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TECHNICAL NOTE

A geological and geophysical database for the assessment of offshore freshened groundwater resources

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Abstract

Fresh groundwater resources in coastal regions are vital for modern society, but are under considerable pressure due to population growth, seasonal peaks in demand, pollution and climate change. In recent years, interest in offshore freshened groundwater (OFG) has surged, as potential resource for addressing these challenges. Recent studies have documented OFG occurrences on many continental margins and islands, with global volume estimates ranging between 10^5-10^6 km^3. However, these global estimates rely on simplified assumptions regarding aquifer geometry and properties, as they only are intended to give an idea of the scale of these resources. Focused studies on specific coastal regions are required to evaluate the distribution of these resources locally. However, these studies are often hampered by the technical challenge and high cost of acquiring and processing data in marine regions. Thus, the understanding of aquifers, including their occurrence, volumes, and their geological and hydrological properties, remains limited. In this context, this study aims to develop a comprehensive, open access database that integrates existing geophysical, geological, and geochemical datasets to enhance OFG characterisation and modelling capabilities in the Euro-Mediterranean region. Moreover, this database aims to support hydrological studies on offshore aquifers and coastal hydrology, and help modelling of groundwater flow from recharge areas. The remaining challenges regarding data accessibility and resolution are then discussed, underscoring the need for further interdisciplinary research and data sharing to ensure the sustainable management of this valuable resource.

Keywords Offshore freshened groundwater · Database · Water-resources management · Coastal aquifers · Euro-Mediterranean margins

Introduction

Fresh groundwater resources in coastal regions are crucial for modern society, yet they are under immense pressure due to factors such as population growth, seasonal peaks in demand, pollution and/or climate change (Ferguson and Gleeson 2012; Nowroozi et al. 1999; Vengosh et al. 1999; Werner et al. 2013; Weinthal et al. 2005). In Europe, the last years of extended drought have left several Atlantic and circum-Mediterranean coastal regions with protracted water shortages (Toreti et al. 2024).

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Recent research indicates that previously unexplored offshore aquifers can host large amounts of fresh or low salinity water (OFG), which is potentially exploitable for human consumption, farming and industrial uses, especially in times of increased demand in coastal regions (Micallef et al. 2021; Zamrsky et al. 2022; Bertoni et al. 2020). However, the extent of these resources, and the sustainability of their use in the Euro-Mediterranean region and globally, is currently unknown.

The occurrence of OFG has been documented in many continental margins and off some islands (e.g., Lofi et al. 2013; Sheng et al. 2023; Micallef et al. 2020; Gustafson et al. 2019; Attias et al. 2020). It is estimated the global volume of OFG is between 10^5 and 10^6 km^3 (e.g., Adkins et al. 2002; Cohen et al. 2010; Micallef et al. 2021; Post et al. 2013). These estimates are useful for understanding the scale of global resources. However, they cannot

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document their actual distribution, as they rely on simplified models that do not reflect the heterogeneity commonly observed in aquifer geometry and in properties such as hydraulic conductivity and porosity in continental margins worldwide (Micallef et al. 2021).

To provide the Euro-Mediterranean regions with tools for the evaluation of OFG, it is necessary to develop a targeted database with a focus on regions with proven water scarcity, to support the assessment of this potential resource, and the monitoring of coastal aquifers.

The identification of OFG is complex and relies on the integration of different geophysical, geological, and geochemical datasets (e.g., Hermans et al. 2023; Sheng et al. 2024). New marine data acquisition campaigns for OFG research are often challenging and expensive. Therefore, it is fundamental to collect all currently available data, including past offshore exploration efforts (e.g., hydrocarbons industry), which have collected valuable data applicable to OFG studies (Quiroga et al. 2023; Lipparini et al. 2023).

Recent efforts to collect data, by combining existing databases and reviews have been undertaken by the OFF-SOURCE COST Action (CA21112), a scientific network established to assess the potential of OFG as an unconventional water source in coastal regions of the COST Member Countries.

This compilation of a Euro-Mediterranean database of OFG represents one of the main tasks of OFF-SOURCE and is based upon previous global databases. The global overview of OFG by Post et al. (2013) outlined the known characteristics of 33 selected sites scattered over the world's margins, defining standard criteria for record and location comparison. An update of the latter work was presented as an expanded global database of OFG, gathering data from 305 occurrences and expanding the list of properties characterising the systems (Micallef et al. 2021). The selection criteria considered locations at or above one kilometer from the coast and at least a 10-kilometre distance between records.

