KARMA

Karst **A**quifer **R**esources availability and quality in the **M**editerranean **A**rea

Evaluation of karst groundwater-dependent ecosystems (KGDE) environmental status

Deliverable 3.5

Authors: Lena Siegel (KIT), Nico Goldscheider (KIT), Marco Petitta (URO), Bartolomé Andreo Navarro (UMA), Michel Bakalowicz (UM), Juan Antonio Barberá Fornell (UMA), Rachida Bouhlila (ENIT), Avihu Burg (GSI), Joanna Doummar (AUB), Inez Ezzine (ENIT), Jaime Fernández-Ortega (UMA), Mohamed Ghanmi (ENIT), Hervé Jourde (UM), Amal Mhimdi (ENIT), Tanja Pipan (ZRC SAZU), Nataša Ravbar (ZRC SAZU), Aleksandra Maran Stevanović (NHMBEO), Zoran Stevanović (UB)

Date: 27 October 2022

This project has received funding from the European Union's PRIMA research and innovation programme

Technical References

Project Acronym	**KARMA**
EU Programme, Call and Topic	PRIMA, Multi-topic 2018, Water resources availability and quality within catchments and aquifers
Project Title	Karst Aquifer Resources availability and quality in the Mediterranean Area
Project Coordinator	Prof. Dr. Nico Goldscheider, Karlsruhe Institute of Technology (KIT), nico.goldscheider@kit.edu
Project Duration	September 2019 - August 2022
Deliverable No., Name	D3.5 Evaluation of karst groundwater-dependent ecosystems (KGDE) environmental status
Dissemination Level*	Public (PU)
Work Package	WP3: Water Quality
Task	Task 3.4: karst groundwater-dependent ecosystems
Lead beneficiaries	Karlsruhe Institute of Technology (KIT), Sapienza University of Rome (URO)
Contributing beneficiaries	University of Malaga (UMA), University of Montpellier (UM), Ecole nationale d'Ingenieurs de Tunis (ENIT), American University of Beirut (AUB)
Due Date	Month 36
Actual Submission Date	27-10-2022

* PU = public

CO = Confidential, only for members of the consortium (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

Version History

Version	Date
1.0	27 October 2022

Project Partners

(Coordinator)

Author contributions: This work is based on the master thesis by Lena Siegel, which was completed at the Karlsruhe Institute of Technology (KIT) for the degree of M.Sc. in Geoecology and supervised by Nico Goldscheider (KIT) and Sebastian Schmidtlein (KIT). The first concepts, the template for KGDE data collection and the first phase of data collection were accomplished by Nico Goldscheider and Marco Petitta (URO). The following KARMA partners, project advisors and external colleagues contributed to this deliverable as co-authors by providing data and information about KGDE: Bartolomé Andreo Navarro (UMA), Michel Bakalowicz (UM), Juan Antonio Barberá Fornell (UMA), Rachida Bouhlila (ENIT), Avihu Burg (GSI), Joanna Doummar (AUB), Inez Ezzine (ENIT), Jaime Fernández-Ortega (UMA), Mohamed Ghanmi (ENIT), Hervé Jourde (UM), Amal Mhimdi (ENIT), Tanja Pipan (ZRC SAZU), Nataša Ravbar (ZRC SAZU), Aleksandra Maran Stevanović (NHMBEO) and Zoran Stevanović (UB). Additional data were collected and made available by Diana M. P. Galassi, Barbara Fiasca, Želimir Pekaš, Romeo Eftimi, Daniel Scarry, Konstantinos Voudouris, John Gunn and Carlos Almeida. The planned representation of KGDEs on MEDKAM, which is not yet implemented in this deliverable, will be done in close cooperation with Julian Xanke (formerly part of the KARMA team at KIT).

Executive Summary

Work Package 3 of the KARMA project deals with the water quality of Mediterranean karst groundwater resources, and within this framework, the aspect of the environmental status of karst groundwater dependent ecosystems (KDGEs) is considered as well. Thereby, this Deliverable 3.5 depicts the evaluation of KGDEs in the Mediterranean area in terms of their distribution, basic properties, threats and conservation status. Additionally, the distribution of KGDEs in the Mediterranean Area will be presented on MEDKAM, the Mediterranean Karst Aquifer Map and Database, which is another product of the KARMA project within Work Package 5. The provided list cannot be considered exhaustive of existing GDEs in Mediterranean Karst, but it has the main scope of demonstrating their significant relevance in the region.

Groundwater from karst aquifers is a valuable and frequently used water resource and at the same time the foundation of many ecosystems. Therefore, this Deliverable aims to provide an overview of karst groundwater-dependent ecosystems in the Mediterranean area, characterising them and defining their threats and protection status. That is relevant because the growing utilization of karst groundwater by humans and other anthropogenic interventions endanger the ecosystems.

In order to characterise the current status, data was collected from experts within the KARMA project as well as from external professional. In addition, an extensive literature review was conducted. With this information, 113 KGDEs were briefly assessed on general characteristics and seven detailed case examples were elaborated.

It shows that KGDEs contribute considerably to regional species and habitat richness. For example, 65% of KGDEs are inhabited by endemic species and especially in arid regions, KGDEs provide refuges for many species. The most common threats to the ecosystems are direct human disturbances such as mass tourism or overfishing, and in arid regions water shortage is particularly threatening as well. Although a large part of the ecosystems is under protection, efficient measures to keep the ecosystems intact are lacking. Furthermore, this study shows that especially caves and springs are still insufficiently represented and considered in current protected areas, although they are of great importance in terms of biodiversity.

Table of Contents

1. Introduction

1.1 Karst groundwater-dependent ecosystem (KGDE)

Karst aquifers in the Mediterranean region are not only important in terms of water resource management and human use. They are also associated with many valuable ecosystems. These ecosystems can be located both in the subterranean aquifer itself but also where karst groundwater emerges at the surface. Ecosystems in general comprise all organisms and abiotic pools and the interaction between them. Also, intact ecosystems can provide essential services like water purification (Chapin et al. 2011, Griebler et al. 2019). Groundwater-dependent ecosystems (GDEs) are known as ecosystems whose composition, structure and functioning rely on groundwater supply. They can represent both terrestrial and aquatic ecosystems (Kløve et al. 2011a). GDEs that derive their groundwater supply from karst aquifers are called karst groundwater-dependent ecosystems (KGDEs). The various geomorphological forms in karst, the special hydrogeology and additional climate differences within the study area enable the development of different environments and diverse karst groundwater-dependent ecosystems (Bonacci et al. 2009).

The dependency and supply of groundwater can range from continuous to seasonally or occasionally, but also from obligate to facultative (Kløve et al. 2011a; Bertrand et al. 2012, European Commission et al. 2015). It also varies between the different types of GDE including springs, rivers, lakes, wetlands or caves (Kløve et al. 2011a). Springs for example would not exist without the groundwater supply whereas for other types like rivers the groundwater might be only an additional water contribution that can change their properties. The hydroperiod reflects the timing and duration of groundwater discharge and depends on several parameters like climate, aquifer type and land use (Kløve et al. 2011a). It also determines the water availability and therefore influences the abundance and species composition of a GDE and leads to specialization of species according to the conditions found in their habitat (Bertrand et al. 2012). Generally, species with lower spreading ability and longer generation times are associated with GDEs of permanent discharge and stable conditions, whereas species with stronger spreading ability are favoured in more variable non-permanent discharge habitats (Bertrand et al. 2012). Due to the variability of GDEs which is illustrated by the different hydroperiods, GDEs all together comprise many sorts of habitats and hence they host an impressive abundance of species, which make them important for biodiversity conservation.

1.1.1 Underground karst groundwater-dependent ecosystems

In contrast to other aquifer types, the process of karstification in karst aquifers provide the foundation of large subterranean cavities which in turn represent diverse habitats and comprise a valuable species composition (Hérivaux and Maréchal 2019). Caves and other underground habitats are associated with special environmental conditions to which species have to be adapted to (Culver and Pipan 2013; Howarth and Moldovan 2018a). First and foremost, the darkness impacts the life of species in these habitats. Usually, the key source of energy in an ecosystem is photosynthesis and by that the utilisation of sun energy by microbes and plants (Ravbar and Pipan 2022). In underground habitats like caves where light is missing and no photosynthesis can take place, organic matter which is introduced from outside is vital for the energy supply of the ecosystem. In many cases, the transport of organic matter into the cavities is accomplished by the water flowing or percolating into it (Culver and Pipan 2013). That also illustrates the important relation between surface and subterranean karst features and therefore also the susceptibility of underground waters to negative anthropogenic impacts at the surface (Bonacci et al. 2009). Another rarely occurring possibility for the energy supply is the primary production based on chemical-driven microbial production, so-called chemoautotrophy (Culver and Pipan 2013; Ravbar and Pipan 2022). Furthermore, organisms that live in caves evolved morphological and physiological adaptation strategies like reduced pigments or eyes, a slower metabolism and starvation resistance, as well as the production of less but larger eggs and an increased life span. The term troglomorphy concludes the convergence of these adaptations among cave species (Howarth and Moldovan 2018a; Ravbar and Pipan 2022). The term "troglo" describes holes, caves, or other cavities originally including all kinds of cave fauna, terrestrial and aquatic, while the term "stygo" refers to subterranean waters. Since the concept of stygofauna covers aquatic fauna, troglofauna is now specifically used for terrestrial cave fauna (Gunn 2004). Concerning the classification of cave species, the Schiner-Racovitza classification can be used: Trogloxenes are species that only visit caves occasionally and cannot live and reproduce in caves. Troglophiles can live and reproduce in both subterranean and surface environments and may show some adaptations to the darkness. Troglobionts are exclusive subterranean inhabitants and can be found in the deepest areas of cavities. Therefore, they are highly adapted to the underground habitat (Howarth and Moldovan 2018a).

Caves host many endemic species which has several reasons. Due to the adaptation to the cave conditions, cave fauna might not be able to leave their cave. Photophobia, which describes the avoidance of sunlight and a hiding reflex, might be one reason for the limited dispersal and therefore the high degree of endemism of cave species (Howarth and Moldovan 2018a). Furthermore, many cave systems are physically isolated which prevents the spread of the species (Howarth and Moldovan 2018a). At the same time, this leads to the island effect as described by Darwin and thus to the diversification of species in the cave (Hérivaux and Maréchal 2019). As a result, subterranean species often occur only in small areas or even only in a single cave making them endemic and particularly vulnerable. Moreover, many of these species are probably rare in number too, although that could be related to the undersampling of hardly accessible habitats (Niemiller et al. 2018). The Encyclopedia Biospeleologica represents a valuable and extensive collection on troglo- and stygobionts worldwide including karst areas and cave species of Mediterranean countries as well. Therefore, this work illustrates the remarkable biodiversity of underground habitats (Juberthie and Decu 1994, 2001).

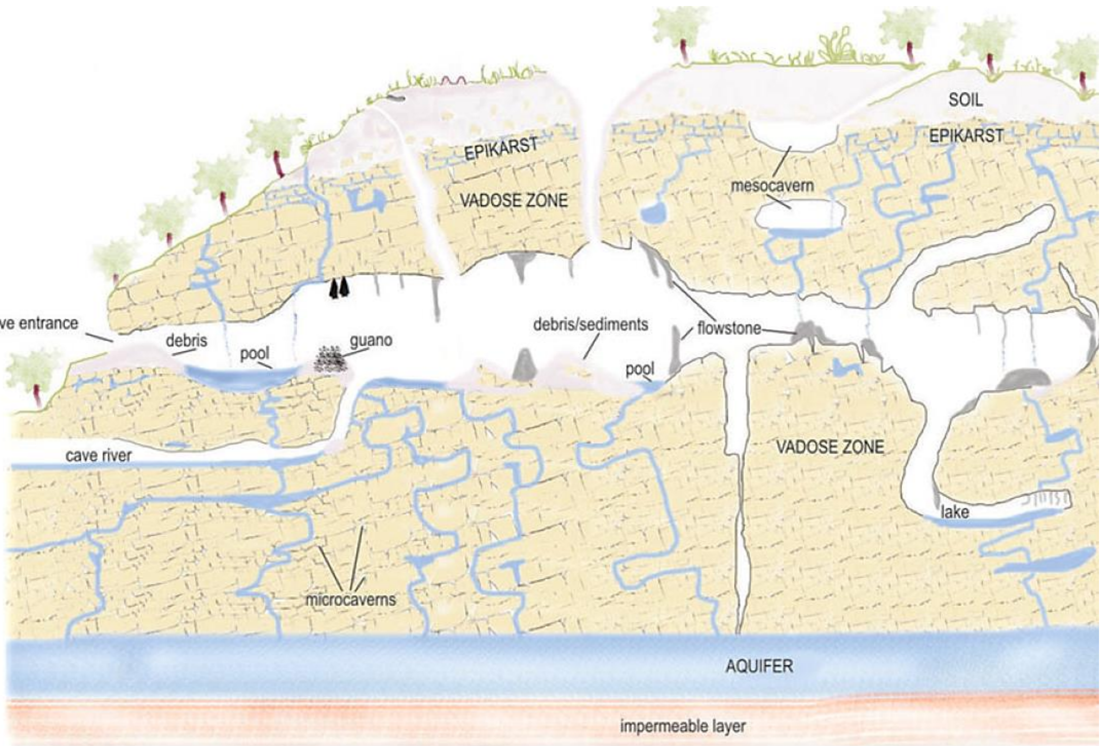


Fig. 1: conceptual cross-section of a karstic system including the epikarst, the vadose zone and the aquifer in the phreatic zone. The vadose zone comprises a cave with several terrestrial and aquatic microhabitats. Drawing by O. T. Moldovan out of Howarth and Moldovan (2018b).

Within the cavities, underground lakes and streams are habitats for aquatic cave species. In addition, many different cave microhabitats can exist (Fig. 1). Drip pools, damp walls, plant roots on the ceiling or sediments like mud, clay or guano deposits are a few examples of such microhabitats (Howarth and Moldovan 2018b). The existence of different microhabitats within a small area promotes the diverse species composition in the cave as species can use different niches within the limited space (Bonacci et al. 2009; Howarth and Moldovan 2018b).

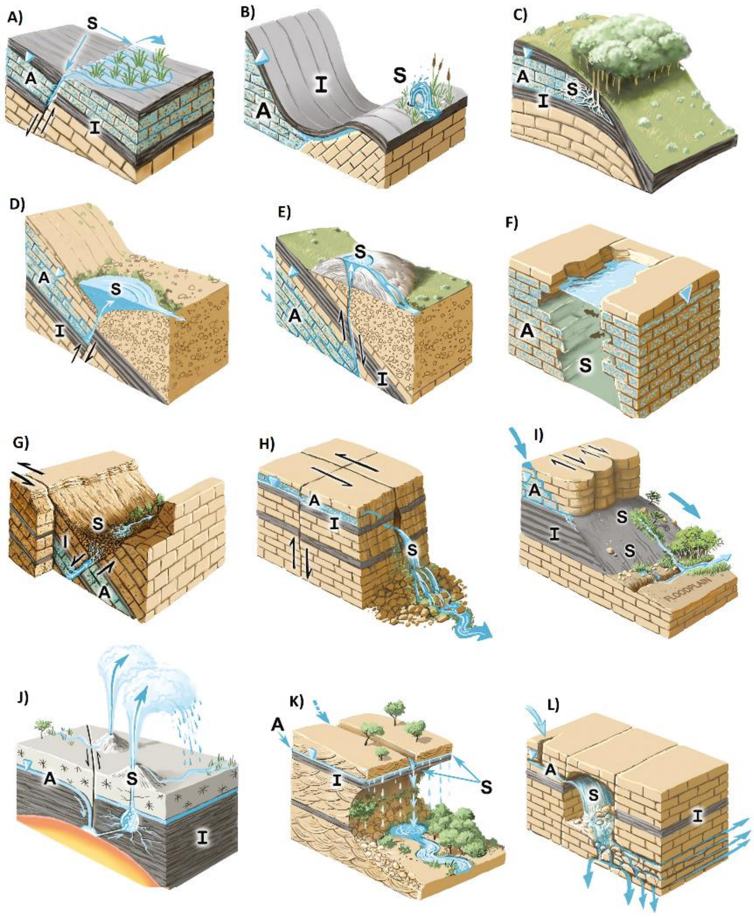
The epikarst also depicts an underground habitat for species that live in smaller cavities. The sampling of them is not easy, because the epikarst is hardly accessible, but species living in the epikarst can get washed out naturally and then they can be collected in drip pools, ponds or streams of accessible caves (Ravbar and Pipan 2022; Bruno et al. 2018). Sampling of the seeped or dripped water shows a notable diversity, dominated by copepod species that in some cases even exceeds the number of stygobionts in the respective cave. However, due to the lacking epikarst investigations many epikarst species still remain unknown (Culver and Pipan 2013).

Not only the Troglo- and Stygobionts are of interest when it comes to subterranean ecosystems and biodiversity. At the transition of above and below ground, the cave entrance also presents a habitat for a wide range of organisms. This ranges from mosses and ferns that prefer the humid rocky walls to birds that use the cave entrance to build their nests as it is relatively secure from predators (Culver and Pipan 2013). Probably the most prominent cave visitors (Troglophiles) are bats which use the caves for hibernating, raising the young or just as temporary sleeping places (Culver and Pipan 2013). Cave visitors import organic matter into the cave, for example by depositing guano, which in turn can serve as energy source for other species (Gunn 2004).

It can be concluded that any type of cavity corresponds to habitats for a variety of specialized species. Only a small percentage of caves and even less smaller cavities associated with the epikarst are protected in any sense of legislation (Culver and Pipan 2013; Niemiller et al. 2018). One aspect that might be related to the missing conservation of cave ecosystems could be the fact that subterranean invertebrates and other small organisms are more easily neglected than larger vertebrates, even though they depict a significantly higher diversity and endemism and take care of important groundwater ecosystem services and other benefits for humans (Niemiller et al. 2018).

1.1.2 Aboveground karst groundwater-dependent ecosystems

Not only the underground KGDEs provide habitats for specialized and rare species. Karstic springs are prime examples of aboveground KGDEs presenting the interface of the karst aquifer and the surface water. According to Cantonati et al. (2020) springs are diverse, endangered and socio-ecological interacting ecosystems. Despite it, they are insufficiently studied and appreciated by the public partly due to the lacking knowledge of their distribution and types (Cantonati et al. 2020; Stevens et al. 2021). In general, springs can be classified according to various characteristics of which some already correspond to their function as an ecosystem. Springer and Stevens (2009) published a classification system based on the “sphere of discharge” of the spring which reflects the geomorphology of the discharge point and distinguishes between 12 spheres of discharge (Fig. 2). By that, their approach includes more than the commonly used types of helocrene (diffusely seeping, wet meadows), limnocrene (spring on the bottom of a pool, lentic) and rheocrene (flowing, lotic) springs. Additionally some spheres of discharge are particularly diverse in their geomorphological characteristics and therefore correspond to more microhabitats (Springer and Stevens 2009; Stevens et al. 2021). These include the types of hanging gardens, gushets or hillslope springs (Springer and Stevens 2009; Stevens et al. 2021). The existence of several microhabitats at one spring can support the species richness at this spring ecosystem.



spring type	microhabitat diversity
A) helocrene	2.8
B) fountain	3.5
C) hypocrene	3.3
D) limnocrene	3.0
E) mound-forming	3.0
F) exposure	2.2
G) rheocrene	3.8
H) gushet	4.0
I) floodplain vs. upland hillslope	3.0
J) geyser	3.0
K) hanging gardens	3.8
L) cave springs	3.7

Fig. 2: illustration of the 12 types of the sphere of discharge defined by Springer and Stevens (2009), images taken out of Stevens et al. (2021). On each figure, A stands for aquifer, I for impermeable barrier (aquitard), S for surface groundwater expression (springs). The table on the right presents the names of the sphere of discharge types and the respective microhabitat diversity (number of microhabitats at one spring) of it. Values are taken from Springer and Stevens (2009) and are based on the occurrence likelihood of microhabitats in springs from the Colorado Plateau.

Springs are not only of ecological interest because of the habitat heterogeneity and the groundwater-adapted species. Also, other terrestrial and aquatic species inhabit the environment of springs, especially during droughts in arid regions springs can be a refuge for many species (Kløve et al. 2011a; Cartwright et al. 2020). Furthermore, springs support the biodiversity of associated wetlands and downstream waterbodies (Eamus et al. 2016).

Karst springs represent the groundwater discharge of a karst aquifer. Therefore, the discharge usually comprises exclusively groundwater and is often highly variable responding quickly to rainfall or snowmelt events (Kløve et al. 2011a). The discharge variability, which is also correlated to changes in the water quality, depends on the stage of the karstification. If the system's porosity is rather matrix-dominated and no enlarged conduits have built yet, more or less continuous discharge patterns are also possible at karst springs (Krešić and Stevanović 2010). That is important, because the associated flora and fauna of a spring ecosystem are adapted to the water regime and therefore differs between springs with continuous and variable discharge (Kløve et al. 2011a). Such spring-dependent species are called crenobionts and are mostly restricted in their distribution (Stevens et al. 2021).

In regard to karst springs, some special springs have to be mentioned. A specific type of spring is an estavelle, which serves only temporarily during high-hydraulic heads as spring and at low-hydraulic head conditions it acts as ponor (Krešić 2013). Another speciality found in karst areas are limestone-precipitating springs (LPS) when carbonate-saturated groundwater emerges and limestone is deposited (Krešić 2013; Cantonati et al. 2020). This habitat type is also listed in Annex I of the European Union (EU) Habitats Directive (EC 1992). LPS host a specific flora and fauna comprising calcifying mosses, cyanoprokaryotes and diatoms as well as other vascular plants, caddisflies and a carbonate encrusted moth-fly that depend on this specific type of karst spring (Cantonati et al. 2020).

In addition to the springs ecosystems, other karst water bodies can be classified as KGDE depending on the groundwater contribution to it. Herein, rivers which are dominantly fed by karstic springs are included as KGDEs. Also, exfiltration occurring when the groundwater levels are higher than the stream water levels, depicts a groundwater contribution to river ecosystems (Kløve et al. 2011a). Groundwater can play a substantial role for river ecosystems and ensure ecologically relevant geochemical properties in the river particularly during base flow conditions (European Commission et al. 2015). In natural river systems, the water levels of the river and aquifer are usually coupled so that high water levels in the river correlate with high aquifer levels (Kløve et al. 2011a). Nevertheless, this can be altered by any type of interference with hydrological conditions like water abstraction for irrigation or hydropower regulation and hence have impacts on the ecological character of the river and its surroundings (Kløve et al. 2011a). Other typical karst forms regarding rivers are sinking streams. They depict rivers or streams that vanish into the underground via ponors and continue to flow underground and thereby recharge the aquifers. Usually both stygophiles and surface species that accidentally get transferred to the underground live in the waters of sinking streams, whilst stygobionts are rather rare (Ravbar and Pipan 2022). Referring to the limestone-precipitating springs, some rivers in karst areas form lakes which are separated by natural dams created through precipitation of limestone from emerging carbonate-saturated groundwater (Krešić 2013).

Beside this type of lakes formed in rivers, lakes in the common sense can also be assigned to KGDEs, depending on the hydrology. However, the importance of groundwater contributions to a lake in regard to the ecological character is not fully understood yet (Kløve et al. 2011a). In this study, lakes that are located in karst areas and are supplied in a large extent by karst waters, are recognized as karst groundwater-dependent lakes. A special case of karstic lakes, are intermittent lakes, which are regularly flooded and drained (Ravbar et al. 2021). Some lakes exist for several months of the year whereas other karst depressions are flooded rarely only during times of higher water tables (Ravbar et al. 2021; Petrič and Kogovsek 2005). The karst depressions in which those lakes can be found are connected to karst conduits and springs that get activated when groundwater level rises (Kløve et al. 2011a; Petrič and Kogovsek 2005). In times of lower groundwater levels, the same conduits function as swallow holes and drain the lakes to the underground (Kløve et al. 2011a).

In addition to springs, rivers and lake ecosystems, wetlands can display KGDEs as well. Generally, wetlands appear where the water table is close or at the surface or the land surface is covered by water. They comprise areas where water is the most important factor determining the environment and the species in place (Ramsar Convention Secretariat 2016). Wetland KGDEs show a large variety of forms ranging from alkaline fens in mountainous regions to coastal marshlands. Hence, the ecological character varies strongly between the different wetlands. Altogether they share the similarity of being replenished by karstic springs or by direct connection to the groundwater table.

1.2 Threats of karst groundwater-dependent ecosystems

Threats to karst groundwater dependent ecosystems are manifold. Contamination, declining groundwater levels and habitat destruction and disturbances by humans are major threats and therefore explained more in detail below. Moreover, the projected climate change and related consequences can enhance the damage. Another threat that affect some KGDEs include the introduction of invasive species that can replace the native flora and fauna, change habitats, reduce biodiversity in the long term and lead to a change or reduction in provided ecosystem services (Mollot et al. 2017; Rinke et al. 2019).

1.2.1 Contamination

A major threat for the degradation of KGDEs is groundwater contamination. Point recharge via swallow holes, fast infiltration and transport make karst aquifers particular vulnerable. Pollutants can fast and easily spread in the conduit system of karst aquifers which have low self-treatment abilities (Goldscheider 2005, Ford and Williams 2010). Compared to other hydrological systems, karst systems are susceptible to a wider range of environmental impacts because underground waters are associated with additional threats like the (illegal) dumping of solid and liquid waste in dolines or other sink points (Ford and Williams 2010).

Primarily, the leaching of nitrate and pesticides applied for agricultural purposes are the origin of the contamination (Kløve et al. 2011b). On the other hand, in urbanized areas, leakage of sewage inputs and inappropriate wastewater treatment is a large problem as well (Erostate et al. 2020; Kløve et al. 2011b). By now, substances like pharmaceuticals, residues of personal care products, artificial sweeteners and nanoparticles are additional frequently occurring pollutants in aquifers (Griebler et al. 2019). The pollution deteriorates the water quality in regard to drinking water utilisation by humans, but it has severe consequences for the ecosystem as well. The intruded substances change the redox state due to the high oxygen demand for the microbial degradation of these substances (Griebler et al. 2019). Depending on the type of pollution, this can lead to a loss of groundwater species as they get toxicated or the oxygen demand cannot be provided anymore (Griebler et al. 2019). Also, changes in the temperature, moisture and chemical composition can impact population dynamics and species assemblage (Kløve et al. 2011a; Griebler et al. 2019; Chapin et al. 2011). Especially for lake and wetland KGDEs which are associated with longer residence times of the water and by that also of the pollutants, eutrophication is an often occurring form of degradation. This is caused by the excessive input of nutrients, sediments and organic matter (Erostate et al. 2020).

1.2.2 Declining groundwater levels

Declining groundwater levels which are caused by overexploitation of the aquifers lead to a shortage of potable water or water for irrigation. Further consequences of overexploitation of aquifers can be land subsidence and salinization by saltwater intrusion (Griebler et al. 2019). The latter leads to a further degradation of remaining groundwater resources. However, declining groundwater levels do not only reduce the services provided for humans, but also lead to a loss of habitats and species. In turn their functioning and services gets also lost (Griebler et al. 2019). Declining groundwater levels can lead to the separation of a KGDE from its aquifer. As a result, for example aquatic vegetation which is part of the species assemblage of the KGDE is replaced by terrestrial vegetation (Erostate et al. 2020). Hence, for the management of groundwater resources, a trade-off between the need for drinking water and irrigation and the sustainable management of the groundwater resource in terms of preserving the ecosystem and its associated services is necessary but often difficult (Kløve et al. 2011b).

1.2.3 Habitat destruction and disturbances

The destruction of karst groundwater-dependent habitats and the disturbance by humans comprise a wide variety of human actions. The drainage of wetlands to apply for development needs or additional agricultural spaces is a frequently occurring approach, that transforms and constrains the hydrological system and the natural flow (Erostate et al. 2020). Other disturbances include excavations in river beds that disturb the hyporheic zone (Galassi et al. 2014), the capturing of springs, vegetation removal and general urbanization (Kostoski et al. 2010; Erostate et al. 2020). In general, habitat destruction and land-use changes belong to the main causes of species extinctions and loss of biodiversity (Chapin et al. 2011). Additionally, population growth and tourism are an increasing pressure in the Mediterranean (Kløve et al. 2011b; Erostate et al. 2020; Fosse 2021). This increases on one hand the water demand and on the other also the amount of wastewater and potential contamination. Tourism can also directly affect ecosystems by intruding into them and destroying sensitive vegetation structures (Kostoski et al. 2010). Moreover, the development of facilities needed for tourists takes up space – in many cases adjacent to a natural amenity. Therefore, urbanization occurs often close to the waterbodies and lead to the destruction of surrounding ecosystems and habitat fragmentation (Fosse 2021; Kostoski et al. 2010). On the other hand, tourism can also be seen as a chance. It serves economic interests and depicts an ecosystems service with growing recognition (Erostate et al. 2020; Kløve et al. 2011b). Therefore, the total economic value of an ecosystem increases and the degradation of it would destroy that economic value and touristic appeal (Fosse 2021).

1.2.4 Role of climate change

The changing climate does not depict an independent threat itself but it intensifies the existing pressures on KGDEs (Erostate et al. 2020). One issue of the changing climate is the increasing number of droughts and heavy rainfall events. During prolonged drought, soils lose their capability to absorb and infiltrate water. As a result heavy rainfall runs off at the surface directly entering surface water bodies without replenishing the aquifers (Galassi et al. 2014; Griebler et al. 2019). Additionally, droughts lead to the temporal drying up of riverbeds and wetlands putting more pressure on them (Griebler et al. 2019). On the other hand, flash floods can erode soils, damage river habitats and adjacent wetlands and reduce microhabitat heterogeneity. Another consequence is the compaction of river sediments that alters the vertical connectivity between the hyporheic zone and the aquifer below. All of this results in a loss of biodiversity in terms of species and habitats (Galassi et al. 2014). Regarding urban areas, climate change represented by intense rainfall events pose a pollution risk for groundwater-dependent ecosystems. The large amount of surface runoff during these events can lead to the uncontrolled release of untreated wastewater, when the runoff water is collected in overflow channels containing contaminants and then get discharged into rivers and streams (Griebler et al. 2019). In contrast to the impact of changing precipitation patterns, the increase of the average temperature affects KGDEs less (Kløve et al. 2014), because groundwater temperature is less dependent on the air temperature than surface waterbodies. Still, even a slight increase of groundwater temperature causes alterations of the dissolved oxygen concentrations influencing biogeochemical reactions which in turn can lead to the deterioration of the water quality and change microbial communities (Kløve et al. 2014; Retter et al. 2021). Furthermore, surface water temperature is more directly related to air temperature and hence the rising temperature alters the thermal regime of surface waterbodies and by that the species distribution and assemblage structure of these ecosystems (Kløve et al. 2014).

