Hydrogeology Journal
https://doi.org/10.1007/s10040-024-02810-1

PAPER

Carbonate rocks and karst water resources in the Mediterranean region

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Received: 10 October 2023 / Accepted: 3 July 2024
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Abstract

Carbonate rocks in the Mediterranean region form karst landscapes with a variety of morphological and hydrological features, and are of particular interest from a water management perspective as they represent major karst aquifers. The Mediterranean Karst Aquifer Map and Database (MEDKAM) provides a 1:5,000,000 scale map showing the distribution of carbonate and evaporite rocks that can host karst groundwater resources, with additional information on other hydrogeological settings, selected terrestrial and submarine karst springs, caves and karst groundwater-dependent ecosystems. A statistical evaluation shows that carbonate rocks cover ~39.5% of the Mediterranean region within a 250-km focus area from the coastline. North Africa has the largest continuous area of carbonate rocks, while smaller countries in the Middle East and the Dinarides have the largest proportion of carbonate rocks in relation to their total area. Carbonate rocks are also widespread in coastal areas, occurring along ~33.6% (14,000 km) of the total Mediterranean coastline, including large islands such as Crete and Mallorca, and ~25.9% (6,400 km) of the continental coastline. Two additional maps display (1) groundwater recharge, showing a climatic gradient from north to south, and (2) groundwater storage trends, indicating a mean annual karst groundwater loss from 2003 to 2020 of 436 million m^3 in the 250-km area. This study quantifies the carbonate rocks in the Mediterranean region and shows their importance for groundwater resources. MEDKAM will serve as a basis for further research and improved international cooperation in karst groundwater management.

Keywords Hydrogeological mapping · Carbonate rocks · Karst groundwater resources · Groundwater recharge · Mediterranean region

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Introduction

Carbonate rocks form karst aquifers that serve as important freshwater resources for humans and ecosystems, but pose an ongoing challenge for research and management due to their unique hydraulic properties (Goldscheider and Drew 2007; Stevanović 2019). Recent evaluations by Chen et al. (2017) indicate that exposed karstifiable carbonate rocks cover 21.6% of the European land surface; however, the total area of carbonate rock occurrence is much larger, as it also includes nonexposed carbonate rocks confined by younger formations. The exposed karst surfaces correspond to the main recharge zones of karst aquifers, which are often hydraulically connected over large areas and across national boundaries (Hartmann et al. 2014). Karst aquifers are often the source of large springs (Bonacci et al. 2023; Fan et al. 2023; Stevanović and Milanović 2023) and have unique underground cave systems, both of which host diverse ecosystems (Siegel et al. 2023). Karst landscapes serve as recreational areas, and many karst features are classified as World Heritage Sites (Goldscheider 2019; Gunn 2021). Furthermore, carbonate rocks serve as important industrial raw material, host oil and gas reservoirs, contain commercial ore bodies, and provide information about the Earth's evolution through biological, chemical, mineralogical, and isotopic signatures (Mackenzie 1978), and are part of the global carbon cycle (Hartmann et al. 2009).

Carbonate rocks are a group of sedimentary rocks composed of carbonate minerals. Typical examples are limestone, composed of calcite ($CaCO_3$), and dolomite (or dolostone), composed of dolomite [$CaMg(CO_3)_2$] (note that the term "dolomite" is used both for the mineral and the rock). The metamorphism of limestone and dolomite leads to the formation of marble, which has a nearly identical mineralogical and geochemical composition as the parent rock but with larger crystals and less intergranular porosity (Goldscheider and Drew 2007). The peculiarity of carbonate rock is related to its strong solubility, which occurs mainly along fractures and bedding planes due to the flow of (ground)water with CO_2 from the atmosphere and soil. This karstification occurs mainly in the shallow phreatic zone and is a self-reinforcing process leading to the formation of a network of channels (Ford and Williams 2007; Bakalowicz 2005) that are embedded in and interact with a rock matrix that is less karstified. Karst aquifers are characterised by a high degree of hydraulic anisotropy (higher conductivity in the direction of the channels than perpendicular to them), heterogeneity (higher porosity and permeability in the channels than in the matrix) and temporal variability in water availability (variable water level, storage volume and spring discharge) and water quality (Ravbar 2013; Stevanović 2015). Managing karst aquifers is, therefore, challenging.

The distribution of karstifiable rocks is well documented in many countries and regions; however, on a continental scale, there are only a few approaches that show the distribution of carbonate rocks. The global distribution of karst formations was first shown by Ford and Williams (1989), revised by Williams and Ford (2006) and further used in Ford and Williams (2007), albeit highly generalized. More recently, the World Karst Aquifer Mapping Project (WOKAM) has prepared a much more detailed map and database that is available in digital and printed form at scales of 1:25,000,000 and 1:40,000,000 (Chen et al. 2017; Goldscheider et al. 2020); however, the inconsistent database at the supra-regional level is the difficulty of such a large-scale map development. In recent decades, large-scale continuous maps of geologic, lithologic, and water resource information have also been developed, although the degree of accuracy generally decreases with the size of the area under consideration. The Global Lithologic Map (GLiM), for example, provides lithological information translated from existing regional geologic maps and literature; however, the merging of different datasets often involves uncertainties and regional differences (Hartmann and Moosdorf 2012). In order to better harmonize such differences, the International Hydrogeological Map of Europe (IHME1500) has been developed since the 1960s under the auspices of the International Association of Hydrogeologists (IAH) and with the support of the Commission on the Geological Map of the World (CGMW). In 2002, the Worldwide Hydrogeological Mapping and Assessment Programme (WHYMAP) was launched by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the German Federal Institute for Geosciences and Natural Resources (BGR) to map invisible subsurface water resources (Richts et al. 2011). In this context, various maps have been developed that provide global information on groundwater resources, groundwater vulnerability to flood and drought events (Richts and Vrba 2016), and there is also the already mentioned WOKAM (Chen et al. 2017).

The objective of this study is to provide a compendium of the developed Mediterranean Karst Aquifer Map and database (MEDKAM; Xanke et al. 2022), based on the International Hydrogeological Map of Europe (IHME1500). The mapping approach follows WOKAM. MEDKAM was developed at a digital scale of 1:1,500,000 and printed at a scale of 1:5,000,000, providing more detailed, more accurate and new information on the following:

- Quantification of the spatial distribution of different karstifiable rocks in the Mediterranean countries and

other basic information on other aquifer types depending on their formation and aquifer properties.
- Quantification of the distribution of coastal karst in the Mediterranean region and the bordering states.
- Terrestrial and submarine karst springs and information on their range of discharge as well as karst caves and their spatial extent.
- Distribution of the long-term mean karst groundwater recharge as well as the trends in karst groundwater storage.

MEDKAM is a contribution to the World-wide Hydrogeological Mapping Programme (WHYMAP) of the UNESCO Intergovernmental Hydrological Programme (IHP) and is available for download as a digital version at the product center of German Federal Institute for Geosciences and Natural Resources (BGR; Xanke et al. 2022).

Geographical setting

The evolution of the Mediterranean karst landscape is closely linked to geotectonic processes since the late Mesozoic (Duggen et al. 2003; Cavazza and Wezel 2003), with today's landscape strongly impacted by the collision of Eurasia and Africa since the late Cretaceous that created several mountain belts stretching from North Africa and the Iberian Peninsula across Europe, the Balkan region and the Caucasus to the Middle East. These characteristic landscapes are further shaped by local climatic conditions—for example, higher precipitation rates at higher elevations combined with the tectonically highly deformed carbonates. This leads to stronger karstification (development of, e.g. sinkholes, karren, dolines) than in the lower elevations with a predominantly dry climate and only slightly tectonically stressed terrain (hilly terrain with deep dry valleys). A partial drying of the Mediterranean Sea during the late Miocene (Messinian salinity crisis), 6–5 million years ago (Jolivet et al. 2006; Roveri et al. 2014), and subsequent water level changes in the following millions of years until today, have led to deep karstification at various levels, especially in the coastal area. As a result, some of the karst systems emerge at the current sea level, while some are also found inland above, or below, which then emerge as submarine springs near the coast (Bakalowicz 2018).

A clear delineation of the Mediterranean region is difficult because all common classifications—such as climatic (Koeppen 1936; Peel et al. 2007) or Mediterranean vegetation cover use (Olson et al. 2001) or geographically by surface catchments or bordering states—include some shortage in coverage. In each of these classifications, certain areas, often near the coast, are not included (e.g. large parts of Northern Africa when using the climatic classification approach), while areas far from the Mediterranean Sea are included (e.g. the entire basin of the Nile when using the hydrologic basin approach); also, in these cases, only surface characteristics are decisive for the delineation. In the case of the hydrogeological consideration of the Mediterranean area and in particular of the karstifiable rocks, a focus area of ~250 km around the Mediterranean Sea is suggested by Siegel et al. (2023), which on one hand includes the most important karst landscapes along the coast, considers narrow countries like Italy as a whole and includes the Mediterranean area of the aforementioned criteria. However, the decisive factor for this type of delineation is that it includes the unique deep karstification caused by the Messinian salinity crisis, which has partly reached far into the inland around the Mediterranean Sea (Audra et al. 2004; Fleury et al. 2007; Bakalowicz 2014).