Building up on the previous compilations, a multidisciplinary team has gathered information from public repositories, industry sources and recent OFG research with the aim to develop a comprehensive database of OFG systems on the margins of European and other Mediterranean countries. This paper presents the preliminary results of this effort, detailing the multidisciplinary criteria defined to structure the database according to main classes of indicators and current outputs available. In line with a full open-access policy, the data are stored in an open GIS resource, ensuring public availability. The ultimate aim of this database is to provide a solid foundation for advancing hydrogeological studies on OFG, with a specific focus on European coastal regions and continental margins and to contribute to the development of an integrated data analysis approach for this region.

Database scope and structure

Objectives of the database

The OFF-SOURCE database used the open access data from Micallef et al. (2021) as the basis for the initial location listing and table attributes. A database workshop was organised to bring action members together for a wide-ranging, multidisciplinary discussion on the data types and their format required to achieve the research objectives. As such, geographical, geological, geophysical and hydrogeological information were primarily taken into consideration. No constraints were applied to geographical information, such as distance between data features or a maximum number of elements, as the aim was to achieve the highest possible data density. This approach maximizes the integration of all possible evidence in a basin or margin to allow the best possible constraint of the spatial extent of OFG bodies. This aspect is particularly relevant for achieving spatial delimitation of areas of interest, to go beyond the current point data format, and consequently for the modelling tasks of the OFF-SOURCE Action that require constrained 3D geological and hydrological models.

Definitions of data sources

The database consists of two geopackages, which represent an open, standards-based, platform-independent and compact format for storing geodata. This format can contain multiple layers of vector features, raster data, and non-spatial attributes. The developed geopackages contain four main data sources: borehole data, electromagnetic (EM) data, onshore indicators, and submarine and coastal springs. The two geopackages are described as follows:

1) Indirect measurements containing:
2) Electromagnetic data encompass all survey types detecting indications of OFG bodies. The general term EM broadly covers controlled source electromagnetic (CSEM) surveys as well as other related techniques utilized for such analyses. Within the EM category, data are organized into two subclasses: a general data subclass, representing point locations identified from literature and reports without precise survey paths, and a line subclass, documenting clearly defined EM survey 2D and 3D grids.
3) Onshore indicators refer to observations of onshore hydrological systems that provide clues of their offshore extent. Post et al (2013) included in this type of indicator radiocarbon dating of water, favourable geological conditions extending from onshore to offshore, particularly

where seaward dipping formations extend towards the shelf, and hydrogeological modelling to assess how the system extension far beyond the shoreline.

4) Direct measurements containing:
5) Submarine and coastal springs are indicators of freshened groundwater seepage at coastal and transitional domains predominantly characterized by saltwater occurrence. Coastal springs refer to locations on the coast, some of which may only be directly accessible during low tide periods. Submarine springs account for cases of freshwater seepage from the seabed toward the water column and can occur hundreds to thousands of metres away from the shoreline.
6) Borehole data comprises information retrieved from any type of borehole subsurface sampling that includes information relevant for the characterization of OFG bodies. This classification includes all types of core retrieval methods, from shallow sediment sampling near the seafloor to deeper drilling boreholes. The borehole information analysed includes sedimentology, geochemistry and petrophysical logs. The sources of well data were varied, but a major benefit was indeed the public availability of borehole data from the offshore exploration industry, particularly from the oil and gas industry, which is no longer in moratorium. In addition, access to proprietary well data was granted for specific projects with the authorisation of the data owners.

Data parameters

A number of parameters were discussed for inclusion in the database. Table 1 lists these parameters with a brief description of each. As previously mentioned, the list contains the main parameters needed to achieve the objectives of the OFF-SOURCE working groups. However, considerations were made for an expanded or thematic parameters list (e.g., water chemistry or biological indicators) as this resource evolves.

Key spatial information includes site and expedition names, data sources and types, acquisition year, the number of data points recorded, and geographic coordinates (in the WGS84 coordinate system). Additionally, the dataset provides information on the depths of the top and base of the aquifer, aquifer thickness, geological boundaries, the number of identified bodies, and details on geological formations and their ages. The database also contains information on the mechanisms responsible for the emplacement of OFG, which may include: 1) Meteoric recharge: active meteoric recharge due to an existing connection between onshore and offshore aquifers; 2) Paleo-recharge: recharge occuring primarily during glacial periods, when sea level was lower changing the hydraulic gradients; 3) Diagenesis: post-sedimentary alteration of minerals (e.g., silica, gypsum, clays) releasing freshwater into the sediments; 4) Gas hydrate decomposition: During the decomposition of gas hydrates, crystalline solids made of water and gas formed in the pore spaces of marine sediments, freshwater is released into the sediments, as no salt ions are included in their formation. In many cases, the presence of OFG results from a combination of these emplacement mechanisms. A block of information relates to hydrogeological properties, such as permeability, porosity, and water salinity. It also includes the specific storage (Ss), which is calculated based on the relationship between storativity and aquifer thickness (Freeze and Cherry 1979). Another important parameter is the probability of the presence of OFG (PROBABILITY), based on the available data. This qualitative parameter is categorized into four classes:

(1) Proven by direct measurement (e.g., sampling, borehole measurements);
(2) Highly probable (e.g., geophysical inversion);
(3) probable (e.g., geophysical data), and
(4) Low probability (e.g., seismic data interpretation).