1.3 Karst groundwater-dependent ecosystems in the Mediterranean Area

Karst aquifers are widely distributed in the Mediterranean area and contribute significantly to the water supply in this region (Stevanović 2019). For a sustainable management of Mediterranean karst groundwater resources, the consideration of ecosystems that also rely on the groundwater is an essential component, as they also provide us with important ecosystem services. Thus, the inclusion of karst groundwater-dependent ecosystems as one research subject of the KARMA project is important. Progress on the hydrogeological and ecological understanding of KGDEs is relevant in order to design appropriate management strategies which allow the utilization of the groundwater and the conservation of the ecosystems at the same time.

Furthermore, KGDEs in the Mediterranean area are important to pay attention to because the Mediterranean area in general is known to be a biodiversity hotspot with conservation priority (Myers et al. 2000). Especially, the high diversity and endemicity of vascular plants stands out in the Mediterranean area (Cowling et al. 1996; Myers et al. 2000). Cowling et al. (1996) suggest that the high regional diversity of vascular plants in the Mediterranean basin might be due to the high climatic and topographical heterogeneity that can be found here. In addition to the high plant diversity, another study on biodiversity in groundwater habitats in Europe state eight hotspots of which all except one are located at least in parts of it in the Mediterranean area (Iannella et al. 2020). Hence, this illustrates that KGDEs in the Mediterranean have great potential in terms of species richness, endemicity and thus great conservation value.

1.4 Research questions

This Deliverable presents a selection of 113 KGDEs in the Mediterranean area and addresses their distribution and basic properties with the focus on endemism, as well as on the protection and threats of them. Additionally, detailed descriptions of seven KGDEs are given. The provided selection cannot be considered exhaustive of existing KGDEs in the Mediterranean area, but it has potential to illustrate the significant relevance of such ecosystems in the region.

The objective is to answer the following questions:

1. Which criteria can be used to classify and evaluate KGDEs?

2. How are KGDEs distributed and which KGDEs in the Mediterranean region stand out in terms of ecological value and ecosystem services?

3. What are the major risks that endanger KGDEs in the Mediterranean?

4. How can KGDEs be protected and which measures are already applied to do so?

2. Collecting data on karst groundwater-dependent ecosystems in the Mediterranean area

2.1 Study area delineation

The KARMA project is designed to deal with karst areas of the Mediterranean area. The MEDKAM which is another product of this transboundary project serves as spatial orientation and large-scale delineation for the entire project. For the present study, the MEDKAM section serves as orientation but there is need for a focus area to narrow down the area for which KGDEs are actively searched and selected. The term "Mediterranean" refers to different characteristics and as a result comprises different regions, which complicates a clear definition of Mediterranean area. In the following five concepts on what "Mediterranean" can mean and which regions are covered by those concepts, are presented.

2.1.1 Mediterranean climate zones

The typical Mediterranean climate describes temperate climate with a dry season during summer, precipitation mainly occurring in winter and generally hot or warm summers. This refers to the climate classes of Csa and Csb after Köppen and Geiger (Schönwiese 2020). According to this climate classification, C refers to warm temperate climates with an average temperature of the coldest month between +18 °C and -3 °C (Beck et al. 2018). The s refers to the dry season in summer which is defined by the maximum monthly precipitation sum of the winter being three times higher than the minimum monthly precipitation sum in summer (Beck et al. 2018). Additionally, a and b correspond to the maximum monthly averaged temperature. If this is larger than 22 °C the a is added, and if it is less than 22 °C but at least for four months above 10 °C the b is added to the classification (Beck et al. 2018). In other words, these describe hot and warm summers respectively.

As shown in Fig. 3a), large parts along the Mediterranean coastline do not show typical Mediterranean climate. Especially in Northern Africa and Spain large parts classified differently. Also, the Dinarides and the Northern and Eastern part of Italy are not included in the Mediterranean climate zone. As they present important karst areas the climatological classification of Mediterranean does not fit well for the delineation of the focus area for this project. Furthermore, Mediterranean climate which is represented by the classes Csa and Csb does not only occur around the Mediterranean Sea, but also in other parts of the world like Australia, South Africa, Chile or the West coast of the United States.

2.1.2 Mediterranean biome

The biome of "Mediterranean Forests, Woodlands & Scrub" describes the typical Mediterranean vegetation. It comprises typically sclerophyll vegetation and the two forms of Macchie and Garrigue are commonly found in this area (Breckle and Rafiqpoor 2019). Macchie describes a medium large evergreen shrub vegetation form which develops on slopes where larger trees cannot grow or depends on regular degradation by cutting, whereas Garrigue depicts scrublands with open spaces and lower shrubs. They develop through degradation by grazing or regular fires (Breckle and Rafiqpoor 2019). Due to the scarce vegetation cover, soil gets washed away which again decreases the chances that trees can grow there again. The area of this Mediterranean biome overlaps in large parts with the Mediterranean climate zones (cf. Fig. 3). Therefore, these concepts share some of the advantages and disadvantages regarding the use of it for the definition of the study area for this project. In contrast to the climatological classification, the Mediterranean biome covers larger areas. Spain is almost completely included and also Northern Africa is covered in a larger extent. Still, large karstic regions of Italy (Southern Alps and Central Apennine mountains) and the Dinaric Karst region are excluded, which is not suitable for this study.

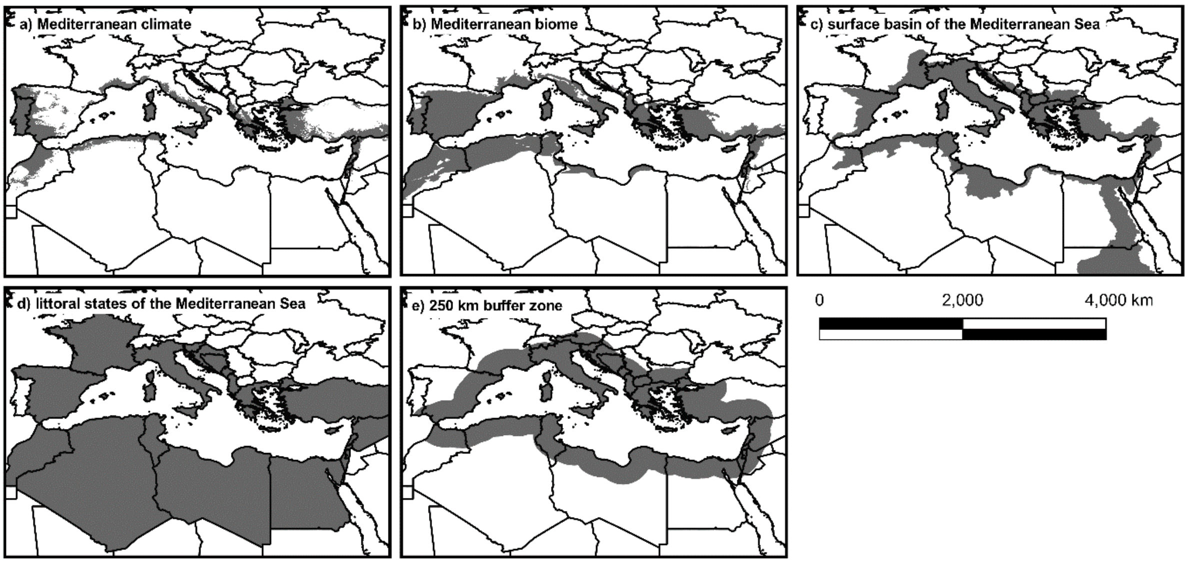


Fig. 3: illustration of four concepts (a-d) of Mediterranean: a) climate classes of Csa and Csb after Köppen-Geiger, b) biome: Mediterranean Forests, Woodlands & Scrub, c) surface drainage basin of the Mediterranean Sea, d) littoral states, e) represents a buffer zone of 250 km width around the Mediterranean coastline.

2.1.3 Surface basin of the Mediterranean Sea

Fig. 3c) displays the surface basin of the Mediterranean Sea. One thing that appears directly is the catchment of the Nile that extends far into the African continent. Regarding the Dinaric Karst region, and the areas north-east and west of the Nile catchment, the surface basin comprises only a thin stripe along the coast. Hence, large parts of the karst regions that are situated in these regions do not overlap with the Mediterranean surface basin, which is a disadvantage of this concept of Mediterranean area. Also, even though this study deals with groundwater, the surface basin is not suitable as reference for flow directions and delineation because the surface basin is not applicable for groundwater flow in karst aquifers.

2.1.4 Littoral states of the Mediterranean Sea

Defining the Mediterranean area as the total surface area of all littoral states of the Mediterranean Sea seems to be a simple and practical way. This concept ensures that the entire coastline is included in the concept of the Mediterranean Sea (Fig. 3d). It also constitutes practical advantages for the search for KGDEs, because it can be searched in the respective countries without the need to check for any other spatial restrictions. However, one disadvantage of this concept is that some littoral states reach really far into the inner country. For example, Algeria's southern border is up to 2000 km away from the Mediterranean coastline. These inner parts do not represent the typical Mediterranean characteristics really well. Moreover, by this, the extent of the area would be too large. Secondly, some countries like Austria, Bulgaria, North Macedonia and Portugal are not located at the Mediterranean coastline but at least parts of them are not too far away from it and share other Mediterranean properties. As a result, this concept is useful for the literature search on KGDEs but it is not perfectly suitable for the delineation of the focus area.

2.1.5 Buffer zone around the coastline of the Mediterranean Sea

Another approach to define a focus area is to create a buffer zone along the coastline of the Mediterranean Sea. By this the definition is based on the distance of a location to the Mediterranean coastline. Hence, to be part of the focus area, a location must be within a maximum distance to the coastline. The width of the buffer is chosen to be 250 km (Fig. 3e). This is oriented on the extent of the above described Mediterranean properties. Additionally, the selected 250 km buffer zone includes the major karst regions that are presented on the MEDKAM and therefore should be included in the focus area. The buffer zone was applied by using QGIS (version 3.16.12 Hannover). Even though this concept includes subjective assessments, this proves to be suitable as it combines the other concepts well. Moreover, this is meant to give a focus area on and not a definite limitation. This study does not intend to give a complete list of all KGDEs in the Mediterranean region, but instead a selected overview of KGDEs in this area in order to show the general importance and conservation value of groundwater dependent ecosystems.

2.2 KARMA collection

As part of the KARMA project, the project partners were asked for information on KGDEs in their countries/regions. A template for the data collection was created by the project members Prof. Nico Goldscheider and Prof. Marco Petitta in order to provide guidance to the partners on which information is wanted. Also, the template is useful to make the data collection itself more uniform and to share the data. In addition to the project partners, several project advisors and external professionals were contacted and asked for KGDE examples located in the Mediterranean area.

The data received from the project partners included 98 locations representing KGDEs. In some cases, the contributions included potential KGDEs or reserves which could partly consist of KGDEs. For those, further literature research was needed to either confirm or reject it as KGDE. Moreover, some of the received features were specified later on, for example from a reserve to a particular part like a spring, lake or cave. As a result, the collected contributions were modified if needed to make the dataset as a whole more consistent and precise. However, this depends on additional information from project partners and further literature about the given locations. Hence, some KGDE entries kept quite vague or had to be sorted out, because it could not be ensured that they actually present an (intact) KGDE.

2.3 Literature research

The second approach for the selection of KGDEs in the Mediterranean area is based on an online literature research, predominantly by using the literature search engine Google scholar and the scopus literature database search engine. The main focus for that is to search for KGDEs in parts of the focus area which are not or only scarcely covered by the preceding data collection. This includes mainly the riparian regions of the North African countries (Algeria, Libya, Egypt) and the Eastern Mediterranean Sea (Türkiye, Syria, Jordan). Considering the focus area, the search is focussed on the 250 km buffer zone, but also ecosystems located outside this but inside the MEDKAM section can be added if enough information is available.

Searching KGDEs in the focus area is conducted by using different search terms referring to it. Frequent keywords are “karst groundwater”, “ecology”, “ecosystem”, “spring ecology”. Those keywords are added to the name of the region/country of interest. Furthermore, already known springs and caves from the collections of MEDKAM and WOKAM are checked for any ecosystem properties. For this, keywords like “species composition” and “biodiversity” are entered together with the karst feature’s name in the literature search engines. Unfortunately, ecological information for many of them is lacking, so that they cannot be characterized and described as KGDE even though some of them probably function as an ecosystem.

On the other hand, publications on internationally protected sites are considered for the search for potential KGDEs. Ramsar Sites are protected by an intergovernmental convention on wetlands of international importance enforced in 1971. At the beginning of the convention, the focus was put on the conservation of wetlands as habitat for waterfowl but by now it is extended to general biodiversity conservation and sustainable development (Ramsar Convention Secretariat 2016). Two important directives of the EU in terms of nature conservation are the Habitats directive (92/43/EEC) and the Birds directive (2009/147/EC) (EC 1992, 2009). Whilst the Habitats directive aims to preserve or improve the quality of valuable habitats and safeguard rare, endangered, vulnerable or endemic species, the Birds directive targets the protection of all birds naturally occurring in the EU (EC 2008). The sites protected under the Habitats directive are called Special Areas of Conservation (SAC) and the ones of the Birds directive Special Protection Areas (SPA). By the designation of these sites, the EU wide Natura 2000 network is created, which aims to secure Europe's most valuable species and habitats (EC 2008).

Further hints for the search on KGDEs gave international biodiversity programmes that designated hotspot areas. One of them is the Plantlife International which founded the Important Plant Area (IPA) programme to address plant diversity protection (Radford and Odé 2009). They identify IPAs applying internationally consistent criteria which represent species richness, threatened species and habitats (Radford and Odé 2009). The IPA programme evaluates the conservation activities in terms of efficiency as well as target new sites for future protection (Radford and Odé 2009). Additionally, the publications on Freshwater Key Biodiversity Area (KBA) in the Mediterranean which are identified and published by the International Union for Conservation of Nature (IUCN) were consulted (Darwall et al. 2015; Máiz-Tomé et al. 2017). Freshwater Key Biodiversity Areas are selected based on the vulnerability and irreplaceability of a freshwater habitat (Darwall et al. 2015). The aim of the project is to provide essential information needed for guiding conservation investments (Darwall et al. 2015). All the publications and datasets listed above are consulted to find KGDEs in the Mediterranean area. For that, it is reviewed if any of those sites is located in karst areas and if they could represent KGDEs. In order to do so, terms like "hydrogeology", "karst groundwater" or "karst spring" were accompanied by the name of the site for the search.

Additional literature search is conducted on the selected KGDEs to complement the preceding data collection. Especially, information on ecological and hydrological properties and general descriptions of the habitats are of interest, as well as the way a KGDE is utilised and threatened. For this purpose, open-access databases like the Natura 2000 network viewer (https://natura2000.eea.europa.eu/) or the Ramsar sites information service (https://rsis.ramsar.org/ris-search/) were consulted. Among others, they provide standardised information on species occurrence, major threats, the utilisation and mostly a general description of the site. Therefore, the Standard Data Forms (Natura 2000) and Ramsar Sheets which are available for many of the selected KGDEs, serve as valuable data source.

2.4 Additional spatial data

To characterize and describe KGDEs in a comprehensive way, aspects regarding different scientific disciplines like climate, hydrogeology and ecosystem ecology should be considered. Hence, additional data with global coverage is included in the project too. The following data is accessed and processed for the characterisation of the KGDEs by using the software of the QGIS application (version 3.16.12 Hannover). This application was also used to create the maps found in this work.

Regarding climate information, annual mean temperature and annual precipitation, an aridity index and the Köppen-Geiger climate classification are chosen. For the mean temperature and annual precipitation, data from two climate models are used to derive a mean value from these two datasets. One of the datasets is the Chelsa climate dataset by Karger et al. (2018) which refers to temperature and precipitation data of the years 1979-2013 and delivers a resolution of approximately 1 km (30 arc sec, 0.0083°). The same resolution is also provided by the second dataset WorldClim 2 by Fick and Hijmans (2017) which in contrast relates to the data from 1970-2000. Since the data is modelled, deviations from the prevailing climatic variables at the KGDE sites are possible. It must also be noted that the annual precipitation at some KGDE locations shows particularly high interannual variance between dry and rainy years, which is not reflected by recording a single average value for the annual precipitation. Yet to ensure a uniform data source and methodology for the entire data collection, these climate models are used as data source. In order to avoid major mistakes by large deviations, the values extracted from the climate models are compared with data from literature or adjacent climate stations where it was possible. When the deviation is substantially large, the modelled values are replaced by the values provided in the literature or climate stations. This is the case for the KGDEs of Ein Feshkha, Ein Gedi and the Siwa oasis. Data on the aridity is provided by Karger et al. (2018) as well and consists of a simple aridity index (AI) made out of the ratio between precipitation and potential evapotranspiration (P/PET). Based on this ratio, sites with AI > 1 refer to humid and otherwise with AI < 1 to arid conditions (Schönwiese 2020). The World Atlas of Desertification gives another classification based on this ratio. It describes sites with AI < 0.65 as drylands and all others as non-drylands, with drylands being those which are susceptible to desertification (Cherlet et al. 2018).

Additionally, data on the Köppen-Geiger classification from GloH20 (Beck et al. 2018) is used as another climatological variable for the characterisation of the KGDEs. The data is based on several climate models and has a high resolution (0.0083°, approx. 1 km²) which makes it possible to consider climate-effects on a relatively small scale which might be relevant for the KGDEs. As the data is only provided for land surface areas, the two selected submarine spring KGDEs are not covered. To account for this, the closest available Köppen-Geiger class is extracted and assigned to them.

Furthermore, altitude data was derived from GMTED2010 terrain data which is provided by and downloaded at the USGS Earth Explorer (Danielson and Gesch 2011). The dataset provides terrain data at different resolutions and for this work the highest resolution of 7.5 arc sec, approximately 250 m, is selected. In order to cover the area of the KGDE selection, four panels are needed and have to be merged. In the following, the altitude values are extracted for the KGDE point locations.

To provide an overview of the general large-scale class of ecosystems (biomes) that are present in the study area and further characterize the KGDE location, the map of “Terrestrial Ecoregions of the World” by Olson et al. (2001) is employed. It includes a division into eight biogeographic realms, 14 biomes and 867 comparatively detailed units of ecoregions. As the entire study area belongs to the Palearctic realm and the ecoregions are too detailed in scale for this study, the biomes serve as biogeographical information in the following.

Moreover, a database of protected areas from all over the world by UNEP-WCMC and IUCN (2022) is a valuable data source in order to figure out more about the protection status of the KGDEs. Because it is an international database with global coverage it is suitable for a consistent comparison and classification of the KGDEs in terms of conservation. Among others, it contains the IUCN protection category of a protected site where it is available and applicable. The IUCN defines seven protection categories named with roman numerals, ranging from Ia being the strictest to VI being the most liberal protection category (cf. Tab. 1) (Dudley 2013). Each category is associated with specific properties of the protected feature and certain objectives for it. As the classification is designed to account for protected areas worldwide, the definition is intentionally kept general (Dudley 2013).

Additionally, the IUCN database contains the type of protection area (e.g. Ramsar, UNESCO heritage, National park, Biosphere Reserve) and the spatial level of designation (national, EU, international). The type of protection area is less relevant for this study because due to the various national legislations, protected areas are called differently which makes this difficult to evaluate. At the same time, this demonstrates the need for a globally applicable classification of protected areas as the IUCN protection category provides. Also, it must be noted that even though names of national legislations may be the same as the IUCN categories, they do not always match the objectives of the respective category.

Tab. 1: names of the IUCN protection categories (IUCN report).

category	name
Ia	strict nature reserve
Ib	wilderness area
II	national park
III	natural monument or feature
IV	habitat/species management area
V	protected landscape/seascape
VI	protected area with sustainable use of natural resources

2.5 Creation of a consistent dataset for evaluation

Based on all the above mentioned collected data, the goal is to derive a comprehensive and descriptive table with simple categories and some numeric variables, which allow a basic evaluation and illustration of the distribution and frequency of KGDEs and their properties. Also, this integrates all data in one clearly arranged document. Table 2 gives an overview of the variables/categories that make up the dataset. General information of each KGDE include the name, the coordinates in WGS84 coordinate reference system, the altitude, the country and the region which it is part of. Here, the region refers to the classification into major regions from the United Nations Statistics Division (UNSD). Secondly, the dataset contains ecological information which consist of the ecosystem type, the biome (Olson et al. 2001), the binary variables (yes/no) of the occurrence of endemic species and of the occurrence of stygo- or troglobionts. In addition, to the endemic species occurrence, two more variables about endemism are included. When dealing with endemism the spatial concept to which a species is described as “endemic” is crucial. Unfortunately, many sources only state that endemic species occur without mentioning the space to which their distribution is restricted too. As a result, further checks have to be made to figure out to which spatial extent “endemic” species of an ecosystem are limited. The results are recorded in a categorial variable called “narrowest endemism concept” which reflects the narrowest spatial extent over which one of the endemic species of the respective KGDE is distributed. For this, four options are possible. The narrowest concept concerns species that only inhabit one given site, e.g. if they are restricted to one lake or cave ecosystem. Endemic species that are distributed at the given KGDE and only its closer surroundings including rather small geographical units (same karst system, smaller mountain ranges, valleys etc.) are allocated to the category of local endemism. The third category comprises nationally endemic species and the last one regional endemic species. Here, region describes any transboundary geographical units like the Atlas mountain range, the Iberian Peninsula, or the Balkan area.

Tab. 2: grouped list of the variables used for the characterization of the KGDEs.

general information	ecology	hydrology	climate	human interaction
- name - coordinates - altitude - country - region	- ecosystem type - components - biome - occurrence of endemic species - narrowest level of endemism - species groups of endemic species - stygobionts/ troglobionts	- position in hydrological cycle - hydroperiod	- annual mean temperature - annual precipitation - aridity index - Köppen-Geiger climate classification	- utilisation by human - main threats - IUCN protection category - type of protection area - spatial level of designation

The second additional variable on endemism includes the taxonomic groups of the present endemic species of each KGDE. For reasons of practicality, the groups do not cover the entire kingdom of animals and plants systematically. Instead, groups that are mentioned regularly in the reviewed literature and data sheets of protected areas are selected. Hence, plants are not subdivided any further. Vertebrates are split into the five classes (reptile, fish, amphibian, mammal, bird) although there are no birds that are endemic to any of the selected KGDEs. Regarding invertebrates, species groups are included based on their occurrence in the literature and by that the occurrence within the selected KGDEs.

Regarding hydrological properties, the dataset contains two variables. The first one is the position within the hydrological cycle. Here, each ecosystem was assigned a position that depends on both the location and the ecosystem type. It partly reflects the hydrological function of the KGDEs as well. A second variable describes the hydroperiod of the KGDEs, which distinguishes between permanent and non-permanent water flow (for springs, rivers) or water occurrence (for wetlands, lakes and caves). As Kløve et al. (2011a) suggest, the hydroperiod can be an interesting aspect for classifying GDEs.

The last field of topic that is covered in the dataset deals with the human interactions with the KGDE. One part of it is the information extracted out of the IUCN database described earlier. The second part are the main threats and the utilisation. To gather those, the Standard data forms of Natura 2000 sites and the Ramsar Sheets are the main source. Regarding the threats, only the threats which were considered as high threat are included in the dataset. For KGDEs which are not covered in Ramsar Sheets or Standard Data forms other literature sources and the data collection from the KARMA partners are the only data source.

Finally, it is important to point out that despite the extensive literature review and data collection, this study can only cover a selection and not a full-featured complete dataset on all KGDEs in the Mediterranean. Also, among the KGDE examples presented here, several gaps remain open and in turn the evaluation only refer to the available and found data.

3. Distribution and characterization of karst groundwater-dependent ecosystems in the Mediterranean area

3.1 Spatial distribution

In total 113 KGDEs all around the Mediterranean Sea are chosen and characterized. Tab. 3 lists all KGDEs and the country in which they are located in. The map in Fig. 4 gives an overview of the distribution of them in respect to administrative regions. The most of the selected KGDEs (68) are located in Southern Europe. From the major regions of Northern Africa (15), Western Europe (14) and West Asia (13) almost the same number of KGDEs were identified and chosen. Bulgaria is presented by 3 KGDEs and Bulgaria is the only country within the study area that belongs to Eastern Europe following the definition of the UNSD.

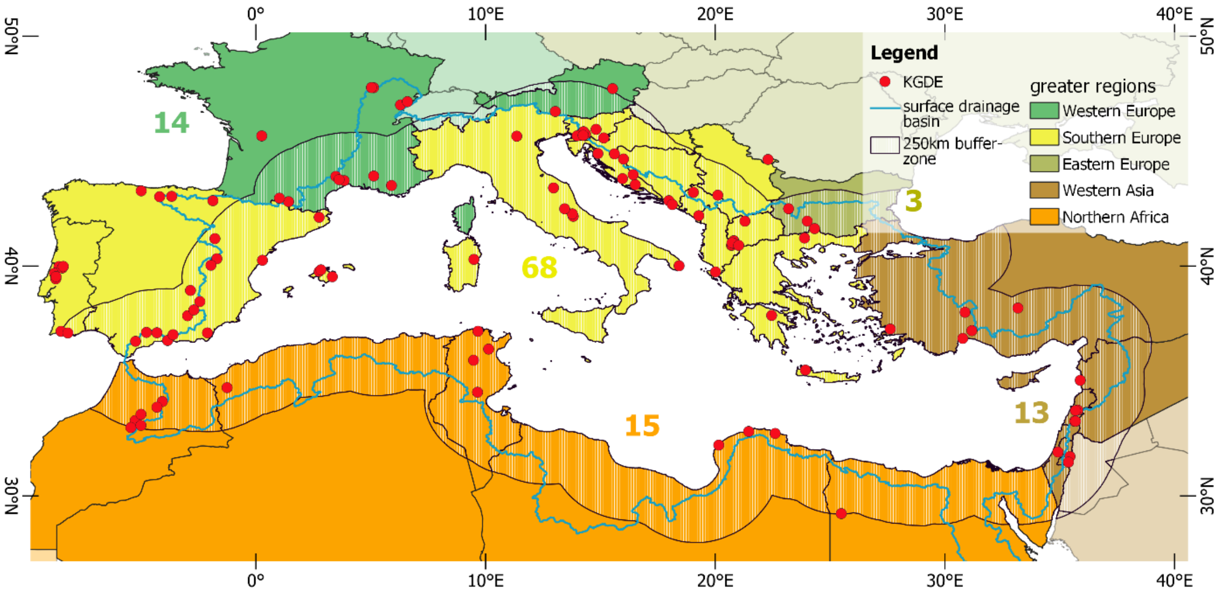


Fig. 4: distribution of the KGDES (red points) within the study area. The colours of the countries correspond to the division into region by the UNSD and the respective numbers correspond to the number of KGDEs in the associated region. For orientation, the watershed of the surface catchment of the Mediterranean Sea is shown as a blue line and the area of the 250 km buffer is line-hatched in white.

Another type of regional classification is the one of the biogeographical divisions into biomes. Fig. 5 depicts the prevailing biomes of the study area and all 113 KGDEs. The predominant biome in the study area are the Mediterranean Forests, Woodlands and Scrub. Hence, 73, almost two thirds of the selected KGDEs, are located in this biome. "Temperate Broadleaf and Mixed Forests" is the second most represented biome with 28 KGDEs. In contrast, the oases of Ein Feshkha and Ein Gedi are situated in a for the study area comparatively exceptional and surprising biome, namely Desert and Xeric Shrublands. The oases however do not represent this biome and therefore demonstrate how the emerging groundwater can change the landscape and how this forms habitats that differ from the biome, that is actually given at their location. Thus, the ecosystems can serve as refuge for species that could not survive in the surrounding landscape (Cartwright et al. 2020) and therefore enhance the regional biodiversity. Additionally, there are two submarine springs KGDEs for which there is no biome classification, as they are no terrestrial ecosystem.

Tab. 3: all selected KGDEs sorted alphabetically according to the country in which they are situated.