The focus of the map development of Xanke et al. (2022) and the extension of the karst feature database for karst springs and caves was on the entire Mediterranean region, including countries within the extent of the printed MEDKAM (Fig. 1). The creation of the database on karst

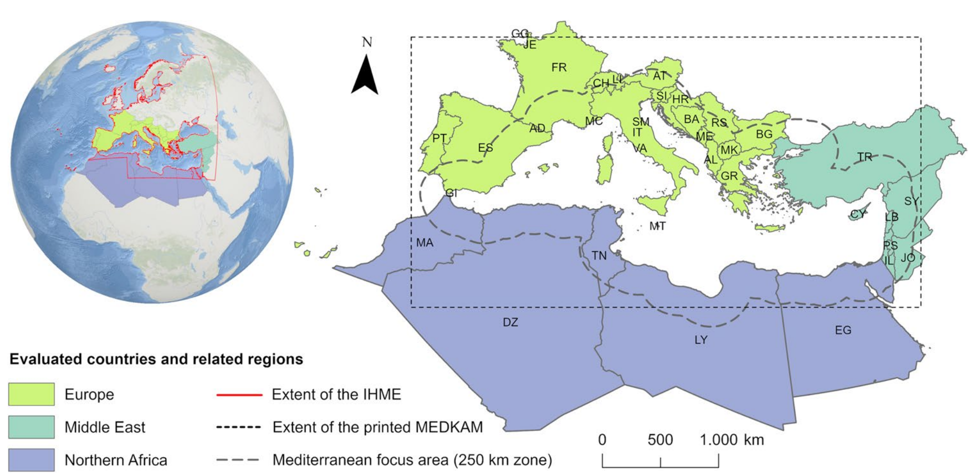

Fig. 1 Location of the Mediterranean region, which includes all colored regions/countries and the Mediterranean focus zone (250 km), extension of the printed MEDKAM and the regions and countries of Europe, North Africa and the Middle East evaluated in this study

groundwater-dependent ecosystems (Siegel et al. 2023) was on the 250 km focus area around the coastline (Fig. 1).

The statistical evaluation of karst distribution in this manuscript is done for (1) the whole Mediterranean region (which includes all colored regions/countries as shown in Fig. 1), (2) the main geographical areas of Europe, Middle East and North Africa, (3) each individual country that lies to a significant extent within the 250 km focus area, as well as Portugal, which is often considered to be part of the Mediterranean region , and (4) the Mediterranean focus area (250 km zone). Countries that were not included in the statistical analysis due to their small size (<250 km^2) but are located in the study area are Monaco (MC), San Marino (SM), and the Vatican City State (VA).

Materials and methods

Map of karstifiable rocks and other aquifer types

Basic mapping approach and legend

The basis for the MEDKAM is the International Hydrogeological Map of Europe (IHME1500), which consists of 30 hydrogeological map sheets (five of which are unpublished) covering almost the entire European continent and parts of the Middle East (BGR and UNESCO 2019; Günther and Duscher 2019; Duscher et al. 2015) and has recently been extended by four additional map sheets to the North African region (unpublished). The development of the IHME map series began in the 1960s under the auspices of the International Association of Hydrogeologists (IAH) and with the support of the Commission on the Geological Map of the World (CGMW). The scientific editing, cartography, printing and publication of the map sheets and explanatory notes were directed and financially supported by the German Federal Institute for Geosciences and Natural Resources (BGR) and the United Nations Educational, Scientific and Cultural Organization (UNESCO). The map has been available since 2013 in printed form and as a vector dataset in Shapefile format for geographic information system (GIS) visualization and data processing (Duscher et al. 2015). The hydrogeological content is based on contributions from the respective mapped countries, coordinated on a transnational basis. The attributes of the IHME contain different levels of lithological description that allow the assignment of the formations to the MEDKAM units. To fill in the missing parts in North Africa and the Arabian Peninsula, complete the Mediterranean mapping region and enable statistical calculation of the entire countries, the digital version of the British Geological Survey's quantitative maps of African groundwater resources (MacDonald et al. 2012) and the United States Geological Survey's bedrock geology of the Arabian Peninsula (Pollastro 1998) were used. They have been carefully analyzed with regard to the MEDKAM lithology and have undergone the same review process as the IHME; however, for further use of MEDKAM, only the IHME-based shapefile is available for download (see section "Map availability").

The proposed map provides information on the distribution of carbonate rocks and evaporites in the Mediterranean and in other hydrogeological settings; however, the term "karstifiable rocks" mainly refers to carbonate rocks and evaporites, which consist of easily soluble minerals and are major karst aquifers. In the following, carbonate rocks are, therefore, referred to as karst aquifers. Carbonate rocks generally consist of more than 75% carbonate minerals (Ford and Williams 2007), although this is usually not indicated in geological and lithological maps and must be derived from general nomenclature. In the case of IHME, this nomenclature and categorization is given and is, therefore, regarded as a reliable basis—for example, limestone, dolomite or chalk are considered to be relatively pure carbonate rocks, as defined above. However, a mixture with or an alternation between sedimentary and carbonate rocks is often found in the description and requires classification by regional experts or derivation from literature and more detailed regional maps. In this assessment, it is assumed that the exposed carbonate rocks are karstified to some extent, without specifying the extent. Therefore, a lithological classification was developed following the World Karst Aquifer Mapping Project (Chen et al. 2017) and the geological units were grouped into four hydrogeologically meaningful units:

1. Karst aquifers in sedimentary and metamorphic carbonate rocks
2. Karst aquifers in evaporite rocks
3. Various hydrogeological settings in other sedimentary and volcanic formations (karst aquifers are possibly present at depth)
4. Local, poor and shallow aquifers in other metamorphic rocks and igneous rocks (no karst aquifers present at depth)

The improvement over WOKAM is that it is no longer necessary to distinguish between areas with continuous and discontinuous carbonate (or evaporite) rocks because the more detailed scale of IHME (1:1,500,000) enables a more precise delineation of the carbonate (and evaporite) rock areas. The unit "various hydrogeological settings in other sedimentary and volcanic rocks" includes a wide variety of geological formations with different hydraulic properties, but also indicates the possible presence of confined karst aquifers at greater depth. "Local, poor and shallow aquifers in other metamorphic and igneous rocks" are grouped into one unit. As crystalline rocks generally form the geologic basement, karst aquifers are usually not present at depth in these regions. This improvement allows a more detailed statistical analysis of the distribution of karst aquifers in the Mediterranean and an indication of areas where karst aquifers may be present at depth, covered by other formations.

Similar to WOKAM, the map unit “Karst aquifers in sedimentary and metamorphic carbonate rocks” includes sedimentary limestones, dolomites and chalks, which are mostly biochemical sediments, as well as limestones and dolomites that have undergone some degree of metamorphism, e.g. into marble or limestone shale. Since it is very difficult to distinguish between sedimentary diagenesis and metamorphism, these rock types are combined into a single unit as they are usually referenced by their content of carbonate minerals (>75%; Ford and Williams 2007), although this information is not usually detailed on maps or in publications (nor in the IHME), it is a common approach to rock mapping and characterization. The “Karst aquifers in evaporite rocks” mapping unit, by definition, includes chemical sedimentary rocks that consist mainly of highly soluble minerals such as gypsum, anhydrite or halite. These types of rocks typically form in basins where arid climates cause the water to become supersaturated, resulting in the precipitation of these minerals. The unit of “various hydrogeological settings in other sedimentary and volcanic formations” is probably the largest group and includes unconsolidated sediments of various compositions, including alluvial fans, sandy and gravelly sequences as well as silty and clayey low-conductivity layers. Also included here is the group of consolidated sedimentary rocks such as shale or sandstone. All of these sedimentary and volcanic rocks can be deposited over karst formations. “Local, poor, and shallow aquifers in other metamorphic and igneous rocks” are the most clearly defined. These formations generally do not include carbonate rocks and are usually dominated by low hydraulic conductivity and, hence, low aquifer productivity.

The approach to identifying the nonexposed carbonate rocks is the same as in Chen et al. (2017). Data on covered rock formation are typically poor and must, therefore, be inferred from the extent of individual geosystems (USGS 2021; Pawlewicz et al. 2002; Persits et al. 1997; Pollastro et al. 1999) or other data sources. If karst aquifers are exposed within such a delineated geosystem and are adjacent to sedimentary rocks, it is reasonable to assume that the karst is dipping beneath them. However, the focus here was on large continuous karst areas and not on small-scale sequences of subdivided rock formations as occurs, for example, in mountain ranges due to the strong thrusting and folding. Information on nonexposed carbonate rocks is important because they may contain significant karst groundwater bodies, which are often present in confined conditions.

Reclassification, evaluation and iterative improvement of the map

For the reclassification of the lithological units from the IHME to the MEDKAM classification, first, an assignment to the rock groups in the attribute table was made. If the assignment was not conclusive, the more detailed lithological descriptions in the IHME were used as a reference. In a second step, official regional karst and lithological maps were used for comparison with the IHME and, if necessary, further adjustments were made by reclassification. However, the reference maps sometimes have a different scale and, therefore, differ in the topology of the individual geological polygons, and in this case, do not always match the polygons of the IHME. In some regions, a compromise had to be made between accurate selection of individual polygons and consistent classification of karst areas over a larger area, often resulting in generalization from continuous small karst outcrops. As noted previously, the greatest difficulty is in assigning lithological descriptions of sequences of carbonate rocks and sedimentary formations to either unit—for example, marlstone and sandstone intercalations have been assigned to sedimentary formations in many areas. However, when additional carbonate intercalations are described and regional maps also indicate carbonate rocks, an assignment to the karst aquifer unit has been made.

In some regions, the various rock descriptions of the IHME are not very precise. In particular, the alternation of limestone, sand, marl or claystone is difficult to classify as pure karst because of the lack of information on the proportions of each type of rock. For this reason, an attempt has been made to make a classification based on existing geological and lithological maps and descriptions, as well as on regional experts. Nevertheless, it cannot be excluded that, especially in the case of the mixed rock sequences, the assignment could have been made to another hydrogeological unit—for example, shale is by definition a sedimentary rock, but often undergoes some degree of metamorphism (e.g. slate) and could also be classified as a metamorphic rock. In this study, however, slates are classified as sedimentary rocks. The combination “slates, quarzites, sandstones, shales” is assigned to sedimentary rocks, while the combination “slates, phyllites, mica schists and graywackes of various metamorphic degrees, partly gneissic” is assigned to metamorphic rocks. Since these descriptions are not always precisely distinguishable, by adapting them to regional lithological maps, it is possible that areas with the same IHME classification are assigned to a different MEDKAM unit.