If no information is available, it means that no evaluation has been carried out. Finally, the database includes metadata related to the data sources, including references, contact information, and, where available, additional contextual information.

Data contribution, sharing and dissemination

A call for data contribution was issued to the COST Action members to aid the compilation of information. The task was arranged such that each member would gather information from their country, an aspect of relevance since national public data repositories tend to be in their native languages. Data were also obtained from the results of action-supported short-term scientific missions (STSMs) that addressed different research objectives, including producing or compiling database-specific information. Regardless of the type of data source, the collected information followed the parameter list shown in Table 1.

The complete data listing was subsequently divided into the types of data sources established for the database. As one of the main objectives of creating the database is to understand the spatial distribution of OFG resources, point, line or polygon shapefiles of individual data source types were created to act as the main shareable resources. The shared data is stored in the open repository provided by the open science framework (OSF) under the OFF-SOURCE project (Giustiniani et al. 2023). This repository compiles all the OFF-SOURCE open access outputs and deliverables

Table 1 list of parameters included in the database

GIS database field	Description
SITE	Data source name, e.g. original expedition name
DATA_SOURCE	Data source/type
SGD_TY	Submarine groundwater discharge type
SGD_GEN_TY	Genesis of the submarine groundwater discharge
NUM_REC	Number of data points
YEAR	Acquisition year
EXPEDITION	Name of the expedition or project
LARGE_DSET	Data source part of a larger dataset (e.g. multiple drillings during the same expedition)
HOLE_D	Depth of the borehole (m)
Y	y coordinates in WGS84, e.g. "35.36"
X	x coordinates in WGS84, e.g. "35.36"
Z	Elevation (m below sea level)
MARGIN_TY	Continental margin type
SF_DEPTH	Seafloor depth (m)
OFFRE_DCE	OFG distance to shore (km from coastline)
OFGcloSHRE	OFG closest distance to shore (km from coastline)
OFFfarSHRE	OFG farthest distance to shore (km from coastline)
OFGtopSS	Depth of top of OFG (m below sea level)
TOPgeoBOUR	Geological boundary on the top of the aquifer
OFGbotSS	Depth of base of OFG (m below sea level)
BOTgeoBOUR	Geological boundary on the bottom of the aquifer
OFGtopSSF	Sub-seafloor depth of top of OFG (m)
TOPgeoBOUR	Geological boundary on the top
OFGbotSSF	Sub-seafloor depth of base of OFG (m)
THICKNESS	Thickness of the aquifer (m)
N_BODIES	Number of bodies
GEO_AQUIF	Geology of aquifer
AGE_AQUIF	Age of the aquifer
FORM_NAME	Formation name
DEP_ENV	Depositional environment
EMP_MECHS	Emplacement mechanism
POROSITY	Porosity (%) of the aquifer formation
EFF_PORSITY	Effective porosity (%) of the aquifer formation
MIN_SAL	Minimum salinity (g/l)
TOPaqSALg	Top of aquifer salinity gradient (g/m)
BOTaqSALg	Bottom of aquifer salinity gradient (g/m)
FLOW_RATE	Flow rate (m/s)
Ss	Specific storage coefficient of the aquifer formation (m^{-1})
PROBABILITY	Probability of OFG presence
REFERENCE	Reference
DATA_PROVI	Affiliation
DATA_CONT	Email address
NAME	Contact person
COMMENTS	Any additional information about the data

produced by the working groups. As a complement to the data product dissemination, a WebGIS version of the OFF-SOURCE database is available for consultation at (OFF-SOURCE Database 2025a, b). The database can also be accessed through the NextGIS plugin for QGIS, allowing higher versatility of basemaps and addition of other data. Moreover, there data can be consulted through a dedicated WMS/WFS geoserver (OFF-SOURCE Database 2025a, b,