ID	name	country	ID	name	country
1	Butrint	Albania	58	Studenchishte marsh	N. Macedonia
2	Drilon	Albania	59	Veli Dab	N. Macedonia
3	Rhar Bou Ma'za	Algeria	60	Matka	N. Macedonia
4	Lappenbach tufa springs	Austria	61	Alviela spring, Mira Minde polje	Portugal
5	Nassköhr bogs	Austria	62	Nascente do Rio Ancos	Portugal
6	Vjetrenica cave, Popovo polje	Bosnia and Herzegovina	63	Fontes do Lis	Portugal
7	Yagodinska	Bulgaria	64	Nascente do Rio Nabao	Portugal
8	Lepenitsa	Bulgaria	65	Fontes de Estombar	Portugal
9	Duhlata	Bulgaria	66	Olhos des Agua	Portugal
10	Plitvice Lakes	Croatia	67	Sistema Espeleologico do Dueca	Portugal
11	Krka river, Skradinski buk	Croatia	68	Moinhos Velhos Cave system	Portugal
12	Ombla spring	Croatia	69	Pester polje	Serbia
13	Jadro spring	Croatia	70	Djerdap gorge	Serbia
14	Vruljas of Velebit channel	Croatia	71	Postojnska jama	Slovenia
15	Cetina	Croatia	72	Skocjan caves	Slovenia
16	Siwa Oasis	Egypt	73	Cerknica lake	Slovenia
17	Lez	France	74	Planinsko polje	Slovenia
18	Fontaine-de-Vaucluse, Sorgue	France	75	Pivka lakes	Slovenia
19	Touvre	France	76	Doblicica, Jelsevnik	Slovenia
20	Aube	France	77	Vir pri Sticni	Slovenia
21	Argens	France	78	Cuevas del Drach	Spain
22	Loue	France	79	Lagunas de Ruidera	Spain
23	Langres Plateau peat swamp	France	80	Lago de Banolas	Spain
24	Dessoubre	France	81	Laguna de Fuente de Piedra	Spain
25	Foux de la Vis	France	82	Lagunas de Archidona	Spain
26	Bernadouze bog	France	83	Lagos de Covadonga	Spain
27	Baget-Sainte Catherine system	France	84	Cueva de Nerja	Spain
28	Cent-fonts	France	85	Karst en yesos de Sorbas	Spain
29	Aggitis river	Greece	86	Nacimiento del rio Guadalquivir	Spain
30	Stymfalia lake	Greece	87	Nacimiento del rio Segura	Spain
31	Agyia springs	Greece	88	Manantial de Alcossebre	Spain
32	Dan	Israel	89	Nacimiento del rio Ebro	Spain
33	Banyas	Israel	90	Nacimiento del rio Tajo	Spain
34	Ein Feshkha,Tsukim	Israel (West Bank)	91	Font des Verger	Spain
35	Ein Gedi	Israel	92	Ojo Guarena	Spain
36	Ayalon	Israel	93	Nacimiento del rio Mundo	Spain
37	Capo Pescara springs	Italy	94	Manantial de Arteta	Spain
38	Presciano springs	Italy	95	Cueva del Gato	Spain
39	Chiarino springs	Italy	96	Torcas de Palancares	Spain
40	Frasassi caves	Italy	97	Parque del Monasterio de Piedra	Spain
41	Su Gologone	Italy	98	Laguna del Padul	Spain
42	Buso della Rana	Italy	99	torrents of Serra de Tramuntana	Spain
43	Grotta Zinzulusa	Italy	100	Nahr al Marqiyah	Syria
44	Ammiq wetland	Lebanon	101	springs of Jebel Zaghouan	Tunisia
45	Safa and Barouk springs	Lebanon	102	Lac Ichkeul	Tunisia
46	Ain Elshakika	Libya	103	Ain Charchara, Hammam Haddej	Tunisia
47	Ayn Zayanah	Libya	104	Grotte ain Dhab	Tunisia
48	Wadi Derna	Libya	105	Kizören Obrouk	Türkiye
49	Afennourir lake	Morocco	106	Güllük Lagoon	Türkiye
50	Lacs d'Imouzzer du kandar	Morocco	107	Düden	Türkiye
51	Aguelmam Azegza	Morocco	108	Egirdir	Türkiye
52	Aguelmam Sidi Ali - Tifounassine	Morocco	109	Köprücay river, Oluk Köprü spring	Türkiye
53	Friouatto	Morocco	110	Skadar lake	transboundary
54	Oued Chaara	Morocco	111	Ohrid lake	transboundary
55	Piva and Tara River (Durmitor)	Montenegro	112	Prespa lake	transboundary
56	St. Naum	N. Macedonia	113	Una	transboundary
57	Biljanini springs	N. Macedonia			

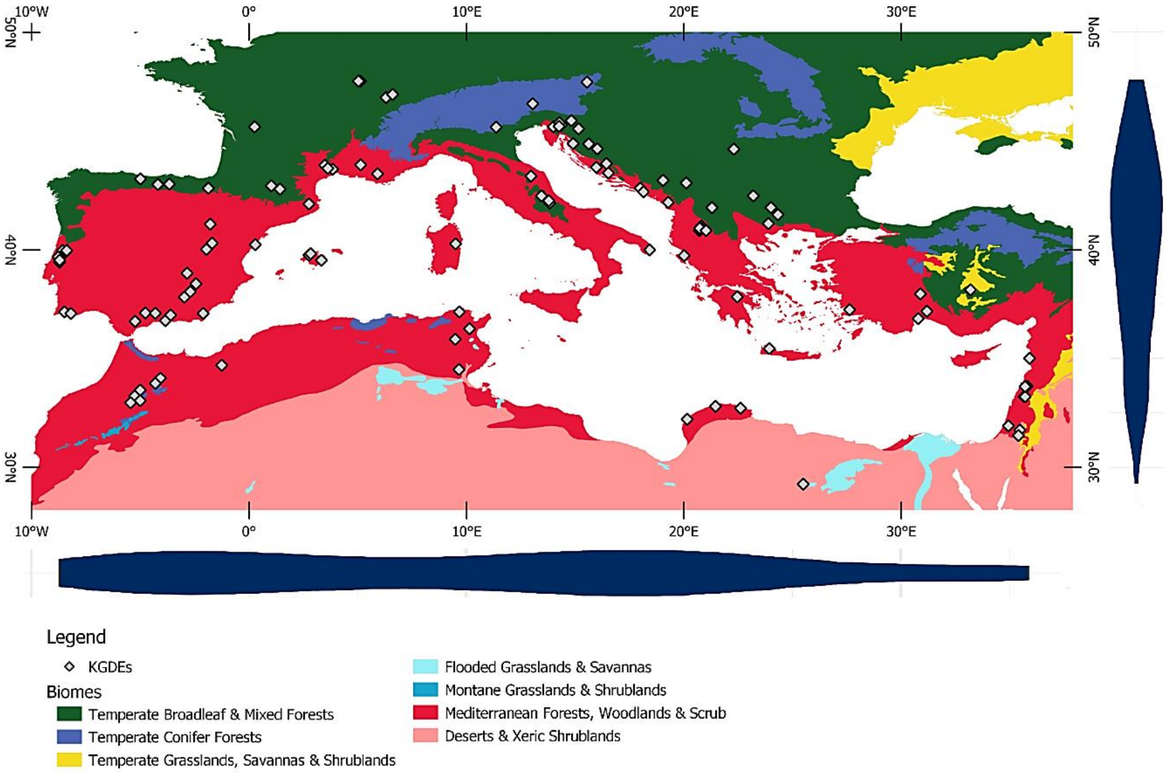


Fig. 5: KGDE locations (grey rhombi) displayed on a biome classification map according to Olson et al. (2001). The violin chart on the below the map shows the longitudinal distribution of KGDEs with two clusters between -5 to 0 °and 15 to 20 °. On the right, the same is presented for the latitudinal distribution with one main cluster at

Concerning the distribution of the selected KGDEs within the study area, the violin charts beside and underneath the map in Fig. 5 display the latitudinal and longitudinal distribution of the KGDEs. Here it is visible, that the data collection shows two clusters in longitudinal direction at -5° to 0° and 15° to 20°E and that the most KGDEs are situated between 40° and 45°N regarding the latitudinal distribution. These clusters correlate with the Balkan peninsula and more specifically the Dinarides and secondly with the Iberian Peninsula and the Northern Moroccan Atlas. Smaller accumulations of KGDEs can be identified in the Eastern Mediterranean region and the Gran Sasso mountains. It must be noted again, that this can only represent the distribution of the collected data.

KGDEs in the Mediterranean area cover a large range of altitudes, which is illustrated in the selection by KGDEs ranging from 391 m below sea level at the Ein Feshkha oasis up to 2075 m above sea level at the Aguelmam Sidi Ali - Tifounassine wetland. Many of them are located directly at the coast but several KGDEs can also be found up high in mountain ranges like the Atlas. Others are located even underneath the sea level like the example of the Ein Feshkha oasis at the Dead Sea shore. The distribution in altitude of the selected KGDEs is illustrated in the violin chart of Fig. 6. A majority of the selected KGDEs are situated in heights between 0 and 300 m above sea level. However, the given 113 KGDEs represent only a selection of KGDEs in the Mediterranean area thus the distribution pattern would probably change if more KGDEs would be included.

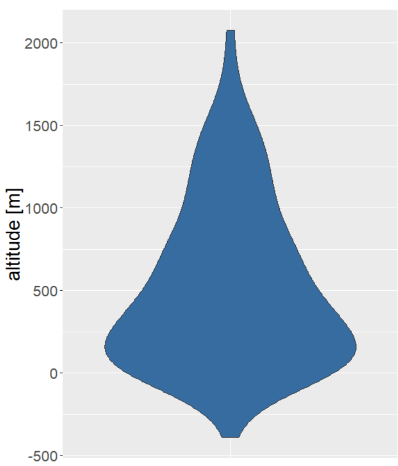


Fig. 6: distribution of the KGDE selection in altitude.

3.2 Ecosystem types

A first step of the characterization of the KGDEs is the determination of their ecosystem type. However, since many KGDEs consist of several components and different habitats, the ecosystem type is therefore not clearly delineated in some cases. Hence, an attempt was made to use the main type for which the most information can be collected without neglecting the other components. This becomes particularly clear by dealing with spring ecosystems. Here, the aquifer cavities and the following river parts are considered too as they all interact. This must always be kept in mind when discussing the type of ecosystems. Fig. 7 shows the distribution of the types among the KDGE selection. According to the data selection, rivers (29), springs (28) and caves (23) are the most common KGDEs. Lakes follow with 16 examples and 11 karst groundwater-dependent wetlands were found. More special KGDE in types in the collection include the two lagoons of Güllük lagoon in Türkiye and the Ayn Zayanah in Libya. Furthermore, there are the submarine springs "Vruljas" in the Velebit channel off the coast of Croatia and the submarine springs of Olhos de Água in Portugal. Additionally, the KGDE collection contains the sublacustrine springs of Veli Dab in Lake Ohrid and the dolines Torcas de Palancares that are occasionally flooded.

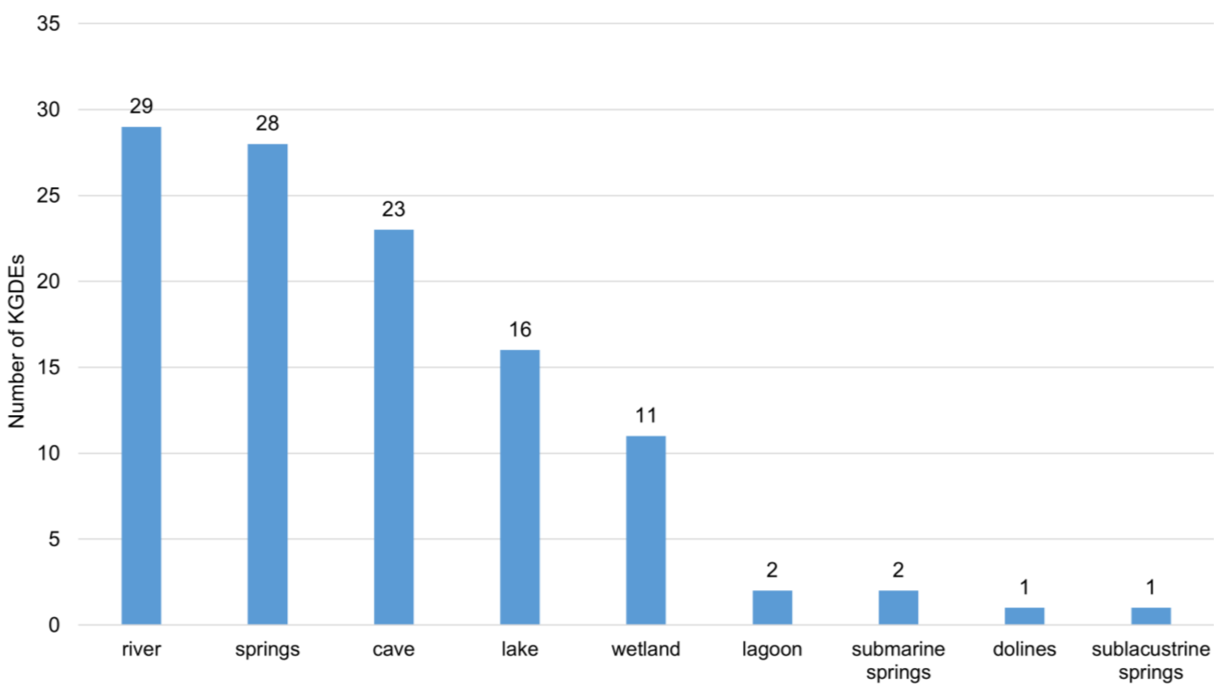


Fig. 7: number of the ecosystem types among the selected KGDEs.

Beside the main types of ecosystems, the KGDE collection covers a wide range of habitats and landform features. Wetland forms such as mires, bogs, alkaline fens, marshes and wet meadows can be identified. As it is typical for karst landscapes, the KGDEs also contain deep river gorges, canyons, sinking streams, torrents, dolines, uvalas and poljes. In addition, oases, wadis and saline lakes have been identified as several KGDEs which are situated in drier climates. Furthermore, waterfalls and limestone-precipitating springs are part of some of the selected KGDEs like the well-known Plitvice lakes, the Lagunas de Ruidera or in the Parque del Monasteria de Piedra. Cavities ranging from large caves to the epikarst are also habitats for many species in several of the KGDEs. As shown in Fig. 7 the four ecosystem types of lagoons, submarine and sublacustrine springs, dolines are only represented with one or two examples of KGDEs. Therefore, these ecosystem types and hence these KGDEs are not included in any further analysis steps for which ecosystem type is put in context with other variables.

3.3 Hydrology

Fig. 8 shows the distribution of the KGDEs within the hydrological cycle. Most of the selected KGDEs are situated at the surface-groundwater interaction zone (31) and the same number of KGDEs (31) are associated with surface flow. Further 26 examples are found at the surface too but are related to water storage as in a lake or wetland ecosystem. Typically for karst groundwater-dependent ecosystems, a large part of the selected KGDEs is also subterranean (20). These are represented by the caves and smaller cavity habitats. Even though, many KGDEs are located close to the sea, only some of the chosen KGDEs interact directly with seawater. Three examples show direct groundwater-sea interactions and the two lagoons represent KGDEs at the surface water-sea interaction zone. Apart from them, many other KGDEs are close to the Mediterranean coast and hence, their downstream parts are connected to the sea too. Examples for this are the lake Butrint in Albania which is connected to the Mediterranean Sea by an approximately 2.5 km long canal or the Ombla spring which emerges close to the coast and enters the Ombla bay already after 20 m and therefore gets affected by the sea shortly after the emergence.

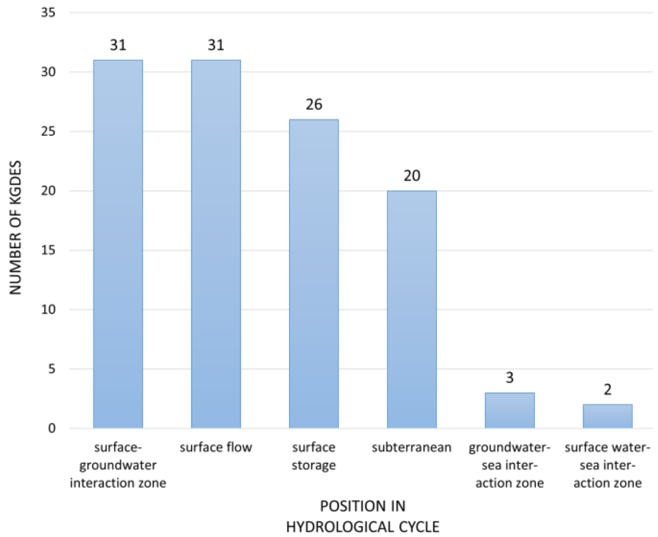


Fig. 9: distribution of the selected KGDEs among the positions in the hydrological cycle.

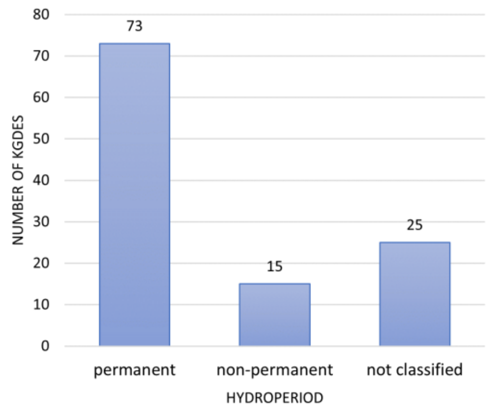


Fig. 8: number of selected KGDEs that show permanent/non-permanent water flow or occucrence. For 25 KGDEs the classification was not possible

Within the data collection, 73 KGDEs are assigned to the hydroperiod of permanent discharge or occurrence of water (Fig. 9). Among those KGDEs, many KGDEs still show a great variability in their water regime as it is typical for karst hydrology. For 15 KGDEs it is registered that they are non-permanent. Examples for that depict the intermittent lake occurrences in the Cerknica or Planinsko polje or the episodically flooded dolines Torces de Palancares. As there is no consistent and complete data source for the hydroperiod, a total number of 25 KGDEs could not be assigned clearly. The lack of recent literature for some of those is also a problem for the classification especially for KGDEs that are threatened to dry out due to climate change or overexploitation.

3.4 Species properties

In this project, the focus is put on endemic species at the KGDEs because entire species assemblages are not available in most of the cases. In contrast the presence of endemic species is mostly reported (if investigated) for the ecosystems, so that the availability of this data is better. Because underground ecosystems are also part of this project, the presence of troglobionts and stygobionts was also considered. Fig. 10 shows the percentages of KGDEs that host endemic species and stygobionts or troglobionts for each ecosystem type. Almost, two thirds (65%) of the selected KGDEs prove to harbour at least one endemic species. Regarding the ecosystem types, caves, lakes and springs reveal even higher percentages of endemic species occurrence. The maximum value is found for caves: 78% of the selected cave ecosystems host endemic species. Slightly less often do they occur in lakes (75%) and springs (71%). The high percentage for caves can be explained by the strong isolation of cave ecosystems (Lauritzen 2018; Goldscheider 2019). The high number of endemic species in spring ecosystems confirms the often stated importance of adequate springs conservation (Cantonati et al. 2020; Cartwright et al. 2020; Stevens et al. 2021). This result can be attributed to the fact that springs often form individualistic ecosystems and harbour spring-dependent taxa which are often adapted to the specific condition of the one spring they live in (Cartwright et al. 2020; Stevens et al. 2022). Three quarters of the selected lake ecosystems are inhabited by endemic species. This high number could be due to the isolation of some of these ecosystems, such as Lake Ohrid and Lake Prespa (Albrecht and Wilke 2008). Furthermore, in the course of this study it seemed that lakes are relatively well studied and that a lot of information is available for these ecosystems. Hence, there could be a bias induced by the high level of knowledge. Lower frequencies of endemic species occurrence show the river and wetland KGDEs with 59% and 45%. Regarding the stygo- and troglobionts it is obvious that they most frequently occur in caves (78%) and on second place springs KGDEs follow with a percentage of 32%, as some stygo- and troglobionts get washed out of the cavities from time to time. Rather rare are stygo- and troglobionts in lakes and rivers, with 19% and 10% of the selected KGDEs respectively. For none of the wetland KGDEs stygo- or troglobionts were recorded.

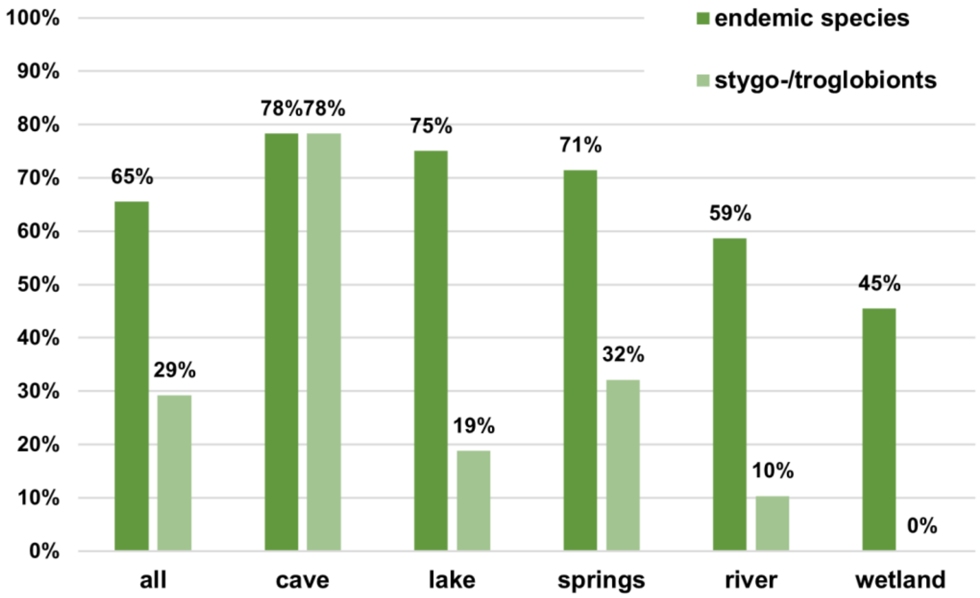


Fig. 10: percentage of KGDEs and examples of the ecosystem types that host endemic species (dark green) and stygo- or troglobionts (light green).

Additionally, the distribution of endemic species was evaluated. By looking at Fig. 11 it becomes apparent, that from the two clusters from -5° to 0° E and 15 to 20° E displayed in Fig. 5, the second cluster further east consists of more KGDEs with endemic species. The yellow violin chart in Fig. 11 shows the distribution of KGDEs with endemic species and here the two clusters in the longitudinal direction are recognisable, but the area between 15° and 20° E is clearly more pronounced. Furthermore, the KGDE cluster in this longitudinal range cannot be discerned in the distribution of KGDEs without endemic species (dark green chart).

This suggests that KGDEs between the longitude of 15° and 20° E harbour more endemic species and therefore have a higher value for the conservation of biodiversity. This longitudinal range correlates again with the karst area of the Dinarides, where the KGDEs harbour exceptional numbers of endemic species. Yet, it has to be noted, that the research on karst and KGDEs is highly advanced in the Dinarides compared to other regions and therefore the results might be biased and other regions could in reality harbour more KGDEs with endemic species as well.

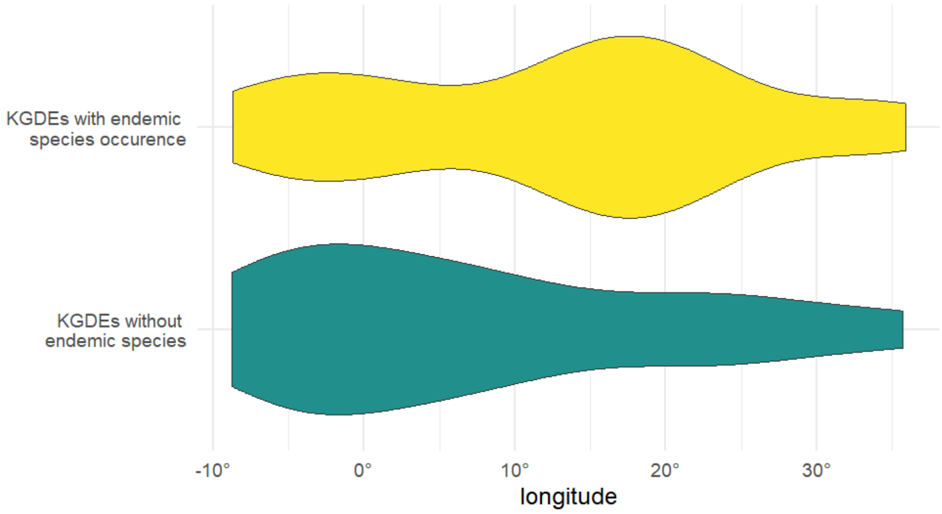


Fig. 11: longitudinal distribution of the selected KGDEs subdivided into KGDEs with at least one endemic species (yellow) and no endemic species (dark green).

As the level of endemism is an important aspect, when dealing with endemic species, it was evaluated to which spatial extent the species are restricted to. For each KGDE the endemic species with the narrowest distribution is taken as reference. No endemic species could be identified for 40 KGDEs. In contrast, 32 KGDEs harbour for at least one species that does only occur in this exact ecosystem (cf. Fig. 12). This corresponds to 28% and by that more than a quarter of the selected ecosystems. At additional 22 KGDEs, endemic species with local distribution were found.

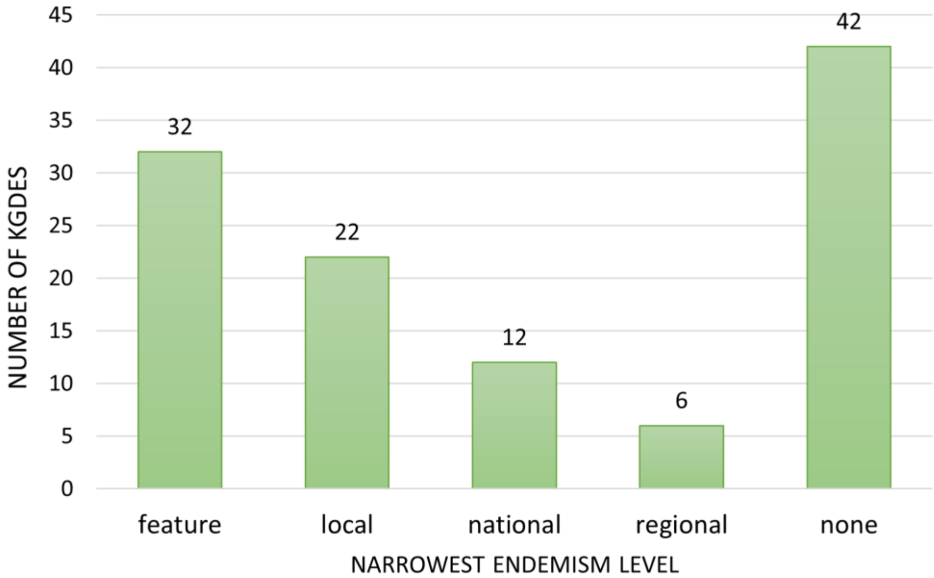


Fig. 12: bar charts illustrating the number of KGDEs that are allocated to the different endemism levels. The endemic species with the narrowest distribution range/endemism level is taken as reference. 40 KGDEs include no endemic species.

As far the available data allows it, the taxonomy of the endemic species at the given KGDEs is considered as well. It is tried to get a rough representation of the taxonomy to which the endemic species belong to. For this purpose, a simplified and selective grouping of species taxa is selected in order to make best use of the available data and at the same time cover the relevant groups for KGDEs.

The most frequent species group with endemic representative is fish (cf. Tab. 4). At 26 of the 113 KGDEs, there was at least one endemic fish. Amphibians follow with endemic representatives at 20 KGDEs, but the occurrence of *Proteus anguinus* in several KGDEs of the Dinaric Karst plays a substantial role for this result. Mollusca and Crustacean share the third position with both being presented with at least one endemic species at 18 KGDEs. Among the endemic Mollusca species, the Gastropoda dominate. This is in accordance with the representative groundwater taxa for KGDEs stated by Ravbar and Pipan (2022). Also, worth mentioning are plants and the Hexapoda which reveal endemic species at 17 and 14 KGDEs respectively. Tab. 4 additionally shows the frequency of species groups with endemic representatives among the ecosystem types. This reveals that for springs and rivers, fish are the species group having most frequently endemic representatives. On the contrary, in caves Crustacean prevail as taxonomic group of endemic species (cf. Tab. 4). Endemic Crustaceans are also proven for five spring ecosystems. The frequent presence of endemic Crustacean in caves and springs fits in with the fact that Crustacean are considered the most diverse group among the stygobionts (Moldovan 2018). For the selected lake KGDEs, the evaluation shows that the most frequently occurring species group with endemic members are plants (at 5 KGDEs) and Mollusca (at 5 KGDEs).

Tab. 4: number of KGDE examples that host an endemic representative of the given species groups. The first row contains the data for all KGDEs together, whereas the KGDE collection is subdivided by their ecosystem type in the following rows and then the number of KGDEs of the given types for which endemic representatives of the given species class are recorded is shown. The species group with the highest frequency of each ecosystem type and of all KGDEs together is printed in bold.

type	**fish**	**amphibian**	**reptile**	**mammal**	**plant**	**Crustacean**	**Hexapoda**	**Mollusca**	**Plathel-minthes**	**Diatomea**	**other**
all	**26**	20	5	1	17	18	14	18	5	5	5
river	**9**	6	1	0	6	0	4	3	0	0	0
spring	**8**	5	2	0	2	5	1	5	2	3	1
cave	2	5	0	1	3	**10**	6	3	1	0	3
lake	**5**	3	2	0	**5**	2	2	**5**	1	1	1
wetland	**2**	1	0	0	1	1	1	1	1	1	0
sublacustrine springs	0	0	0	0	0	0	0	**1**	0	0	0

These results however are probably biased by the fact, that for several ecosystems no information on invertebrate fauna is available and therefore only the occurrence of larger vertebrates and plants is described. This is especially the case for many African KGDEs. Moreover, individual studies usually focus on single taxons, such as Mollusca or Diatomea (Prié 2008; Hauffe et al. 2011; Föller et al. 2015; Cvetkoska et al. 2018; Lai et al. 2020), allowing them to be better known and classified, while other species remain undetermined or undiscovered. As a result, the number of species and thereby also endemic species might be underestimated.

3.5 Climate

Regarding climate, the distribution of KGDEs is shown in Fig. 13 which displays a topographic basemap (Esri World Topo Map) and the KGDEs coloured by the Köppen-Geiger class (Beck et al. 2018) present at their location. The predominant climate type is Csa referring to temperate climate with dry and hot summers. This is found at 41 KGDEs and corresponds to a typical Mediterranean climate. Related to this, there are 8 KGDEs in the climate type of Csb, temperate climate with dry and warm summers. Additionally, temperate climate without a dry season is identified for 27 KGDEs (Cfa: 9, Cfb: 18). In total 17 KGDEs are located in areas with dry climate (B-climates). One can be found in dry cold deserts (BWk) and four in dry hot deserts (BWh), ten KGDEs are situated in areas with dry cold Steppe (BSk) climates and two in dry hot Steppe climates (BSh). Moreover, 20 of the chosen KGDEs are located in areas with D-climates, cold climates. 19 of those area associated with Dfb, warm-summer humid cold climate, and only one KGDE is situated in cold-summer humid cold climate (Dfc). As it can be seen on the altitude values of the KGDEs in Fig. 6, many are located in mountain ranges, which affects the climate. This can explain the larger number of KGDEs with colder and wetter climates than as one might assume when dealing with the Mediterranean area. Also, that is one reason, why the study area is not limited to areas of typical Mediterranean climates as described in chapter 2.1.