Database on karst springs, caves and groundwater-dependent ecosystems

The database collects and standardizes existing relevant information related to karst aquifers. In particular, the data on karst springs and caves established in the WOKAM project (Chen et al. 2017) are extended and insufficient data from countries and are being improved and completed. Another new development is the inclusion of selected karst groundwater-dependent ecosystems (KGDE) compiled by Siegel et al. (2023). Due to the large amount of data and the larger scale of MEDKAM, it is possible to show different types of karst features such as the distinction between continental and submarine springs and different types of KGDEs. The supplementary data are based on literature research and data provided by regional experts. In this study, only a selection of the karst features collected for MEDKAM and stored in the database is presented. The criteria used to select the karst features shown in this paper are location within the Mediterranean area (250-km zone), regional importance such as spring flow, or length of cave. Consideration has also been given to consistent documentation of large regions; therefore, a few smaller springs or caves are also shown. It should be noted that the number of karst features, springs, caves, KGDEs stored in the MEDKAM database is only a selection of the actual number of existing features. In many countries, sufficient data sets are not publicly available, or if they are, they are not of sufficient accuracy and quality.

Karst springs are documented with their low-flow and high-flow discharge values, which represent the range of reported discharge data, but are not necessarily the minimum and maximum values. Where only one value was available, it was assigned to the appropriate category (low or high); in some cases, only the mean discharge was available. Special attention is given to coastal and submarine springs. Karst caves are documented with their depth and length where this information was available. A new and important aspect of MEDKAM is the karst groundwater-dependent ecosystems, which provide an indication of the state of water quality. Although these ecosystems are only briefly mentioned, they play an important role locally, often providing habitat for rare species and plants. A multidisciplinary characterization of selected KDGEs is documented by Siegel et al. (2023).

Assessment of karst groundwater recharge

An existing karst-specific simulation model (VarKarst-R; Hartmann et al. 2020) was used to determine the 30-year average (1990–2019) of groundwater recharge in the MEDKAM region, at a spatial resolution of 0.25° and using global climate data products as input (precipitation, temperature: GLDAS, Rodell et al. 2004; potential evapotranspiration: GLEAM, Martens et al. 2017). For the MEDKAM region, the recharge map from Hartman et al. (2020) was resolved at a higher spatial resolution and interpolated to include previously unmapped areas. This was done for simplification and presentation reasons and is, therefore, subject to some uncertainty in ~18% of the area, especially in the Middle East and North Africa. From the distribution of mean annual karst groundwater recharge, a country-specific average was calculated.

Assessment of trends in karst groundwater storage

The study of trends in karst groundwater storage was based on the work of Xanke and Liesch (2022). They investigated the extent of changes in groundwater storage (GWS) over the period 2003–2020 for the Euro-Mediterranean region using the latest data from the Gravity Recovery and Climate Experiment (GRACE/GRACE-FO; Save et al. 2016; Save 2020) satellite mission and recently reanalyzed ERA5 land climate data from the European Centre for Medium-Range Weather Forecasts (Hersbach et al. 2020). For this study, these trends in groundwater storage were masked by the MEDKAM carbonate outcrops. It should be emphasized that the GRACE data are based on an accuracy of 0.5°. The values should, therefore, always be considered as a product of their environment and only apply to the entire vertical groundwater column. Overlapping aquifers and catchments are, therefore, included in the signal and, therefore, do not apply exclusively to the karst, but are projected onto it. From the distribution of mean annual trends in karst groundwater storage, a country-specific average was calculated.

Results

Distribution of carbonate and evaporite rocks

The analysis of the spatial distribution of the different hydrogeological units (Fig. 2) shows that 26.1% of the whole Mediterranean region is covered by carbonate rocks corresponding to more than 3.2 million km^2, and only 0.9% consists of exposed evaporite rocks (Table 1; Fig. 3). Much more prevalent are the various hydrogeological settings in other sedimentary and volcanic formations, covering 64.2% of the total Mediterranean region. Local poor and shallow aquifers in other metamorphic and igneous rocks are much less prevalent and account for 8.8%, much of which is found in European countries.

Within the Mediterranean focus area, 39.5% is covered by carbonate rocks and 1.7% by evaporite rocks. This shows

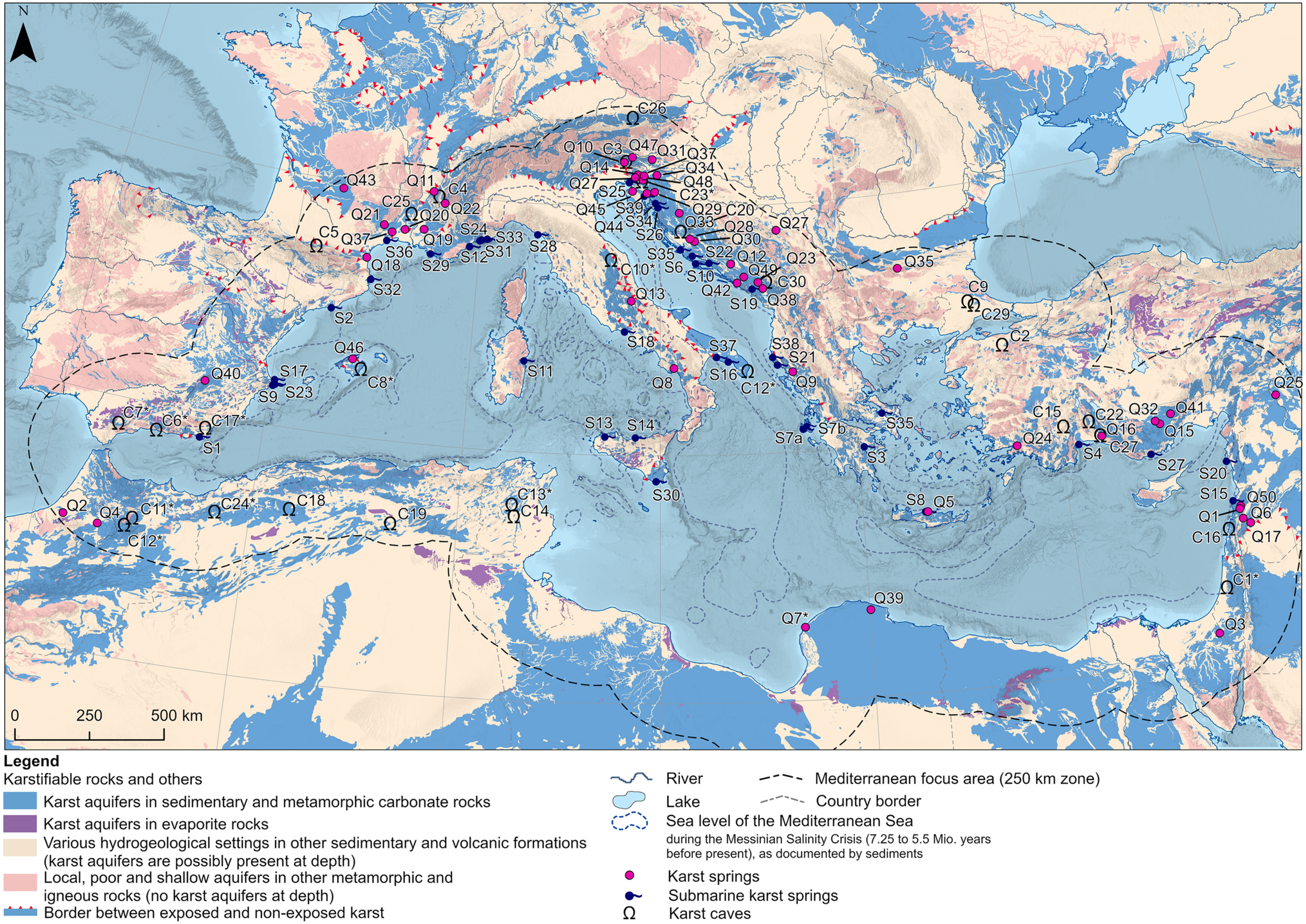

Fig. 2 The Mediterranean Karst Aquifer Map (MEDKAM) with references to other hydrogeological settings, as well as information on the borders between exposed and non-exposed karst, and a selection of karst springs (see table in section "Karst springs"), submarine springs (see table in section "Submarine karst springs") and caves (see table in section "Karst caves"). An indication of the level of karstification around the Mediterranean basin is given by the Mediterranean Sea level during the Messinian salinity crisis and the almost drying up of the sea (Xanke et al. 2022). The map was created for the entirety of the countries for which this section of the figure provides only partial coverage (e.g. countries of North Africa and the Middle East)

Table 1 Size of the hydrogeological settings and their percentages in the main geographical regions and in the corresponding whole Mediterranean region as well as in the Mediterranean focus area (250 km zone). Information on the size of the countries in this study is taken from the International Hydrogeological Map of Europe (IHME1500)

Geographical area	Total area[a]	Karst aquifers in sedimentary and metamorphic carbonate rocks		Karst aquifers in evaporite rocks		Various hydrogeological settings in other sedimentary and volcanic formations		Local, poor and shallow aquifers in other metamorphic and igneous rocks	
	1,000 km^2	1,000 km^2	%	1,000 km^2	%	1,000 km^2	%	1,000 km^2	%
Europe	2,019	521	25.8	23	1.1	1,075	53.2	400	19.9
Middle East	1,108	338	30.5	28	2.5	634	57.2	108	9.8
North Africa	5,537	1,400	25.3	25	0.5	3,860	69.7	252	4.5
Mediterranean region	8,664	2,259	26.1	76	0.9	5,569	64.2	761	8.8
Mediterranean focus area (250-km zone)	3,123	1,233	39.5	52	1.7	1,541	49.3	297	9.5

[a]Water surfaces of lakes not included

that groundwater resources in karst areas are quite significant in the Mediterranean region. The various hydrogeological settings in other sedimentary and volcanic formations cover 49.3%, while local poor and shallow aquifers in other metamorphic and igneous rocks only account for 9.5% (Table 1; Fig. 3).