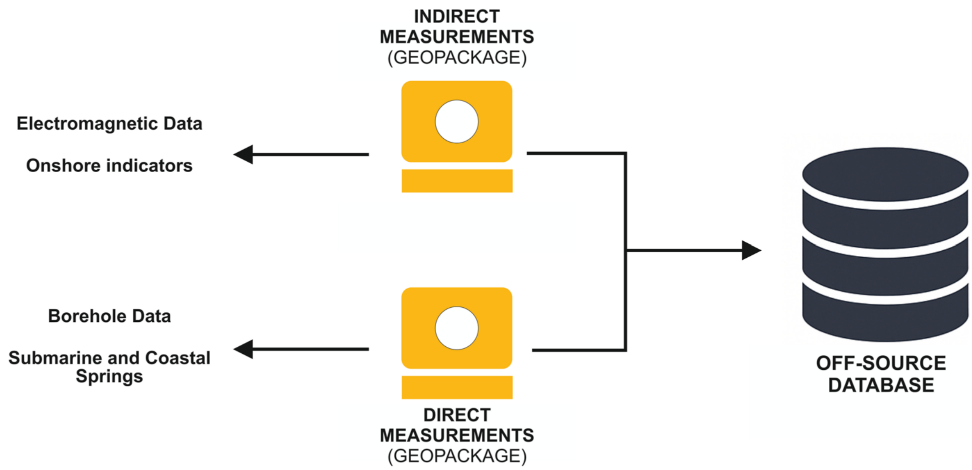

Fig. 1 Conceptual diagram of the database

WMS/WFS). In Fig. 1, a conceptual diagram of the database showing its structure is presented.

Utility and limitations of the OFG Database

The OFF-SOURCE database represents ongoing efforts to create a robust support data framework for the use of industrial, governmental, and academic entities. One of its key advantages is the integration of multiple sources, as exemplified in Fig. 2. The combination of borehole, geophysical and field-based observations enhances the robustness for the assessment of offshore groundwater. On a broader scope, the research conducted to assess offshore aquifers, and their onshore connectivity, has direct applications on coastal hydrological processes such as saltwater intrusion into coastal aquifers or pollutant transport from onshore to offshore areas (Arévalo-Martínez et al. 2023). Data integration allows an enhanced spatial coverage: geophysical data and submarine discharge indicators help fill gaps where borehole data are limited, improving interpretations at a regional scale.

An integrated database also supports process-based studies by enabling the investigation of groundwater flow mechanisms, salinity gradients and potential offshore freshwater reserves. A fundamental aspect is the applicability of the data for hydrological models that will be able to provide crucial information about the spatial distribution and evolution of OFG reservoirs.

Public accessibility is also a key feature of this dataset. By making it openly available, the dataset provides an opportunity to foster collaboration and drive innovation in offshore hydrogeology and resource management. Providing access to industry and government institutions creates opportunities for reciprocal data and knowledge exchange, helping to advance the field of OFG resources. Additionally, open access enables contributions from a broad range of users, including those working with national datasets in their native languages. This strengthens the dataset's value as a truly international community effort.

While the OFF-SOURCE database enhances data accessibility and fosters collaborative research in offshore hydrogeology, several limitations must be acknowledged. Integrating data from different sources, collected with different resolutions and even in different decades, presents challenges. Data with different resolutions may not allow straightforward integration of different datasets. Data collection standards also differ, as they are often constrained by the specific goals for which the data were acquired for. The most direct example is provided by the exploration boreholes, as their usually deeper targets mean that the OFG-relevant intervals were routinely bypassed. The issues with data gaps and uneven coverage are still a major concern, as often mentioned in this work. The contrast between areas that have a higher density of available observations with others that are poorly covered, or not covered at all, affects the reliability of the mapping of these resources. The latter means that additional hydrogeological studies are required to verify the occurrence and sustainability of the exploitation of this resource, namely the impacts on water quality and available volume through time. Furthermore, the absence of standardized acquisition protocols prevents rigorous verification of data quality and precludes any systematic assessment of uncertainty. As a result, users must approach the database critically, fully aware of the potential inconsistencies and limitations embedded in the integrated sources. An key limitation concerns non-public datasets, which are often inaccessible due to licensing restrictions, institutional agreements, or paid access. While their spatial location could be included to guide future research, restricted access prevents full integration into the OFF-SOURCE database, limiting its completeness, transparency, and reproducibility of the database, particularly in regions with sparse publicly available data. These challenges highlight the need for long-term efforts to promote open data policies and develop collaborative frameworks that enhance

