reading 2014), offering transferable workflows for delineating offshore aquifers. In hydrogeology, supervised and unsupervised ML models have been widely applied to groundwater quality assessment, aquifer properties, vulnerability, recharge, and groundwater-level prediction (Adombi et al. 2021). The applications to OFG research have been so far much more limited (Haffert et al. 2024; Thomas et al. 2025). However, it is recognised that implementing ML techniques to determine OFG occurrences has the potential to overcome some of the constraints imposed by traditional methodological approaches. ML frameworks guided by domain expertise are better suited for use in OFG research to complement, rather than replace, process-based models by diagnosing structural mismatches and reducing uncertainty in predictions.

Impacts, economy and environment: Utilisation and challenges

Assessing OFG's resource potential requires evaluating its competitiveness relative to established alternatives such as desalination and conventional freshwater supplies. This requires analysing several key parameters, including the quality of the water, extraction and transport costs, environmental impacts, and treatment requirements. In an early assessment of extraction feasibility, Bakken et al. (2012) evaluated the technical requirements and constraints for offshore groundwater abstraction, transport, and treatment, concluding that OFG could serve as a viable drinking water source without significant technical, economic, or environmental impediments.

Potential adverse impacts associated with the utilisation of OFG include reduced availability of onshore groundwater and subsidence (Yu and Michael 2019), loss or contamination of submarine groundwater discharge affecting ecosystems (Varma and Michael 2012) and seawater intrusion in coastal aquifers (Post and Houben 2017). Additional concerns involve brine disposal, marine habitat disturbance and drilling-related pollution (Ghaffour et al. 2013).

In parallel to technical and environmental considerations, the broader sustainability and societal dimensions of OFG development must be assessed. Early stakeholder consultations by the OFF-SOURCE network highlighted widespread concern that OFG development could replicate past patterns of over-abstraction seen in many coastal aquifers, especially where institutional capacity is limited. A consistent message was that OFG should not be pursued as an isolated solution but recognised as a component of an integrated water resource management strategy, particularly where population growth as well as climatic variability and hydrological extremes are intensifying groundwater demand and reducing reliability of traditional sources.

An OFF-SOURCE report identified four potential utilisation scenarios for OFG: (a) direct use with minimal treatment for non-potable applications; (b) reverse osmosis treatment to meet full potable water standards; (c) strategic reserve accessed only during supply emergencies; and (d) offshore use without land transport to support marine industrial operations (OFF-SOURCE 2024). Stakeholder consultations emphasized that realizing these scenarios requires building synergies with existing offshore industries—including oil and gas, wind energy, and carbon storage—through shared infrastructure, coordinated economic models, and aligned regulatory frameworks.

Legal challenges and ownership

As scientific evidence of vast quantities of OFG grows and demand of freshwater for coastal areas increases, both sovereign states and private entities will begin to contemplate accessing OFG to supplement or even replace dwindling onshore reserves of freshwater. While solutions to the technical and financial hurdles are being explored, questions of ownership and governance on OFG resources will naturally arise.

As of 2025, 171 states have ratified (or acceded to) the United Nations (UN) Convention on the Law of the Sea (UNCLOS), meaning that the Convention offers a nearly universal framework for allocating sovereign rights over marine resources. Pursuant to UNCLOS, coastal States have full sovereignty over the Territorial Sea, extending up to twelve nautical miles from the low-tide line, including the water column, seabed, and subseafloor (Figure S1 of the ESM). Beyond the Territorial Sea and for two hundred miles from the low tide line, in an area called the Exclusive Economic Zone (EEZ), nations have exclusive sovereign rights to all natural resources. The Territorial Sea and the EEZ together are often called the continental shelf, although in some cases the continental shelf does not extend for the full length of the EEZ, and in other cases the continental shelf extends further than the EEZ, which gives the UNCLOS Member State additional rights. Since deposits of OFG will be located within the continental shelf, the right of a coastal nation to explore and exploit the freshened water lying exclusively within its marine territory will not be disputed, and nations will establish their own laws and regulations regarding exploration, extraction, transport, and use of the resource.

