KARMA

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

Preparation of KARMA policy briefs and a brochure

Deliverable 1.7

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Date: February 2023
Update March 2023

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 – February 2023
Deliverable No., Name	Deliverable 1.7 Preparation of KARMA policy briefs and a brochure
Dissemination Level*	PU (public)
Work Package	WP 1: Project Management, Dissemination & Communication
Task	Task 1.3 Dissemination of KARMA results and products
Lead beneficiary	Karlsruhe Institute of Technology (KIT)
Contributing beneficiary/ies	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), University of Malaga (UMA), University of Montpellier (UM), Sapienza University of Rome (URO), Ecole nationale d'Ingenieurs de Tunis (ENIT), American University of Beirut (AUB)
Due Date	Month 30
Actual Submission Date	Month 42

* 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	February 2023
2.0	March 2023

Project Partners

(Coordinator)

Participant No *	Organisation	Country
1 **(Coordinator)**	Karlsruhe Institute of Technology (KIT)	Germany
2 **Partner 1**	Federal Institute for Geosciences and Natural Resources (BGR)	Germany
3 **Partner 2**	University of Malaga (UMA)	Spain
4 **Partner 3**	University of Montpellier (UM)	France
5 **Partner 4**	University of Rome (URO)	Italy
6 **Partner 5**	American University of Beirut (AUB)	Lebanon
7 **Partner 6**	Ecole National d'Ingénieurs de Tunis (ENIT)	Tunisia

Executive Summary

Throughout the duration of the KARMA project a series of policy briefs were generated to summarize specific topics concerning the Mediterranean karst aquifers in a short and descriptive form. In March 2023 eight policy briefs are completed and uploaded to the KARMA website.

For the Deliverable 1.7 we provide the policy briefs in order of completion dates:

Nr.	Title	Completion date
1	Karst groundwater pollution risk in the Mediterranean region	January 2022
2	Investigation of changes in groundwater storage in the Euro- Mediterranean region using GRACE satellite data	January 2022
3	Modeling karst spring discharge with Artificial Neural Networks	January 2022
4	Reservoir modeling	November 2022
5	Karst groundwater-dependent ecosystems in the Mediterranean region	December 2022
6	Karst groundwater availability in the Mediterranean region	February 2023
7	Early Warning System for karst groundwater contamination	March 2023
8	Groundwater vulnerability mapping to pollution in Mediterranean karst sites	March 2023

The KARMA Project

Karst groundwater pollution risk in the Mediterranean region

Key findings

This study examines karst groundwater pollution risk on a large-scale, using land use data

The Copernicus Global Land Service provides a detailed distribution of land use.

A grouping of similar land uses and its re-classification enables the definition of pollution risk

Especially in karst areas, where the soil protection function is often inadequate or completely absent, a direct input of contaminants is probable

The risk of karst groundwater pollution exists primarily in built-up and human-cultivated areas.

Karst groundwater resources are particularly vulnerable to the input of contaminants from the surface. Especially in areas with high population density and intensive land use (agriculture, livestock), but also in industrial areas, there is a contamination risk from waste, wastewater or other hazardous substances.

On a local and regional scale, the vulnerability and contamination risk of karst aquifer is generally be derived from different hydrologic and hydrogeologic conditions and land use. However, at the large scale, specification of locally very heterogeneous hydrogeologic conditions is much more difficult and would need to be generalized and simplified. Parameters that express the local protective function of the aquifer, such as land cover, depth of the water table, and degree of karstification, cannot be easily regionalized and evaluated on a supraregional basis and would be very inaccurate. Furthermore, there is also often a lack of comprehensive data.

Karst aquifers are often much more vulnerable to pollution compared to porous and fractured aquifers due to their often limited soil cover and high permeability. For this reason, it is easier to derive the groundwater quality risk in karst areas directly from a land use map and thus better estimate the pollution risk for individual regions.

For the assessment of pollution risk of karst aquifers in the Mediterranean region, Copernicus Global Land Service data (Buchhorn et al. 2020) were used and reclassified into a pollution risk map and further applied to the karst aquifer map developed in the KARMA project.

Copernicus land use data classify the land surface into different land

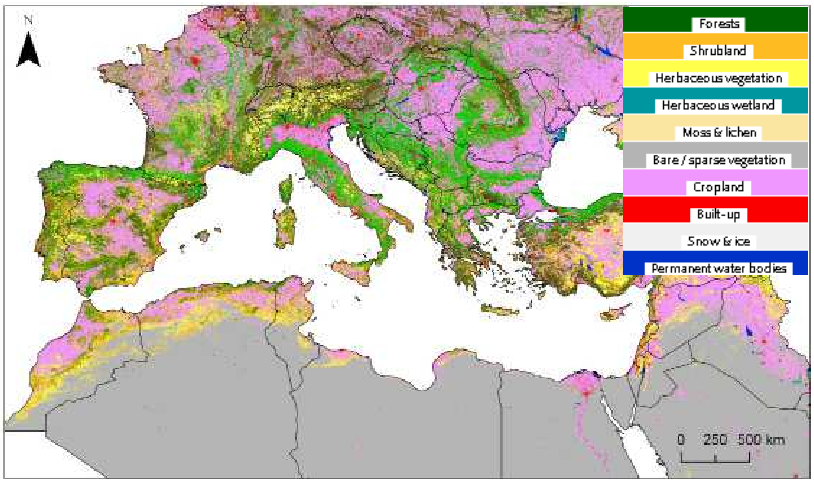

Figure 1 Land cover map from the Copernicus Global Land Service (Buchhorn et al. 2020).

Table 1 Re-classification of copernicus land use data to pollution risk.

Copernicus classification	Group	Pollution risk
Built-up	Built-up	High
Cropland	Cultivated and managed areas	Moderate to high
Harbecous vegetation	Semi-natural vegetation	Low to moderate (comment: Manure is spread in some meadows)
Harbecous wetland		
Shrubland		
Forests	Bare soil & sparse vegetation	Low
Moss & lichen		
Bare / sparse vegetation		
Snow & ice		
Permeanent water bodies		

use classes. These range from cropland and urban areas to forests, shrublands, sparse vegetation, snow cover, and permanent water bodies. Each of these land uses classes poses a different (natural) threat to groundwater. To avoid assigning each of these individual land use classes into separate risk levels, it is easier to group similar land use classes based on a common risk level (Table 1).