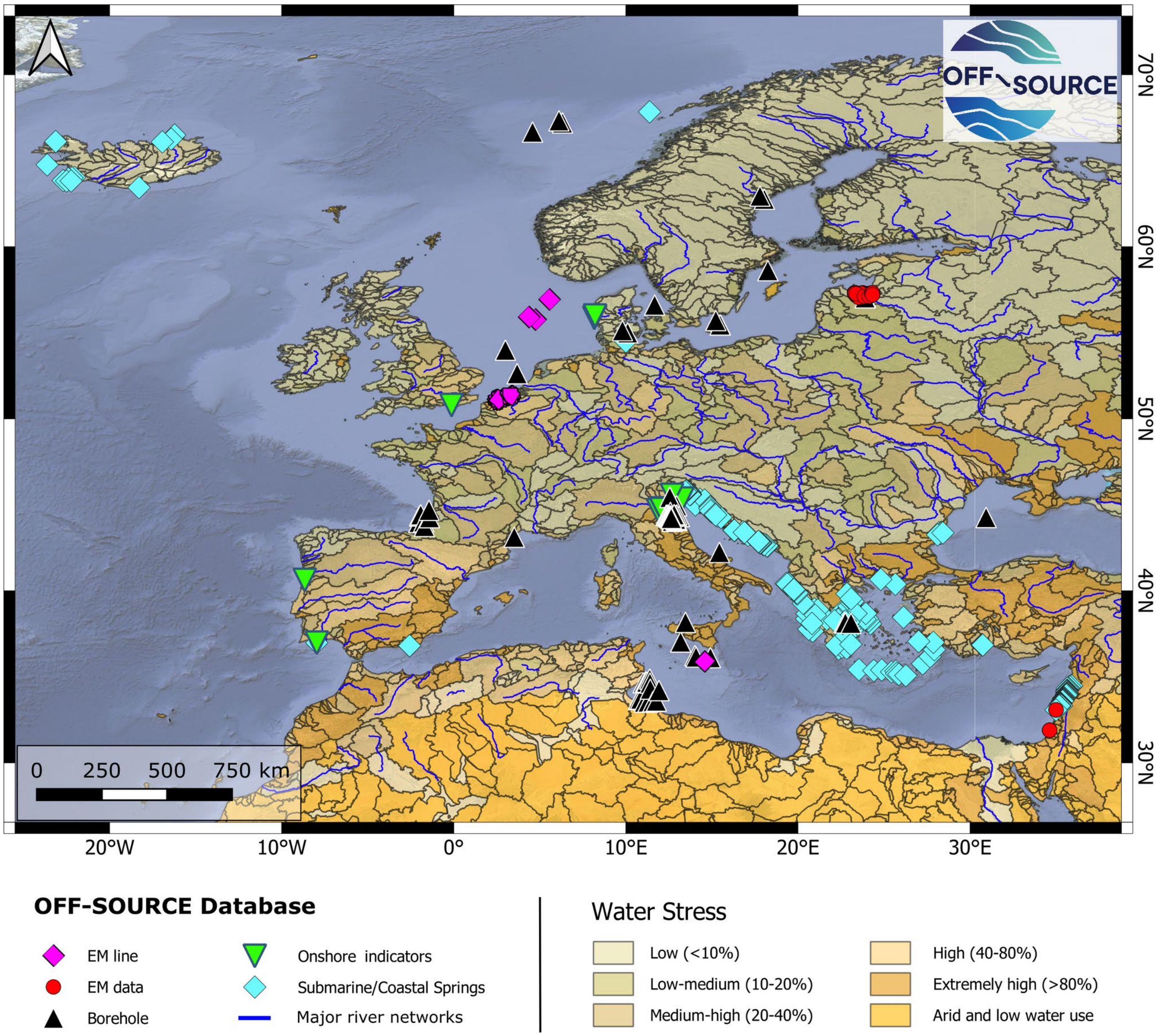

Fig. 2 Map depicting the data type and spatial coverage included in the OFF-SOURCES database

data reliability, accessibility, and equitable use within the offshore hydrogeological research community. However, in some cases, the locations of these restricted datasets can be included to at least provide spatial references that can guide further research or facilitate future data access through institutional agreements. Despite this partial inclusion, restricted access still poses challenges for transparency, reproducibility, and equitable use, especially for researchers or stakeholders with limited resources. Overcoming these limitations will require long-term efforts toward more open data policies and collaborative frameworks that balance accessibility, data ownership, and confidentiality.

Examples of the database applicability

Figure 2 summarises the main classes of data included in the compilation, displayed alongside the major river networks and water stress estimations for the region of interest. The water stress is defined as the ratio of total water withdrawal relative to the available renewable water and groundwater resources (Hofste et al. 2019). The estimation of available renewable water considers the effects of upstream consumption and major dams on downstream water levels. Higher values indicate more intense competition for water resources (Hofste et al.

2019). Aligning with the previously mentioned limitations, the coverage of collected data is not uniform, a pattern clearly depicted by the borehole and coastal springs classes. Borehole data are largely available in regions with a history of past and present hydrocarbon exploration such as, Italy, France, the North Sea, and offshore Tunisia. Only boreholes where OFG-relevant salinity levels were detected are displayed, hence the limited number shown (Fig. 2), but hundreds or thousands of now undisclosed borehole information sets are available in public repositories that can be evaluated for the occurrence of low salinity offshore aquifers. A high-level initial assessment that can be made using boreholes is the comparison of the depth of the OFG aquifer's top and the recorded salinity (Fig. 3). Focusing only on recorded salinity values below 34 g/l, promising locations occur in northern Europe, Italy and Tunisia, although the latter two show the OFG aquifers at greater depths. This database further helps identify specific areas of interest, with the northern Adriatic Sea emerging as a particularly promising region from an OFG perspective. Borehole data from the public Videpi database (ViDEPI project 2009) proved especially useful for locating OFG-related information. In particular, the area south of the Po Delta, Italy, shows considerable potential, where multiple subseafloor aquifers with salinity levels below 25 g/l were