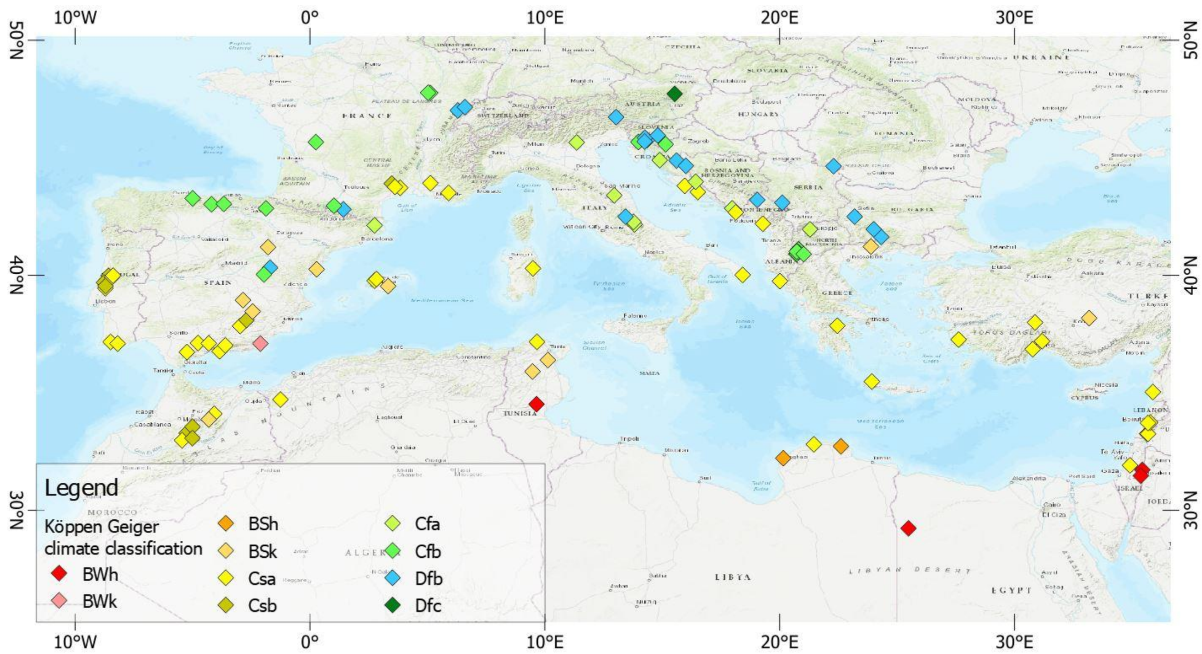


Fig. 13: illustration of the Köppen-Geiger classification of the KGDE locations based on data from Beck et al. (2018). It is displayed on a topographic basemap. basemap data source: Esri, HERE, Garmin, Intermap, INCREMENT P, GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, GIS User Community.

More climatic variables present the aridity, temperature and precipitation (cf. Fig. 14). In total, 30% of the selected KGDEs are located in areas that are associated as drylands because the AI < 0.65. Nevertheless, as it can be seen in the violin chart of Fig. 14c), the majority of KGDEs (59%) is in the range of AI < 1. This reflects arid conditions in which precipitation is less than potential evapotranspiration (Cherlet et al. 2018; Schönwiese 2020), which in turn may indicate a negative water balance and thus water scarcity or declining water resources. The annual mean temperature ranges from 4 °C which can be found at the Nassköhr bogs in Styria/Austria and 24 °C at the Ein Gedi oasis in Israel. The annual precipitation ranges in the data collection between 13 mm to 1674 mm. Here the location of the minimum annual precipitation is the one of the Siwa oasis in Egypt and the one of the maximum is the Skocjan caves in Slovenia.

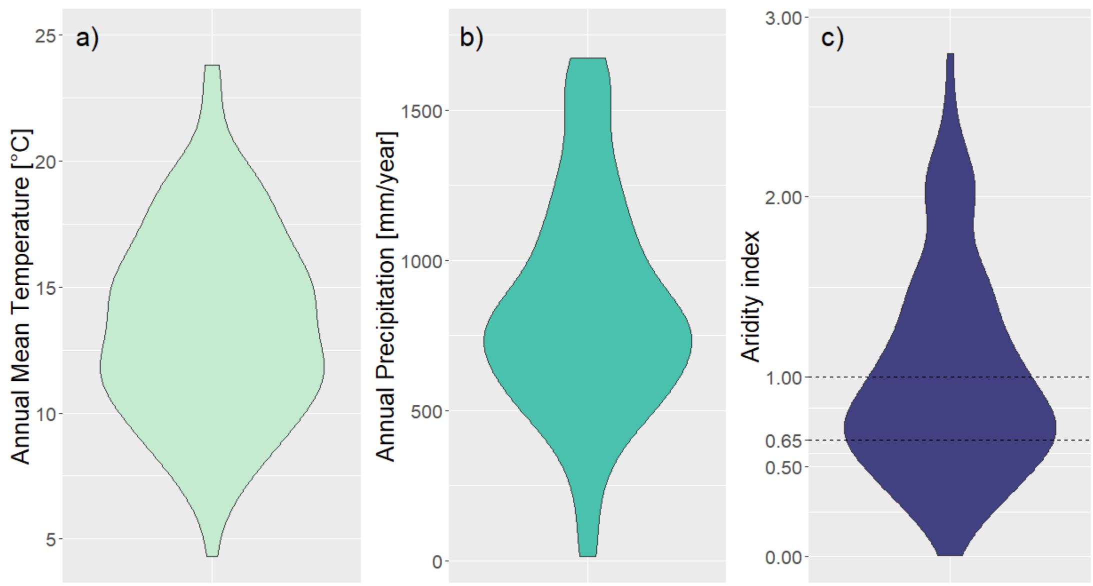


Fig. 14: violin charts showing the distribution of the KGDEs according to three climate variables: a) annual mean temperature in °C, b) annual precipitation in mm/year, c) aridity index.

3.6 Ecosystem utilisation

Out of the 113 selected KGDEs, for 102 KGDEs utilisation by humans in some way is verified. Among them many even serve multiple purposes at once. This proves how valuable KGDEs are for human beings and that they depict important ecosystem service providers. 65% of all selected KGDEs provide recreational and cultural services (cf. Fig. 15). This makes it the most frequently represented type of use and includes all types of touristic, leisure, spiritual and religious activities as well as archaeological and paleontological interests.

In second place comes water supply as service from 36% of the KGDE selection. Here, it was not further distinguished between water supply for irrigation or for drinking water. Except for water, there are other biological resources that are provided by 24% of the listed KGDEs. This category includes food provisions or other biological resources that are needed by humans. It comprises types of uses like hunting, fishing, fish or mussel farming but also grazing at the shore. Other services that are not covered in the previous categories include the utilisation of water for hydropower plant, quarrying and mining, peat extraction from wetlands, salt extraction and woodcutting. Activities like those take place at 8% of the KGDEs.

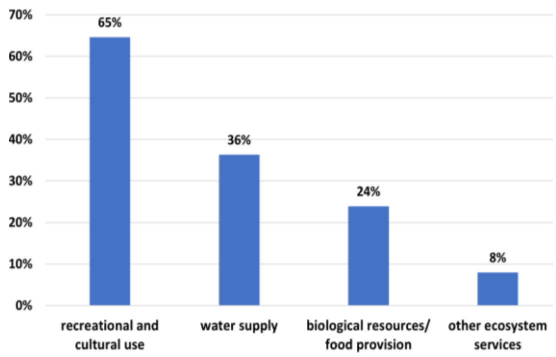


Fig. 15: percentage of KGDEs that serve a given purpose.

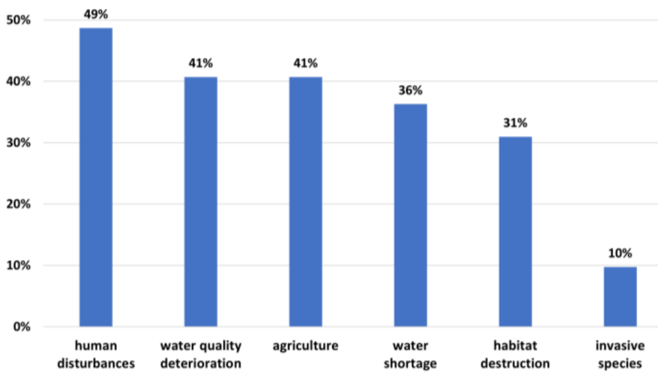
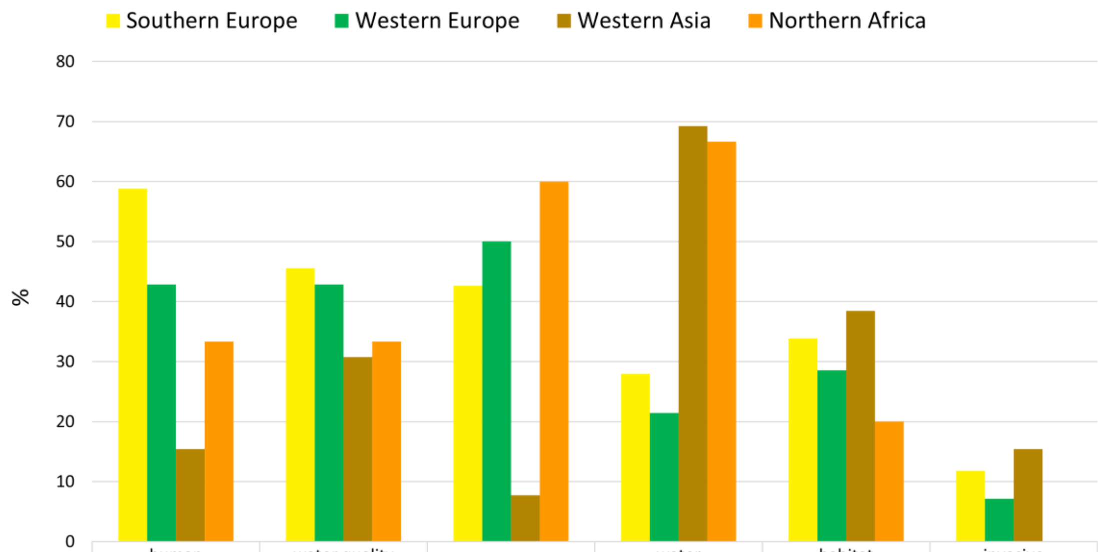


Fig. 16: percentages of the selected KGDEs that must face the given threats and pressures.

3.7 Threats for the ecosystem

Regarding the threats for the selected ecosystems, human disturbances which represent a wide variety of influences by humans, present the most frequent type (49%) of threat to the ecosystems included in this study. This comprises all harmful human activities, including touristic activities, fishing, hunting as well as human induces changes in the hydrological conditions. Here, it has to be pointed out that not all the KGDEs that provide any recreational services are under threat due to these activities. It is usually only a problem when tourism is excessive or uncontrolled or many tourists behave irresponsible. Water quality deterioration is a major threat for 41% of the selected KGDEs. The same number of ecosystems is threatened by agricultural activities. Even though agriculture itself is not a direct threat, it depicts a driver of several threats including excessive groundwater extraction for irrigation or water-logging and soil degradation due to poorly done irrigation and plant removal (Eamus et al. 2016). Agricultural practices encourage water quality deterioration by the application of biocides or fertilisers and can lead to habitat destruction if natural areas get transformed to agricultural land (Kløve et al. 2011b; Erostate et al. 2020). Agriculture was included in this part as a separate category because in literature "agriculture" is often stated as threat or risk without any further specification how it is expressed. The next category represents water shortage, which is found at 36% of the given KGDEs. According to the data, just slightly less ecosystems (31%) are subject of habitat destruction, which include activities like the construction of dams, hydropower plants as well as industrial development and urbanization. Additionally, fires, peat extraction, deforestation or other vegetation removals are included in this category. Less frequent is the threat of invasive species (10%) for the KGDEs considered in this study.



	human disturbances	water quality deterioration	agriculture	water shortage	habitat destruction	invasive species
Southern Europe	59	46	43	28	34	12
Western Europe	43	43	50	21	29	7
Western Asia	15	31	8	69	38	15
Northern Africa	33	33	60	67	20	0

Fig. 17: distribution of the different threat categories among the regions Southern Europe, Western Europe, Western Asia and Northern Africa.

The distribution of the threats among the major regions of the study area is displayed in Fig. 17. Eastern Europe is not included here, because it is not representative with only three KGDEs. According to the literature search and data collection, water shortage as a result of increased droughts and overexploitation is the dominant problem in Western Asia and Northern Africa. Human disturbances are most frequently found problematic in Southern Europe, namely at 59% of the selected KGDEs there. This could correspond to the touristic popularity, as the Mediterranean in general is one of the most visited destinations in the world, with around 400 million international tourist arrivals (Fosse 2021). Based on the data collection, water quality deterioration threatens KGDEs of all regions similarly frequent. It has to be noted here, that these results are based only on the data of the here selected KGDEs and cannot be taken as statistically valid distributions of the threats.

3.8 Protection

Mainly based on the IUCN database of protected areas, the KGDEs protection status was evaluated. This has revealed that 12% of the selected KGDEs are not protected or at least not recorded in the IUCN database and no information on any designation of protection was found. In total, 66% of the KGDEs are protected by national legislations, 49% by laws of the EU and 27% by any other international programmes. This last category includes Ramsar Sites, UNESCO world heritage sites and UNESCO MAB Biosphere Reserve. According to our data, the shares of KGDEs in the different regions that are not protected reaches the highest number in Western Asia with 23% of the KGDEs being not protected, followed by Northern African KGDEs from which 20% are not protected. Furthermore, 12% of the Southern European KGDEs are not part of a protection areas. In contrast, all of the here presented Western European KGDEs as well as the three Bulgarian KGDEs in Eastern Europe are protected.

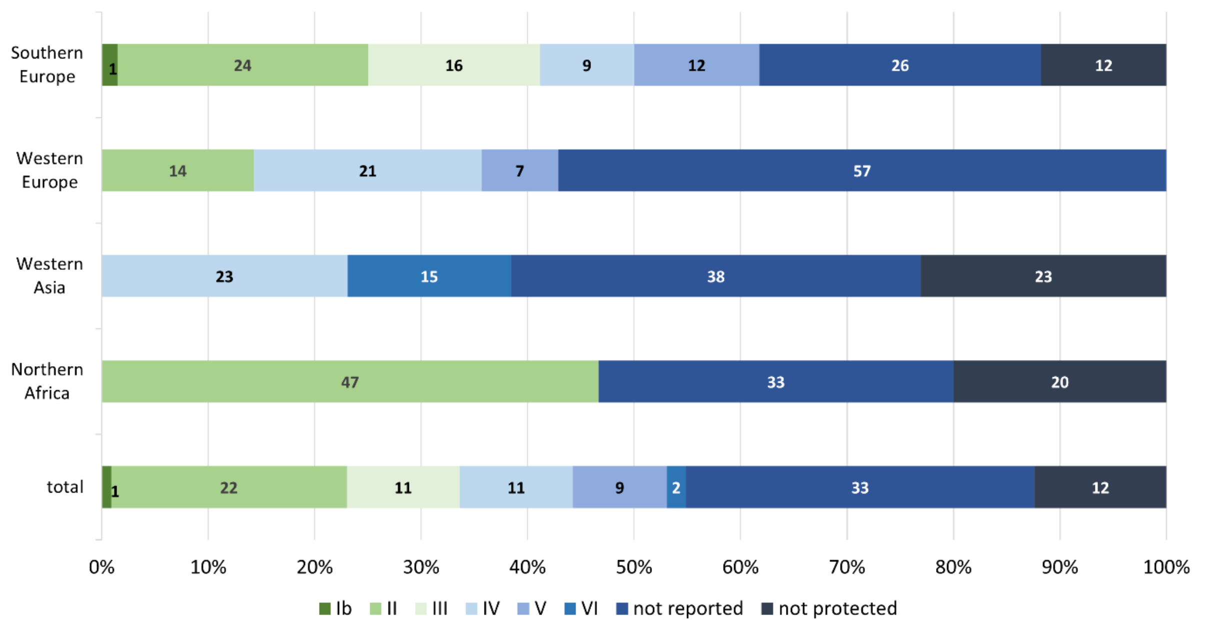


Fig. 18: stacked bar chart representing the percentages of KGDEs in protected areas of the different IUCN categories. It shows both, the distribution of all KGDEs among the IUCN protection categories together and subdivided into the regions. The category not reported refers to KGDEs that are protected by any protection type, but no IUCN category is recorded, whereas the category not protected refers to all KGDEs for which no protection area is designated.

The type of protection in terms of the extent of the restrictions and objectives for the given protected area, is represented by the IUCN protection categories. Fig. 18 shows the percentages of KGDEs included in protected areas of the different IUCN protection category. In cases, for which KGDEs are part of more than one protected area and hence more than one category is given, the "lowest" and thereby strictest category was chosen. The category "not reported" refers to KGDEs which are protected but no IUCN category is assigned to the respective protected area. Unfortunately, for 33% of the selected KGDEs the respective protected areas are not classified into one of the IUCN categories. That is why it is hard to draw general conclusions on the protection category in the end.

Where there was data available for the protected areas of Northern Africa KGDEs (47% of all in Northern Africa), the areas were classified in category II, National Park, which refers to a comparatively high conservation status. Among the KGDEs recorded for Western Asia, 23% are part of protected areas that are allocated to category IV and 15% to category VI. The highest share of unclassified protected areas is given for the KGDEs in Western Europe (57%). This might correspond to the large number of Natura 2000 sites, which are not allocated to any IUCN protection category. The southern European KGDEs in the data collection comprise the highest variety in protection types and also include the only KGDE example (Laguna de Fuente de Piedra) that is located in a protected area classified in the strictest category (Ib).

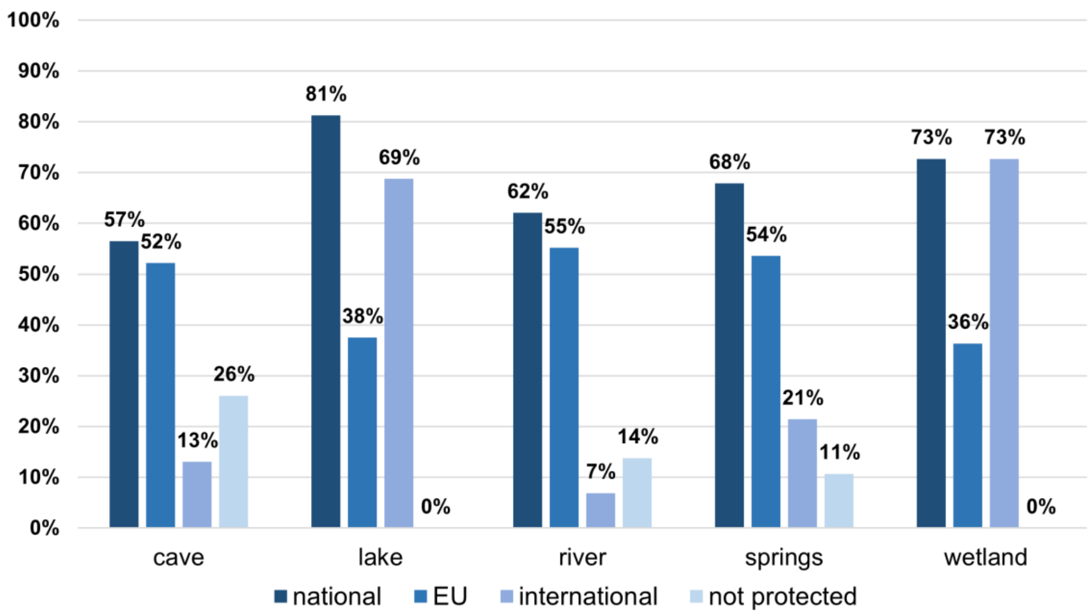


Fig. 19: bar chart showing the percentage of KGDEs that are protected under national, EU and international agreements grouped by the ecosystem types (cave, lake, river, springs, wetland).

The comparison of the spatial level of designation of the protected areas involving KGDEs between the ecosystem types also reveals interesting dissimilarities (cf. Fig. 19). All included lake and wetland KGDEs are covered by any protection program, whereas more than one quarter (26%) of the cave ecosystems are not protected. Rivers and springs show a similar pattern, which is illustrated by high shares of KGDEs that are under national protection and slightly less KGDEs under protection based on EU law. Only a small amount of these KGDEs are situated in internationally designated protected areas (cf. Fig. 19). In the most cases, the springs area is protected together with the downstream river and therefore are included in a larger protected area comprising not only the spring but also the river. As a result, springs and rivers seem to be protected similarly in this work. Similar patterns are visible for wetland and lake ecosystems as well. Beside the fact that they are all protected, they present high shares of nationally and internationally protected sites and lower shares of KGDEs which are protected based on EU law. Here, the analogy probably corresponds to the similarity of those two ecosystem types as both are associated as standing waterbody. The large share of lake and wetland ecosystems protected by international conventions could correspond to their important role as habitat for birds. Due to the migration of birds, the protection of these ecosystems is a global-scale responsibility and requires collaboration between states (Ramsar Convention Secretariat 2016). Among the selected KGDEs, caves are the least frequently protected ecosystem type. 57% of the caves are part of a nationally protected area and 52% of an EU law based protected area. Only 13% are included in a protected area by international conventions. This fits in with other studies on subterranean ecosystems that state a lack of recognition and conservation of these habitats (Culver and Pipan 2013;

Niemiller et al. 2018). It might be attributed to the fact that caves were not perceived as species-rich valuable ecosystems for a long time and only in the last two decades research has made great progress in revealing the actual species richness of caves (Niemiller et al. 2018). In this study, the data on the cave protection types is based on the IUCN database and therefore the cave KGDEs are classified as being protected when the area above it is part of a protection area. Not all of these caves, are then specifically conserved. However, as most critical threats for cave ecosystems derive from the land use and pollution occurring at the surface, protecting the landscape above and the surface waters support cave ecosystems as well (Bonacci et al. 2009).

4. Detailed illustration of karst groundwater-dependent ecosystem examples

The following chapter presents seven detailed descriptions of interesting KGDEs examples in the Mediterranean area in order to demonstrate the diversity and the complex socio-economic interactions of the ecosystems. Also, the seven KGDEs are chosen in order to cover the different regions, ecosystem types and geographical settings within the study area, as well as special habitat forms of some KGDEs.

4.1 Vjetrenica cave and Popovo polje

The first example given here is the Vjetrenica cave and Popovo polje KGDE which is one representative of the many KGDEs found in the Dinaric Karst and includes many properties that are typical for this region. It is located in the south of Bosnia Herzegovina and is formed in karst which is characterized by a high purity of carbonate rock. The river Trebisnjica, which flows in a concrete canal since the late 1970s traverses the polje (Lučić 2007). At the southwestern edge of the Polje, close to the town of Zavala, the entrance to the Vjetrenica cave can be found (Culver and Pipan 2013; Lučić 2019). After the Postonja-Planina cave system in Slovenia, the Vjetrenica cave is the second most diverse cave in the world (Culver and Pipan 2013; Niemiller et al. 2018). Tab. 5 shows the collection of basic information on this ecosystem, as they were compiled for the analysis of part 3.

Tab. 5: compiled data for the KGDE Vjetrenica cave and Popovo polje, coordinates and other spatial data refer to the entrance of the Vjetrenica cave

name	**type**	**associated components**	**position in hydrological cycle**	**hydroperiod**
Vjetrenica Cave, Popovo Polje	cave	cave, polje	surface-groundwater interaction zone	intermittent
endemic species	**narrowest endemism concept**	**species groups of endemic species**	**troglo- or stygobionts**	**use**
yes	feature	fish, amphibian, crustacean, hexapoda	yes	paleontological site, tourism
risk	**IUCN category**	**protection type**	**designation level**	**country**
tourism, hydrological changes	V	Nature monument	National	Bosnia and Herzegovina
region	**altitude (m)**	**latitude (WGS84)**	**longitude (WGS84)**	**aridity index**
Southern Europe	248	42.846031	17.983808	2.115
mean temperature (°C)	**annual precipitation (mm)**	**climate class**	**surrounding biome**	**surrounding ecoregion**
14	1548.65	Cfa	Mediterranean Forests, Woodlands and Scrub	Illyrian deciduous forests

4.1.1 Popovo polje and Trebisnjica river

The north-western area of the polje between the towns of Poljice and Hutovo (cf. Fig. 20) is characterized by alluvial deposits and hills. Before the riverbed of Trebisnjica river was covered with shortcrete and tunnels were excavated for a hydroelectric power plant, this part of the Popovo polje was seasonally flooded so that a lake was present during winter (Gunn 2004; Lučić 2007). This intermittent lake used to eventually drain by a pronounced subterranean network of conduits (Lučić 2019). Likewise, the occurrence of intermittent lakes can also be observed in the Slovenia, e.g. in the Cerknica and the Planinsko Polje or the Pivka intermittent lakes (Ravbar et al. 2021; Petrič and Kogovsek 2005), which are also part of the KGDE collection presented here. In contrast to the Popovo Polje, there the natural hydrological conditions of the intermittent lakes are still intact (Ravbar et al. 2021). In the Popovo Polje the construction works for the river regulation terminated this effect (Gunn 2004).

Fig. 20: satellite image showing the area of the Popovo Polje and the nearby Mediterranean coastline. An overview map is given in the topright corner. source: Google: Images c 2022 Landsat / Copernicus, Data SIO, NOAA, U.S. Navy, NGA, GEBCO c TerraMetrics ODER Images: c maxar technologies, CNES / Airbus, Maxar Technologies, Data SIO, NOAA, U.S. Navy, NGA, GEBCO

Within the polje, many karst features can be found and particularly diverse are the forms of cavities like caves, potholes, ponors and estavelles in the Popovo polje (Lučić 2007). Regarding the ecological value of the Popovo polje, the presence of several threatened freshwater Mollusca and fish species is worth mentioning, but at the same time the freshwater habitats of the polje are adversely affected by the changing hydrological conditions (Darwall et al. 2015). The flood prevention via the Trebisnjica hydrosystem has a tremendous negative impact on the fauna of this region (Milanovic 2002). Several species of this region, that rely on the connection of the underground waters to the surface by the numerous ponors and estavelles, are disturbed by hydrotechnical and other construction works, that destroy their habitat and change the hydrological regime of the polje. This includes species such as the cave amphibian *Proteus anguinus*, a regionally endemic fish the Popovo minnow (*Delminichthys ghetaldii*) as wells an cave tube worm (*Marifugia cavatica*) and a mollusc (*Congeria kusceri*) (Milanovic 2002; Gunn 2004; Lučić 2007). The decreased water flow through the underground conduits even influences the outflow of submarine springs at the Adriatic coast which in turn brought troubles for a commercial oyster and mollusc farm because the freshwater inputs were too low (Milanovic 2002).

In addition to the ecological value, Lučić (2007) describes ecosystem services and provisions that are partly unique to this type of ecosystem or even to this special location. Examples for this are the former use of estavelles for fishing or the application of grain mills in the shafts (Fig. 21b) but after the canalisation of the Trebisnjica, most of the mills stopped working and also the fishing activities were terminated after this (Milanovic 2002, Lučić 2007).

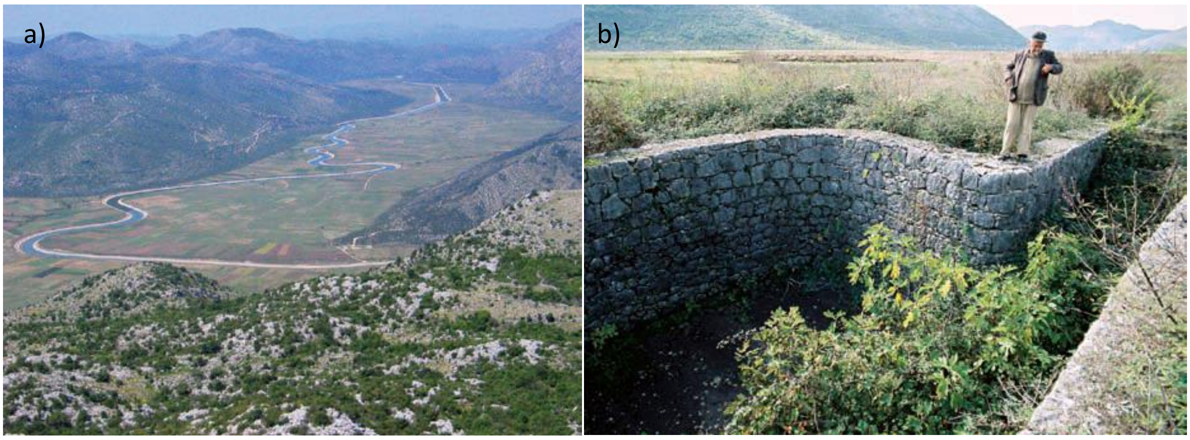


Fig. 21: a) Popovo Polje and Trebnisjica river in the lower NW part, b) sinkhole transformed to a mill and now covered by plants (both photographs taken from Lučić (2007)).

4.1.2 Vjetrenica cave

Vjetrenica cave has a total length of 7014 m and is only slightly cross-linked. The main channel at the central level is developed to the south/southeast and has several chambers (Lučić 2019). There is also a network of several streams and lakes with varying water levels. In terms of ecology, the cave stands out due to the high habitat variety (Culver and Pipan 2013; Howarth and Moldovan 2018b; Lučić 2019). There are several terrestrial microhabitats that distinguish themself by the surface structure and the humidity. Moreover, aquatic habitats like streams with varying velocity and bed compositions or permanent and occasional lakes represent the large diversity of habitats (cf. Fig. 22).