Looking at the main geographical areas (as defined in Fig. 1, including the entire territory of each country, even if not fully covered by Fig. 2), the proportion of carbonate rocks is the highest in the countries of the Middle East, at 30.5% (Table 1; Fig. 3), although the proportions vary greatly between the individual countries, ranging from 22.0% in Turkey to 72.7% in Jordan. The proportion of karst in European countries reaches 25.8%, with a wide range of proportions when looking at individual countries. Among the four largest European countries, the proportion ranges from 16.7% in Spain, 22.0% in Italy and 26.9% in Greece to 36.9% in France (Table 2). Much higher proportions are found in smaller countries such as Bosnia and Herzegovina (42.0%) or Montenegro (66.1%).

The North African countries, with 25.3%, have the lowest proportion of carbonate rocks of the three major regions, but they also have the largest and, in some cases, the most extensive continuous carbonate areas. Libya tops the list with 31.0% karst, corresponding to an area of 504.9 thousand km^2. In Egypt, the proportion is 38.9%, with 402.5 thousand km^2 of karst, and in Algeria, 301.5 thousand km^2 of karst make up ~13.0% of the total area, although these are not large continuous carbonate areas as in Libya and Egypt, but numerous small areas.

Evaporite rocks are much rarer, occurring in only 2.5% of Middle Eastern countries, 1.1% of European countries and 0.5% of North African countries. Turkey and Spain have by far the largest areas of evaporite rocks, with 20.7 and 20.4 thousand km^2 respectively, while Tunisia has the highest proportion at 5.5%.

In general, the smaller Mediterranean countries sometimes have relatively high proportions of karst in relation to their total area. Malta stands out as an island state with 100% karst. The Palestinian Territories (West Bank and Gaza Strip) also have a high proportion of karst (78.8%), as do Lebanon

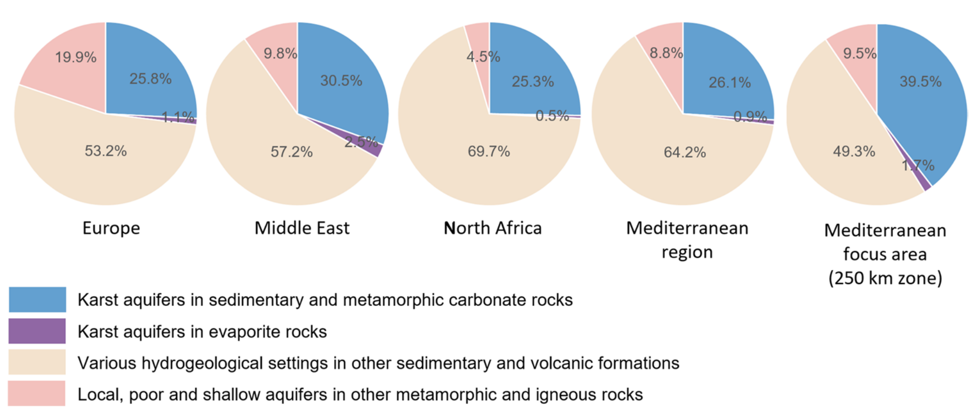

Fig. 3 Hydrogeological settings and their percentages in the main geographical regions (see colored areas in Fig. 1) and in the corresponding whole Mediterranean region as well as in the Mediterranean focus area (250 km zone)

Table 2 Size of countries and percentage of different hydrogeological settings. Information on the size of countries in this study is taken from the International Hydrogeological Map of Europe (IHME1500)

Country	Total area[a]	Karst aquifers in sedimentary and metamorphic carbonate rocks		Karst aquifers in evaporite rocks		Various hydrogeological settings in other sedimentary and volcanic formations		Local poor and shallow aquifers in other metamorphic and igneous rocks	
	1,000 km^2	1,000 km^2	%	1,000 km^2	%	1,000 km^2	%	1,000 km^2	%
Albania	28	8	26.9	0	0.0	17	58.8	4	14.3
Algeria	2,316	301	13.0	6	0.3	1,902	82.1	107	4.6
Andorra	0	0	2.3	0	0.0	0	45.5	0	52.2
Austria	84	21	25.4	0	0.0	38	45.5	24	29.1
Bosnia and Herzegovina	51	21	42.0	0	0.0	24	47.7	5	10.3
Bulgaria	113	32	28.3	0	0.0	56	49.3	25	22.4
Croatia	56	22	39.2	0	0.0	34	59.5	1	1.3
Cyprus	9	2	24.9	0	0.0	5	55.0	2	20.1
Egypt	1,034	402	38.9	9	0.8	534	51.7	89	8.6
France	561	207	36.9	0	0.0	248	44.2	106	18.9
Greece	28	8	26.9	0	0.0	17	58.8	4	14.3
Israel	22	10	44.9	0	0.0	12	54.7	0	0.3
Italy	302	66	22.0	2	0.8	192	63.7	41	13.6
Jordan	89	64	72.7	0	0.0	23	25.9	1	1.4
Lebanon	10	7	68.0	0	0.0	3	32.0	0	0.0
Libya	1,626	505	31.0	0	0.0	1,113	68.4	8	0.5
Malta	0	0	100.0	0	0.0	0	0.0	0	0.0
Montenegro	14	9	66.1	0	0.0	5	32.8	0	1.1
Morocco	406	152	37.4	2	0.5	204	50.3	48	11.8
North Macedonia	25	4	14.0	0	0.0	10	41.3	11	44.7
Palestinian Territories	6	5	78.8	0	0.0	1	21.2	0	0.0
Portugal	90	3	3.5	0	0.0	42	47.3	44	49.2
Serbia	88	11	12.1	0	0.0	62	69.8	16	18.1
Slovenia	20	10	47.3	0	0.0	10	50.4	1	4.3
Spain	506	84	16.7	20	4.0	296	58.5	105	20.8
Switzerland	41	13	30.3	0	0.0	19	45.4	10	24.2
Syria	208	82	39.4	7	3.3	119	57.3	0	0.0
Tunisia	155	39	25.2	8	5.5	108	69.3	0	0.0
Turkey	774	171	22.0	21	2.7	476	61.5	107	13.8

[a]Water surfaces of lakes not included

(68.0%) and Montenegro (66.1%). The proportion of outcropping karst areas below 10% can be found only in Portugal with 3.5%; however, this country is mostly outside the 250-km area of focus. In many countries, the exposed karst does not always represent the actual regional karst groundwater resources, as karst often extends underground (Fig. 2).

The results show that the Mediterranean region, with 2.26 million km^2 of karst or 39.5% of its area, is one of the most karstified regions compared to other large countries and regions of the world. Goldscheider et al. (2020) show in the WOKAM map that China has a slightly larger karst area of 2.54 million km^2, corresponding to 26.5% of its total land area, while Europe has 'only' 21.8%, North Africa 19.6% and Asia 18.6%. However, the proportions of karst in MEDKAM and WOKAM differ because of the different observation and classification scale (WOKAM distinguishes between continuous and discontinuous karst) and partly also because of the different lithological basis.

The presence of karst aquifers and their percentage of the total area can be an indication of the presence of karst groundwater resources and the dependency of humans and the environment on these water resources. However, climatic conditions, i.e. groundwater recharge (see section "Karst groundwater recharge"), as well as the thickness, functioning and storage capacity of karst aquifers, determine the actual availability of these karst groundwater resources.

Table 3 Length of the coastline of individual states, separated into continental coastline and islands, with the corresponding proportion of coastal karst. Information on the length of coastlines in this study is taken from the International Hydrogeological Map of Europe (IHME1500)

Country	Length of coastline including islands	Length of coastal karst, including islands		Length of continental coastline	Length of continental coastal karst	
	km	km	%	km	km	%
Albania	512	201	39.2	498	190	38.2
Algeria	1,296	399	30.8	1,288	399	31.0
Bosnia and Herzegovina	20	20	100.0	20	20	100.0
Croatia	3,982	3,491	87.7	1,492	1,156	77.5
Cyprus	646	63	9.8	-	-	-
Egypt	2,216	205	9.2	2,401	205	8.5
France	1,765	182	10.3	919	161	17.5
Greece	11,712	5,016	42.8	4,129	1,246	30.2
Israel	189	9	5.0	189	9	5.0
Italy	6,971	1,367	19.6	3,765	792	21.0
Lebanon	225	118	52.4	224	118	52.7
Libya	1,835	509	27.7	1,831	504	27.5
Malta	134	134	100.0	-	-	-
Montenegro	218	148	67.9	214	144	67.3
Morocco	461	122	26.5	461	122	26.5
Palestinian Territories	40	0	0.0	40	0	0.0
Slovenia	35	0	0.0	35	0	0.0
Spain	2,556	675	26.4	1,711	143	8.4
Syria	192	46	24.0	192	46	24.0
Tunisia	1,619	86	5.3	1,325	86	6.5
Turkey	5,107	1,219	23.9	3,990	1,069	26.8
Total	41,731	14,010	33.6	24,725	6,409	25.9

Mediterranean coastal karst

Data on the length of coastlines vary considerably depending on the scale and source of the data. Therefore, information on country size and coastline length from other data sources may differ from the data used in this study (IHME1500), which is based on the NATO VMAP data (NIMA 2001). The total length of the continental coastline and mapped islands is ~41,600 km, of which ~24,700 km is the continental coastline and ~16,900 km is the cumulative coastline of the numerous Mediterranean islands. To assess the occurrence of both carbonate and evaporite rocks on the coast, the term coastal karst is used here to encompass both hydrogeological units.

The presence of these rocks on the coast usually implies the presence of submarine karst springs or caves, which makes these coastal sections very vulnerable to saltwater intrusion (Fleury et al. 2023). The coastal karst is, therefore, particularly worthy of protection and requires correspondingly adapted management, especially in the case of islands. The statistical analysis shows that 33.6% of the total Mediterranean coastline, including the islands, is karst, corresponding to a length of ~14,000 km. Of this, the continental coastline alone accounts for ~6,400 km of karst, or 25.9% of the total coastline (Table 3). The country with the longest coastline, including the numerous islands, is Greece with a total length of ~11,700 km, of which 42.8% is karst. If only the continental coastline of ~4,100 km is considered, 30.2% is karst. Italy follows with a total coastline of ~6,970 km, of which 19.6% is karst, and Turkey with ~5,100 km total coastline and 23.9% of karst (Table 3). Countries with a very high proportion of coastal karst are Croatia with 87.7%, Montenegro with 67.9% and Lebanon with 52.4%. Some smaller countries or countries with a short coastline, such as Malta and Bosnia and Herzegovina have a karst coverage of 100% in the studied mapping scale and resolution.