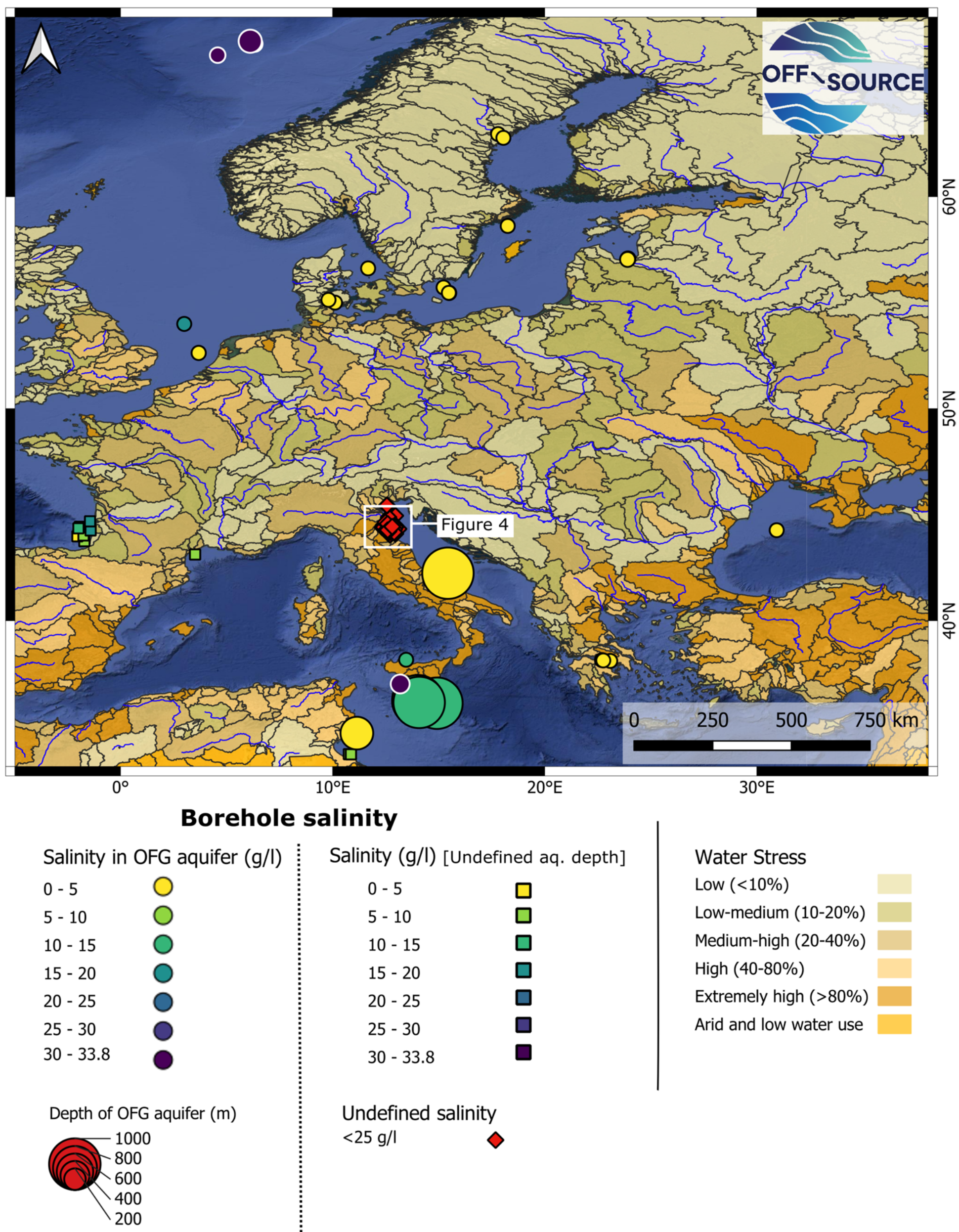

Fig. 3 Map depicting the salinity and depth to the top of the OFG aquifer (aq.) recorded in the database boreholes