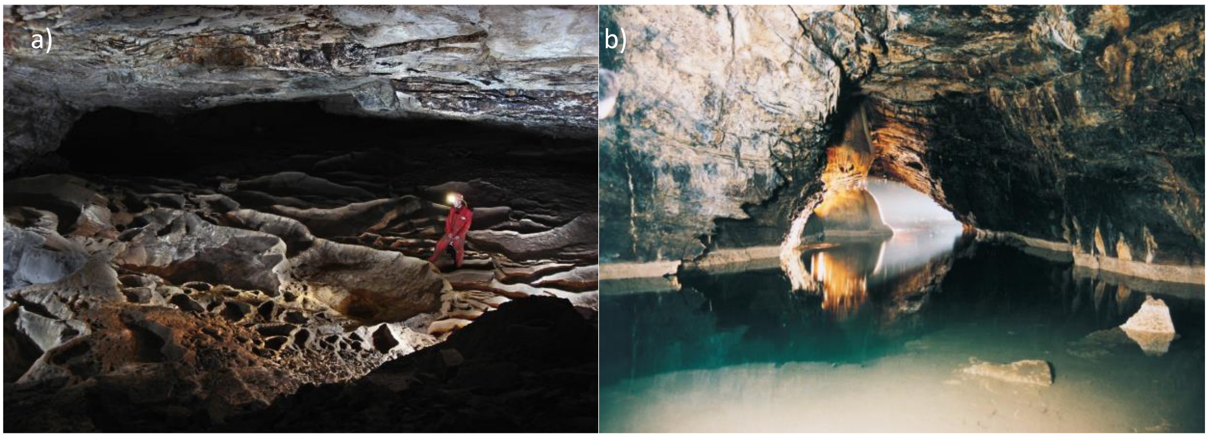


Fig. 22: a) rimstone pools about 1500 m from the entrance (by Darko Bakšić, taken from Lučić (2019)), b) one of the lakes (Great lake), and to the left the Haedzija Cone which is the place of the first sight of Hadesia vasiecki (taken from Lučić (2019)).

One speciality of the caves are hygropetric habitats, flowstones that are enveloped by a thin water flow (Culver and Pipan 2013; Lučić 2019). Here two specialized species of Leptodirinae (*Hadesia vasiceki*, *Nauticella sygiyaga*) can be found. Regarding cave-adapted species, there are 42 stygobionts and 39 troglobionts inhabiting the cave (Culver and Pipan 2013). Generally, the fauna includes 57 species being endemic to the Popovo Polje regions, from which 25 of them are restricted to the Vjetrenica cave and the related Bjelusica and Lukavac spring (Lučić 2019). Another world record set by the Vjetrenica cave, is the highest number of species from the genus Niphargus (Amphipoda), with 10 species living there (Lučić 2019). Culver and Pipan (2013) explain the richness in diversity by the geographical position and the ecological heterogeneity.

4.1.3 Scarce protection and degradation

The ecosystem of the Vjetrenica cave is threatened by the tourist development. Ecologically severe interventions that were made to account for tourists include the defragmentation and destruction of microhabitats like sediments, rocks, flowstones, rimstone pools and lakes to create pathways as well as the installation of electric light which lead to lampenflora (Lučić 2019). The negative impact on the biodiversity of the cave is illustrated impressively by one example stated by Lučić (2019): A battery from a camera dumped in the cave harmed the Crustacean in some of the ponds substantially and lead to their disappearance. Lučić (2019) states that the post-socialist transformation of the country endangers the cave due to the lack of protection by the government. The cave is so far only protected as a Natural monument which is a category V protection area according to the IUCN classification (Dudley 2013) and as a special geological reservation (Lučić 2019). As a protection area of category V leisure and tourism activities are allowed and even aimed for, but they should be incorporated in a sustainable way so that the balance between nature and cultural use is guaranteed (Dudley 2013). Since 2004 the cave is on the tentative list for UNESCO Natural heritage sites, but since then nothing has changed and it is still only a tentative site (Lučić 2019).

4.2 Lake Ohrid

The second example is Lake Ohrid which is chosen due to its exceptional biodiversity making it the most biodiverse lake in the world, when taking the surface area into account (Albrecht and Wilke 2008; Föller et al. 2015). Lake Ohrid is also located in the Balkan region and represents a perennial, oligotrophic karstic lake which is situated in a graben structure of rift formation origin (Albrecht and Wilke 2008). The lake extends across the border of Albania and North Macedonia and has a surface area of 358 km^2 and an average depth of 155 m (reviewed in Wagner and Wilke (2011)). Tab. 6 gives on overview of the properties of Lake Ohrid.

Tab. 6: compiled data for the KGDE Lake Ohrid, coordinates and other spatial data refer to the location in the center of Lake Ohrid as indicated in Fig. 23.

name	**type**	**associated components**	**position in hydrological cycle**	**hydroperiod**
Ohrid lake	lake	lake, springs, wetland	surface storage	perennial
endemic species	**narrowest endemism concept**	**species groups of endemic species**	**troglo- or stygobionts**	**use**
yes	feature	fish, plant, crustacea, mollusca, porifera, plathelminthes, ciliophora, nematoda, diatomea	yes	fish farming, tourism, water supply, archaeology
risk	**IUCN category**	**protection type**	**designation level**	**country**
eutrophication, tourism, agriculture, wastewater, solid waste dumping, fishing, overextraction, climate change, urbanization	III	National Heritage Site, World Heritage Site, Ramsar	National, International	transboundary: Albania & North Macedonia
region	**altitude (m)**	**latitude (WGS84)**	**longitude (WGS84)**	**aridity index**
Southern Europe	689	41.008254	20.735095	0.814
mean temperature (°C)	**annual precipitation (mm/year)**	**climate class**	**surrounding biome**	**surrounding ecoregion**
12	786	Cfb	Mediterranean Forests, Woodlands and Scrub	Pindus Mountains mixed forests

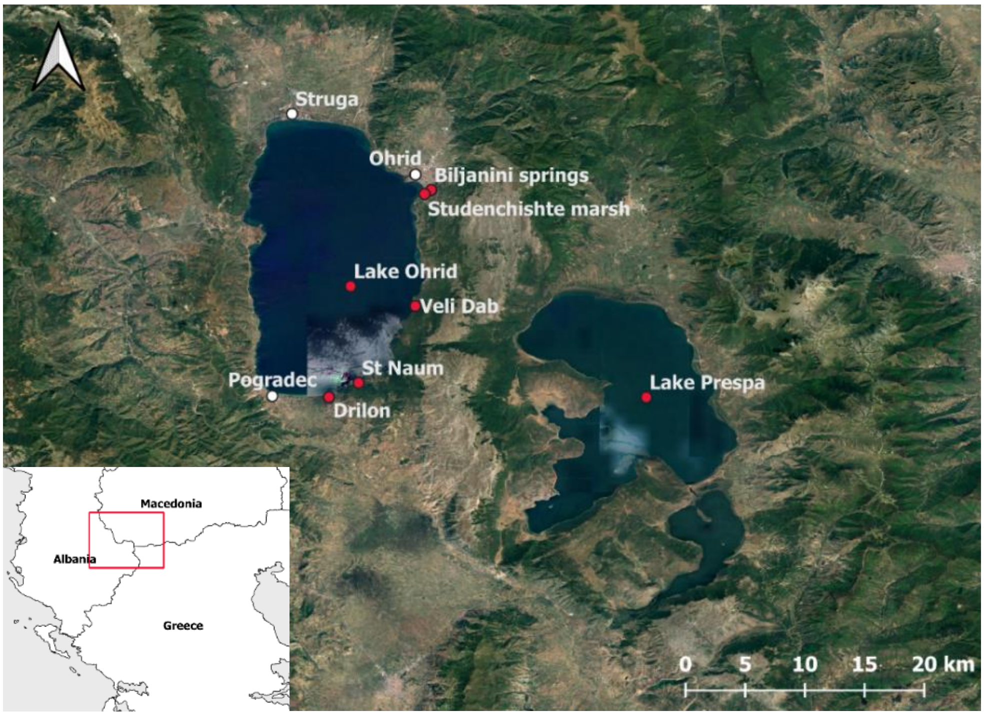


Fig. 23: Lake Ohrid and associated ecosystems as well as Lake Prespa and cities on the shore of Lake Ohrid. Google satellite image: Image © 2022 Copernicus / Landsat © 2022 TerraMetrics map data © Google

4.2.1 Lake Ohrid and related karst groundwater-dependent ecosystems

Associated to the Lake Ohrid are six other selected KGDEs of this study, namely the Drilon springs (also called Tushemisht/Zagorican), St. Naum springs, Veli Dab sublacustrine springs, the Studenchishte marsh, the Biljanini springs and the sister lake Prespa (cf. Fig. 23). Drilon depicts a spring complex on the Albanian Southern shore, whereas the St. Naum springs complex are situated in Macedonia but also on the southern shore of Lake Ohrid. These two spring complexes comprise a substantial part of the water supply for Lake Ohrid (Albrecht and Wilke 2008; GIZ 2017). They are in turn mainly fed by groundwater originating from the Lake Prespa located in the east of Lake Ohrid (Albrecht and Wilke 2008; GIZ 2017). The water flows through karstic conduits between them and emerges at several springs. Veli Dab is a sublacustrine springs complex on the eastern shore which has special habitat conditions. Studenchishte marsh is the last remaining wetland on the shore of Lake Ohrid after many others were destroyed by urban development and also the Studenchishte marsh is under increasing urban pressure (Kostoski et al. 2010; Apostolova et al. 2016). It is located on the eastern shore and is replenished by precipitation and groundwater coming from the karstic aquifer of the Galicia mountains rising up through sediments underlying the wetland (Apostolova et al. 2016). As a result, alkaline fens and their associated flora and fauna supplied by the karstic waters stand out as they have less acidic properties and higher nutrient values supporting a greater biodiversity (Apostolova et al. 2016).

4.2.2 Ancient Lake Ohrid as endemism and biodiversity hotspot

The formation of the actual Lake Ohrid dates back to 1.9 to 1.2 million years ago (Wagner et al. 2017). Hence, it is older than most present lakes which formed only after the last glacial maximum (Neubauer et al. 2015). Ancient lakes like Lake Ohrid stand out and distinguish themselves from younger lakes mostly due to their diversity and endemism, which depicts them as ideal research areas for combined geological, biological and ecological studies, e.g. on evolutionary biology (Albrecht and Wilke 2008; Neubauer et al. 2015).

Albrecht and Wilke (2008) summarized the knowledge on the species occurrence and endemism in Lake Ohrid which resulted in estimates of 1200 native species from which at least 220 are endemic. The number of endemic species is stated even higher reaching more than 300, by Föller et al. (2015) as they reviewed more recent studies and especially accounted the vast number of diatoms which alone contribute 117 endemic species. Endemism occurs on different spatial and taxonomic levels for Lake Ohrid species. Spatial levels include large scales like the watershed or the lake itself but even point endemics occur which can only be found in the single springs complexes (Albrecht and Wilke 2008; Hauffe et al. 2011) making them extremely valuable but at the same time susceptible for biodiversity loss. The Veli Dab area (Fig. 24b) is one of these places as point endemics inhabit the littoral interlithon in the surroundings of the sublacustrine springs (Albrecht and Wilke 2008; Hauffe et al. 2011). Albrecht and Wilke (2008) predict a loss of more than 10% of the Lake Ohrid biodiversity, if the habitat of the Veli Dab springs would be destroyed.

Probably best studied at Lake Ohrid is the gastropod fauna which stands out by its high endemism rate (Albrecht and Wilke 2008; Hauffe et al. 2011; Föller et al. 2015). Regarding gastropods, Hauffe et al. (2011) found out that the most frequent species of Lake Ohrid are the endemic ones whereas species with a wider distribution range are rarely found in Lake Ohrid and then mostly in the upper layer of the lake. Also, the widespread species are increasingly observed in the lake areas which show the strongest human impact (Hauffe et al. 2011). However, Hauffe et al. (2011) state that the spread of invasive widespread gastropods into the Lake Ohrid ecosystem is still limited and has no strong impact on the species assemblage. Another finding of Hauffe et al. (2011) is that eco-insularity plays a role in gastropod distribution in the lake and thus well adapted species of Lake Ohrid could outperform the widespread invasive species but are bound to their small habitat.

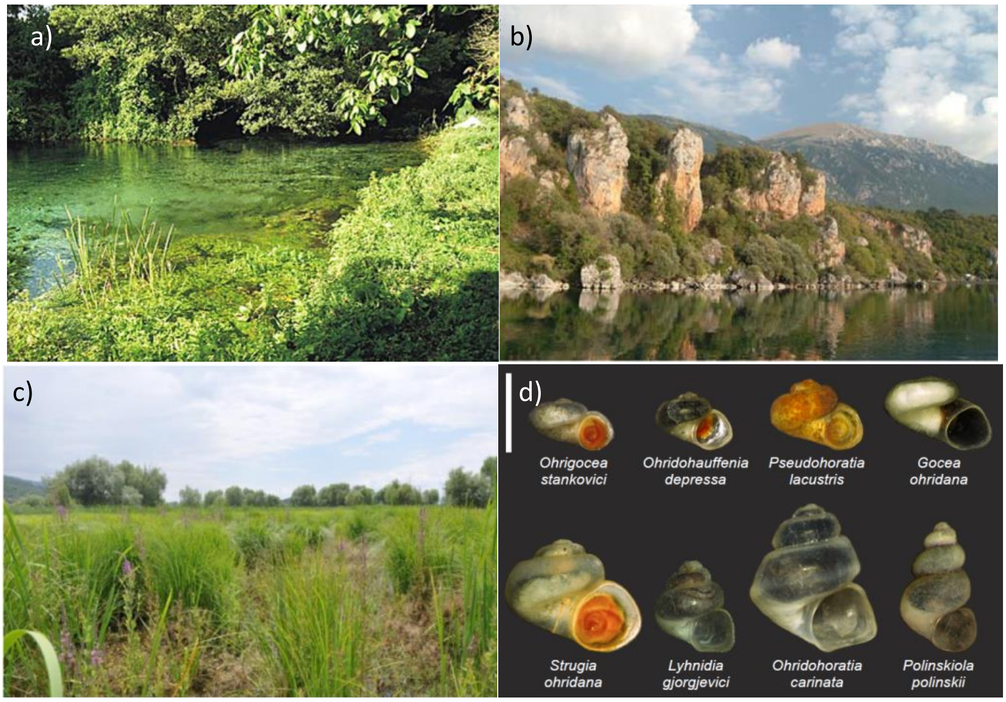


Fig. 24: a) one part of St. Naum spring complex (Albrecht and Wilke 2008), b) steep eastern shore at the location of Veli Dab, where sublacustrine springs occur (Albrecht and Wilke 2008), c) Caricetum elatae as characteristic plant of the Studenchishte marsh (Apostolova et al. 2016), d) representatives of the species flock of non-pyrgulinid Hydrobiidae, the white bar serves as scale and corresponds to 1 mm (Föller et al. 2015).

The ichthyofauna of Lake Ohrid comprises at least 17 native species, of which the Ohrid trout (*Salmo letnica*) takes up considerable economic role and *Salmo ohridana* represents one of the distinct endemic fish species of the lake. However, precise information on the taxonomic status of the fish species is lacking and the classification of some as endemic remains unclear (Albrecht and Wilke 2008).

Even though Lake Ohrid is small compared to other ancient lakes, its complex geological and hydrological structures result in the existence of various habitats which in turn might lead to the observed exceptional variety of ecological niches and biodiversity (Hauffe et al. 2011; Cvetkoska et al. 2018). The development of this diversity is mostly referred to processes of intralacustrine speciation over the entire time since the lake has formed, which in turn led to the existence of monophyletic groups including several species (often called species flocks) being restricted to the lake (Neubauer et al. 2015; Wagner et al. 2017).

4.2.3 Threats and protection

Although the lake is oligotrophic, initial eutrophication is observed (Albrecht and Wilke 2008; Kostoski et al. 2010; Cvetkoska et al. 2018). The sources of the nutrient input and pollution are diverse but are dominated by agricultural and forestry practices and by a lack of appropriate sewage systems (Kostoski et al. 2010; GIZ 2017). Especially in the north of the lake which is also more populated, the eutrophication and wastewater pollution is apparent as the total phosphorus values are 10 times higher there than in the eastern part of the lake (Cvetkoska et al. 2018). This is also expressed in the diatom communities, which is why Cvetkoska et al. (2018) suggest to apply diatom sampling as a tool for biological monitoring of Lake Ohrid, as it is conducted in other waterbodies as well.

The significantly growing population and the accelerating touristic development around the lake amplify these human induced threats (Albrecht and Wilke 2008; Kostoski et al. 2010; Petrevska and Collins-Kreiner 2019). Hence, the respective development infrastructure including the construction of hotels, restaurants and other facilities altered the natural surroundings including the direct shoreline (Kostoski et al. 2010; GIZ 2017; Petrevska and Collins-Kreiner 2019). Especially the development in the direct vicinity of the shore is responsible for habitat destruction and fragmentation (Kostoski et al. 2010), which is particularly worrying, as some of the biodiversity hotspots harbouring point endemics are situated at the coastline (Hauffe et al. 2011). This also includes draining and construction works in riparian wetlands like the Studenchishte marsh causing a decline of wetland plant associations. Other adverse impacts involve the tapping of several karstic springs in the basin for the drinking water supply and the destruction of springs by road construction as it was the case for the karstic spring Bej Bunar which was a type locality of an endemic snail (Kostoski et al. 2010). Other than that, anthropogenic activities on the lake itself also damage the ecosystem. These include overfishing, especially of the two native species *Salmo letnica* and *Salmo ohridana*, but also the general increase of boat traffic and other water sport activities as profitable tourist attractions (Kostoski et al. 2010; Petrevska and Collins-Kreiner 2019). Overall, these direct human pressures on the lake ecosystem prevail, whereas water abstraction is less of a problem, as so far, the lake is still replenished sufficiently, but Lake Prespa experiences extreme exploitation which could lead to a disbalancing of the water supply for Lake Ohrid as well (Kostoski et al. 2010). Although the impact of invasive species seems to be minor, the number of foreign species is increasing and the rainbow trout is assumed to have the potential to displace the Ohrid trout (Hauffe et al. 2011; Albrecht and Wilke 2008; Kostoski et al. 2010).

The high ecosystem value of Lake Ohrid paired with the observed threats and pressures on the lake give rise to the claim from many scientists for appropriate conservation measures and more research on the still largely unknown species composition (Kostoski et al. 2010; Wagner et al. 2017; Cvetkoska et al. 2018). Several protected areas and other conservation and research programs already exist at Lake Ohrid and the actions increased within the last years. For example, the UNESCO site for Natural and Cultural Heritage was extended to the entire lake in 2019 (UNEP-WCMC and IUCN 2022) and in 2021, Lake Ohrid has been designated as Ramsar site too. This gives confidence for the protection of its biodiversity in future. In addition, local programmes on environmental protection and education take place regularly in order to enhance the awareness for environmental issues (Kostoski et al. 2010).

4.3 Ein Gedi and Ein Feshkha

Next, the two KGDEs of Ein Gedi and Ein Feshkha oases are described in detail as they represent two "green islands" in the arid desert surroundings (cf. Tab. 7 & 8). Thereby, Ein Feshkha is the Arabic name, while Tsukim is the Hebrew name of the place and means the same. As illustrated in Fig. 25, both KGDEs are located in the Judean desert close to the western shore of the Dead Sea (Gera 2017; Hirshberg and Ben-Ami 2019). To the east of these ecosystems the Judean Mountains are situated (Ben-Itzhak and Gvirtzman 2005). The two ecosystems harbour diverse flora and fauna species even with some endemic representatives (Burg et al. 2016). The basis for this is solely provided by the springs fed by the karst aquifer in the west which is mainly recharged by winter rainfalls in the Judean mountains (Ben-Itzhak and Gvirtzman 2005). In addition, the region around the springs has a long history and significance for mankind (Gera 2017; Hadas 2012; INPA 2017). One astonishing feature found at the Ein Gedi oasis is an ancient irrigation system from the Roman-Byzantine period. It is based on the springs and serve for the watering of the fields which were arranged in terraces (Hadas 2012).

4.3.1 Hydrogeology

The springs of both ecosystems are fed by the Cretaceous Judea Group aquifer. The aquifer is separated in a lower and an upper subaquifer. Latter displays a phreatic unit, which is separated from the lower by a thin aquitard (Ben-Itzhak and Gvirtzman 2005). Limestone and dolomite together with some marl and chalk make up the Judea Group (Ben-Itzhak and Gvirtzman 2005). It is exposed at the tall cliffs which are the result of the major western rift fault (Burg et al. 2016). The height difference of the hydraulic head between the top of the Judean mountains and the Dead Sea shore reaches up to 800 m on a horizontal distance of 25-30 km, which would apparently suggest a parallel flow along the steep hydraulic gradient from west to east.

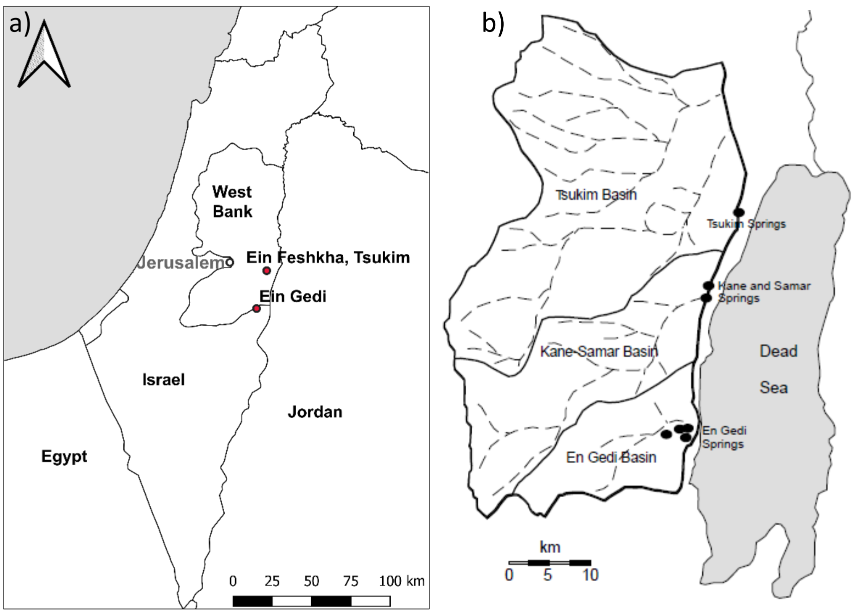


Fig. 25: a) overview map of the location of Ein Feshkha/Tsukim springs and Ein Gedi oasis. b) delineation of the subsurface drainage basins of the three springs by Ben-Itzhak and Gvirtzman (2005), all are located in the proximity to the Dead Sea and derive their water from the aquifers in the west.

In reality, this is not observed as the groundwater flow is diverted by folding structures originating from the Syrian Arc stress field as well as by faults associated to the Dead Sea rift. The groundwater from the aquifer replenishes springs high up at the cliffs like the Ein Gedi springs but most of it crosses the faults and reaches the Dead Sea group sediments (Ben-Itzhak and Gvirtzman 2005; Burg et al. 2016). There groundwater emerges in countless springs at or close to the shoreline as it is the case for Ein Feshkha springs complex (Burg et al. 2016). The main outlets of the entire aquifer are the Ein Feshkha springs complex with calculated 60 MCM/year and the Kane and Samar springs with calculated 30 MCM/year discharge (Galili 2007, 2012). In contrast, the springs at Ein Gedi at the cliffs are the outlet of the upper subaquifer and therefore provides less, namely 3.2 MCM/year. Yet, all four Ein Gedi springs have tap water quality, while all Ein Feshkha springs and seepages are brackish or saline (Ben-Itzhak and Gvirtzman 2005). The precipitation in this region is scarce, thus the springs serve as only water source in this region (Hadas 2012).

4.3.2 Ein Gedi ecosystem

The Ein Gedi oasis ecosystem is fed by four springs. Two of them (Shulamit and Ein Gedi) are located on the slope, while the other two are in the canyons of the Nahal David in the north and the Nahal Arugot stream in the south. The groundwater emerges here from the upper perched subaquifer (Ben-Itzhak and Gvirtzman 2005). Due to the archaeological investigations on the irrigation system, it is known that there had to be ten active springs in the ancient times, of which all except the four left dry by now (Hadas 2012). The over 200 m high cliff where the springs are located transitions a plain area towards the Dead Sea shore (Hadas 2012). The morphology and the geographic location as well as the favourable climatic conditions, but first and foremost the presence of enough high-quality water enables this place to form habitats for a large variety of species (INPA 2017).

Tab. 7: compiled data for the Ein Gedi KGDE, coordinates and other spatial data refer to the Shulamit spring located at the cliff. Annual Precipitation is taken from the database of the Israel Meteorological Service from a local station close to Ein Gedi.

name	**type**	**associated components**	**position in hydrological cycle**	**hydroperiod**
Ein Gedi	springs	springs, river, oasis	surface-groundwater interaction zone	intermittent
endemic species	**narrowest endemism concept**	**species groups of endemic species**	**troglo- or stygobionts**	**use**
no	-	-	no	water supply (mineral water), tourism
risk	**IUCN category**	**protection type**	**designation level**	**country**
contamination, declining groundwater level	IV	Nature Reserve	National	Israel
region	**altitude (m)**	**latitude (WGS84)**	**longitude (WGS84)**	**aridity index**
Western Asia	-177 (The nature reserve extends over the slope from an altitude of about -150 to -350m)	31.469267	35.389261	0.249
mean T (°C)	**annual precipitation (mm/year)**	**climate class**	**surrounding biome**	**surrounding ecoregion**
24	49	BWh	Deserts and Xeric Shrublands	Arabian Desert and East Sahero-Arabian xeric shrublands

The Ein Gedi oasis harbours a great plant diversity covering species with different requirements including acacia and date palm trees, desert shrubs (*Zygophyllum dumosum*) and maidenhair ferns. Also, wetland vegetation like cyprus cane, or the common reed is found here. Additionally, poplars (*Populus euphratica*) and tamarisks (*Tamarix palaestina*) grow in the Wadi Arugot (INPA 2017). Regarding animals, some species rely directly on the water for at least some parts of their life cycle like the river frog (*Rama ridibunda*), a river crab, a river snail and several dragonflies. Many other animals live here as well and benefit from the springs and the vegetation including large mammals like ibexes, rock hyraxes, foxes and striped hyena. Moreover, the ecosystem lies on the route of many up to 200 migratory birds species (INPA 2017).

As the Ein Gedi springs provide much less groundwater than the springs further north, the ecosystem is more susceptible for water shortage (Ben-Itzhak and Gvirtzman 2005). Hence, plans of abstractions from the Ein Gedi springs should consider the environmental impacts first. Additionally, pumping from the basins further north which seem to provide plentiful of water could still lead to damages by water shortage in the Ein Gedi oasis, as the models from Ben-Itzhak and Gvirtzman (2005) imply an overflow from the northern basin to the Ein Gedi basin.

4.3.3 Ein Feshkha springs complex area

The Ein Feshkha ecosystem is located only about 25 km of the Ein Gedi oasis and both are fed by karst springs of the same aquifer. The most apparent differences between the two ecosystems are the location and the type of the springs as well as the much higher discharge of Ein Feshkha springs complex (Ben-Itzhak and Gvirtzman 2005). As Ein Feshkha springs are located much lower, approx. at -400 m below sea level, and emerge from the Dead Sea group sediments and not directly from the Judea group karst aquifer, the springs as well as the ecosystems are strongly influenced by the recession of the Dead Sea shoreline. Firstly, due to the water level decline, the shore expanses and muddy plains are exposed (Burg et al. 2016; Gera 2017). This leads to the formation of streams originating at the springs and flowing through the exposed Dead Sea sediments towards the remaining Dead Sea waterbody. As the sediments consist of soft clay, the rivers create erosional micro-canyons where they flow along (Burg et al. 2016; Gera 2017). Plants can thrive there in contrast to the adjacent inhospitable saline clay sediments. Additionally, the entire wet zone of the natural reserve changes by the decline of the Dead Sea water level.

Burg et al. (2016) summarize that due to the decline of the Dead Sea water level, the Ein Feshkha springs move eastward following the recession of the shoreline as well as further south (cf. Fig. 26), while the total discharge amount does not experience any significant changes. When the Dead Sea lake level declines to a depth of -490 m asl, the springs may dry out due to the local geology (Levy et al. 2020). The displacement and eventually the drying out of the springs will cause a dramatic damage to the ecosystem at its current location in the nature reserve and depicts the dominant threat (Levy et al. 2020). Apart from that, several uncontrolled fires have caused enormous damage to the nature reserve in the last decades. One large fire event on June 24th in 2008 affected the nature reserve dramatically.

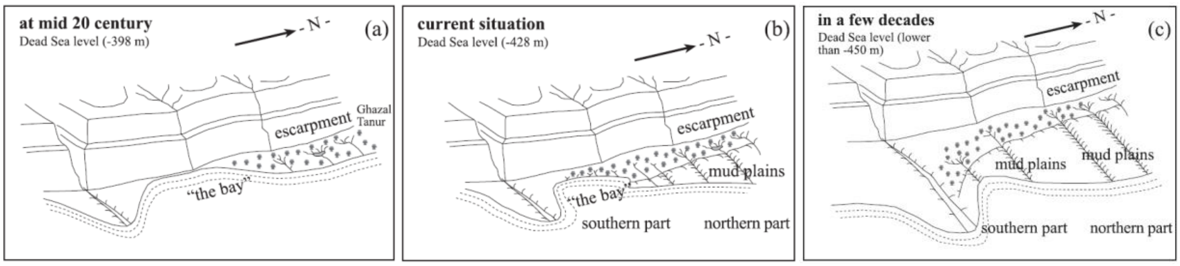


Fig. 26: development and future expectation of the Tsukim/Ein Feshkha ecosystem by Burg et al. (2016): a) in the middle of last century springs were only observed in the northern part and migrating eastwards following the dead sea recession. b) currently northern springs cannot migrate further east and are blocked by impermeable clayey sediments, springs emerge at the southern end. c) for the future it is predicted that even more springs emerge in the south while others in the north dry up and more deep canyons crossing the mud plain will form.

Regarding the flora and fauna of the Ein Feshkha area some similarities can be found to the Ein Gedi oasis. Almost the same large mammals can be observed here as well as a variety of migratory birds (Gera 2017). Additionally, some amphibian and insects depend directly on the water availability supplied by the springs. One species of interest that lives here is the fish *Aphanius dispar richardsoni*, which is endemic to the Dead Sea region (Gera 2017).