Many of the larger Mediterranean islands have a high proportion of coastal karst, such as the Balearic Islands: 43.5% of the coast of Ibiza consists of karst, Menorca has 60.7% and Mallorca has 78.0% coastal karst. The islands of the Dinarides, in particular, have a high proportion of coastal karst, with some islands consisting almost entirely of carbonate rock, such as Cres, Hvar and Dugi Otok (Fig. 4b) or Korčula or Brač (Table 4). The many Greek islands are also strongly characterised by karst, and some have a high proportion of coastal karst such as Kefalonia (87.8%), Lefkada (81.9%) or Zakynthos (60.7%; Fig. 4c). The largest Greek island, Crete, also has a high proportion of its coastline covered by karst, at 65.1% (Fig. 4d).

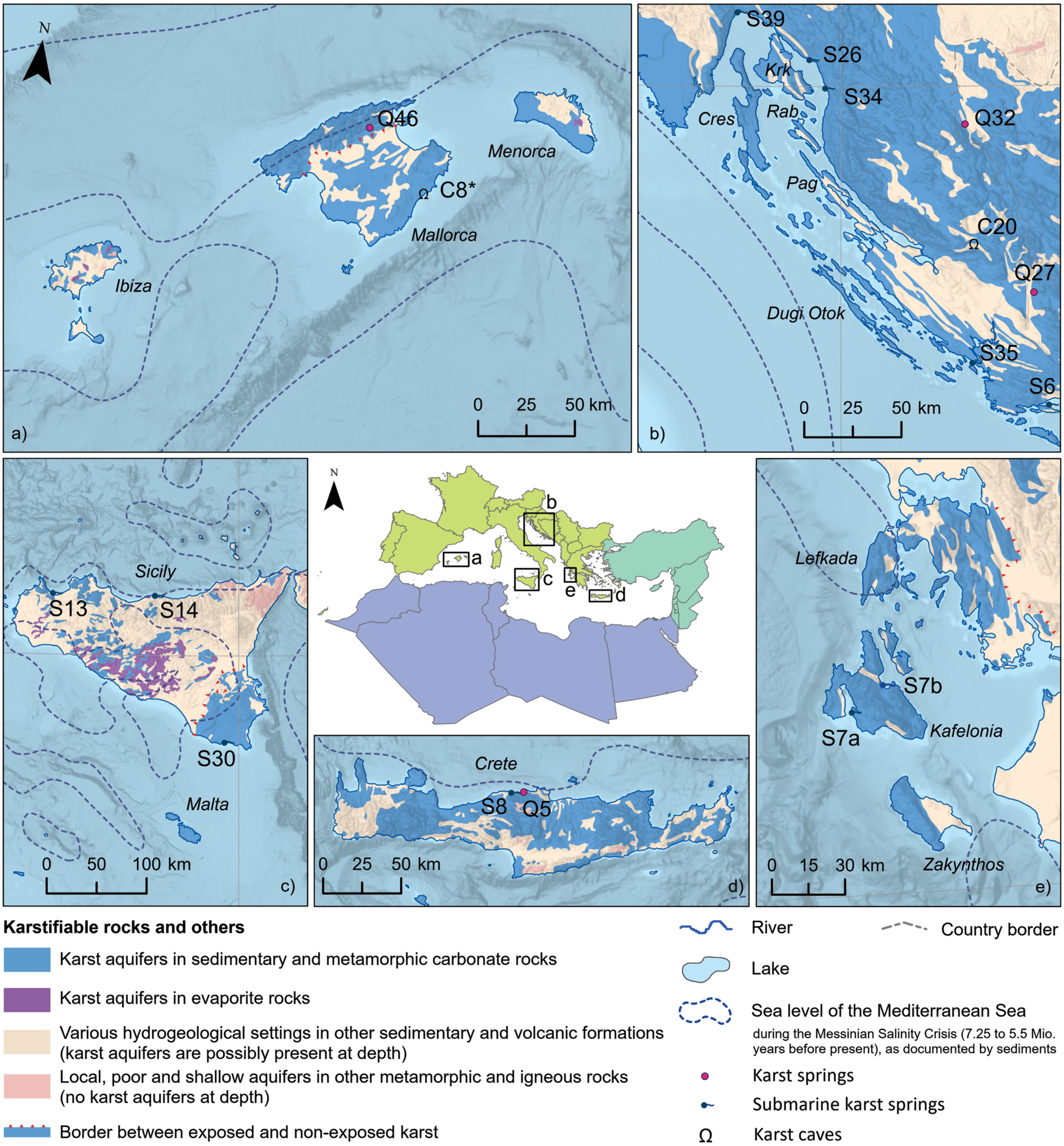

Fig. 4 Selected examples of Mediterranean islands with important absolute or relative occurrence of coastal karst: **a** the Balearic Islands Ibiza, Mallorca and Menorca, **b** islands along the northern part of the Dinaric coast of Croatia, **c** the southern Italian island Sicily, **d** the Greek islands Crete, **e** Ionian islands Lefkada, Kafelonia and Zakynthos

Karst springs

Some of the world's largest springs in the Mediterranean region occur in the Dinarides, such as the Buna spring (Q12 in Table 5) and Vrela Trebišnjice spring (Q49 in Table 5) in Bosnia and Herzegovina, with maximum discharge of 380 and 219 m^3/s, respectively. Springs in the eastern Mediterranean also show discharge maxima of several tens of cubic meters per second, such as the Afqa spring (Q1) in Lebanon with 65.5 m^3/s, which is partly used for local domestic water supply (Schuler and

Table 4 Selection of the larger Mediterranean islands that are not independent states, with indication of the length of the coastline and the proportion of karst. Cyprus and Malta are included in Table 3. Information on the size of countries and the length of coastlines in this study is taken from the International Hydrogeological Map of Europe (IHME1500)

Name	Country	Length of coastline (km)	Length of coastal karst (km)	Percentage of karst on coastline (%)
Brač	Croatia	113.5	113.5	100.0
Chios	Greece	173.4	101.6	58.6
Corse	France	763.9	11.8	1.5
Cres	Croatia	188.5	188.5	100.0
Crete	Greece	845.7	550.3	65.1
Dugi Otok	Croatia	134.1	134.1	100.0
Euboea	Greece	582.1	274.6	47.2
Hvar	Croatia	177.1	177.1	100.0
Ibiza	Spain	138.7	60.3	43.5
Kefalonia	Greece	216.5	190.0	87.8
Korčula	Croatia	122.6	122.6	100.0
Korfu	Greece	198.6	159.5	80.3
Krk	Croatia	137.2	103.2	75.2
Lefkada	Greece	103.2	84.5	81.9
Lesbos	Greece	306.9	40.5	13.2
Mallorca	Spain	389.9	304.2	78.0
Menorca	Spain	171.7	104.2	60.7
Pag	Croatia	209.2	137.8	65.9
Rab	Croatia	73.3	45.0	61.4
Rhodos	Greece	205.3	42.0	20.4
Sardegna	Italy	1,180.3	166.5	14.1
Sicilia	Italy	990.5	265.2	26.8
Zakynthos	Greece	118.7	71.4	60.2

Margane 2013), or the Kırkgöz spring (Q31) in Turkey with 62.8 m^3/s. Many of the springs play an important role in regional water supply, but are also life-giving for unique ecosystems—for example, Montpellier is supplied by the Lez spring (Q37; Bakalowicz 2011), which hosts an important ecosystem and feeds the Lez River with a maximum discharge of 11.9 m^3/s (Siegel et al. 2023). An example of a large karst spring on an island is the Almyros of Heraklion (Q5) in Crete with a maximum discharge of 30.0 m^3/s. However, the countless small karst springs around the Mediterranean, which are only partially documented in this study, also serve the local population for domestic, agricultural, livestock and energy purposes in large parts of the Mediterranean region. Examples are the Maqar spring (Q39), one of many in the Al Jabal Al Akhdar region of northern Libya (Hamad and El Hasia 2022), or the Ain El Gudeirat spring (Q3) in the north-eastern Sinai region of Egypt, which also provides water for irrigation and local water supply (LaMoreaux and Tanner 2001).

Submarine karst springs

A selection of 39 submarine springs in the Mediterranean are presented (Table 6), most of which do not have information on their discharge due to the nature of their submarine location. For this reason, information is only available for a few springs such as for the Chekka spring (S15) in Lebanon, where a maximum discharge of 60 m^3/s was measured, or for the Source de Port-Miou (S29) in France, where a maximum discharge of 50 m^3/s was recorded. Additionally, the Moraig and Toix spring (S23) in Spain has a maximum discharge of 9.0 m^3/s, while the Uji Ftohte (S38) in Albania measured 4.3 m^3/s. A well-known and studied spring is Source de la Vise (S36) in France, which still has a maximum discharge of 0.45m^3/s. These examples show that submarine springs can indeed release significant amounts of freshwater and, therefore, represent a potentially usable water resource despite the technical challenges. A special feature is the Argostoli system on the island of Kafelonia (Fig. 4e), where a submarine swallow hole infiltrates the seawater on the west coast and discharges ~2 weeks later ~15 km away on the east coast, partly through coastal springs but also through a submarine spring (proven by tracer test).

Karst caves

Table 7 gives an overview of 30 selected caves from the MEDKAM database that represent the diversity and size of the known caves in the Mediterranean focus area. The longest is the Schönberg cave system (C26) in the Alps, which is 140 km long and has a remarkable depth of 1,061 m. It is mentioned here because it is still within the 250-km zone, but is not strictly speaking part of the classic Mediterranean. Other large cave systems include the Hammam Trozza (C13) in Tunisia and the Coume Ouarnède cave system (C4) in France, which are both over 100 km long. Other deep caves include the Čehi 2 cave in Slovenia (C3) with 1,502 m depth, the Clot d'Aspres cave system (C4) in France with a depth of 1,066 m and the Željezna Jama cave (C30) in Montenegro, which is 1,027 m deep. An example of a cave on an island is the Cuevas del Drach (C7, Fig. 4a) on Mallorca, which is located on the south-eastern side and is ~1.2 km long.