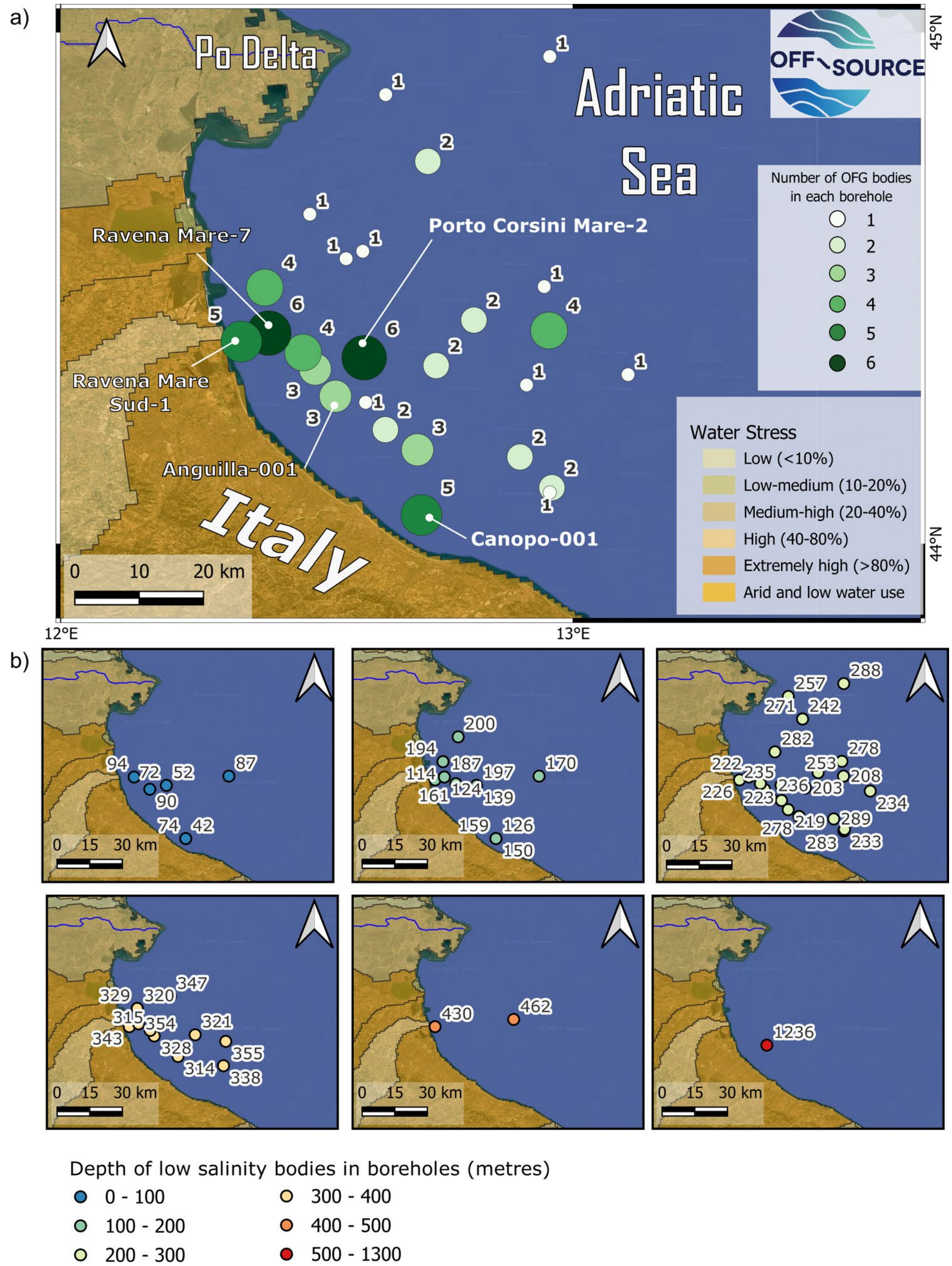

Fig. 4 Boreholes from the Adriatic Sea where aquifer bodies with salinity below 25 g/l were identified. a) Number of low salinity bodies identified per borehole. b) Panels showing the top depth of the low salinity bodies, per 100 m intervals, indicate a predominance between 150 and 350 m below sea floor. The deepest low salinity occurrence was observed in borehole Aguilla 001, at 1236 m

identified (Fig. 4). Up to six layers with a salinity of less than 25 g/l were found in various wells within distances up to 25 km from the shore. The shallowest low salinity aquifer was encountered in borehole Canopo 001, where an aquifer with salinity below 1 g/l lies just 42 m beneath the seabed (Fig. 4b). The deepest one was found in borehole Anguilla 001, at approximately 1236 m below the seabed, with salinity levels ranging between 1 and 25 g/l. These latter values also highlight a limitation of the open data: due to the lack of standardized reporting protocols, salinity is often expressed in ranges or as qualitative estimates (e.g., "greater than 1 g/l"). These resources are hosted in Pleistocene sediments, suggesting a formation mechanism linked to glacial–interglacial cycles (e.g., Campo et al. 2024). Moreover, the occurrence of deeper freshwater beneath saline aquifers onshore suggests a possible hydraulic connection between onshore and offshore aquifers.