High pollution risk, which is not comparable to other land use types, is therefore assigned to urban areas. Areas that are mostly intensively farmed, referred to here as „cropland", are also potentially hazardous areas, although with lower impacts than urban areas. Herbaceous vegetation, wetlands, and shrublands are grouped here into seminatural vegetation, because in many areas they are used as farmland for growing livestock crops and are treated with fertilizer. The lowest risk here is expected from the classes of moss and lichens, forests, sparse vegetation and water bodies, and snow or ice cover, grouped into bare soil and sparse vegetation.

However, borderline cases in the land use classes that might be classified as higher or lower risk than indicated here cannot be distinguished on this scale.

The resulting map of the Mediterranean shows a division into four pollution risk classes for karst aquifers.

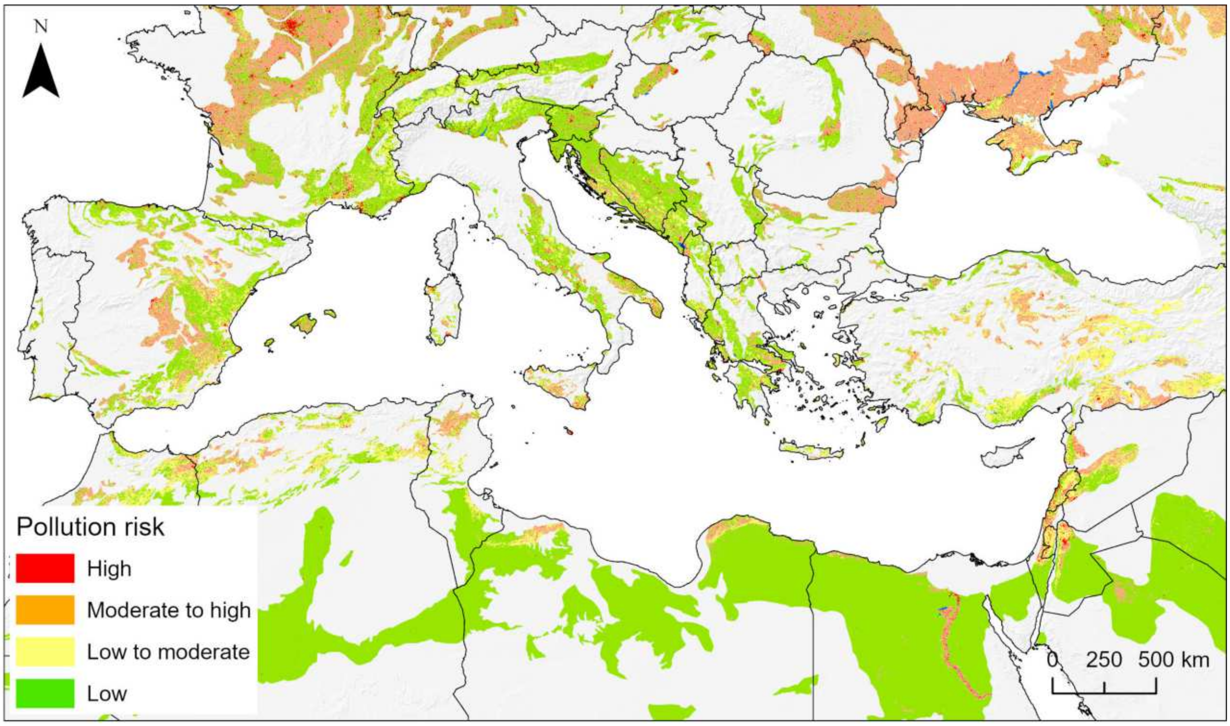

Figure 3 Karst groundwater polution risk map of the Mediterranean region.

References and further Reading

- Buchhorn, M.; Smets, B.; Bertels, L.; Lesiv, M.; Tsendbazar, N.-E.; Masiliunas, D.; Linlin, L.; Herold, M.; Fritz, S. (2020). Copernicus Global Land Service: Land Cover 100m: Collection 3: epoch 2019: Globe (Version V3.0.1) [Data set]. Zenodo. DOI: 10.5281/zenodo.3939050

KARMA policy briefs present relevant scientific results of projects concerning a better karst groundwater management across the scale of the Mediterranean area, single catchments and selected springs.

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The KARMA Project

Investigation of changes in groundwater storage in the Euro-Mediterranean region using GRACE satellite data

Key findings

Significant trends in GWS can be observed in about 87% of the Euro-Mediterranean region.

With an average negative trend of -2.9 mm/year, the Arabian Peninsula is the most affected region.

Western, Central and Eastern Europe show an average negative trend of -1.5 mm/year, North Africa of -0.9 mm/year and Southern Europe -0.7 mm/year. Northern Europe shows a positive trend of 1 mm/year.

An average negative trend can be observed in 36 of the 47 countries. In 11 countries a positive average trend can be observed.

Groundwater is a major contributor to public and industrial water supplies in most countries of the Mediterranean region. In recent decades, anthropogenic use and climatic impact have led to a sharp decline in groundwater levels in many regions. This indicates an imbalance between natural groundwater recharge and groundwater withdrawals, leading to groundwater stress. Countries in the arid and semi-arid regions of North Africa and the Arabian Peninsula are particularly affected.

In recent years, changes in groundwater storage have been investigated with the help of remote sensing data from the Gravity Recovery and Climate Experiment and its follow-up satellite mission (GRACE/GRACE-FO), where two satellites are used to measure the changes in the gravitational field caused by changes in the Earth's surface total water storage (ΔTWS).

A mass balance approach is used to separate the GWS signal from the TWS signal, while the approach assumes that the change in TWS (ΔTWS) consists mainly of changes in soil moisture (ΔSM), snow water equivalent (ΔSWE), surface water (ΔSWA) and groundwater (ΔGW).

$$\Delta TWS = \Delta SM + \Delta SWE + \Delta SWA + \Delta GW$$

The change in GWS (ΔGW) is calculated by subtracting the soil moisture (ΔSM), snow water water equivalent (ΔSWE), and surface water (ΔSWA) data. These data were taken for the study by Xanke and Liesch (2022) from ERA5-land dataset (Muñoz Sabater 2019), while canopy storage was neglected, because its contribution to water storage in non-tropical climates is small.

Xanke and Liesch (2022) calculated GWS signals to perform a trend analysis using the seasonal Mann-Kendall trend test (Hirsch et al. 1982), which can be used to determine the significance of a monotonic trend based on the null hypothesis. Thresholds for significance were defined as very significant (≤0.01), significant (≤0.05), and not significant (>0.05).