However, natural resources do not respect political boundaries, and some deposits of OFG will straddle the continental shelf of one or more nations. Since UNCLOS provides no guidance on transboundary seabed resources, nations will seek guidance when crafting a framework for ownership and governance. OFG is similar to O&G on the marine subsoil, in that the deposits are contained but fluid, so reference to offshore O&G arrangements would be logical. In addition, multiple treaties exist to allocate rights and responsibilities for transboundary offshore resources, especially valuable reserves of O&G, so those agreements could serve as precedents. The most common method of allocating costs and benefits of finding and extracting offshore O&G is known as a joint development agreement (JDA), wherein nations agree in advance to share the costs and revenues of offshore reserves in accordance with the proportional share of the reserve that each of them is assumed to hold. For efficiency and to reduce costs, the parties also agree to appoint one entity to represent them both in the exploration and development activities.

In addition to questions regarding ownership of OFG, nations will also have to consider the environmental impacts of OFG development, such as the effects of operational noise, pollution, and sediment disruption on marine species as well as the potential for seafloor subsidence. The environmental concerns can become more complicated when the impacts are transboundary. Certain global treaties, such as the Conventional on Biological Diversity and the Espoo Convention, may apply, and OFG development will also have to conform to domestic environmental laws and regulations that address marine activities and freshwater quality and distribution.

Within the European context, a key water legislation is the Water Framework Directive (WFD), which establishes a framework for the protection and sustainable management of surface waters and groundwater. When implemented in conjunction with international water treaties and domestic laws, the WFD can serve as a legally binding instrument to prevent water deterioration and preserve groundwater dependent ecosystems. However, the current definition of groundwater in (Article 2, para 2) of the WFD, “water below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil” raises interpretative questions. The wording ‘direct contact with the ground or subsoil’ may be understood as excluding ‘fossil’ groundwater that is disconnected from the land surface. Aquifer is further defined as “subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater" (Article 2, para 11). It then follows that deep aquifers that are not used for groundwater abstraction need not be identified as groundwater bodies. Moreover, it remains unclear whether the terms “subsoil” or “the ground” encompass the seabed and its subsoil, thereby creating uncertainty for the regulation of offshore fresh groundwater.

Furthermore, the Marine Strategy Framework Directive should be revised to ensure that changes in SGD quality and discharge volumes resulting from OFG utilisation are incorporated as pressures that may affect the achievement of good environmental status. Additionally, marine spatial planning (MSP), which is part of the Integrated Maritime Policy of the EU, also lacks mention of OFG. Bringing this topic early into MSP is essential to both give a planning aspect to OFG utilisation, and safeguard other activities from potential OFG utilisation risks. Thus, coastal nations contemplating development of OFG would be wise to plan how to address these various governance and environmental issues.

Summary

The science of OFG has significantly advanced in the last decades, thanks to improvement in research tools, data acquisition and processing, and modelling techniques. However, a series of questions are still open, mainly related to OFG recharge mechanisms, total volumes, connectivity with onshore coastal aquifers, its response to sea-level and climate variability and its influence on marine ecosystems.

Sustained action to consolidate data from various sectors and facilitate collaborative research, knowledge exchange, and policy formulation, are needed to ensure a harmonised approach to OFG research, and to its management and utilisation worldwide.

Continued development of integrated geological and geophysical methods and 3D numerical modelling is needed to provide more robust spatial and volumetric analysis of OFG systems. This can be facilitated by testing theory-guided ML frameworks. ML–enabled database generation (such as from raster digitisation of O&G legacy well data) has also the potential to offer a practical means of mitigating the chronic data scarcity that hampers OFG research.

In terms of utilisation, while some factors, such as transport logistics and local infrastructure, are geographically specific, others, like basic resource availability and treatment technologies, have broader applicability across various regions. OFG should be recognised as one component of an integrated onshore-offshore coastal water-resources strategy—particularly where population growth as well as extreme hydroclimatic variability is intensifying groundwater demand and reducing reliability of traditional sources. This will depend on both global and local factors.

Finally, coastal nations contemplating development of OFG should plan how to address the various governance and environmental issues, drawing from existing offshore resources treaties and regulations. At the European level, the WFD should be modified to cover deep groundwater, which is disconnected from surface systems, both on land and offshore, while the Marine Strategy Framework Directive should be revised to incorporate changes in SGD quality and discharge volumes resulting from OFG utilisation.

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Declarations

Competing interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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