In addition to the formation of the microcanyons described earlier, the rapidly dropping Dead Sea results in another phenomenon. In the last years sinkhole formation is observed increasingly along the retreating shore of the Dead Sea and also a few in the Ein Feshkha area (Ben-Itzhak and Gvirtzman 2005; Hirshberg and Ben-Ami 2019). Hirshberg and Ben-Ami (2019) state that the water-filled sinkholes could serve as another special microhabitat in particular for aquatic insects that live in standing brackish waters. These species which used to be rare in this region could benefit from the sinkhole formation (Hirshberg and Ben-Ami 2019).

Tab. 8: compiled data for the KGDE Ein Feshkha/Tsukim, coordinates and other spatial data refer to the entrance point of the nature reserve. Annual Precipitation is taken from the database of the Israel Meteorological Service from a local station close to Ein Feshkha.

name	**type**	**associated components**	**position in hydrological cycle**	**hydroperiod**
Ein Feshkha, Tsukim	springs	springs, wetland, oasis	surface-groundwater interaction zone	intermittent
endemic species	**narrowest endemism concept**	**species groups of endemic species**	**troglo- or stygobionts**	**use**
yes	local	fish, hexapoda (insecta)	no	tourism
risk	**IUCN category**	**protection type**	**designation level**	**country**
damage to habitats due to rapid move-ment and drying up of springs resulting from the Dead Sea recession, declining groundwater level, fires	NA	Nature Reserve	National	West Bank
region	**altitude (m)**	**latitude (WGS84)**	**longitude (WGS84)**	**aridity index**
Western Asia	-391	31.7146667	35.45394444	0.300
mean T (°C)	**annual precipitation (mm/year)**	**climate class**	**surrounding biome**	**surrounding ecoregion**
24	71	BWh	Deserts and Xeric Shrublands	Arabian Desert and East Sahero-Arabian xeric shrublands

4.3.4 Conservation of the nature reserves

Both KGDEs are protected as nature reserves by the Israel Nature and Parks Authority (INPA 2017, 2019). To preserve the Ein Gedi oasis the INPA regulates touristic activities by establishing trails and charging visitors for the entry to the trails. This was established in 1970 and aims to keep some areas completely undisturbed from visitors. To achieve this, strict rules for visitors are implemented. It involves rules to stay on the marked trails, not eat anything inside the reserve, not climb at rocks or other ancient structures and not feed animals (INPA 2017). Regarding the utilization of the water, an arrangement was achieved that people from the nearby Kibbutz are allowed to use the water for their daily life. In addition, some of the water is captured for the mineral water industry.

In the Ein Feshkha Nature reserve more conservation measures are in action. They use donkeys in order to keep the vegetation low which prevents both the spread of fire and the spread of unwanted plant species like the common reed. Scientists also monitor bird and fish, as the present fish populations are isolated from other ecosystem making them more vulnerable (INPA 2019). Additionally, the visitor access to the reserve is restricted and only allowed when specific rules are considered as it is in the Ein Gedi reserve as well (Burg et al. 2016; Gera 2017). Orderly and dense monitoring of the springs flows and groundwater levels in selected dedicated boreholes is also conducted.

4.4 Grotta Zinzulusa

The next case example is another cave, the Grotta Zinzulùsa or in english Zinzulusa cave, which stands out by its location directly on the Mediterranean coast, which influences the ecosystem properties. To be more precise the cave is located in the South of the Salento peninsula in Apulia, Italy (cf. Fig. 27). Its entrance can be found at the cliffs close to the village of Castro. The coastline is characterized by several caves, as well as steep cliffs and sulphur springs (Talà et al. 2021). Zinzulusa cave was first described in 1793 and since 1975 it is accessible for tourists. Meanwhile, 130 000 visitors come to the cave every year (D'Agostino et al. 2015). Due to its connection to the Mediterranean Sea the cave is of anchialine nature, just like another KGDE included in this study, namely the Cuevas del Drach on the Balearic Island Mallorca. Anchialine caves are characterized by a highly variable mixohalinity and the presence of stygobionts along with species of marine origin (Gunn 2004). Additionally, deep circulation and ascending waters influence depicts the hypogene nature of the Zinzulusa cave (Talà et al. 2021). Tab. 9 shows the characteristics of the cave.

Tab. 9: compiled data for the KGDE Grotta Zinzulusa, coordinates and other spatial data refer to the entrance point of the cave

name	**type**	**associated components**	**position in hydrological cycle**	**hydroperiod**
Grotta Zinzulusa	cave	anchialine cave	groundwater-sea interaction zone	perennial
endemic species	**narrowest endemism concept**	**species groups of endemic species**	**troglo- or stygobionts**	**use**
yes	feature	Porifera, Crustacea	yes	tourism
risk	**IUCN category**	**protection type**	**designation level**	**country**
urban discharge, tourism	none	none	none	Italy
region	**altitude (m)**	**latitude (WGS84)**	**longitude (WGS84)**	**aridity index**
Southern Europe	46	40.012044	18.430740	0.779
mean temperature (°C)	**annual precipitation (mm/year)**	**climate class**	**surrounding biome**	**surrounding ecoregion**
17	634	Csa	Mediterranean Forests, Woodlands and Scrub	Tyrrhenian-Adriatic Sclerophyllous and mixed forests

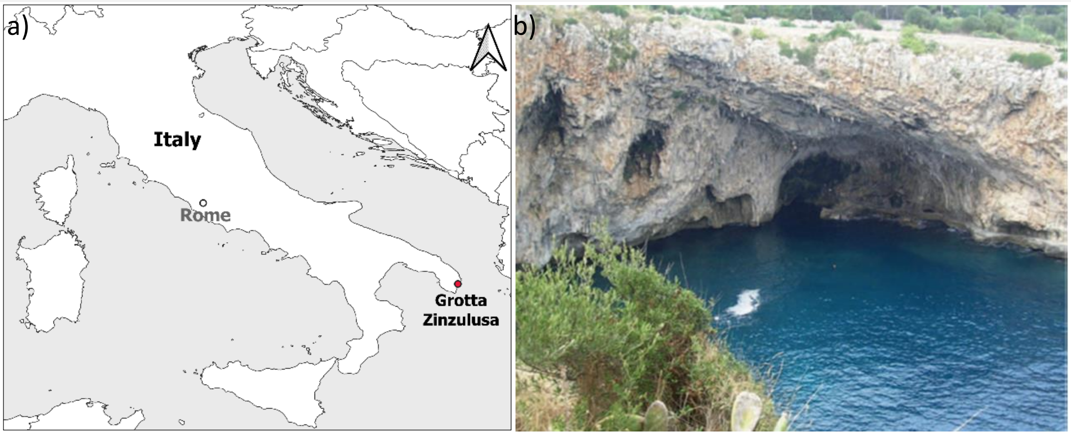


Fig. 27: a) location of Grotta Zinzulusa on the southwestern tip of the Salento peninsula of Italy. b) photograph of natural entrance from the sea-side of the Zinzulusa cave (taken from D'Agostino et al. 2015).

4.4.1 Description of the cave and its development

The cave can be divided in three parts of which the first part starts from the entrance and reaches until a cave room called cripta hall. It includes the first of two ponds, the Conca (Pesce 2001; Talà et al. 2021). The second part ranges from the cripta hall towards the large cave room called duomo. The last and least accessible part behind the duomo includes the second pond, called Cocito and in contrast to the parts closer to the entrance this is a product of karstification and not erosion (Pesce 2001; D'Agostino et al. 2015; Talà et al. 2021). The two ponds distinguish themselves by their water chemistry and hence the species assemblage. Whereas the Conca is brackish and highly influenced by the sea and therefore shows species with marine origin, the Cocito is more oligohaline harbouring stygobionts and chemolithoautotrophic living microorganisms (Pesce 2001; Talà et al. 2021). It comprises a cold freshwater lens of about 1 m overlying the denser brackish water (Pesce 2001; D'Agostino et al. 2015).

The sulphur-rich water of the Cocito pond can be put in context to the local Santa Cesarea terme system (Talà et al. 2021). This geothermal system comprises a deep circulation of sea water infiltrating through the sea bed and moving downwards mainly through Messinian deposits and Mesozoic-Oligocene limestones (Santaloia et al. 2016). Meanwhile the sea-originated water heats up to 85 °C and solves elements like calcium, sulphate, boron or lithium and then rises up again (Santaloia et al. 2016). On its way the water also interacts with clayey deposits containing organic substances which are solved and transported and then can rise up to the Cocito pond (Santaloia et al. 2016; Talà et al. 2021). These compounds in turn can serve as energy sources for oil-degrading bacteria and hence support an efficient biogeochemical nutrient cycling of hydrogen, sulphur and nitrogen (Talà et al. 2021).

4.4.2 Cocito pond biodiversity

The Cocito pond harbours most of the exceptional stygofauna of the Zinzulusa cave and is particularly rich in Crustacean, mostly copepods (Pesce 2001; D'Agostino et al. 2015). Probably the most fascinating species of the Zinzulusa cave is the strictly stygobitic living sponge *Higginsia ciccaresei* which is endemic to this cave (Pesce 2001; Talà et al. 2021). For sponges it is unusual to appear in underground habitats, which made the discovery of this species exciting (Pesce 2001). Another endemic species is the harpaticoid *Psyllocamptus monachus* which is only described in the Concito in Zinzulusa cave (Pesce 2001; Talà et al. 2021). Many other aquatic species in the Zinzulusa cave are also endemic to the region of Apulia. Hence, the Zinzulusa cave is an important place for biodiversity conservation. However, Pesce (2001) already mentioned three species including the *Psyllocamptus monachus* that might be extinct as there were no records of them for a period of 40 years.

Talà et al. (2021) investigated the geochemical processes and the microbiological diversity of the Cocito pond and revealed that the sulphur present in the cave originates dominantly from the metabolism of sulphate-reducing bacteria producing hydrogen sulfide (H_2S) and therefore is not of geochemical origin. They also describe the niche-differentiation and hence the diversity of the microbial communities in the Cocito pool which lead to an efficient exploitation of the limited nutrient sources in that environment. Furthermore, they prove that the Zinzulusa cave ecosystem relies on chemotrophy, as the genetic investigations reveal the presence of sulphur, carbon, hydrogen and nitrogen biogeochemical cycles (Talà et al. 2021). About the origin of the microorganisms, Talà et al. (2021) suggest that they are transferred upwards with the geothermal fluids. This theory is supported by the species characteristics: Many of the species are adapted to warm or even hot thermal waters as they occur in the depth, but not in the Cocito pond. Also, strictly anaerobic prokaryotes occur here even though most of the microhabitats in Cocito are aerobic. This illustrates the range of biodiversity in the Cocito pond regarding stygobitic invertebrates and microorganisms like fungi and bacteria.

4.4.3 Conca pond and terrestrial habitats of Grotta Zinzulusa

The Conca pond is inhabited mainly by sea-originated species but also freshwater species. Just like in the Cocito pond it is dominated by copepods. Still, only a few species which are less restricted to specific temperature and salinity ranges are found in both ponds (Pesce 2001). In contrast to the Cocito pond, the Conca pond is located in the part of the cave that is accessible by tourists and hence is influenced by them. Additionally, the terrestrial part in the front area of the cave depicts a habitat for species of which some are troglophile or troglobionts. Among others this includes several insecta, myriapoda and spiders (Pesce and Ciccarese 2006). In 2013, Dondini et al. (2014) found the bat species *Rhinolophus mehelyi* in the Zinzulusa cave. This was of special interest because this species, restricted to the Mediterranean area, seemed to have declined. Moreover, *R. mehelyi* was thought to be extinct on the mainland of Italy as the last record of them was in the 1960s in the Castellana and Zinzulusa caves (Dondini et al. 2014).

4.4.4 Threats and protection

Zinzulusa cave was designated as one of the most endangered karst communities for 1999 by the Karst Water Institute. This was mainly justified by the threat of the pollution by urban discharges and the disturbances due to the visitors accessing the cave and the respective infrastructure which was installed for the visitors (Pesce 2001; D’Agostino et al. 2015). To reduce the impact of the visitor access, all lights were exchanged to LED applications in 2008. The advantages of LED light are that they have a smaller impact on the microclimate of the cave and are more energy-efficient, whereas the former used tungsten lights reduced humidity and increased the temperature in the cave (D’Agostino et al. 2015). However, this is only a really small contribution towards cave conservation. D’Agostino et al. (2015) claim that to reduce lampenflora, lighting should be generally reduced or completely abandoned in some parts of the cave. Additionally, the implementation of disinfection stations for visitors at the entrance could help to avoid the transfer of bacteria and fungi into the caves by the visitors (D’Agostino et al. 2015). Other pressures for the Zinzulusa environment depict urban discharges entering the caves trough the limestone rocks Hence protection measures, targeting these issues should be implemented as D’Agostino et al. (2015) already suggested.

4.5 Lez spring and river

One example of a KGDE where the karst spring is highlighted is the Lez spring in southern France. Additionally, it was chosen as case example because the aquifer, the spring as well as the river represent habitats for numerous species. The Lez spring is a vauclusian-type spring located in the north of the metropolitan area of Montpellier (cf. Fig. 28). It feeds a river of 28.5 km length which flows in its upper reaches predominantly through agriculturally dominated area before it reaches the city of Montpellier where it flows mostly in a concrete channel or under the influence of other anthropogenic structures (Conseil General de l'Herault 2014). The Lez is particularly famous for one fish species that is only observed in its headwaters (SYBLE 2017). On the other hand, the Lez aquifer provides water for 350 000 people (Hérivaux and Maréchal 2019) by pumping directly from the aquifer with a maximum rate of 6120 m^3/h (Dausse et al. 2019). Tab. 10 contains the properties of the Lez KGDE.

Tab. 10: compiled data for the KGDE Lez, coordinates and other spatial data refer to the springs location

name	**type**	**associated components**	**position in hydrological cycle**	**hydroperiod**
Lez	river	spring, river, aquifer	surface flow	intermittent
endemic species	**narrowest endemism concept**	**species groups of endemic species**	**troglo- or stygobionts**	**use**
yes	feature	fish, mollusc	yes	water supply, tourism
risk	**IUCN category**	**protection type**	**designation level**	**country**
contamination, tourism, overextraction	NA	SAC	EU	France
region	**altitude (m)**	**latitude (WGS84)**	**longitude (WGS84)**	**aridity index**
Western Europe	73	43.718056	3.844167	0.877
mean temperature (°C)	**annual precipitation (mm/year)**	**climate class**	**surrounding biome**	**surrounding ecoregion**
14	774	Csa	Mediterranean Forests, Woodlands and Scrub	NE-Spain and S-France Mediterranean forests

4.5.1 Lez basin and aquifer

The aquifer consists of upper Jurassic and early Cretaceous limestones. The flow is determined by the conduits formed by intense and already long-lasting processes of karstification (Dausse et al. 2019). Additionally, the faults related to the Pyrenean orogeny influence the flow of groundwater in the aquifer. Recently, Dausse et al. (2019) also proved the significant role of the bedding plane between the Kimmeridgian and Berriasian limestone as preferential flow path in the Lez aquifer. This structure supports sustainable use of the water, as it allows the groundwater to flow in large volumes over long distances in the aquifer (Dausse et al. 2019). Yet, vulnerability mapping revealed worryingly results, as almost 50% of the Lez catchment is characterized by a high vulnerability due to thin soil layers found the occurrence of direct infiltration (Hérivaux and Maréchal 2019). At first, good water quality is of importance because the local population relies on it for their water supply (Hérivaux and Maréchal 2019; Dausse et al. 2019). Apart from that, the subterranean biodiversity in the aquifer is exceptional and requires good quality water. Sampling of the groundwater from the Triadou wells which are located in the Lez Basin and reach to a depth of 50 m, revealed the presence of 34 stygobionts (3 Mollusca, 3 Oligochaeta, 28 Crustacean) living in the aquifer (Culver and Sket 2000). Moreover, the spring and river which are replenished by the water from the aquifer represent valuable habitats dependent on the karstic groundwater.

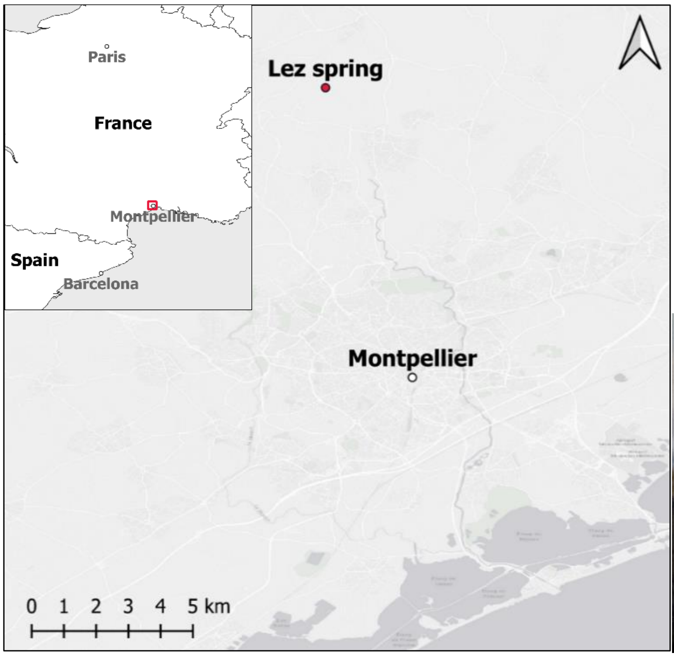


Fig. 28: location of the Lez spring in the North of Montpellier. In the south of Montpellier the Lez river flows via a channel into the Mediterranean Sea. The overview map in the top left corner indicates the location within France. basemap layer source: Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS User Community

Fig. 29: photograph of the Lez sculpin, Cottus petiti, typically staying on the rocky bed of the river (SYBLE 2017).

4.5.2 Lez spring and Lez river

The Lez spring and the headwaters of the river are part of the Natura 2000 network. The Lez is particularly famous for one fish species locally named "Chabot du Lez" (Lez sculpin, *Cottus petiti*) that is only observed in its headwaters. Except there, it was only observed in nearby areas in tributaries of the Lez, like the Lirou where it was confirmed at the confluence (SYBLE 2017). *Cottus petiti*, is a 2 to 6 cm long benthic freshwater fish and by that belongs to one of the smallest fish in Europe (Fig. 29). The optimal habitat consists of shallow flowing waterbodies with loose coarse-grained pebbles and stones in the river bed where they can hide (SYBLE 2017). The Lez is also inhabited by many more fish (*Barbus meridionalis, Lampetra planeri, Parachondrostoma toxostoma*) and other important species that depend on the water like the Eurasion otter (*Lutra lutra*) or the European pond terrapin (*Emys orbicularis*). The diversity of Mollusca species living here stands out and includes the endemic *Paladilhia conica* (Máiz-Tomé et al. 2017). The river section just below the spring is particular rich in species. Additionally, the designation as a Natura 2000 sites is based on the presence of valuable habitats that are listed in the Annex I of the Habitats directive. Of these, *Salix alba* and *Populus alba* galleries take up the largest area, but also, small-scale habitats like calcareous rocky slopes with chasmophytic vegetation exist here (Ministère de la Transition écologique 2019).

4.5.3 Threats and conservation management

In general, the river structure and morphology in the headwaters are attractive for aquatic fauna, as the substrate is loose and diverse and due to the presence of vegetation suitable as hiding place (SYBLE 2017). However, the substrate becomes more compact further downstream and the continuity both in lateral direction as well as along the river course is deteriorated by too high banks on the sides and seven barriers throughout the river. While the barriers hinder the migration capability of the fish and other species severely, the high banks (up to 6 m, where 40-50 cm would be optimal) on the shore prevent the existence of flooding zones which would be important for the species composition along the shoreline (SYBLE 2017). Renaturing and improving the river morphology is therefore a conservation goal. Another pressure on the ecosystem are the water abstractions from the aquifer. The natural spring of the Lez discharges barely or in summer months no water at all (cf. Fig. 30), as the active pumping of the aquifer reduces the flow (Dausse et al. 2019). This is compensated by a continuous discharge of 230 L/s that is provided to the Lez as reserved flow. Another past issue that was improved in 2016 was the location of the artificial outlet which was a few hundred meters downstream of the natural spring which led to a dried up river bed in the upper part during summer droughts. To account for this problem the outlet was relocated 200 m upstream towards the source in order to achieve additional habitat space for wildlife and increase the ecological continuity (SYBLE 2017).

Outdoor sports, leisure and recreational activities are also stated as high pressures on the ecosystem within the protected area. This is expressed by the trampling of vegetation on the banks or in the river itself leading to destruction of the riparian habitats and the riverbed (SYBLE 2017). To address this issue the Conseil General de l'Herault (2014) proposed to install more signs and information for the people as well as to investigate the visitor frequency to better account for that problem in future. Also, chemical analyses on the water quality and the oxygenation reveal that the Lez suffers from nutrient pollution, which is testified by algal blooms and the excessive growth of aquatic plants. This dominantly happens downstream of the confluence of the Lirou. Agricultural activities might be responsible for that as well as the urban settlements in the basin, but the origin of the pollution is not fully clarified yet (SYBLE 2017). Moreover, the monitoring programmes on the fish inventory, the water chemistry and the hydrology of the river continue to evaluate the conservation status and efficiency.

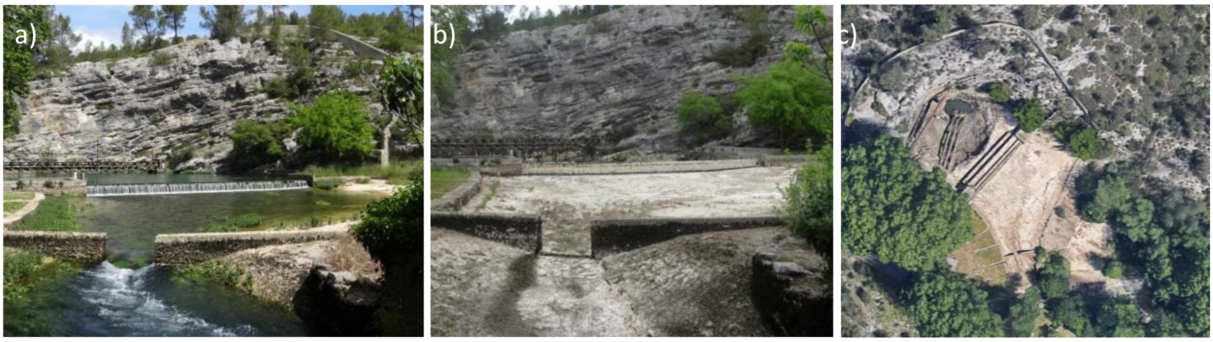


Fig. 30: a) + b) two photographs of the spring area (Conseil General de l'Herault 2014) a) when there is natural outflow from the spring, and b) during times of water shortage. Even now after the relocation of the artificial outlet, the part displayed in b) remains dry. The reserved flow only starts from the point where the picture was taken. c) current satellite image illustrates the dried up and human imprinted spring area: Google Satellite Image © Google © Maxar technologies, map data 2022.

4.6 Lac's d'Imouzzer du kandar

The Lac's d'Imouzzer du kandar KGDE is composed of three lakes in the high-altitude Central Atlas Mountains of Morocco. More precisely they are situated between the cities of Ifrane and Imouzzer du Kandar on altitudes around 1500 m above sea level and they all belong to the basin of the Sebou (Fig. 31). The three mountain lakes are the Dayet Aoua, Dayet Hachlaf and Dayet Ifrah. Whereas the first two consist out of valleys and show an elongated shape, the Dayet Ifrah is a doline with comparatively round and regular outline. All three karst lakes are linked to the same groundwater table which represents the connectivity. There basin is mainly composed of lower Lias dolomites (Sayad et al. 2020).

All the lakes are fed by groundwater as well as by rainfalls and melted snow (Himmi et al. 2019). In the last three decades, the groundwater levels dropped extremely (Himmi et al. 2019) which has led to several pressures on the lake ecosystems. Tab. 11 summarizes again the properties of the lakes.

Tab. 11: compiled data for the KGDE Lacs d'Imouzzer du kandar, coordinates and other spatial data refer to the location of Dayet Hachlaf.

name	type	associated components	position in hydrological cycle	hydroperiod
Lacs d'Imouzzer du kandar	lake	lakes, marshes	surface storage	intermittent
endemic species	**narrowest endemism concept**	**species groups of endemic species**	**troglo- or stygobionts**	**use**
yes	national	reptile	no	grazing, water supply, tourism
risk	**IUCN category**	**protection type**	**designation level**	**country**
drought, overextraction, grazing, solid waste dumping, tourism	II	national park, Ramsar, permanent hunting reserve	national, international	Morocco
region	**altitude (m)**	**latitude (WGS84)**	**longitude (WGS84)**	**aridity index**
Northern Africa	1666	33.550240	-5.001357	0.703
mean temperature (°C)	**annual precipitation (mm/year)**	**climate class**	**surrounding biome**	**surrounding ecoregion**
11	556	Csb	Mediterranean Forests, Woodlands and Scrub	Mediterranean woodlands and forests

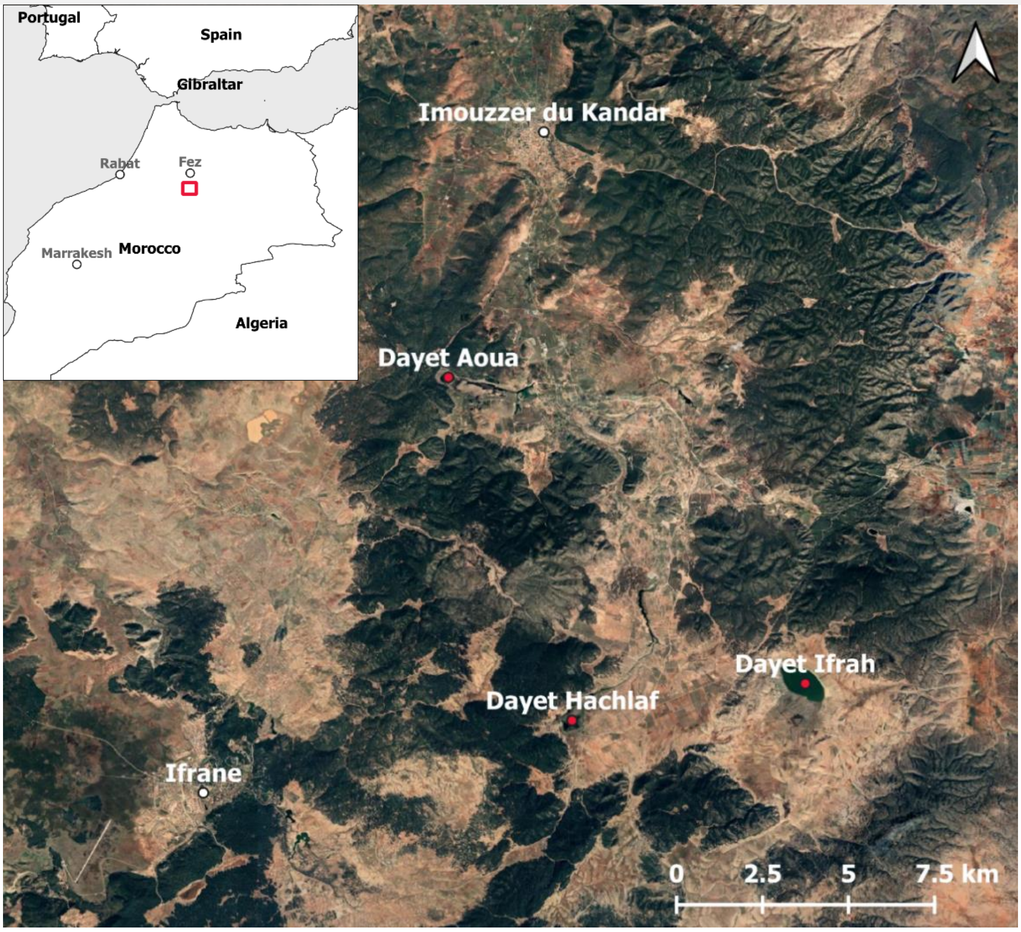


Fig. 31: location map of the lake complex situated between the two cities of Ifrane and Imouzzer zu kandar which includes the three lakes Dayet Hachlaf, Dayet Ifrah, and Dayet Aoua. The overview map in the top left corner indicates the location of the lake complex (red square) in Morocco. Map data source: Google Satellite: Image © CNES / Airbus, Maxar Technologies, © TerraMetrics © 2022

4.6.1 Ecological and socio-economic value of the lake complex

The complex of the three lakes is important from many points of view. First and foremost, the landscape around the three lakes stands out for its morphological and biological diversity and attracts a large number of visitors (Himmi et al. 2019). Especially, Dayet Aoua is popular for any type of leisure activity like water sports, fishing, hiking or picnics on the shoreline. The administrations also strongly promote this development, as it brings economic benefits. For example, they introduced some fish to Dayet Aoua to rise the attractivity of the place for sports fishing, or organize a summer festival (Festival des lacs) representing a mixture of a cultural, artistic and sports event which should attract tourists (Himmi et al. 2019; Sayad et al. 2020). Visitor numbers at the Dayet Aoua range between 500 to 2000 people per week which demonstrates the socio-economic value of the lake (Sayad et al. 2020). Additionally, a land use analysis of Ichen et al. (2021) revealed that agricultural activities as well as the planting of tree farms increased in the given region between 1989 to 2019. At the same time, more private wells have been built near the shoreline especially at Dayet Aoua by farmers for irrigation (Sayad et al. 2020), which leads to an overexploitation of the already declining groundwater level.

From an ecological perspective, the lakes have great potential to contribute to the biodiversity of freshwater habitats and species. Therefore, the lakes Dayet Aoua and Dayet Hachlaf have been included in the list of freshwater key biodiversity areas (Darwall et al. 2015). On the other hand, Nogueira et al. (2021) have shown that none of the aquatic species that resulted in the inclusion to the list (still) occur there. Nogueira et al. (2021) attribute this to two reasons: The first is based on criticism of the selection process for the key biodiversity areas, which at that time still contained weaknesses and was primarily based on desk-work refined by experts knowledge and incorrect or outdated data. The second reason, is that it is quite possible that the species were still present there some time ago, but the ecosystems have changed considerably and conditions have deteriorated rapidly (Nogueira et al. 2021). Nevertheless, during their investigations Nogueira et al. (2021) found four species of interest near the two lakes Aoua and Hachlaf. One of them is the mollusca *Unia foucauldianus*, which only exists in Morocco (Froufe et al. 2016; Nogueira et al. 2021). The results of Nogueira et al. (2021) show that the habitat quality of the lakes for freshwater species is declining and that without appropriate management, more species will disappear.