The trend analysis of GWS was carried out for the period 2003 to 2020

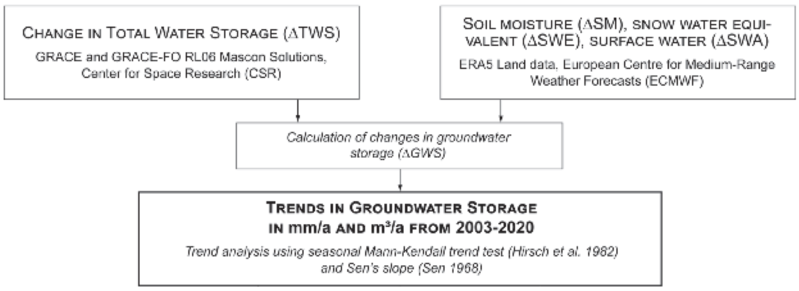

Figure 1 Data, workflow and the relevant calculation steps of the analyses of GWS trends.

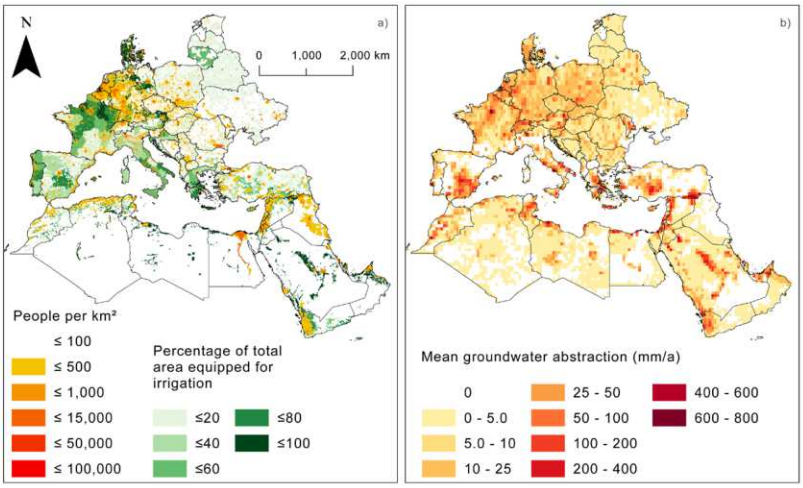

Figure 2 a) areas equipped for irrigation (FAO 2021) and population density (CIESIN 2018) and b) mean annual net groundwater abstraction (WaterGAP; Müller Schmied et al. 2021).

and given as an annual mean value. The trend shows whether there is an increase or decrease in GWS in a given area over the period considered. A negative trend is equivalent to a decrease in groundwater resources and a positive trend indicates an increase. It should be noted that GRACE-derived data always refer to the entire vertical aquifer column and thus the sum of GWS changes in multilayer aquifer systems and observed groundwater level records of individual aquifers may therefore differ.

About 82% of the study area reveal highly significant trends in GWS ($p \leq 0.01$), while 5% are still significant ($p \leq 0.05$). About 13% have no significant trend ($p > 0.05$). Of the significant trends, about 80% are negative and 20% have positive values. Negative trends on average are found in 36 of the 47 countries, while 11 countries have a positive mean trend. The overall mean value of trends in the Euro-Mediterranean region is -2.1 mm/year. Weak to moderately negative mean trends are observed in Western, Central, and Eastern Europe, as well as in North African countries. The Arabian Peninsula, on the other hand, is the most affected region with strong negative trends, e.g., in Iraq (-8.8 mm/year) and Syria (-6.0 mm/year; Figure 3).

Although the negative trends cannot be attributed to any specific cause, it is obvious that groundwater resources are declining across the entire region, especially in highly urbanized and agricultural areas (Figure 2a and 2b; Xanke and Liesch 2022).

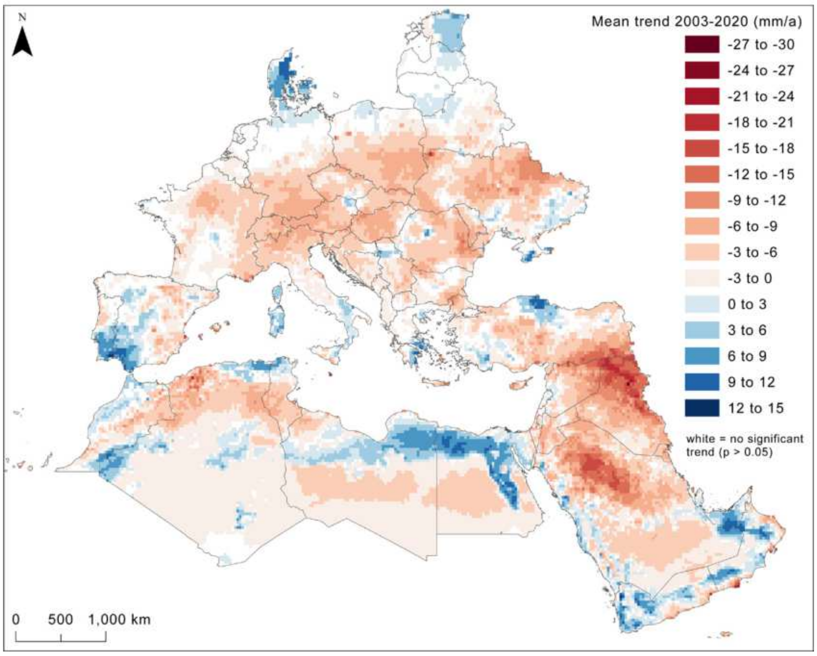

Figure 3 Mean annual trend of GRACE-derived GWS for the period 2003-2020.

References and further Reading

- CIESIN (2018) Center for International Earth Science Information Network (CIESIN), Columbia University. Documentation for the Gridded Population of the World, Version 4 (GPWv4), Revision 11 Data Sets. NASA Socioeconomic Data and Applications Center (SEDAC, Palisades, NY). https:// doi. org/ 10. 7927/ H45Q4 T5F. Accessed July 2021
- FAO (2021) AQUASTAT database. AQUASTAT website. https:// www. fao. org/ aquas tat/ stati stics/ query/ index. html. Accessed February 2021
- Müller Schmied H, Cáceres D, Eisner S, Flörke M, Herbert C, Niemann C, Peiris TA, Popat E, Portmann FT, Reinecke R, Schumacher M, Shadkam S, Telteu CE, Trautmann T, Döll P (2021) The global water resources and use model WaterGAP v2. 2d: model description and evaluation. Geosci Model Dev 14(2):1037–1079
- Xanke J, Liesch T (2022) Quantification and possible causes of declining groundwater resources in the Euro-Mediterranean region from 2003 to 2020. Hydrogeology Journal, 1-22.