Karst groundwater recharge

Karst groundwater recharge shows a clear trend from north to south (Fig. 5). Countries in the Alpine region and parts of the Dinarides have the highest average karst groundwater recharge of more than 800 mm/year in Switzerland, Austria and Slovenia. In Croatia, Bosnia and Herzegovina and Albania, the recharge is still between 500 and 800 mm/year. Lower average recharge rates of 300 to 500 mm/year are found in Italy, Serbia, France, Portugal and Northern

Table 5 Selected springs from the MEDKAM database with estimations for low-flow and high-flow discharge (m^3/s)

ID	Name	Country	Longitude	Latitude	Low (m^3/s)	High (m^3/s)
Q1	Afqa	Lebanon	35.893600	34.067550	0.1	64.5
Q2	Ain Al Laf'a	Morocco	–6.462580	33.847490	0.2[b]	ND
Q3	Ain El Gudeirat	Egypt	34.404390	30.640440	0.02	0.2
Q4	Ain Ribaa	Morocco	–5.232118	33.757743	1.0[b]	ND
Q5	Almyros of Heraklion	Greece	24.872480	35.410210	3.3	30
Q6	Anjar	Lebanon	35.939060	33.775486	0.48	9.2
Q7[a]	Ayn Zayanah	Libya	20.159586	32.211600	5.0[b]	ND
Q8	Basso Bussento group	Italy	15.540000	40.137200	0.2	60
Q9	Bistrica (Syri I Kalter)	Albania	20.195200	39.926440	13.5	36
Q10	Boka	Slovenia	13.485874	46.321800	0	100
Q11	Bournillon (Source du)	France	5.434349	45.054841	0	80
Q12	Buna	Bosnia and Herzegovina	17.908740	43.257010	3	380
Q13[a]	Capo Pescara springs	Italy	13.821573	42.163795	5.5	7.5
Q14	Divje jezero	Slovenia	14.032789	45.982689	ND	60
Q15	Düdenbaşı	Turkey	33.726680	36.952010	0.03	16.7
Q16	Dumanli[c]	Turkey	31.553452	36.921409	25	50
Q17	Figeh	Syria	36.161543	33.611977	2.1	23.4
Q18	Font Estramar	France	2.958325	42.859012	0.8	20
Q19	Fontaine-de-Vaucluse	France	5.132778	43.917778	3.1	81.4
Q20*	Fontaine de Nîmes	France	4.348898	43.840438	0.09	18.38
Q21[a]	Foux de la Vis	France	3.483763	43.900002	1.2	> 30
Q22	Gillardes (Source des)	France	5.888000	44.759500	0.5	60
Q23	Glava Zete	Montenegro	18.996960	42.675130	2	100
Q24	Gökova springs	Turkey	28.426054	37.037400	10.2	13.5
Q25	Gökpınar. Mugla	Turkey	38.036874	37.024109	6.2	15
Q26	Gradac	Serbia	19.856170	44.210440	0.4	10
Q27	Hubelj	Slovenia	13.918356	45.899864	0.04	60
Q28	Izvor Krke	Croatia	16.240090	44.042570	1.2	100
Q29	Izvor Kupe	Croatia	14.694140	45.491510	1.1	100
Q30	Izvori Cetine	Croatia	16.437270	43.965270	0.6	60
Q31	Kamniška Bistrica	Slovenia	14.594674	46.327850	2.1	62.6
Q32	Kırkgöz	Turkey	33.582590	37.058190	7.1	62.8
Q33	Klokot	Bosnia and Herzegovina	15.806750	44.824030	2.3	70
Q34	Krka	Slovenia	14.776623	45.889899	0.8	80
Q35	Kumanitsa	Bulgaria	24.708350	42.753750	0.5	3
Q36[a]	Lez (Source du)	France	3.844122	43.718235	0	11.9
Q37	Ljubljanica	Slovenia	14.300385	45.950265	1.5	120
Q38	Mareza	Montenegro	19.182530	42.479920	2.0	20
Q39	Mqar	Libya	22.520500	32.623000	ND	ND
Q40[a]	Nacimiento del rio Mundo	Spain	–2.438531	38.455362	0	100
Q41	Olukköprü spring	Turkey	34.182060	37.179670	7	30
Q42	Ombla	Croatia	18.141550	42.675570	4	138
Q43	Ouysse (Source de l')	France	1.584203	44.790271	0.5	150
Q44	Riječina	Croatia	14.427135	45.425682	0	150
Q45	Rižana	Slovenia	13.890424	45.528058	0.3	80
Q46	Ses Font Ufanes	Spain	2.961845	39.802997	0	30
Q47	Soča	Slovenia	13.728532	46.412272	1.1	100
Q48	Unica	Slovenia	14.250353	45.820185	0.2	90
Q49	Vrela Trebišnjice[d]	Bosnia and Herzegovina	18.428360	42.853590	2.5	219
Q50	Zarka spring (El Assi)	Lebanon	35.944326	34.136104	6.9	24.3

ND not defined

[a]Connected to an important karst groundwater-dependent ecosystem (Siegel et al. 2023)

[b]Only mean discharge was available and classified as "low" discharge

[c]Formerly one of the largest karst springs in the world, but submerged in a reservoir since 1982

[d]These springs were submerged at the end of the 1960s during the construction of the Bileća reservoir and are its main water source

Table 6 Submarine karst springs with estimations for low-flow and high-flow discharge (m^3/s)

ID	Name	Country	Longitude	Latitude	Low	High
S1	Aguadulce	Spain	–2.249925	36.792473	ND	ND
S2	Aigua Dolç and la Falconera	Spain	1.849875	41.215732	ND	ND
S3	Anavalos Kiveri	Greece	22.737265	37.518283	ND	ND
S4	Antalya	Turkey	30.6788347	36.7905208	ND	ND
S5	Anthedon	Greece	23.51455	38.482027	ND	ND
S6	Arbanija and Slanita	Croatia	16.325141	43.519898	ND	ND
S7[a,b]	Argostoli (a=swallow hole, b=spring)	Greece	20.470881	38.175685	ND	ND
S8	Bali	Greece	24.78715	35.41252	ND	ND
S9	Benissa and Calpe	Spain	0.096236	38.666637	ND	ND
S10	Brač Island	Croatia	16.458537	43.294363	ND	ND
S11	Bue Marino	Italy	9.623155	40.246866	ND	ND
S12	Cannes	France	7.084438	43.542896	ND	ND
S13	Castellamare	Italy	12.877892	38.049807	ND	ND
S14	Cefalù	Italy	14.044757	38.037825	ND	ND
S15	Chekka	Lebanon	35.72068	34.329819	0.2	ND
S16	Chidro	Italy	17.683414	40.303202	2.5[b]	ND
S17	Denia	Spain	0.129757	38.841706	ND	ND
S18	Gaeta	Italy	13.569334	41.231956	ND	ND
S19	Gurdić and Škurda	Montenegro	18.745531	42.477181	ND	ND
S20	Latakia	Syria	35.787184	35.48411	ND	ND
S21	Lera Pass	Albania	19.611853	40.148594	0.4[b]	ND
S22	Makarska	Croatia	17.009245	43.297702	ND	ND
S23	Moraig and Toix	Spain	0.168832	38.709284	0.3	9
S24	Mortola	Italy	7.554824	43.777485	0.02	0.2
S25	Nabrežina	Italy	13.6672236	45.7404762	ND	ND
S26	Novi Vinodolski	Croatia	14.794591	45.122805	ND	ND
S27	Ovacik	Turkey	33.198631	36.126952	1.0[b]	ND
S28	Polla di Cadimare	Italy	9.871071	44.062526	ND	ND
S29	Port-Miou (Source sous-marine de)	France	5.513319	43.205184	3.0	50
S30	Pozzalo	Italy	14.84062	36.71742	ND	ND
S31	Roquebrune-Cap Martin	France	7.485171	43.746165	0.1	0.2
S32	Rosas springs	Spain	3.242482	42.222494	ND	ND
S33	San Remo	Italy	7.787234	43.815296	ND	ND
S34	Senj	Croatia	14.897833	44.991176	ND	ND
S35	Šibenik	Croatia	15.839243	43.717598	ND	ND
S36	Source de la Vise	France	3.670188	43.440172	< 0	0.45
S37	Taranto	Italy	17.223062	40.448685	ND	ND
S38	Uji Ftohte	Albania	19.439414	40.385471	1.8	4.3
S39	Volovsko	Croatia	14.318947	45.342365	ND	ND

ND = not defined; *<0* = source of estavelle type that functions as a sink for marine water in low-flow conditions

[a] *a* = swallow hole, *b* = spring

[b] Only one discharge value was available and classified as "low" discharge

Macedonia, while recharge rates of less than 100 mm/year are found in the MENA region and the Middle East, with Libya and Egypt having the lowest average recharge rates of 13.5 and 1.6 mm/year respectively, apparently due to the extensive desert regions in their central and southern parts (Table 8).