The lake complex is also designated as Ramsar site due to its rich plant and habitat diversity and especially the importance for waterfowl population. Moreover, the Moroccan endemic lizard *Psammodromus microdactylus* can be found here (Himmi et al. 2019). The rich plant diversity is illustrated by several habitats occupied by plants ranging from aquatic species (e.g. *Ranunculus* sp., *Potamogeton* sp., *Zannichellia palustris*) over plants in marshy areas (e.g. *Typha angustifolia, Phragmites australis, Juncus inflexus, Scirpus holoschoenus, Persicaria lapathifolia*) to belts of black poplar trees (*Populus nigra*) and white willow (*Salix alba*) (Himmi et al. 2019). Regarding waterfowls in this region, about 50 different species can be observed at the lakes over the course of the year (Himmi et al. 2019). In particular wintering birds including endangered species like the white-headed duck (*Oxyura leucocephala*) inhabit the lakes and its surroundings (Ouassou et al. 2021). For that, the Dayet Ifrah is of highest importance, as most were sighted here (Ouassou et al. 2021). Even though plants and birds are less sensitive to the declining water level than aquatic species, their basis for good living conditions is also the diminishing water, which puts them under pressure (Ouassou et al. 2021; Himmi et al. 2019).

4.6.2 Threats and protection

Declining water levels pose the highest threat to the lake ecosystems (Ouassou et al. 2021; Nogueira et al. 2021). The land use analysis of (Ichen et al. 2021) revealed a loss of 17 % of the total water surfaces from 1989 to 2019. The lakes used to be considered permanent bodies of water, but in recent decades at least Dayet Auoa and Dayet Hachlaf have repeatedly dried up completely which affected the aquatic habitats and species severely (Sayad et al. 2020; Nogueira et al. 2021). Reasons for this development involve the population growth in that region which leads to a higher demand of natural resources like groundwater and agricultural products. Ichen et al. (2021) assume that the plantation of apple trees which have a comparatively high water demand contribute substantially to the exploitation of the local aquifer. Generally, the increasing pressure on the natural ecosystems in this region is attributed to the socio-economic development in the area which is characterized by the increase of all sorts of agricultural and leisure activities (Ichen et al. 2021; Himmi et al. 2019). Moreover, the changing climate expressed by droughts in the recent decades exacerbates the drop of the groundwater table (Sayad et al. 2020).

Although the lakes receive great recognition for their ecological relevance and are listed as a Ramsar site and located in a Category II National Park, effective protection measures and appropriate management are lacking (Nogueira et al. 2021; Ouassou et al. 2021). Hence, many authors claim improvements for the conservation of the region's biodiversity. Ichen et al. (2021) claim that a management plan should focus on two aspects. First, the conservation of the natural forests including suitable native tree species and secondly, the organisation of local exploitation activities in cooperatives to mitigate the negative anthropogenic influence on the ecosystems. Even though some plans are already in progress, the enforcement of it faces challenges as a wide range of actors and stakeholder are involved which leads to conflicts of interests especially with the local population (Ouassou et al. 2021). Still, an integrated and cooperative management plan on the use of the natural resources of the region including the groundwater is absolutely essential to achieve a sustainable exploitation of them whilst the ecosystems can prevail their biodiversity (Ichen et al. 2021). Only by the regulation of water withdrawals towards a sustainable use, it can be ensured that the ecosystem services on which the local population depends on will continue to be available to them in the future.

4.7 Figeh springs and Barada river

The last case example of KGDEs is the Figeh springs and Barada river in Syria. This ecosystem is not included in the selection of 113 KGDEs of the Mediterranean area, because it does not longer account to be a functioning ecosystem. Still, it is mentioned here as an example to represent many other KGDEs that got destroyed. Already in the previous examples, it was shown that ecosystems are threatened to die (cf. 4.6 Lac's du Imouzzer du kandar) or parts of the ecosystems have been destroyed (cf. 4.2.3 Bej Bunar spring at Lake Ohrid). Therefore, giving an example of a highly degraded ecosystem completes the overview KGDEs in the Mediterranean area. Tab. 12 shows basic properties for this degraded KGDE.

Tab. 12: compiled data for the degraded KGDE Figeh springs and Barada river, coordinates and other spatial data refer to the location of Figeh springs

name	**type**	**associated components**	**position in hydrological cycle**	**hydroperiod**
Figeh springs and Barada river	river	springs, river	surface flow	NA
endemic species	**narrowest endemism concept**	**species groups of endemic species**	**troglo- or stygobionts**	**use**
no	-	-	no	water supply
risk	**IUCN category**	**protection type**	**designation level**	**country**
drought, overextraction, contamination	-	none	-	Syria
region	**altitude (m)**	**latitude (WGS84)**	**longitude (WGS84)**	**aridity index**
Western Asia	854	33.617483	36.180052	0.304
mean temperature (°C)	**annual precipitation (mm/year)**	**climate class**	**surrounding biome**	**surrounding ecoregion**
16	416	Csa	Mediterranean Forests, Woodlands and Scrub	Eastern Mediterranean conifer-sclerophyllous-broadleaf forests

4.7.1 Overview of the geography and hydrogeology

Barada springs are located approximately 25 km northwest and Figeh springs 15 km northwest of Damascus, the capital of Syria (Fig. 32). Barada springs are supplied by a karst aquifer consisting of Jurassic limestones, whereas the Figeh springs originate from the Upper-Cretaceous (Cenomanian-Turonian) limestone and dolomite aquifer but receives parts of its water also from the Jurassic aquifer (Kattan 1997). Recharge mainly occurs via snow fall in the high altitude mountains during winter, which leads to a buffered recharge and displays a storage effect (Abou Zakhem and Kattaa 2016). Figeh springs are located on the left bank of Barada river, which represents the largest river of the region and receives a substantial part of its water from the Figeh springs (Kattan 1997). The Figeh springs are utilized as water source since the Roman time and in the early/mid 1980s the authorities started to drill boreholes in the vicinity of the spring to pump the groundwater while it was taken from the natural flow before (Kattan 1997; Abou Zakhem and Kattaa 2016). From there the water is transported in pipelines towards reservoirs of the city Damascus where most of the high-quality water is consumed (Châtel and Rab'a 2014; Abou Zakhem and Kattaa 2016). At the time of the publications from Kattan (1997) and Melhem and Higano (2001) the Barada river has still been a perennial river at least in its upper reaches. At that time Figeh springs discharged 7.71 $m^3 s^{-1}$, from which 4.6 $m^3 s^{-1}$ has been utilized but the rest has contributed to the river flow (Melhem and Higano 2001). Also, the surface water of Barada river has been extensively used by farmers for irrigation. After reaching the Ghoutta basin, the river course is divided into channels crossing Damascus and leading towards the Lake Ateibeh (Melhem and Higano 2001). Already back then the river only reached the Lake Ateibeh during the spring of heavy rain periods (Kattan 1997; Melhem and Higano 2001).

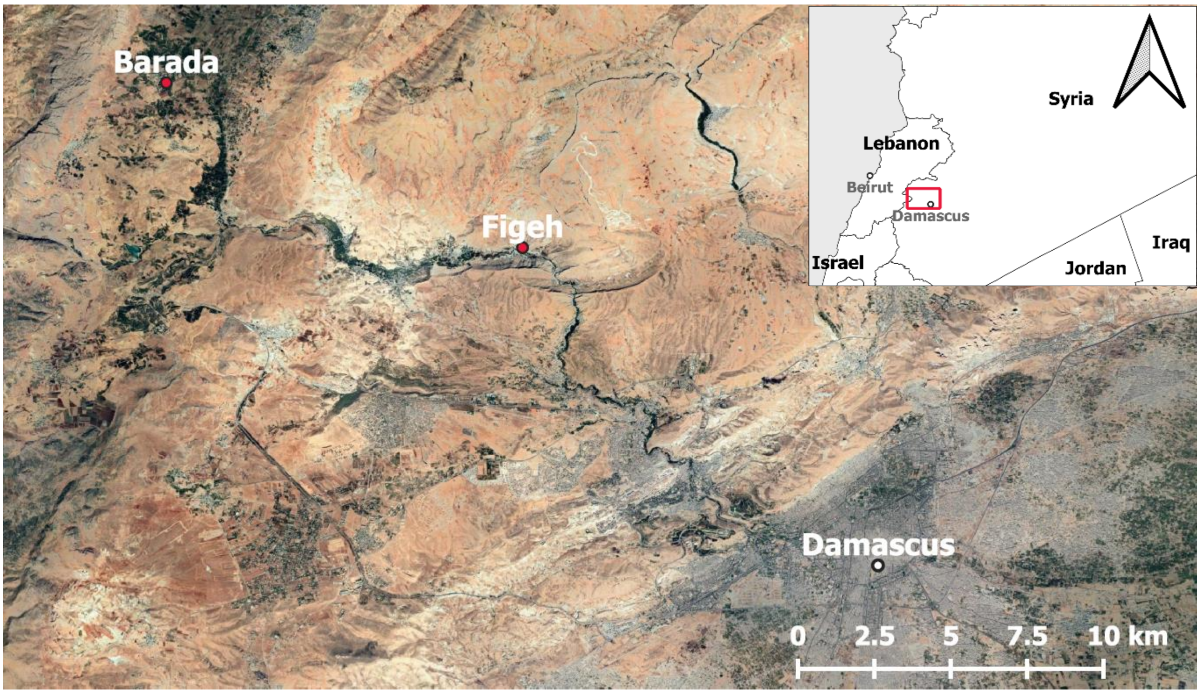


Fig. 32: satellite image of the Barada river course. The location of the Barada spring, the Figeh spring and the city of Damascus is given. The topright corner shows an overview map of the region. The springs are located in the southwest of Syria close to the Lebanese border. Google Satellite Image: © Maxar Technologies, CNES / Airbus © 2022 TerraMetrics

4.7.2 Issues of growing water shortage

The productive Figeh springs covered the entire water demand of Damascus until the 1990s and were still able to provide a reserved flow for the Barada river (Châtel and Rab'a 2014). Since then, the water demand grew so that almost no reserved flow remained (Châtel and Rab'a 2014). Abou Zakhem and Kattaa (2016) state that only two thirds of the required water in Damascus can be provided by the Figeh springs. This illustrates the rapidly increasing water demand but on the other hand how the region suffers under drought conditions which is depicted by a decline in both precipitation and discharge of 12% between the 1980s and 2013 (Abou Zakhem and Kattaa 2016). For the future, Abou Zakhem and Kattaa (2016) propose a further -27% of precipitation and -47% of discharge for the Figeh springs until 2050. Due to the rising water demand and as the Barada river has not been able anymore to supply the farmers adequately with water, more and more boreholes have been drilled to exploit groundwater (Châtel and Rab'a 2014; Baba et al. 2021). Also, in the vicinity of the Barada springs, pumping has started to further supply the reservoirs for the city Damascus (Châtel and Rab'a 2014). The over-exploitation by pumping via rising numbers of unsustainable wells even at location where it is geologically unsuitable has consequently led to groundwater deterioration (Châtel and Rab'a 2014; Baba et al. 2021). A Syrian water expert cited by Châtel and Rab'a (2014), concluded that the management of water supply is less of importance than a better management of the water demand and hence a decline in water consumption, as the resources are already affected by overexploitation. This is confirmed by Kattan (1997) who noticed an increase in the water turnover time and that water is taken faster from the reservoir than it can be recharged.

Even though, no precise numbers can be found, the above-mentioned development illustrates the severe degradation of the river ecosystem due to water abstractions and climate change amplified water shortage. Already Melhem and Higano (2001) states that the "river has become completely dead". Barada River used to be a vital water resource and at the same time the foundation of old and large trees and orchards which supplied the locals with food (Melhem and Higano 2001; Châtel and Rab'a 2014). It was also attributed as a place of culture and inspiration for the residents (Melhem and Higano 2001). In the early 2000s, orchards older than 400 years as well as riparian trees like poplars and willows started to suffer and eventually died which led to the abandonment of the region by many local farmers (Châtel and Rab'a 2014). With regard to aquatic species, the fish *Pseudophoxinus syriacus* was observed in the last remainder of the Barada spring area in 2008, where it is endemic, but until now it is assumed to gone extinct, as the area has almost fully dried up (Freyhof et al. 2014). Another fish species, the *Acanthobrama tricolor,* which was last observed in 1908 in the Barada river is also assumed to be critically endangered or might even be extinct as it was nowhere else recorded than in the Barada and the Golan Area in 1980s (Freyhof et al. 2014). Since recent surveys are lacking, it cannot be said with certainty that the two species no longer occur there or are even completely extinct (Freyhof et al. 2014). Still, the condition of the river suggests that they are.

4.7.3 Issues of pollution

Besides the water shortage induced by exaggerated pumping and droughts associated with the changing climate, Melhem and Higano (2001) state pollution as another major cause of the degradation of the Barada river ecosystem. Pollution originates from several sources comprising domestic, agricultural and industrial wastewater inputs, which all together make up approximately 200 million m^3 of wastewater entering the Barada river every year (Melhem and Higano 2001). Uncontrolled economic development plays a major role in this problem, as many industries along the river still rely on old technologies that require a lot of water and cause pollution that is then discharged into the river without prior treatment. As the Barada river itself is situated on permeable rocks, infiltration of the contaminated water into the aquifer depicts a further risk for the groundwater and not only the surface water (Baba et al. 2021). Especially since the local people depend on the water as drinking water but also for growing food, where the substances can accumulate in the plants, the pollution is a big problem not only for the ecosystem but also for the population there (Baba et al. 2021; Châtel and Rab'a 2014). Overall, Melhem and Higano (2001) state that the lack of an environmental law is detrimental as well as the fact that the environmental ministry is only reacting on environmental problems rather than trying to prevent them.

Since the start of the war in 2011, other risks to surface and groundwater have been added. The use of chemical weapons can contaminate the water as well and depending on the applied substances they depict a high risk for both the health of human and organisms in the water (Baba et al. 2021). Even though the data situation since the beginning of the war is poor and no investigations could have been carried out on the contamination by chemical weapons, it can be assumed that the region of the Barada River is also affected, as one of the attacked sites is Ein Tarma which is only 400 m away from the river (Baba et al. 2021).

As the country is still caught up in geopolitical difficulties, quick improvements to the current situation seem almost impossible. Nevertheless, it should be reiterated that environmental laws that include subsidies for the development of clean technologies, and then also the corresponding efficient implementation and control of the law, are urgently needed (Melhem and Higano 2001). Likewise, wastewater treatment plants should be modernised and more parts of the settlements should be connected to them. The last point to be mentioned here is that the goals can only be achieved in cooperation with the local population. Therefore, awareness of the relation between high quality living standards and a healthy environment that is able to provide ecosystem services must also be created among them (Melhem and Higano 2001). Finally, it must be said that due to the instabilities of the last decade, there are hardly any current reports or scientific publications from the area. As a result, much remains unclear or can only be assumed. The major problems of water shortage due to overuse and climate change, but also the dramatic pollution due to lack of management, were already apparent much earlier and were also one of the reasons for people to start protests in 2011 (Châtel and Rab'a 2014). Therefore, it can be assumed that the situation has worsened even more and that an improvement for the local people but also for the last remnants of the ecosystem is very unlikely.

5. Joint discussion of the general evaluation and the case examples

To answer the initial questions given in chapter 1.4 the findings of the case examples and the general evaluation of the KGDEs are considered. Evaluating KGDEs altogether is complicated as they differ highly in their types. Additionally, the climatic and other spatial related differences in the Mediterranean are high and therefore influence the shape and expression of KGDEs in the landscape. Hence, criteria like climate characteristics, biomes, coordinates and altitude values are relevant for a first categorisation of KGDEs within the Mediterranean. Furthermore, to specify the value of KGDEs the ecosystem type is of pronounced importance, as this determines the present habitats and distinguishes the ecosystems among each other. The ecosystem type also influences other ecosystem characteristics like their utilization or the frequency of stygo- and troglobionts that can be observed there. Other than the stygo- or troglobionts, the presence of endemic species and their level of endemism can be used for the evaluation, as this indicates the peculiarity and the isolation of this KGDEs compared to its surroundings. Moreover, the hydroperiod as given in Kløve et al. (2011a) can be used to assess KGDEs and with the adjusted definition used here, it can be applied on all types of ecosystems. As this study also aimed to investigate risks and conservation of those ecosystems, these two characteristics were used for the evaluation too.

These are already several criteria for the evaluation of KGDEs, however, they all remain comparatively vague, as the available information on this spatial scale does not allow more specific and detailed criteria. More precise criteria could involve holistic species composition data including species richness and other biodiversity indices. Also, accurate hydrological information on the discharge pattern and discharge flow rate could supplement the given criteria (Cantonati et al. 2020). Ravbar and Pipan (2022) suggest characteristics like the existing habitat types, groundwater taxa and ecohydrogeological processes for the categorisation of KGDEs. Furthermore, the chemical status of the water comprises a relevant criterion for the classification (Cantonati et al. 2020). In this context, it would be interesting to evaluate the difference between karst systems with autogenic and allogenic recharge and solemnly autogenic systems, as this brings differences in the water chemistry as well as in the nutrient supply and species assemblage (Gunn 2004; Ravbar and Pipan 2022).

On the other hand, there are additional criteria that could be applied to KGDEs of the same ecosystem type. For example, for springs, there is the springs classification by Springer and Stevens (2009), for caves and other subterranean cavities depth and void size could be used and for river, lake and wetland ecosystems a criterion that accounts the degree of groundwater dependency would be interesting although it is hard to determine (Eamus et al. 2016). All of these additional criteria were not applied in this study, because for the majority of the selected KGDEs barely any information regarding these criteria was available. Hence, a meaningful and representative evaluation of these criteria would not be possible.

In terms of data availability, problems of outdated and non-comparable information arose which is why some aspects in the literature were considered with caution and hence were excluded from the analysis. In addition, available detailed information on some KGDEs could not be included in the comparisons, as for most others the relevant information is not available. Therefore, the holistic assessment of the 113 KGDEs is kept general. Comparable data is provided by the Standard data forms of Natura 2000 sites and the Ramsar Sheets, as they provide a standardized template and consistent way for completing the dataset. Another helpful tool for future investigations like this, could become the comprehensive springs database which is hosted by Springs Stewardship Institute (https://springsdata.org/). It allows efficient and consistent data entries on springs worldwide by providing a guideline on how to record and classify springs uniformly (Stevens et al. 2016). In the end, data on springs can get entered, archived and provided online to other researchers. Uniformly designed data collections would allow studies like this to get easier access to the needed data and allow better conclusions from the data.

Regarding the second main question on the distribution of KGDEs in the Mediterranean it is concluded that they can be found almost everywhere, where there is karst. Two main areas represent the Dinaric karst regions, which also stands out for KGDEs with exceptional high biodiversity and the Spanish karst areas. Together they already account for 40 (Dinarides: 18, Spain: 22) of the total selected 113 KGDEs. Although these numbers have to be treated with caution, as the collection does not cover all existing KGDEs, these two clusters stand out considerably. Moreover, other studies describe Northern Spain and the Dinaric karst as groundwater/subterranean biodiversity hotspots (Iannella et al. 2020; Culver et al. 2021) and thereby confirm the results of this study. Three other regions with several KGDEs are the Central Apennines, the Moroccan Atlas Mountain range and the Eastern Mediterranean region. There might be other regions hosting valuable KGDEs which remain undetected due to the lacking data and research coverage.

In terms of ecological value also the Dinaric KGDEs stand out with a high frequency of endemic species, large habitat and ecosystem type diversity and the two most biodiverse caves in the world (Niemiller et al. 2018; Culver et al. 2021). But here, it must be noted too that there can be a bias due to the different progress of research in the regions. The Dinarides are a core area and prime example for karst research and the associated groundwater-dependent ecosystems (Stevanović et al. 2021), whereas in other regions, such as North Africa, there are hardly any studies on this topic. Another aspect about the distribution of KGDEs concerns the examples in comparatively arid and water-limited regions. Even though, only a few are situated in these regions, they are of special relevance, because the groundwater that emerges there changes the landscape substantially. It creates “green islands“ in otherwise desert environments, which serve as habitat for many species that rely on the water but also on other resources that are derived from groundwater-dependent ecosystems. This significance is also illustrated by the difference of the actual expression of the ecosystem involving wetland vegetation and the usual vegetation described by the biome or ecoregion. The most extreme examples are the two oases Ein Gedi and Ein Feshkha where the region’s biome is describes as Desert and Xeric Shrublands. Hence, especially in water-limited regions, KGDEs depict valuable ecosystems, contributing to regional biodiversity, serving as refuge for aquatic but also terrestrial species and providing essential resources for local residents (Cartwright et al. 2020).

The third research question concerned the risks that endanger Mediterranean KGDEs. Within this study, it was found that threats from human intervention and disturbance directly to the ecosystem are the most common threats and can be largely attributed to tourism and recreational activities. This is most evident in the southern European examples, which also fits with the popularity of this region for recreational activities (Erostate et al. 2020; Fosse 2021). In many cases excessive tourist development goes along with the construction of facilities, like hotels, restaurants and recreational services, which in turn leads to the problem of habitat destruction (Kostoski et al. 2010; Fosse 2021). This adverse effect was also confirmed in the case examples of Lake Ohrid or the Lez spring. It is expressed by direct effects like trampling or removing sensitive vegetation contaminant or trash inputs from visitors, increased boat traffic and impacts on the species distribution by hunting, fishing or the introduction of invasive species (Kostoski et al. 2010). The damaging influence of mass tourism and population growth on these sensitive ecosystems in general is dominant in the Mediterranean area (Erostate et al. 2020; Fosse 2021). To address this problem, appropriate restrictions for visitors are necessary combined with the education of them, because environmental awareness among the local population but also among visitors is substantial to achieve conservation efforts (Kostoski et al. 2010). Furthermore, the conversion from mass tourism towards sustainable tourism is needed including for example circular-waste management in tourist facilities especially of the water resources and investments for the restoration programmes for degraded ecosystems (Fosse 2021).

In contrast, in Western Asia these types of risks are rarely a problem, but water shortage is the dominant risk for 69% of the KGDEs there. It is also the most common hazard in North Africa. The problem is mostly due to decreasing rainfall combined with poor management of groundwater, resulting in overexploitation. That is for example shown in the two case examples of the lake complex in Morocco (Lacs d'Imouzzer du kandar) and the degraded Barada river ecosystem. There, the conflict of interest between water supply for local industries and agriculture and a sustainable reserved groundwater contribution for the ecosystems is prevailing. That is why the implementation of conservation strategies of the KGDEs and management strategies for the groundwater utilization are mostly complicated.

This leads to the remaining question on how to conserve the KGDEs adequately. One principal planning approach for the management of GDEs that have to face declining groundwater levels is developed by (Chambers et al. 2013). It consists of several steps to identify the hazards and model the associated consequences in order to design management strategies based on these results. Regarding the management strategies, two concepts are suggested, either a top-down or a bottom-up approach. Thereby, top-down refers to the approach of starting from the assessed risks or specific scenarios of how groundwater levels will change. On the contrary, the bottom-up approach is based on specific conservation objectives, for example the protection of an endemic species as it aims to identify and maintain the requirements as well as the thresholds of environmental change that this species can tolerate (Chambers et al. 2013).

Apart from that, the case examples of this study demonstrate some explicit conservation measures from Northern Africa and the Arabian Peninsula where overexploitation and droughts are of particular relevance. This includes local water management strategies, reforestation with native trees, subsidies for modern water-saving technologies, appropriate and sustainable agricultural practices (Melhem and Higano 2001; Ichen et al. 2021). Once more, the importance of environmental awareness and the recognition of limited water resources among the local population has to be emphasized in order to successfully implement such laws and management strategies (Melhem and Higano 2001).

Other exemplary conservation measures are the supply of the Lez river with a reserved flow, regular monitoring of the endemic but also other species in the river, as well as the installation of information boards for visitors (SYBLE 2017). Fish breeding programmes for some native fish of Lake Ohrid and several offers on environmental education including regular school excursions represent further examples (Kostoski et al. 2010). The conservation management of the Ein Gedi and Ein Feshkha also comprise monitoring programmes, restrictive measures to prevent human disturbances in the nature reserves and water management plans for the Ein Gedi springs (INPA 2017). In principle, the study also shows that although there are many protected areas and conservation programmes, the KGDEs are under great pressure. This demonstrates the often very low protective effect of these designated areas. This has already been criticised from many experts and several reasons and possible improvements are provided.

Nogueira et al. (2021) discuss the process of the delineation for freshwater key biodiversity areas initiated by the IUCN and find several shortcomings due to outdated or lacking distribution data for the trigger species which are relevant for the designation. Their suggestions on how to improve the process involves among others regular field surveys to validate the data applied for the designation and to monitor changes in the ecosystem. Of course, this requires economic and human resources and hence long-term (financial) support for the designation of hotspot areas for protection in order to establish the cooperation between politicians, local stakeholders and researchers (Nogueira et al.

2021). As already indicated by this, the missing knowledge on species occurrence and the ecosystem ecology is a prevailing issue for species and ecosystem protection and must be improved by studies and monitoring of species assemblages (Albrecht and Wilke 2008; Nogueira et al. 2021; Stevens et al. 2022). Even though this is only explicitly stated in the literature for a few ecosystems, it is a problem for many of them. This became particularly apparent in the course of the literature research, as the state of research for the ecosystems varies extremely. Especially for the ecosystems in North Africa and West Asia, the dominant focus in on the plant occurrence and the vertebrates living there. Hence, it is necessary to extend future studies to the invertebrate fauna. Nogueira et al. (2021) used eDNA analyses and also recommend this approach for the investigation on the species inventory and monitoring because it does not rely on special taxonomic knowledge. Beside a better knowledge of the species inventory, more investigations about the ecosystem’s dependency on the quantity and the chemical status of the groundwater supply are important for designing appropriate protection strategies (European Commission et al. 2015).

Another issue concerning conservation efficiency that is stated in literature and can be confirmed by this study is the unbalanced representation of taxa in legislations that determine the species that have to be protected (e.g. Annex II of Habitats directive (EC 1992)). Invertebrates are regularly under-represented and the contained invertebrates are dominated by popular and charismatic taxa like Lepidoptera or Odonata (Niemiller et al. 2018). Hence, most aquatic invertebrates, stygo- and troglobionts are neglected and therefore no projects can be funded for their protections (Niemiller et al. 2018). This is confirmed, as the reviewed data tables of Ramsar and Natura 2000 site concentrate on vertebrates whereas information on invertebrates is scarce. Furthermore, even though Ramsar convention by now aims to consider the wetland ecosystems comprehensively (Ramsar Convention Secretariat 2016), the earlier focus on waterfowl is still noticeable in many Ramsar sites descriptions. Exceptions from these legislations comprise national legislations of Slovenia that protect entire subterranean environments or of Croatia where many stygo- and troglobionts are strictly protected (Niemiller et al. 2018). Both issues, the one of the lacking data on holistic species assemblages of the ecosystems and the neglected taxa in legislations and other conventions affect springs and cave KGDEs in particular because they mostly stand out by invertebrate diversity and are less recognized by the public (Niemiller et al. 2018; Stevens et al. 2022). This demonstrates the needs for a better recognition and protection of these ecosystem types and therefore more studies on these ecosystems should be conducted.

6. Conclusion

In this Deliverable a selection of 113 karst groundwater dependent ecosystems (KGDEs) in the Mediterranean area are characterized by using multidisciplinary criteria involving climatic, hydrogeological and ecological properties as well as information on the socio-economic context of the ecosystems. These criteria are chosen according to the data availability and the spatial scale of this study and are therefore kept quite general. More specific criteria like the biogeochemical water quality status or the degree of groundwater dependency are presented but could not be applied here. The provided list intends to illustrate the high value and importance of KGDEs in the Mediterranean region and is not meant to represent an exhaustive collection of KGDEs in the study area.

By applying the criteria on the selected KGDEs the variety and the importance of such ecosystems throughout the Mediterranean area is demonstrated. Although KGDEs can be found all over the study area, two clusters in Spain and the Dinarides stand out in particular. The latter also stands out by exceptional biodiversity, high frequency of endemic species and a great variety of karst landforms. Yet, the Dinaric Karst is a core area for karst research and therefore the advanced state of research could distort the results as other regions are not that deeply studied and might harbour undetected endemic species and generally a higher biodiversity than this study was able to . Furthermore, the importance of KGDEs in arid regions is illustrated, although such represent only a small fraction of the KGDE collection. In arid regions the emerging groundwater often serves as only water resource and creates valuable habitats in the otherwise dry surroundings.

The increasing anthropogenic pressures endanger many of the selected KGDEs. Above all, direct human intrusions prevail and need to be addressed by restrictions and enhanced public education on these valuable and often sensitive ecosystems. Tourism and population growth enhances this affect and is associated with other threats like habitat destruction, overexploitation of the groundwater resource and also its pollution. Therefore, appropriate management strategies are necessary and sustainable development should be achieved. Especially in the regions of Western Asia and Northern Africa, a better groundwater management should be established in order to tackle declining groundwater levels and water quality degradation. Furthermore, the shortage of studies covering invertebrate taxa and the conservation legislations recognizing them, leads to additional conservation issues. Especially cave and spring KGDEs suffer under these circumstances as they are particularly valuable due to their special, often adapted and endemic invertebrate fauna. More research on these taxa is necessary and the extension of species lists in legislations are claimed to improve funding opportunities for such ecosystems.

References

Abou Zakhem, Boulos; Kattaa, Bassam (2016): Cumulative drought effect on Figeh karstic spring discharge (Damascus basin, Syria). In Environmental Earth Sciences 75 (2). DOI: 10.1007/s12665-015-5013-3.