KARMA policy briefs present relevant scientific results of projects concerning a better karst groundwater management across the scale of the Mediterranean area, single catchments and selected springs.

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The KARMA Project

Modeling karst spring discharge with Artificial Neural Networks

Key findings

Highly accurate predictions of karst spring discharge can be achieved (NSE between 0.77 and 0.88) provided that there is sufficient input data

1D-Convolutional Neural Networks are a suitable architecture to predict karst spring discharge time series

Model results can compete with lumped parameter model results at the same sites

Modeling Karst water resources is challenging, because water flow is highly variable due to the unknown conduit networks. Therefore a large variety of different modeling approaches exists, most of them requiring a certain level of background knowledge about the system in order to achieve high quality results. In contrast, deep learning approaches can be applied without detailed system knowledge necessary, by being able to establish a relationship between relevant forcings, such as climatic inputs, and outputs, i.e. spring discharge, automatically.

In the KARMA project Convolutional Neural Networks (CNN) are applied to model karst spring discharge. CNNs have been shown to be fast and reliable for the closely related application of groundwater level forecasting. According to a study of Wunsch et al. (2021), CNNs are significantly faster and more stable than other ANN methods such as and NARX (nonlinear autoregressive models with exogenous inputs) and LSTM (long short-term memory networks), and usually show similar or better accuracy in predicting groundwater levels, which makes them the preferable approach for modeling karst spring discharge. Even though such data driven approaches rely on a comparably large data basis and do usually not enhance system knowledge such as lumped parameter models can do, they are a powerful tool to achieve high quality simula tions in a relatively short time.

In total, discharge of five karst springs was modeled: Aubach spring in Austria, Lez spring in France, Unica springs in Slovenia, Gato cave spring in Spain and Qachqouch spring in Lebanon, using precipitation, temperature, relative humidity, evapo(trans)piration and snow as input variables. Time resolutions ranged from hourly (Aubach) to daily (all other springs) total data lengths from abour 4 years (Qachqouch) to nearly 60 years (Unica). To evaluate the performance of the models, Nash-Sutcliffe Efficiency (NSE), squared Pearson r (R^2), root mean squared error (RMSE), Bias (Bias) as well as Kling-Gupta-

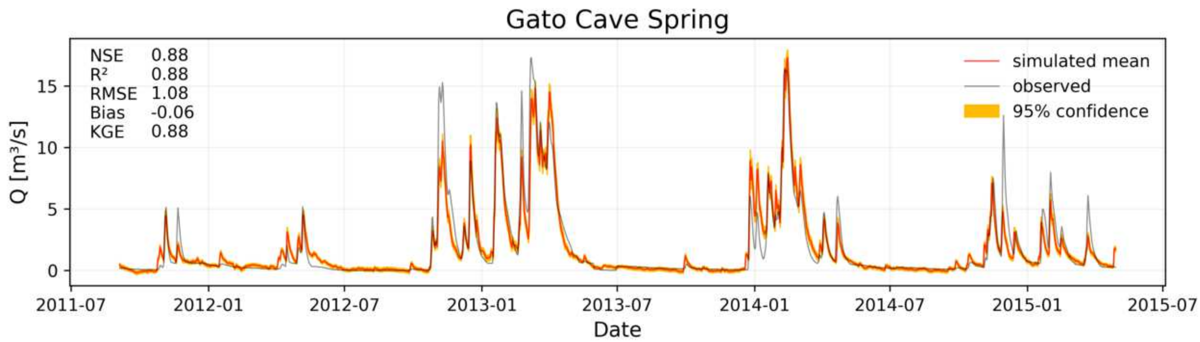

Figure 1 Modeling results for Gato cave spring.

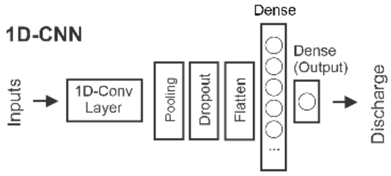

Figure 2 CNN model design used to simulate karst spring discharge

Efficiency (KGE) were considered. Further, individual performance on high, medium and low flow were investigated.

Aubach Spring

The model was able to accurately model the spring discharge during most periods of the test period (1/2020-10/2020) with high NSE (0.82) and KGE (0.90) values. The snowmelt-influenced period from April to Mid-June is accurately modeled as well as the peaks in summer and early autumn. While high and medium flow are systematically underestimated, low flow is slightly overestimated.

Lez Spring

The modeling results for 2018 and 2019 at Lez spring in France show satisfying performance measure values (NSE, KGE = 0.77, R^2 = 0.78). The time series in general is characterized by distinct dry periods without any recharge due to anthropogenic water extraction in the saturated zone of the aquifer, which are quite accurately simulated. Similarly as for Aubach spring, the model systematically underestimates high and medium flow, while low flow periods are overestimated on average. However, low flow is not systematically too high, but rather unprecise for some events.

Unica Springs

At Unica springs, the CNN model can profit from a very long data basis of daily data (since 1961) during training and therefore shows high performance in terms of the error measures (NSE & R^2 > 0.85, KGE = 0.74), capturing the major dynamic of the spring quite accurately, despite climate input variables were only available for two different climate stations, thus very few for such a large catchment (>800 km²).

Gato Cave Spring

For Gato Cave spring a very long data basis of daily values is available for training, and the CNN model achieves high accuracy with NSE, R^2 and KGE values of 0.88. The general dynamics of the discharge is nicely captured, and most peaks are neither over nor underestimated significantly.

Qachqouch Spring

Qachqouch Spring has comparably poor data availability with less than four years of daily data. Additionally, even when data is available, there is a significant amount of time without (relevant) discharge. This corresponds to the unsatisfying modeling results, with NSE, R^2 and KGE < 0.5. Here the limitations of the CNN approach, which relies on a high amount of data to learn the system relationships, are clearly visible.

Conclusions

The results show that the 1D-CNN approach can be easily implemented to successfully and accurately model karst spring discharge under different climatic conditions, as long as a sufficient amount of historical data is available. It is possible to model systems showing significant different properties such as catchment size, complexity and hydraulic properties. Four out of five springs were modeled with good to very high accuracy, only for Qachqouch spring the approach was not successful, most certainly because of insufficient data availability for both climatic inputs and spring discharge.