The average annual karst recharge volume in the Mediterranean region is 740,339 million m^3, while within the

Table 7 Selected karst caves from the MEDKAM database of the Mediterranean region

ID	Name	Country	Longitude	Latitude	Length (km)	Depth (m)
C1[a]	Ayalon	Israel	34.92798	31.91032	2.7	100
C2	Ayvaini Cave	Turkey	28.42250	40.07350	5.5	ND
C3	Čehi 2	Slovenia	13.51470	46.36730	5.5	1,502
C4	Clot d'Aspres C.S	France	5.57460	45.02210	40	1,066
C5	Coume Ouarnède C.S	France	0.86640	42.97250	105.8	975
C6[a]	Cueva de Nerja	Spain	–3.84483	36.76199	4.8	158
C7[a]	Cueva del Gato	Spain	–5.23820	36.72721	4.5	ND
C8[a]	Cuevas del Drach	Spain	3.33028	39.53583	1.2	25
C9	Dupnisa Cave	Turkey	27.33220	41.50260	3.2	ND
C10[a]	Frasassi caves	Italy	12.96195	43.40033	20	ND
C11[a]	Friouatto	Morocco	–4.07234	34.10468	0.27	ND
C12[a]	Grotta Zinzulusa	Italy	18.43074	40.01204	0.26	ND
C13[a]	Grotte ain Dhab	Tunisia	9.48143	35.90235	3	ND
C14	Hammam Trozza	Tunisia	9.58000	35.55000	120.4	23
C15	İnsuyu Cave	Turkey	30.22270	37.39340	8.1	ND
C16	Jeita Grotto	Lebanon	35.38289	33.56362	9	ND
C17[a]	Karst en yesos de Sorbas	Spain	–2.10807	37.09194	50	ND
C18	Kef el Kaous	Algeria	1.38000	35.12000	4.1	ND
C19	Kef Toghobeit	Algeria	5.08270	35.05200	3.9	722
C20	Kita Gaćešina—Draženova puhaljka	Croatia	15.85710	44.26920	26.4	737
C21[a]	Oued Chaara	Morocco	–4.30768	33.86006	7.7	ND
C22	Pınargözü Cave	Turkey	31.18270	37.41480	16	720
C23[a]	Postojnska Jama	Slovenia	14.20821	45.78293	24.12	115
C24[a]	Rhar Bou Ma'za	Algeria	–1.25400	34.70900	18.4	35
C25	Saint-Marcel d'Ardéche Cave	France	4.54100	44.33210	51.2	233
C26	Schönberg-Höhlensystem	Austria	13.77230	47.70150	140.1	1,061
C27	Tilkiler Cave	Turkey	31.51067	36.95344	6.8	159
C28	Migovec System	Slovenia	46.25000	13.76000	43	972
C29	Yenesu Cave	Turkey	27.56320	41.37090	1.6	ND
C30	Železna Jama	Montenegro	19,22890	42.74340	17,5	1,027

[a]Connected to an important karst groundwater-dependent ecosystem (Siegel et al. 2023)

Mediterranean focus area (250 km zone), it is 244,569 million m^3. At the level of individual countries (the whole area of countries is considered), France has the highest mean annual karst recharge with 83,435 million m^3, followed by Turkey with 39,081 million m^3 and Italy with 32,418 million m^3. Due to the simplified method of calculating mean annual recharge, this is only a solid estimate that should be validated and improved for some regions.

Data on recharge rates or total renewable groundwater from other sources, such as the WaterGAP model (Müller Schmied et al. 2021) or the Food and Agriculture Organisation's AQUASTAT database (FAO 2023), show different values (even when downscaled to karst areas). This is due to the different calculation methodology and database, illustrating the challenge of obtaining accurate and reliable data on groundwater recharge.

Trends in karst groundwater storage from GRACE

It can be seen from Fig. 6 that karst aquifers in all parts of the Mediterranean are affected by a decrease in groundwater storage, although in some areas there is also a slight increase. In the whole Mediterranean karst region, a mean trend of –1.1 mm/year is detected corresponding to an annual lost volume of 2,544.3 million m^3. Within the Mediterranean focus area, the mean trend is –0.3 mm/year, summing up to a total annual loss of 436.2 million m^3. Of the 28 countries studied, 23 show an average negative trend in karst groundwater storage change, while only 5 show a positive trend. The strongest negative trends are observed in Malta with –19.3 mm/year, followed by Cyprus with –9.3 mm/year and Austria with –6.0 mm/year. Slightly negative trends are observed in

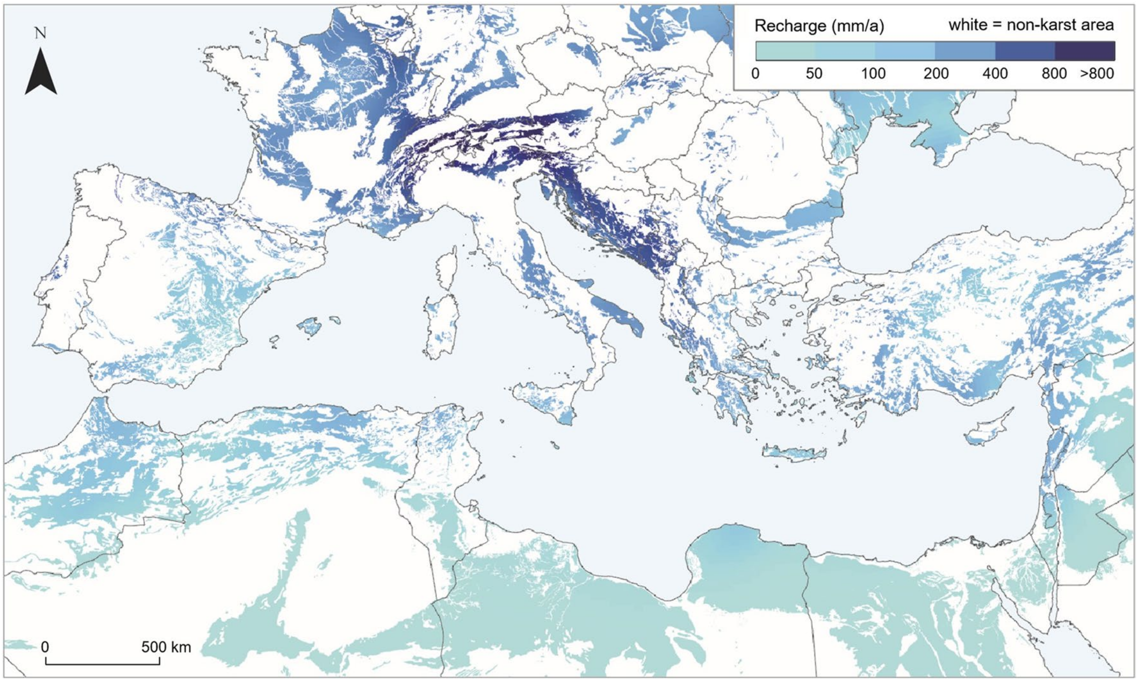

Fig. 5 Groundwater recharge, expressed as a 30-year average (1990–2019), derived from the karst-specific simulation model VarKarst-R (Hartmann et al. 2020)

large parts of France, particularly in the Paris region and the southern part of the country; northern Italy, the entire Middle East and parts of the Algerian highlands are particularly affected by strong negative trends. The Dinarides, some areas of eastern Turkey and the coastal fringes of the major karst platforms in North Africa are also affected; however, the latter region also has extensive areas of slightly increasing groundwater storage, as do small areas in southern Spain, southern Italy, Greece and throughout Turkey (Fig. 6). Portugal with 3.0 mm/year, Egypt with 2.1 mm/year, Libya with 1.4 mm/year, Greece with 0.3 mm/year and Lebanon with 0.03 mm/year show on average positive trends. This could either be due to a small increase in natural karst groundwater recharge, or return flows from agricultural irrigation could also be responsible for increasing groundwater storage, which would be plausible in countries with generally very low karst groundwater recharge rates. However, this would not explain small positive trends in nonarable desert regions such as Libya and Egypt. As a result of the different proportions of karst areas in the countries, the annual water loss rates are also very different—for example, Turkey has an average annual loss of 693.8 million m^3, followed by France with 645.0 million m^3 and Algeria with 558.8 million m^3. The positive GRACE trends in Egypt and Libya, with their extensive karst aquifers, add up to a mean annual increase of 856 million and 728.8 million m^3 respectively, while in countries with smaller karst areas, the increase is only a few million m^3 (Table 9). The results show the high pressure on the karst groundwater resources in the Mediterranean region and, thus, also on the people and the environment that depend on them. Sustainable use is, therefore, particularly important in arid countries, especially in the context of climate change, which is predicted to be more pronounced in the Mediterranean (Zittis et al. 2019).

Conclusion and outlook

This study provides an improved detailed assessment of the spatial distribution of carbonate and evaporite rocks as karst aquifers and other hydrogeological formations in the Mediterranean region and the Mediterranean focus area defined by a 250-km zone. It includes karst formations both on the continent and on the main islands and provides the first statistical evaluation of coastal karst. It also presents a selected dataset of a unique combination of terrestrial and submarine karst springs and their range of discharge, of karst caves and their spatial extent. In addition, the results of existing studies on karst groundwater recharge and on the trends in karst groundwater storage were applied to MEDKAM, which provides more accurate and quantified information on potential karst groundwater resources.

The main findings of this study are:

Table 8 Country-specific mean value of long-term mean groundwater recharge in carbonate and evaporite rocks (1990–2019)

Country	Total area of carbonate and evaporite rocks	Country-specific mean value of long-term groundwater recharge in carbonate and evaporite rocks (1990–2019)	
	1,000 km^2	mm/year	Million m^3/year
Albania	8	503.7	3,861
Algeria	308	50.8	15,641
Andorra	11	292.0	3.2
Austria	21	841.6	17,922
Bosnia and Herzegovina	21	658.0	14,091
Bulgaria	32	225.2	7,213
Croatia	22	598.5	13,219
Cyprus	2	180.5	408
Egypt	411	1.6	648
France	207	403.1	83,435
Greece	8	225.8	1,731
Israel	10	64.1	622
Italy	69	472	32,418
Jordan	64	19.8	1,272
Lebanon	7	215.8	1,485
Libya	505	13.5	6,825
Malta	0.03	65.0	0.02
Montenegro	9	672.6	6,130
Morocco	154	102.4	15,726
North Macedonia	4	359.1	1,278
Palestinian Territories	5	105.8	501
Portugal	3	398.6	1,257
Serbia	11	422.4	4,540
Slovenia	10	841.8	8,068
Spain	105	179.4	18,793
Switzerland	13	934.4	11,699
Syria	89	78.7	6,992
Tunisia	48	67	3,185
Turkey	191	204.4	39,081
Mediterranean region	2,345	317.2	740,339
Mediterranean focus area (250-km zone)	1,284,500	190.4	244,569