Albrecht, Christian; Wilke, Thomas (2008): Ancient Lake Ohrid: biodiversity and evolution. In *Hydrobiologia* 615 (1), pp. 103–140. DOI: 10.1007/s10750-008-9558-y.

Apostolova, Nadezda; Scarry, Daniel; Verhoeven, Jos T.A. (2016): Studenchishte Marsh as an Integral Part of Ancient Lake Ohrid: Current Status and Need for Protection. 33rd ed. Wetland Science & Practice (2).

Baba, Alper; Karem, Ruwad AL.; Yazdani, Hamidreza (2021): Groundwater resources and quality in Syria. In *Groundwater for Sustainable Development* 14. DOI: 10.1016/j.gsd.2021.100617.

Beck, Hylke E.; Zimmermann, Niklaus E.; McVicar, Tim R.; Vergopolan, Noemi; Berg, Alexis; Wood, Eric F. (2018): Present and future Köppen-Geiger climate classification maps at 1-km resolution. In *Scientific data* 5, pp. 180-214. DOI: 10.1038/sdata.2018.214.

Ben-Itzhak, Leehee Laronne; Gvirtzman, Haim (2005): Groundwater flow along and across structural folding: an example from the Judean Desert, Israel. In *Journal of Hydrology* 312 (1-4), pp. 51–69. DOI: 10.1016/j.jhydrol.2005.02.009.

Bertrand, Guillaume; Goldscheider, Nico; Gobat, Jean-Michel; Hunkeler, Daniel (2012): Review: From multi-scale conceptualization to a classification system for inland groundwater-dependent ecosystems. In *Hydrogeol J* 20 (1), pp. 5–25. DOI: 10.1007/s10040-011-0791-5.

Bonacci, Ognjen; Pipan, Tanja; Culver, David C. (2009): A framework for karst ecohydrology. In *Environ Geol* 56 (5), pp. 891–900. DOI: 10.1007/s00254-008-1189-0.

Breckle, Siegmar-W.; Rafiqpoor, M. Daud (2019): Vegetation und Klima. Berlin, Heidelberg: Springer Berlin Heidelberg.

Bruno, Maria Cristina; Cottarelli, Vezio; Grasso, Rosario; Latella, Leonardo; Zaupa, Silvia; Spena, Maria Teresa (2018): Epikarstic crustaceans from some Italian caves: endemisms and spatial scales. In *BG* 33 (0). DOI: 10.21426/B633035812.

Burg, Avihu; Yechieli, Yoseph; Galili, Udi (2016): Response of a coastal hydrogeological system to a rapid decline in sea level; the case of Zuqim springs – The largest discharge area along the Dead Sea coast. In *Journal of Hydrology* 536, pp. 222–235. DOI: 10.1016/j.jhydrol.2016.02.039.

Cantonati, Marco; Stevens, Lawrence E.; Segadelli, Stefano; Springer, Abraham E.; Goldscheider, Nico; Celico, Fulvio et al. (2020): Ecohydrogeology: The interdisciplinary convergence needed to improve the study and stewardship of springs and other groundwater-dependent habitats, biota, and ecosystems. In *Ecological Indicators* 110. DOI: 10.1016/j.ecolind.2019.105803.

Cartwright, Jennifer M.; Dwire, Kathleen A.; Freed, Zach; Hammer, Samantha J.; McLaughlin, Blair; Misztal, Louise W. et al. (2020): Oases of the future? Springs as potential hydrologic refugia in drying climates. In *Front Ecol Environ* 18 (5), pp. 245–253. DOI: 10.1002/fee.2191.

Chambers, J. M.; Nugent, G.; Sommer, B.; Speldewinde, P.; Neville, S.; Beatty, S. et al. (2013): Adapting to climate change: A risk assessment and decision making framework for managing groundwater dependent ecosystems with declining water levels. Guidelines for use. Gold Coast, Queensland: National Climate Change Adaptation Research Facility.

Chapin, F. Stuart; Matson, Pamela A.; Vitousek, Peter Morrison (2011): Principles of terrestrial ecosystem ecology. 2. ed. New York, NY, Heidelberg: Springer.

Châtel, Francesca de; Rab'a, Mohammad (2014): Waterless Wadi Barada: Manufacturing Scarcity in a Syrian River Valley. In *Middle East Report* (271), pp. 10–17. Available online at https://www.jstor.org/stable/24426553.

Cherlet, Michael; Hutchinson, Charles; Reynolds, James; Hill, Joachim; Sommer, Stefan; Maltitz, Graham von (Eds.) (2018): World atlas of desertification. Rethinking land degradation and sustainable land management. Third edition. Luxembourg: Publications Office of the European Union.

Conseil General de l'Herault (2014): Rapport d'activité Animation 2014. Site d'Importance Communautaire Le Lez - FR 9101392.

Cowling, Richard M.; Rundel, Philip W.; Lamont, Byron B.; Kalin Arroyo, Mary; Arianoutsou, Margarita (1996): Plant diversity in mediterranean-climate regions. In *Trends in Ecology & Evolution* 11 (9), pp. 362–366. DOI: 10.1016/0169-5347(96)10044-6.

Culver, David C.; Deharveng, Louis; Pipan, Tanja; Bedos, Anne (2021): An Overview of Subterranean Biodiversity Hotspots. In *Diversity* 13 (10), p. 487. DOI: 10.3390/d13100487.

Culver, David C.; Pipan, Tanja (2013): Subterranean Ecosystems. In Simon A. Levin (Ed.): Encyclopedia of biodiversity. Amsterdam: Elsevier, pp. 49–62.

Culver, David C.; Sket, Boris (2000): Hotspots of Subterranean Biodiversity in Caves and Wells. In *Journal of Cave and Karst Studies* 62 (1), pp. 11–17.

Cvetkoska, Aleksandra; Pavlov, Aleksandar; Jovanovska, Elena; Tofilovska, Slavica; Blanco, Saul; Ector, Luc et al. (2018): Spatial patterns of diatom diversity and community structure in ancient Lake Ohrid. In *Hydrobiologia* 819 (1), pp. 197–215. DOI: 10.1007/s10750-018-3637-5.

D'Agostino, Delia; Beccarisi, Leonardo; Camassa, Michele; Febbroriello, Peter (2015): Microclimate and microbial characterization in the Zinzulusa show cave (South Italy) after switching to LED lighting. In *JCKS* 77 (3), pp. 133–144. DOI: 10.4311/2014EX0123.

Danielson, Jeffrey J.; Gesch, Dean B. (2011): Global multi-resolution terrain elevation data 2010 (GMTED2010). Open-File Report.

Darwall, William; Carrizo, S.; Numa, Catherine; Barrios, Violeta; Freyhof, Jörg; Smith, K. (2015): Freshwater Key Biodiversity Areas in the Mediterranean Basin Hotspot: International Union for Conservation of Nature.

Dausse, Amélie; Leonardi, Véronique; Jourde, Hervé (2019): Hydraulic characterization and identification of flow-bearing structures based on multi-scale investigations applied to the Lez karst aquifer. In *Journal of Hydrology: Regional Studies* 26. DOI: 10.1016/j.ejrh.2019.100627.

Dondini, Gianna; Tomassini, Alessandra; Inguscio, Salvatore; Rossi, Emanuela (2014): Rediscovery of Mehely's horseshoe bat (*Rhinolophus mehelyi*) in peninsular Italy. In *Hystrix, the Italian Journal of Mammalogy* 25 (1), pp. 59–60. DOI: 10.4404/hystrix-25.1-9248.

Dudley, Nigel (Ed.) (2013): Guidelines for applying protected area management categories including IUCN WCPA best practice guidance on recognising protected areas and assigning management categories and governance types. Gland: IUCN (Best practice protected area guidelines series, 21).

Eamus, Derek; Fu, Baihua; Springer, Abraham E.; Stevens, Lawrence E. (2016): Groundwater Dependent Ecosystems: Classification, Identification Techniques and Threats. In Anthony J. Jakeman, Olivier Barreteau, Randall J. Hunt, Jean-Daniel Rinaudo, Andrew Ross (Eds.): Integrated Groundwater Management. Cham: Springer International Publishing, pp. 313–346.

EC (1992): Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora. In *OJ L 206, 22.7.1992*, pp. 7–50.

EC (2008): Natura 2000: protecting Europe’s biodiversity. With assistance of European Commission. Directorate General for the Environment: Publications Office.

EC (2009): Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds. In *OJ L 20, 26.1.2010*, pp. 7–25.

Erostate, M.; Huneau, F.; Garel, E.; Ghiotti, S.; Vystavna, Y.; Garrido, M.; Pasqualini, V. (2020): Groundwater dependent ecosystems in coastal Mediterranean regions: Characterization, challenges and management for their protection. In *Water research* 172. DOI: 10.1016/j.watres.2019.115461.

European Commission, Directorate-General for Environment; Petitta, Marco; Hinsby, Klaus; Schutten, Johan; Craig, Matt; Prchalova, Hana (2015): Technical report on groundwater associated aquatic ecosystems. Edited by Tony Marsland. Luxembourg: Publications Office (9). Available online at https://data.europa.eu/doi/10.2779/6042.

Fick, Stephen E.; Hijmans, Robert J. (2017): WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. In *Int. J. Climatol* 37 (12), pp. 4302–4315. DOI: 10.1002/joc.5086.

Föller, K.; Stelbrink, B.; Hauffe, T.; Albrecht, C.; Wilke, T. (2015): Constant diversification rates of endemic gastropods in ancient Lake Ohrid: ecosystem resilience likely buffers environmental fluctuations. In *Biogeosciences* 12 (23), pp. 7209–7222. DOI: 10.5194/bg-12-7209-2015.

Ford, Derek; Williams, Paul W. (2010): Karst hydrogeology and geomorphology. [Rev. ed.]. Chichester, England, A Hoboken, NJ: John Wiley & Sons.

Fosse (2021): The future of Mediterranean tourism in a (post) covid world, Available online at: https://www.ecounion.eu/en/portfolio/blue-tourism/, checked on 8/29/2022.

Freyhof, Jörg; Ekmekçi, Fitnat; Ali, Atheer; Khamees, Najim; Ozulug, Müfit; Hamidan, Nashat et al. (2014): Freshwater fishes. In: The status and distribution of Freshwater biodiversity in the Eastern Mediterranean. IUCN programs, pp. 19-42.

Froufe, Elsa; Gonçalves, Duarte V.; Teixeira, Amílcar; Sousa, Ronaldo; Varandas, Simone; Ghamizi, Mohamed et al. (2016): Who lives where? Molecular and morphometric analyses clarify which Unio species (Unionida, Mollusca) inhabit the southwestern Palearctic. In *Org Divers Evol* 16 (3), pp. 597–611. DOI: 10.1007/s13127-016-0262-x.

Galassi, Diana M. P.; Stoch, Fabio; Fiasca, Barbara; Piermarocchi, Andrea; Di Lorenzo, Tiziana (2014): Ecosistemi dipendenti dalle acque sotterranee: biodiversità, funzioni ecosistemiche ed effetto dei cambiamenti climatici. In *Biologia Ambientale* 28.

Galili, U. (2007): Summary of hydrometric measurements in Samar and Kane springs in the years 2004-2006. (in Hebrew). In *The Israeli Hydrological Service, Report hydro.* (2), 30pp.

Galili, U. (2012): Summary of hydrometric measurements in Tsukim springs in the years 2003-2011. (in Hebrew). In *The Israeli Hydrological Service, Report hydro.* (1), 33pp.

Gera, Avivit (2017): Enot Tsukim Nature Reserve. brochure. With assistance of Noa Motro, Miriam Feinberg Vamosh, Adi Greenbaum, Tania Slutzky, Yuval Artman. Available online at https://en.parks.org.il/reserve-park/enot-tsukim-nature-reserve/, checked on 8/2/2022.

GIZ (2017): Initial Characterisation of Lakes Prespa, Ohrid and Shkodra/Skadar. Implementing the EU Water Framework Directive in South-Eastern Europe. Edited by Ralf Preveling, Uwe Brämick, Holger Densky, Bill Parr, Michael Pietrock. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Goldscheider, Nico (2005): Karst groundwater vulnerability mapping: application of a new method in the Swabian Alb, Germany. In *Hydrogeol J* 13 (4), pp. 555–564. DOI: 10.1007/s10040-003-0291-3.

Goldscheider, Nico (2019): A holistic approach to groundwater protection and ecosystem services in karst terrains. In *Carbonates Evaporites* 34 (4), pp. 1241–1249. DOI: 10.1007/s13146-019-00492-5.

Griebler, Christian; Avramov, Maria; Hose, Grant (2019): Groundwater Ecosystems and Their Services: Current Status and Potential Risks. In Schröter, Slobodien (Eds.): Atlas of Ecosystem Services. 1st ed. Springer International Publishing, pp. 197–203.

Gunn, John (2004): Encyclopedia of Caves and Karst Science. 1st ed.: Routledge.

Hadas, G. (2012): Ancient agricultural irrigation systems in the oasis of Ein Gedi, Dead Sea, Israel. In *Journal of Arid Environments* 86, pp. 75–81. DOI: 10.1016/j.jaridenv.2011.08.015.

Hauffe, T.; Albrecht, C.; Schreiber, K.; Birkhofer, K.; Trajanovski, S.; Wilke, T. (2011): Spatially explicit analysis of gastropod biodiversity in ancient Lake Ohrid. In *Biogeosciences* 8 (1), pp. 175–188. DOI: 10.5194/bg-8-175-2011.

Hérivaux, C.; Maréchal, JC. (2019): Prise en compte des services dépendants des aquifères dans les démarches d'évaluation des services écosystémiques. BRGM (RP-68929-FR).

Himmi, Oumnia; El Agbani, Mohammed Aziz; Qninba, Abdeljebbar; Ouassou Asmaa; Dakki, Mohamed; Amhaouch, Zouhair et al. (2019): Maroc - Lacs d'Imouzzer du Kandar. Fiche descriptive Ramsar. Institut Scientifique – Université Mohammed V de Rabat/ GREPOM BirdLife Maroc. Available online at https://rsis.ramsar.org/ris/2374.

Hirshberg, Ofir; Ben-Ami, Frida (2019): Sinkholes as a source of life in the Dead Sea region. In *Aquat Sci* 81 (1). DOI: 10.1007/s00027-018-0611-2.

Howarth, Francis G.; Moldovan, Oana Teodora (2018a): The Ecological Classification of Cave Animals and Their Adaptations. In Oana Teodora Moldovan, Ľubomír Kováč, Stuart Halse (Eds.): Cave Ecology, vol. 235. Cham: Springer International Publishing (Ecological Studies), pp. 41–67.

Howarth, Francis G.; Moldovan, Oana Teodora (2018b): Where Cave Animals Live. In Oana Teodora Moldovan, Ľubomír Kováč, Stuart Halse (Eds.): Cave Ecology, vol. 235. Cham: Springer International Publishing (Ecological Studies), pp. 23–37.

Iannella, Mattia; Fiasca, Barbara; Di Lorenzo, Tiziana; Biondi, Maurizio; Di Cicco, Mattia; Galassi, Diana M. P. (2020): Jumping into the grids: mapping biodiversity hotspots in groundwater habitat types across Europe. In *Ecography* 43 (12), pp. 1825–1841. DOI: 10.1111/ecog.05323.

Ichen, Abdellah; Messaoudi, Chaimae; El Malki, Meysara; El Mderssa, Mohammed (2021): Étude diachronique de l'occupation du sol de la zone humide de Dayet Aoua dans le Moyen Atlas au Maroc / A diachronic study of the land uses of the Dayet Aoua wetland in the Middle Atlas in Morocco. In *ecmed* 47 (1), pp. 107–115. DOI: 10.3406/ecmed.2021.2123.

INPA (2017): En Gedi Nature Reserve. With assistance of Avi David, Miriam Feinberg Vamosh, Shalom Kveller, Adi Greenbaum. Israel Nature and Parks Authority. Available online at https://en.parks.org.il/reserve-park/en-gedi-nature-reserve/, checked on 8/2/2022.

INPA (2019): Conservation activities of the Nature and Parks Authority. Israel Nature and Parks Authority. Available online at https://en.parks.org.il/reserve-park/enot-tsukim-nature-reserve/, checked on 9/5/2022.

Juberthie, Christian; Decu, Vasile (1994): Encyclopaedia Biospeologica I. 1st volume. Edited by Christian Juberthie, Vasile Decu: Société de Biospéologie.

Juberthie, Christian; Decu, Vasile (2001): Encyclopaedia Biospeologica III. 3rd volume. Edited by Christian Juberthie, Vasile Decu: Société de Biospéologie.

Karger, Dirk N.; Conrad, Olaf; Böhner, Jürgen; Kawohl, Tobias; Kreft, Holger; Soria-Auza, Rodrigo W. et al. (2018): Data from: Climatologies at high resolution for the earth's land surface areas.

Kattan, Z. (1997): Environmental isotope study of the major karst springs in Damascus limestone aquifer systems: case of the Figeh and Barada springs. In *Journal of Hydrology* 193 (1-4), pp. 161–182. DOI: 10.1016/S0022-1694(96)03137-X.

Kløve, Bjørn; Ala-aho, Pertti; Bertrand, Guillaume; Boukalova, Zuzana; Ertürk, Ali; Goldscheider, Nico et al. (2011a): Groundwater dependent ecosystems. Part I: Hydroecological status and trends. In *Environmental Science & Policy* 14 (7), pp. 770–781. DOI: 10.1016/j.envsci.2011.04.002.

Kløve, Bjørn; Allan, Andrew; Bertrand, Guillaume; Druzynska, Elzbieta; Ertürk, Ali; Goldscheider, Nico et al. (2011b): Groundwater dependent ecosystems. Part II. Ecosystem services and management in Europe under risk of climate change and land use intensification. In *Environmental Science & Policy* 14 (7), pp. 782–793. DOI: 10.1016/j.envsci.2011.04.005.

Kløve, Bjørn; Ala-aho, Pertti; Bertrand, Guillaume; Gurdak, Jason J.; Kupfersberger, Hans; Kværner, Jens et al. (2014): Climate change impacts on groundwater and dependent ecosystems. In Journal of Hydrology 518, pp. 250–266. DOI: 10.1016/j.jhydrol.2013.06.037.

Kostoski, G.; Albrecht, C.; Trajanovski, S.; Wilke, T. (2010): A freshwater biodiversity hotspot under pressure – assessing threats and identifying conservation needs for ancient Lake Ohrid. In *Biogeosciences* 7 (12), pp. 3999–4015. DOI: 10.5194/bg-7-3999-2010.

Krešić, Neven (2013): Water in Karst. Management, Vulnerability, and Restoration. McGraw-Hill Professional.

Krešić, Neven; Stevanović, Zoran (2010): Groundwater hydrology of springs. Engineering, theory, management, and sustainability. Amsterdam: Butterworth-Heinemann. Available online at http://www.sciencedirect.com/science/book/9781856175029.

Lai, Giuseppina Grazia; Padedda, Bachisio Mario; Ector, Luc; Wetzel, Carlos Eduardo; Lugliè, Antonella; Cantonati, Marco (2020): Mediterranean karst springs: diatom biodiversity hotspots under the pressure of hydrological fluctuation and nutrient enrichment. In *Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology* 154 (5), pp. 673–684. DOI: 10.1080/11263504.2019.1674402.

Lauritzen, Stein-Erik (2018): Physiography of the Caves. In Oana Teodora Moldovan, Ľubomír Kováč, Stuart Halse (Eds.): Cave Ecology, vol. 235. Cham: Springer International Publishing (Ecological Studies), pp. 7–21.

Levy, Yehuda; Burg, Avihu; Yechieli, Yoseph; Gvirtzman, Haim (2020): Displacement of springs and changes in groundwater flow regime due to the extreme drop in adjacent lake levels: The Dead Sea rift. In *Journal of Hydrology* 587, p. 124928. DOI: 10.1016/j.jhydrol.2020.124928.

Lučić, Ivo (2007): Shafts of Life and Shafts of Death in Dinaric karst, Popovo Polje Case (Bosnia & Hercegovina). In *AC* 36 (2). DOI: 10.3986/ac.v36i2.201.

Lučić, Ivo (2019): Vjetrenica Cave, Bosnia and Herzegovina. In: Encyclopedia of Caves: Elsevier, pp. 1110–1117.

Máiz-Tomé, L.; Darwall, W.R.T.; Numa, C.; Barrios, V.; Smith, K. G. (2017): Freshwater Key Biodiversity Areas in the north-western Mediterranean sub-region: IUCN, International Union for Conservation of Nature.

Melhem, Rimah; Higano, Yoshiro (2001): Policy Measures for River Water Management in Barada Basin, Syria. In *SiRS, SRS* 32 (3), pp. 1–23.

Milanovic, Petar (2002): The environmental impacts of human activities and engineering constructions in karst regions. In *Episodes* 25 (1), pp. 13–21. DOI: 10.18814/epiiugs/2002/v25i1/002.

Ministère de la Transition écologique (2019): Le Lez. FR9101392. NATURA 2000 - STANDARD DATA FORM. DGALN/DEB/SDET/ET5. Available online at https://natura2000.eea.europa.eu/.

Moldovan, Oana Teodora (2018): An Overview on the Aquatic Cave Fauna. In Oana Teodora Moldovan, Ľubomír Kováč, Stuart Halse (Eds.): Cave Ecology, vol. 235. Cham: Springer International Publishing (Ecological Studies), pp. 173–194.

Mollot, G.; Pantel, J. H.; Romanuk, T. N. (2017): The Effects of Invasive Species on the Decline in Species Richness. In : Networks of Invasion: A Synthesis of Concepts, vol. 56: Elsevier (Advances in Ecological Research), pp. 61–83.

Myers, N.; Mittermeier, R. A.; Mittermeier, C. G.; Da Fonseca, G. A.; Kent, J. (2000): Biodiversity hotspots for conservation priorities. In *Nature* 403 (6772), pp. 853–858. DOI: 10.1038/35002501.

Neubauer, Thomas A.; Harzhauser, Mathias; Georgopoulou, Elisavet; Kroh, Andreas; Mandic, Oleg (2015): Tectonics, climate, and the rise and demise of continental aquatic species richness hotspots. In *Proceedings of the National Academy of Sciences of the United States of America* 112 (37), pp. 11478–11483. DOI: 10.1073/pnas.1503992112.

Niemiller, Matthew L.; Taylor, Steven J.; Bichuette, Maria Elina (2018): Conservation of Cave Fauna, with an Emphasis on Europe and the Americas. In Oana Teodora Moldovan, Ľubomír Kováč, Stuart Halse (Eds.): Cave Ecology, vol. 235. Cham: Springer International Publishing (Ecological Studies), pp. 451–478.

Nogueira, Joana Garrido; Sousa, Ronaldo; Benaissa, Hassan; Knijf, Geert de; Ferreira, Sónia; Ghamizi, Mohamed et al. (2021): Alarming decline of freshwater trigger species in western Mediterranean key biodiversity areas. In *Conservation biology : the journal of the Society for Conservation Biology* 35 (5), pp. 1367–1379. DOI: 10.1111/cobi.13810.

Olson, David M.; Dinerstein, Eric; Wikramanayake, Eric D.; Burgess, Neil D.; Powell, George V. N.; Underwood, Emma C. et al. (2001): Terrestrial Ecoregions of the World: A New Map of Life on Earth. In *BioScience* 51 (11). DOI: 10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2.

Ouassou, Asmaâ; Dakki, Mohamed; El Agbani, Mohammed-Aziz; Qninba, Abdeljebbar; El Hamoumi, R'himou (2021): Distribution and Numbers of Three Globally Threatened Waterbird Species Wintering in Morocco: The Common Pochard, Marbled Teal, and White-Headed Duck. In *International Journal of Zoology* 2021, pp. 1–17. DOI: 10.1155/2021/8846203.

Pesce, Giuseppe L. (2001): The Zinzulusa cave: an endangered biodiversity »hot spot« of South Italy 10, pp. 207–212. Available online at https://core.ac.uk/download/pdf/14401587.pdf, checked on 4/13/2022.

Pesce, Giuseppe L.; Ciccarese, Gaetano (2006): Zinzulusa cave. With assistance of M. M. Camassa, S. Inguscio, V. Fersini. Available online at http://www.grottazinzulusa.it/index.html, updated on 1/18/2006, checked on 8/10/2022.

Petrevska, Biljana; Collins-Kreiner, Noga (2019): From a town to an attraction: the transformation of Ohrid, North Macedonia. In *BAGE* (83). DOI: 10.21138/bage.2808.

Petrič, Metka; Kogovsek, Janja (2005): Hydrogeological characteristics of the area of intermittent karst lakes of Pivka. In *AC* 34/3 (4), pp. 599–618.

Prié, Vincent (2008): Les escargots souterrains, nouveaux marqueurs des hydrosystèmes karstiques: application aux hydrosystèmes karstiques des massifs nord-montpelliérains. In *karst* 52 (1), pp. 7–16. DOI: 10.3406/karst.2008.2632.

Radford, Elizabeth A.; Odé, Baudewijn (2009): Conserving important plant areas. Investing in the green gold of south east Europe. Salisbury: Plantlife International.

Ramsar Convention Secretariat (2016): An Introduction to the Convention on Wetlands (previously The Ramsar Convention Manual). Gland, Switzerland.

Ravbar, Nataša; Mayaud, Cyril; Blatnik, Matej; Petrič, Metka (2021): Determination of inundation areas within karst poljes and intermittent lakes for the purposes of ephemeral flood mapping. In *Hydrogeol J* 29 (1), pp. 213–228. DOI: 10.1007/s10040-020-02268-x.

Ravbar, Nataša; Pipan, Tanja (2022): Karst Groundwater Dependent Ecosystems—Typology, Vulnerability and Protection. In: Tockner, Klement, Encyclopedia of Inland Waters 2nd edition. vol. 3, pp. 460-473. Oxford: Elsevier.

Retter, Alice; Karwautz, Clemens; Griebler, Christian (2021): Groundwater Microbial Communities in Times of Climate Change. In Current issues in molecular biology 41, pp. 509–538. DOI: 10.21775/cimb.041.509.

Rinke, Karsten; Keller, Philipp Steffen; Kong, Xiangzhen; Borchardt, Dietrich; Weitere, Markus (2019): Ecosystem Services from Inland Waters and Their Aquatic Ecosystems. In Schröter, Slobodien (Eds.): Atlas of Ecosystem Services. 1st ed. [Place of publication not identified]: Springer International Publishing, pp. 191–195.

Santaloia, F.; Zuffianò, L. E.; Palladino, G.; Limoni, P. P.; Liotta, D.; Minissale, A. et al. (2016): Coastal thermal springs in a foreland setting: The Santa Cesarea Terme system (Italy). In *Geothermics* 64, pp. 344–361. DOI: 10.1016/j.geothermics.2016.06.013.

Sayad, Ahmed; Essahlaoui, Ali; Ben-Daoud, Mohamed (2020): Dayet Aoua, a Threatened Mountain Geomorphosite for Sustainable Development. In: Proceedings of the 4th Edition of International Conference on Geo-IT and Water Resources 2020, Geo-IT and Water Resources 2020. Al-Hoceima Morocco, 11 03 2020 12 03 2020. New York, NY, USA: ACM, pp. 1–5.

Schönwiese, Christian-Dietrich (2020): Klimatologie. 5th updated edition, edited version, Stuttgart: UTB; Ulmer.

Springer, Abraham E.; Stevens, Lawrence E. (2009): Spheres of discharge of springs. In *Hydrogeol J* 17 (1), pp. 83–93. DOI: 10.1007/s10040-008-0341-y.

Stevanović, Zoran (2019): Karst waters in potable water supply: a global scale overview. In Environ Earth Sci 78 (23). DOI: 10.1007/s12665-019-8670-9.

Stevanović, Zoran; Stevanović, Aleksandra Maran; Pekaš, Želimir; Eftimi, Romeo; Marinović, Veljko (2021): Environmental flows and demands for sustainable water use in protected karst areas of the Western Balkans. In *Carbonates Evaporites* 37 (1). DOI: 10.1007/s13146-021-00754-1.

Stevens, Lawrence E.; Aly, Anwar A.; Arpin, Sarah M.; Apostolova, Iva; Ashley, Gail M.; Barba, Paulo Quadri et al. (2022): The Ecological Integrity of Spring Ecosystems: A Global Review. In Dominick A. DellaSala, Michael I. Goldstein (Eds.): Imperiled. The encyclopedia of conservation. Amsterdam, Netherlands: Elsevier, pp. 436–451, checked on 8/29/2022.

Stevens, Lawrence E.; Schenk, Edward R.; Springer, Abraham E. (2021): Springs ecosystem classification. In *Ecological applications : a publication of the Ecological Society of America* 31 (1), e2218. DOI: 10.1002/eap.2218.

Stevens, Lawrence E.; Springer, Abraham E.; Ledbetter, Jeri D. (2016): Springs Ecosystem Inventory Protocols.

SYBLE (2017): Suivi et conservation du Chabot du Lez (Cottus petiti). Rapport de synthèse.

Talà, Adelfia; Buccolieri, Alessandro; Calcagnile, Matteo; Ciccarese, Gaetano; Onorato, Michele; Onorato, Raffaele et al. (2021): Chemotrophic profiling of prokaryotic communities thriving on organic and mineral nutrients in a submerged coastal cave. In *The Science of the total environment* 755 (Pt 1). DOI: 10.1016/j.scitotenv.2020.142514.

UNEP-WCMC and IUCN (2022): Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM) (Online). UK: UNEP-WCMC and IUCN. Cambridge. Available online at www.protectedplanet.net, checked on 05/05/2022.

Wagner, Bernd; Wilke, Thomas (2011): Preface "Evolutionary and geological history of the Balkan lakes Ohrid and Prespa". In *Biogeosciences* 8 (4), pp. 995–998. DOI: 10.5194/bg-8-995-2011.

Wagner, Bernd; Wilke, Thomas; Francke, Alexander; Albrecht, Christian; Baumgarten, Henrike; Bertini, Adele et al. (2017): The environmental and evolutionary history of Lake Ohrid (FYROM/Albania): interim results from the SCOPSCO deep drilling project. In *Biogeosciences* 14 (8), pp. 2033–2054. DOI: 10.5194/bg-14-2033-2017.