Table 1 Comparison of lumped parameter modeling (LPM) and ANN results for all test sites

Site	Approach	NSE [ ]	KGE [ ]	R^2 [ ]	RMSE [m³/s]	Bias [m³/s]
Aubach	LPM	0.42	0.69	0.49	0.92	0.08
	ANN	0.82	0.90	0.83	0.51	-0.06
Lez	LPM	0.70	0.65	0.76	0.68	0.31
	ANN	0.77	0.77	0.78	0.59	-0.01
Unica	LPM	0.82	0.70	0.88	11.55	3.62
	ANN	0.85	0.74	0.88	10.68	-1.02
Gato Cave	LPM	0.90	0.79	0.92	1.00	0.25
	ANN	0.88	0.88	0.88	1.08	-0.06
Quachqouch	LPM	0.89	0.90	0.89	1.54	-0.02
	ANN	0.46	0.46	0.48	3.42	-0.16

References and further Reading

- Wunsch, A., Liesch, T., Broda, S., 2021. Groundwater level forecasting with artificial neural networks: a comparison of long short-term memory (LSTM), convolutional neural networks (CNNs), and non-linear autoregressive networks with exogenous input (NARX). Hydrol. Earth Syst. Sci. 25, 1671–1687. https://doi.org/10.5194/hess-25-1671-2021
- Wunsch, A., Liesch, T., et al., 2021. Karst spring discharge modeling based on deep learning using spatially distributed input data. Hydrol. Earth Syst. Sci. Discussions. http://dx.doi.org/10.5194/hess-2021-403
- Code is available at GitHub: https://github.com/KITHydrogeology/KARMA_Project

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The KARMA Project

Reservoir modeling

Key findings

Reservoir models are widely used to assess both changes in groundwater resources and discharges at main outlets of karst aquifers, as they are relatively easy to use and several software tools are freely available.

Such models were applied over the whole Mediterranean area to simulate karst spring discharge at various test sites with different hydrological properties, data availability and environmental conditions.

These models are particularly suitable to simulate the response of spring discharge to precipitations, and can be used, even with very few hydrological data, given an accurate conceptual model of the karst system.

They allow gaining insights into the hydrological functioning of a system and therefore are especially suited for research purposes.

They can also be used to predict climate change impacts on water resources with the assumption that system processes and properties do not undergo major changes over long periods of time.

Around 9% of the world's population and up to 90% in some parts of the Mediterranean area such as Montenegro, is dependent on karst water resources for drinking water (Stevanović, 2019). Understanding the functioning of karst systems is therefore a major challenge for water resource management. Among many tools used in karst hydrology, modelling is a key approach that helps, for instance, managing the exploitation of karst auifers or forecasting floods. Numerous approaches such as reservoir models, artificial neural networks, and physical-based models are used to support the sustainable water resource management of karst aquifers (Hartmann et al., 2014; Jeannin et al., 2021). Reservoir models are a conceptual representation of a hydrosystem, which involves the association of several reservoirs (Figure 1). They are connected to each other through flow equations that turn an input signal (precipitation and evapotranspiration) into an output signal (discharge at spring). Each reservoir is described by a variable, its water height, and several parameters related to the flow equation that translates the water height into a discharge.

The structure and parameters of reservoir models can help identifying the main processes and factors that condition the hydrological functioning of a karst system but also developing knowledge of internal flow and storage processes.

At catchment scale, such models can also be used to estimate groundwater recharge and the dimennsions of the catchment. Reservoir modelling has been performed on the 8 KARMA test sites (Figure 2) using the KarstMod platform. This adjustable platform is dedicated to rainfall–discharge modelling and hydrodynamic analysis of karst aquifers (Mazzilli et al., 2019). It provides a modular, user-friendly modelling environment for educational, research and operational purposes. The objectives were to study the characteristics of each karst system and to identify the strengths and weaknesses of the reservoir modelling approach.

The consideration of different test sites allowed different hydrological conditions, system characeristics and inputdata to be studied (Table 1). The results of the models were contrasted either due to (i) difficulties to reproduce

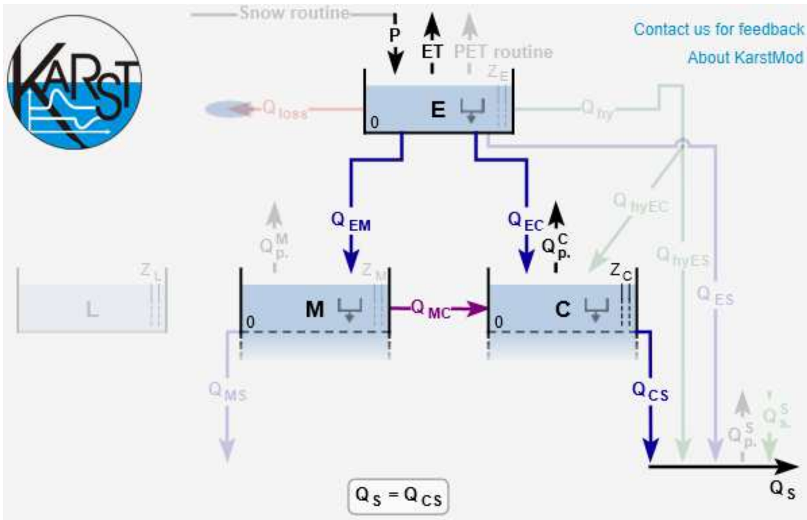

Figure 1: Structure of a reservoir model within the KarstMod modular platform. The conceptual representation of the hydrosystem includes 3 reservoirs (E, M and C) connected to each other through flows QEM, QEC and QMC. P and ET stand for Precipitation and Evaporation over the catchment. Groundwater pumping is simulated with flow QCp. in reservoir C, which water level corresponds to ZC. Reservoir C outflow (QCS) corresponds to the simulated spring discharge QS.

specific hydrological functioning or (ii) uncertainties on the input data. Overall, the simulations range from satisfying to vervy good and give relevant insights into thre systems in terms of aquifer properties. internal flwo dynamics and overall functioning with regards to meteorological regime and catchemnt charateristics.

The use of an external snow module, now implemented in the KarstMod modelling platform, has been required to correctly simulate karst spring discharge on five sites influenced by snow accumulation and melting. Results show that reservoir models do not need long calibration period to provide accurate and relevant simulations, whereas short time series can be detrimental for other modelling approaches. The conceptual model allows for the integration of elements that e.g. artificial neural networks models do not have time to learn (e.g. double porosity behaviour, matrix-conduit exchanges, fast conduit transfer in wet periods). Reservoir models seem also suitable for research purposes, as they provide a model structure and parameters that can be used to better understand the hydrological functioning of a system. The modelling of these 8 karst systems with different characteristics (catchment area, mean discharge and mean annual precipitation) shows the broad applicability of the reservoir modelling approach, whatever the climatic context or the hydrogeological behaviour of the karst system. These models were further used to assess the effect of climate change on some of the KARMA test sites.