- 39.5% of the Mediterranean focus area (250-km zone) is covered by carbonate rocks, corresponding to more than 1.2 million km^2, while only 1.7% consists of exposed evaporite rocks.
- Looking at the total area of each geographical region, Middle Eastern countries have the highest percentage of carbonate rocks (30.5%), followed by European countries (25.8%) and North African countries (25.3%). For evaporite rocks, the same order is found for the Middle East (2.5%), followed by the European countries (1.1%) and the North African countries (0.5%).
- The largest and most extensive continuous carbonate rocks can be found in North African countries with 301,000 km^2 in Algeria, 402,000 km^2 in Egypt and 505,000 km^2 in Libya.
- The highest proportions of carbonate rocks in relation to the total area of the countries (apart from countries <20.000 km^2 such as Montenegro or Lebanon) can be found in Jordan with 72.7%, Slovenia with 47.3% and Israel with 44.9%.
- Coastal karst (carbonate and evaporite rocks) is found along ~14,000 km of coastline around the Mediterranean Sea, including islands, which is 33.6% of the total coastline and ~25.9% of the continental coastline.
- At the country level, the longest discontinuous coastal karst (carbonate and evaporite rocks) is in Greece with

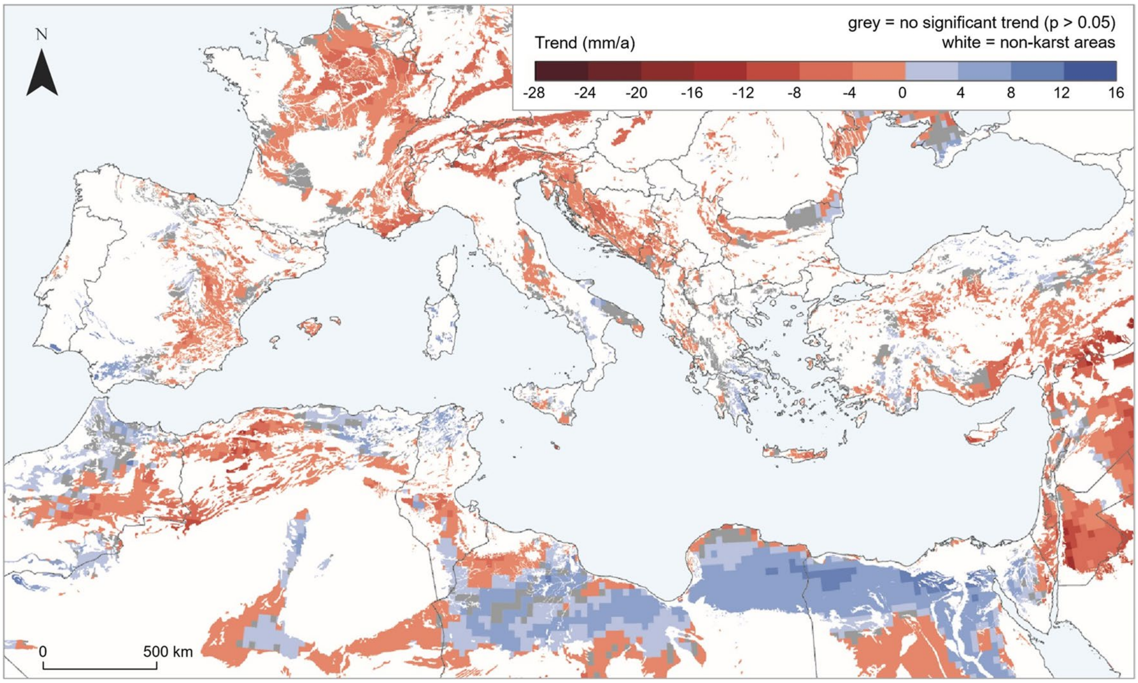

Fig. 6 Extent of trends in groundwater storage (GWS) in karst areas over the period 2003–2020 for the Euro-Mediterranean region using the latest data from the Gravity Recovery and Climate Experiment (NASA 2021) satellite mission and recently reanalyzed ERA5 land climate data (Muñoz Sabater 2019) from the European Centre for Medium-Range Weather Forecasts (modified after Xanke and Liesch 2022). The apparently coarser resolution of the GRACE data in North Africa results from the stereographic projection used, which leads to a stronger distortion in the direction of the equator

~5,016 km, followed by Croatia with ~3,491 km and Italy with ~1,367 km, while Malta and Bosnia and Herzegovina have a 100% proportion of karst on their coast, followed by Croatia with 87.7% and Montenegro with 67.9%.

- The karst groundwater recharge is higher in the northern part of the Mediterranean region than in the southern part and amounts to a total of ~244,600 million m^3/year in the Mediterranean focus area (250-km zone). In terms of volume, France is the country with the largest average annual karst groundwater recharge (83,435 million m^3).
- Negative trends in karst groundwater storage can be observed in many Mediterranean regions, with only a few areas showing slightly increasing trends such as parts of the Atlas Mountains in Morocco, Algeria, and Tunisia. Also, extensive areas in Libya and Egypt show slightly positive trends. For the Mediterranean focus area (250-km zone), an average annual loss of karst groundwater resources of 436.2 million m^3 is calculated.

Carbonate and evaporite rocks and, thus, karst groundwater resources, are widespread in the Mediterranean region and play an important role in supplying freshwater to people and the environment. In the vast majority of Mediterranean countries, karst aquifers cover more than a quarter of the land area, and in some countries well over 50%, which is remarkable compared to other large regions of the world, as statistical evaluations by Goldscheider et al. (2020) show. This wide distribution also means that karst is found along the coast, especially on some of the many islands, most of which are karstified, emphasizing the vulnerability of these areas to saltwater intrusion and making balanced groundwater use particularly important there (Fleury et al. 2023).

Table 9 Country-specific trends in karst groundwater storage in carbonate and evaporite rocks (2003–2020)

Country	Total area of carbonate and evaporite rocks 1,000 km^2	Average of mean annual trend in groundwater storage in carbonate and evaporite rocks (2003–2020) mm	Average of mean annual trend in groundwater storage in carbonate and evaporite rocks (2003–2020) million m^3
Albania	8	–1.62	–12.4
Algeria	308	–1.82	–558.8
Andorra	11	–1.76	–0,019
Austria	21	–6.01	–128.0
Bosnia and Herzegovina	21	–2.86	–61.3
Bulgaria	32	–1.82	–58.2
Croatia	22	–3.06	–67.6
Cyprus	2	–9.26	–20.9
Egypt	411	2.08	856.3
France	207	–3.12	–645.3
Greece	8	0.33	2.5
Israel	10	–2.54	–24.6
Italy	69	–2.18	–149.4
Jordan	64	–4.85	–312.6
Lebanon	7	0.03	0.2
Libya	505	1.44	728.8
Malta	0.03	–19.26	–0.01
Montenegro	9	–2.57	–23.4
Morocco	154	–1.57	–241.8
North Macedonia	4	–0.84	–3.0
Palestinian Territories	5	–1.64	–7.8
Portugal	3	2.96	9.3
Serbia	11	–3.10	–33.3
Slovenia	10	–3.99	–38.3
Spain	105	–1.91	–200.0
Switzerland	13	–5.51	–69.0
Syria	89	–4.87	–432.8
Tunisia	48	–3.01	–142.9
Turkey	191	–3.63	–693.8
Mediterranean region	2,345	–3.01	–2,544.3
Mediterranean focus area (250 km zone)	1,285	–0.34	–436.2

Karst aquifers in the Mediterranean region are under increasing pressure, as indicated by the negative trends in groundwater storage, which has implications for spring discharge and thus for rivers and groundwater-dependent ecosystems, as well as for regional drinking water supplies. Recent climate projections for the Mediterranean are not optimistic, expecting rising temperatures and reduced water availability, although with regional differences (Pal et al. 2004; Mariotti et al. 2015; Lionello and Scarascia 2018; Zittis et al. 2019). According to Xanke and Liesch (2022), the causes of negative trends are diverse and can be attributed regionally to high, unsustainable groundwater abstraction as well as declining natural groundwater recharge. Positive trends, on the other hand, might regionally be associated with return flows from irrigation and not necessarily with increased groundwater recharge.

MEDKAM serves as a basis for various research and management approaches at different scales to keep the karst groundwater resources in the Mediterranean region usable for future generations. The spatial and statistical distribution of karst aquifers provides valuable information for scientific and regulatory purposes and can be used in the context of similarly scaled applications and data sets related to climatic, hydrological or geographical issues such as studies by Zhang et al. (2023), who conducted a global analysis of land use changes in karst areas and assessed their impacts on water resources. Additionally, it can be used to upscale or transfer local and regional management options to a supra-regional scale, which may involve, for example, karst-specific protection measures such as vulnerability mapping approaches (Zwahlen 2003), flood prevention and flood regulation approaches (Stevanović 2010; Jourde et al. 2014), or active karst groundwater management through managed aquifer recharge and storage (Xanke 2017). Further development of MEDKAM could include a more detailed scale, or a further subdivision into different types of carbonate rocks and their genesis or the degree of karstification, both in the subsurface and in the epikarst.

Map availability

The PDF version of the printed MEDKAM and more information on it, as well as a link to download the shapefile, which is free for noncommercial use, can be found here: https://doi.org/10.25928/MEDKAM.1.

Acknowledgements This study is a contribution to the project "Karst Aquifer Resources availability and quality in the Mediterranean Area" (KARMA)

Funding Open Access funding enabled and organized by Projekt DEAL. Financial support of KIT researchers through the German Federal Ministry of Education and Research (BMBF) and the European Commission through the Partnership for Research and Innovation in the Mediterranean Area (PRIMA) program under Horizon 2020 (grant agreement no. 01DH19022A) is greatly appreciated, as well as funding of our KARMA project partners by their respective national funding agencies (MITECO for Spain, ANR for France, MIUR for Italy, CNRS-L for Lebanon, ANPR for Tunisia). Open Access funding enabled and organized by Project DEAL. The authors thank Salah Hamad for contributing data on karst springs for Libya.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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