Numerous coastal springs have been identified along the stretch from the Gulf of Trieste (NE Italy) to Greece (Fig. 2), typically associated with the presence of carbonate lithologies and karst morphologies outcropping along these coastlines (e.g., Savonitto et al. 2023). Another notable cluster of coastal springs can be found along the Israeli coast (Fig. 2).

In contrast, other regions—such as southern Iberia—show sparse observations, which may reflect either less favorable geological conditions for spring formation or simply a lack of available data and systematic sampling.

Offshore from the Maltese Islands, OFGs have been identified in Oligo-Miocene carbonates (Haroon et al. 2021). Low salinity layers have been recognised by the CSEM data acquired offshore Malta, which revealed anomalous resistivity values in low permeability layers that could indicate OFG occurrence. Despite the effectiveness of CSEM in identifying OFG, such surveys remain limited in number for these objectives (Fig. 2) (e.g., Haroon et al. 2021; De Biase et al. 2023).

The Gulf of Gabes in South-Eastern Tunisia is another promising area. Three aquifer systems have been identified in the region, the most extensive of which is composed of siliciclastic material sealed by impervious marl and clay (e.g., Bachtouli et al. 2023). Borehole data from Kerkenah Island and adjacent offshore areas suggest the occurrence of a low-salinity aquifer (~2 g/l), suggesting a hydraulic connection between island, onshore, and offshore groundwater systems at depths of approximately 300 meters below the seafloor. Further southeast, near Djerba Island, a similar onshore–offshore connection is observed within Serravallian-Tortonian siliciclastic formations.

The North Sea is a region with extremely high potential for OFG resources. The two entries recorded on the OFF-SOURCE database (Fig. 3) were initially presented on the compilation by Post et al (2013), but the hundreds of unstudied exploration boreholes from this prolific hydrocarbon basin hold valuable data for OFG assessment. To complement this, the intense development of wind farms in the North Sea and Northern Europe brought a new interest to the shallow subsurface investigation with direct applicability for OFG. Building on legacy data, new ultra-high resolution 2D and 3D seismic surveys are unravelling in high detail the buried stratigraphic units created during the latest glaciations (e.g., Van Cappelle et al. 2024). Such information is highly valuable to map glacial tunnel valleys and other clastic deposits prone to constitute aquifers charged with glacial fresh melt water.

Future work

The updating of this dataset is expected to continue beyond the duration of the OFF-SOURCE project, as part of a long-term effort to build a comprehensive resource for OFG research. To support this goal, the development of a dedicated web-based interface is being explored, which would allow users to upload new data entries. This platform would be supported by artificial intelligence (AI) tools to help with data formatting, validation and integration, and to ensure consistency with existing database standards. Such an approach will not only promote community-driven expansion of the dataset but also ensure the reliability and homogeneity of contributed data. Furthermore, starting from this database, a combination of AI based-methods and numerical modelling could be considered to predict missing data in data-scarce regions (e.g., Oude Essink et al. 2024).

Closing remarks

In summary, the OFF-SOURCE COST Action and its associated outputs, including the presented database, mark a significant advancement in the field of offshore hydrogeology. This multidisciplinary database is a comprehensive and evolving resource for the study of OFG, integrating multiple data types that contribute to a better understanding of subsurface hydrological processes. The availability of such a dataset improves the ability to analyse and model offshore hydrogeological systems, and supports research on groundwater dynamics, subsurface fluid migration and potential freshwater reserves in marine environments. In addition, it supports both fundamental research and practical applications in water resource management and environmental sustainability, with particular importance for water-stressed coastal regions. Contributions in the form of publications, reports, data, and local knowledge to further expand the scope and impact of the OFF-SOURCE database would be desirable.

Community-sourced observations, especially those not captured in the scientific literature, are particularly valuable for enhancing understanding of OFG occurrences. Starting from a Euro-Mediterranean focus, the goal is to grow this initiative into a global resource that captures the full extent of known OFG occurrences worldwide.

In conclusion, the OFF-SOURCE database will continue to be upgraded beyond the project's duration, aiming to become a robust, open resource for OFG research. A web-based interface supported by AI tools is being considered to enable user data uploads with quality control. This will foster community-driven growth while ensuring data consistency. AI and modelling approaches will also be explored to predict missing data in data-scarce regions.

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Availability of data and material The shared data is stored in the open repository provided by the Open Science Framework (OSF) under the OFF-SOURCE project. In addition, a WebGIS version of the OFF-SOURCE database is available for consultation at https://off-source.nextgis.com. WMS/WFS dedicated geoserver allows the consultation of it (https://geoserver.icm.csic.es/geoserver/ogs/wms?version=1.1.0&layers=ogs; http://geoserver.icm.csic.es/geoserver/ogs/ows?version=1.0.0&typeName=ogs)

Declarations

Conflict of interest None.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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