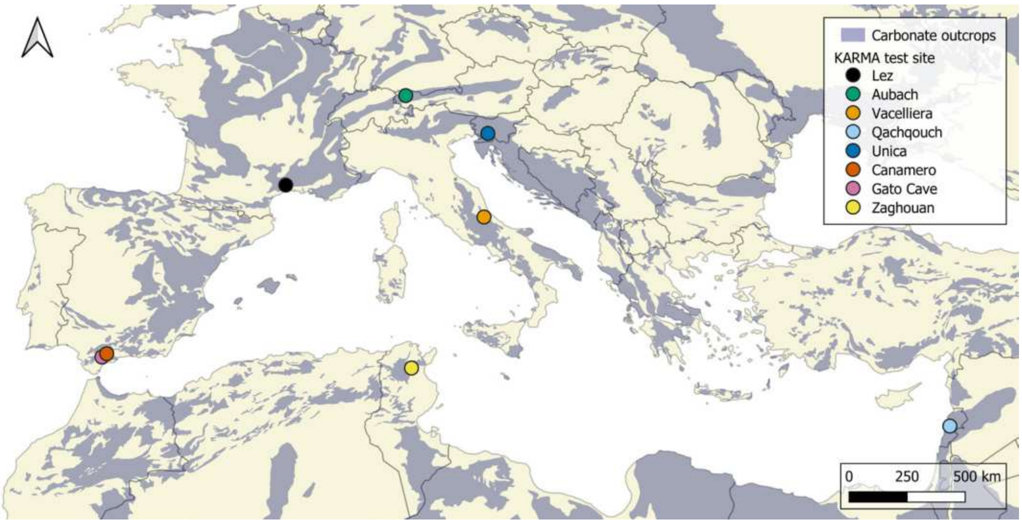

Figure 2: Localisation of the 8 KARMA test sites (delimitation of carbonate outcrops after Goldscheider et al. (2020)).

Table 1: Summary of the main hydroclimatic characterstics of the studied karst systems.

Spring	Country	Climate	Catchment area [km²]	Mean discharge [m³ s⁻¹]	Mean annual precipitation [mm]	Calibration period	Simulation period
Aubach	Austria	Cooltemperate and humid	9	0.91	2113	2014-2019	2014-2020
Canamero	Spain	Mediterranean	20-40	0.92	900	2008-2009	2008-2010
Gato Cave	Spain	Mediterranean	69-79	1.50	1872	1963-2011	1963-2015
Lez	France	Mediterranean	130	0.91	933	2008-2016	2008-2018
Qachqouch	Lebanon	Mediterranean	56	2.01	1293	2015-2019	2015-2020
Unica	Slovenia	Moderate continental	820	21.97	1605	1961-2016	1961-2018
Vacelliera	Italy	Moderate continental	1.3	0.06	1491	2018-2020	2018-2020
Zaghouan	Tunisia	Mediterranean	19	0.10	500	1915-1917	1915-1918

References and further Reading

- Goldscheider, N., Chen, Z., Auler, A.S., Bakalowicz, M., Broda, S., Drew, D., Hartmann, J., Jiang, G., Moosdorf, N., Stevanovic, Z., Veni, G., 2020. Global distribution of carbonate rocks and karst water resources. Hydrogeol J 28, 1661–1677. https://doi.org/10.1007/s10040-020-02139-5
- Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., Weiler, M., 2014. Karst water resources in a changing world: Review of hydrological modeling approaches. Rev. Geophys. 52, 218–242. https://doi.org/10.1002/2013RG000443
- Jeannin, P.-Y., Artigue, G., Butscher, C., Chang, Y., Charlier, J.-B., Duran, L., Gill, L., Hartmann, A., Johannet, A., Jourde, H., Kavousi, A., Liesch, T., Liu, Y., Lüthi, M., Malard, A., Mazzilli, N., Pardo-Igúzquiza, E., Thiéry, D., Reimann, T., Schuler, P., Wöhling, T., Wunsch, A., 2021. Karst modelling challenge 1: Results of hydrological modelling. J. Hydrol. 600, 126508. https://doi.org/10.1016/j.jhydrol.2021.126508
- Mazzilli, N., Guinot, V., Jourde, H., Lecoq, N., Labat, D., Arfib, B., Baudement, C., Danquigny, C., Soglio, L.D., Bertin, D., 2019. KarstMod: A modelling platform for rainfall - discharge analysis and modelling dedicated to karst systems. Environ. Model. Softw. 122, 103927. https://doi.org/10.1016/j.envsoft.2017.03.015
- Stevanović, Z., 2019. Karst waters in potable water supply: A global scale overview. Environ. Earth Sci. 78, 662. https://doi.org/10.1007/s12665-019-8670-9

KARMA policy briefs present relevant scientific results of projects concerning a better karst groundwater management across the scale of the Mediterranean area, single catchments and selected springs.

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The KARMA Project

Photo: Nataša Ravbar

Karst groundwater-dependent ecosystems in the Mediterranean region

Key findings

Karst groundwater-dependent ecosystems (KGDE) in the Mediterranean region were studied, based on expert consultation and literature review of 112 selected examples.

KGDE in the Mediterranean region contribute considerably to biodiversity including endemic species, but suffer increasingly under anthropogenic pressures.

The most common threats identified among the selected KGDE are direct human disturbances, water-quality deterioration and water shortage from aquifer overdraft and/or climate change.

Some KGDE are covered by the RAMSAR convention or Natura 2000 network, but many others are unprotected.

Raising environmental awareness, efficient groundwater protection and management strategies, and increased interdisciplinary research are required.

Introduction

Mediterranean karst aquifers are important freshwater resources and associated with valuable karst groundwater-dependent ecosystems (KGDE). Groundwater-dependent ecosystems (GDE) are ecosystems whose structure and functioning rely essentially on groundwater. GDE provide important ecosystem services, such as fish and plant production, water purification and supply, and recreation (IAH 2016). KGDE receive water from karst. The diverse hydrogeological and climatic conditions in the Mediterranean area enable the development of diverse KGDE. Due to their typical properties, such as rapid infiltration and transport of pollutants, karst aquifers are highly vulnerable to contamination. To demonstrate the importance and diversity of KGDE, data on 112 representative sites in the Mediterranean region was collected and evaluated using multidisciplinary criteria, including climatic, hydrogeological and ecological properties, as well as information on protection, threats and human impacts.

KGDE variety

Karst springs are prime examples of KGDE and represent diverse, endangered and socio-ecological interacting ecosystems. Yet they are insufficiently appreciated by the public, due to lacking knowledge of their distribution and types (Cantonati et al. 2020). In dry climates, KGDE serve as refuge for species, e.g. at Ein Feshkha oasis (Israel), which is fed by springs transforming the arid environment into wet and green areas. Limestone-precipitating springs host unique habitats for specifically adapted species (Cantonati et al. 2020), e.g. the Plitvice Lakes (Croatia). Karst springs also support the biodiversity of associated wetlands, rivers and lakes. It is often difficult to determine the groundwater contribution and requirements of these ecosystems, but essential to design appropriate management strategies.
Other unique habitats related to the hydrologic variability of karst systems are intermittent lakes, e. g. the Pivka intermittent lakes and the Cerkniško polje in Slovenia. The variable hydrologic conditions induce the presence of plant communities and raise the conservation value of these ecosystems (Ravbar and Pipan 2022).

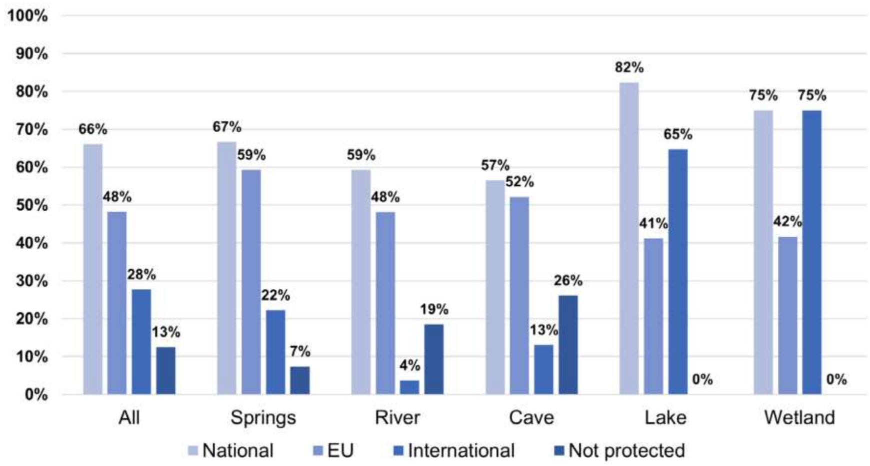

Figure 1: Percentage of the KGDE in the data collection protected by national, EU and international agreements grouped by the ecosystem types (cave, lake, river, springs, wetland).

Underground habitats, such as caves, are associated with special environmental conditions (darkness, limited nutrient supply) to which species must adapt. Stygobionts are aquatic species that only occur in subterranean habitats, mostly crustaceans and other invertebrates, but large cavities can also harbor fish and amphibians. Due to the high degree of isolation, cave species often have a limited distribution, which makes them vulnerable to changing environmental conditions (Ravbar and Pipan 2022).

Protection and management

The data evaluation demonstrates the conservation value of KGDE: 63% of the selected sites have endemic species, most frequently at springs and caves. However, many caves are not protected in any sense of legislation. The data collection includes the two caves with the highest reported biodiversity in the world, Postojna cave (Slovenia) and Vjetrenica cave (Bosnia-Herzegovina) in the Dinaric Karst – a hotspot of KGDE. Increasing anthropogenic pressures endanger KGDE. Although some KGDE are protected under national and international conservation programs, e.g. the Ramsar Convention or the EU Habitats and Birds directive, many others remain insufficiently protected. Direct human impacts prevail and must be addressed by restrictions and increased environmental awareness. Negative impacts include habitat destruction and groundwater pollution; water shortage related to increasing droughts and overexploitation also threatens KGDE.

Groundwater management and land-use planning should aim to minimise negative impact on KGDE to sustain ecosystem functions and services which are important for human well-being (IAH 2016). Therefore, efficient hydrogeological and ecological monitoring are necessary. A reserved ecological flow helps to ensure basic KGDE requirements. Furthermore, the recognition of invertebrates in conservation programs in required, especially for caves and springs, which stand out by exceptional invertebrate diversity. Interdisciplinary ecohydrogeological research provides the basis for suitable ecosystem management and conservation.

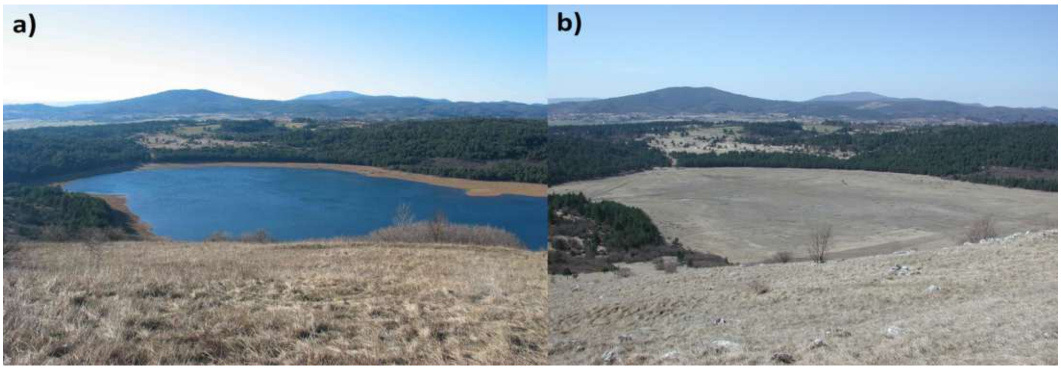

Figure 2: Petelinjsko jezero, one of the Pivka intermittent lakes in Slovenia; a) flooded conditions; b) dry conditions. Photos: Nataša Ravbar.

Figure 3: a) The Postojna-Planina cave system hosts various habitats including seeps (sampling point on the left side of the image), an underground river (on the right side) (photo: Blaž Kogovšek, with permission) b) An endemic of the Dinaric Karst, Proteus anguinus, the first described cave animal in the world. The photo shows a young animal with eyes still visible, later covered with skin (photo: Tanja Pipan).

References and further Reading

- Cantonati M et al. (2020) Ecohydgeology: The interdisciplinary convergence needed to improve the study and stewardship of springs and other groundwater-dependent habitats, biota, and ecosystems. Ecological Indicators.
- IAH (2016) Ecosystem Conservation & Groundwater. International Association of Hydrogeologists. Strategic Overview Series.
- Ravbar N, Pipan T (2022) Karst Groundwater Dependent Ecosystems—Typology, Vulnerability and Protection. In: Tockner K, Mehner T (eds) Encyclopedia of Inland Waters.
- Siegel L et al. (2022) Distribution, threats and protection of selected karst groundwater-dependent ecosystems in the Mediterranean region. Hydrogeology Journal, under review.

KARMA policy briefs present relevant scientific results of projects concerning a better karst groundwater management across the scale of the Mediterranean area, single catchments and selected springs.

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February 2023

POLICY BRIEF - Water availability

The KARMA Project

Photo: Nico Goldscheider

Karst groundwater availavility in the Mediterranean region

Key findings

Karst aquifers represent a relevant source of high-quality waters, due to their occurrence in European territory (>20%) and mainly to their huge volumes of spring discharge

Accurate water balances realized in the study sites confirmed the relevant infiltration rate of karst aquifers in the Mediterranean area, with at least 50% of precipitation feeding groundwater resources

The evaluations at the scale of single catchment until regional ridges (from 25 km² to about 1000 km²) carried out with different methods allow comparable and reliable assessment of groundwater recharge

The APLIS method results to be the more reliable in assessing groundwater recharge, accounting for geological and morphological conditions at the catchment scale, with some limitations

The upscaling process towards the entire Mediterranean area has been performed and synthetized in MEDKAM, highlighting a general underestimation of recharge rate respect with study-site values

Why karst groundwater resource assessment is important?

Mediterranean karst aquifers are important resources for human and environment, due to their occurrence in European territory (>20%) and mainly to the significant spring discharge they usually provided to the freshwater drinking supply of many Mediterranean cities. Assessing karst resource quantities is a fundamental issue to allow their correct management, specially in current times when overexploitation and climate change are summing their negative effects on effective water availability.

The main aim of KARMA project was to improve the management of groundwater availability and quality across all scales, moving from single catchment and/or spring towards a continental scale approach (Fig.1). An accurate evaluation of water availability has been performed in five study areas, corresponding to karst aquifers with a wide range of recharge area, from 25 km² up to 1000 km².

Recharge rate assessent at spring and aquifer scales

The application of different methods for assessing the karst aquifer recharge rate in case studies located in five Mediterranean countries reveals how APLIS method (Andreo et al., 2008) is a consistent tool for recharge estimation at the aquifer scale, offering results coherent with other classical methods as water budget analysis. Specific limits of APLIS have been found for: i) the net recharge of permanent snow cap; ii) the need to include impermeable areas, with consequent infiltration reduction; iii) discrepancies during drought periods, probably due to the enhancement of evapotranspiration effect.

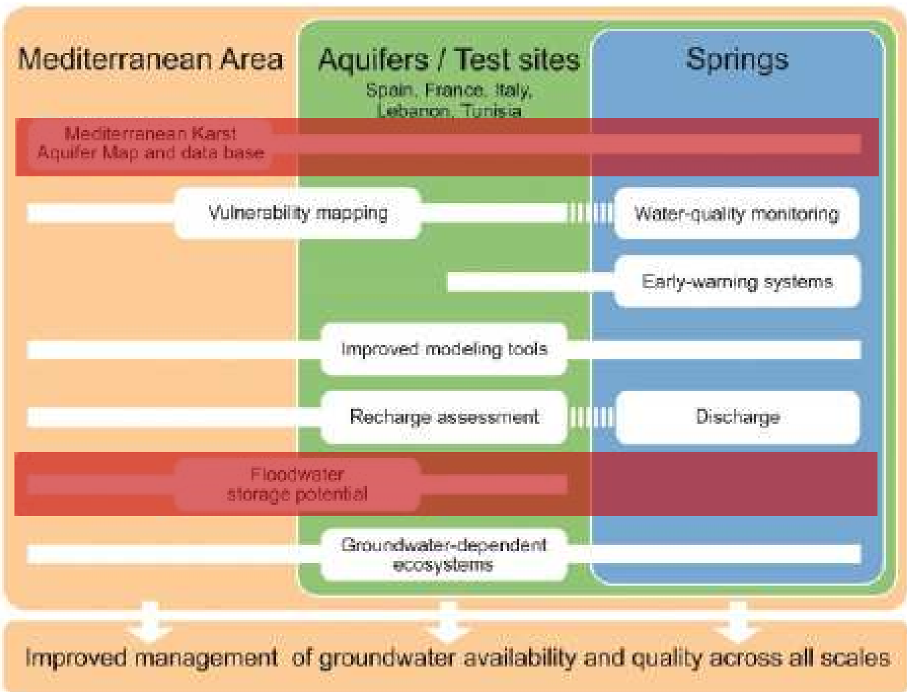

Figure 1: Methodological multiscale approach of KARMA project; the activities related to water availability assessment are highlighted in red.

KARMA - Karst Aquifer Resources availability and quality in the Mediterranean Area

www.karma-project.org

The KARMA project aims to achieve a better karst groundwater management across the scale of the Mediterranean area, single catchments and selected springs.

PRIMA IN THE MEDITERRANEAN AREA

Nevertheless, in each study site the calculation of the distributed recharge rate based on the APLIS application fits with the monitored spring discharge. Additional confirmations are offered by independent classical karst methods to compare recharge and discharge: both stable isotope analyses and their correlation with recharge areas, and the results of tracer tests performed during the project or collected from previous experiences, confirm the conceptual model of recharge for the studied springs. In detail, stable isotope values appear steady respect with past, evidencing the limited vulnerability of the studied aquifers to recent pressures. In addition, collection of tracer test results evaluated a wide time-transit range, since 2 m up to 2 km per day, with a clear influence not only by cave and conduit occurrence, but also by flow rate conditions. The recharge rates account at least for about half of the precipitation amount in each study site, calculated with APLIS, underestimating in some cases the spring discharge. Recorded recharge rates of 65% demonstrate how karst aquifers can retain up to 2/3 of rainfall, to be released by spring discharge frequently by modulated responses. The amount of groundwater availability in study areas depends on the aquifer extension, ranging from 5 million m^3 to more than 600 million of m^3 per year (see figure 2). Discrepancies of recharge calculated with APLIS with real discharge data are generally lower than 15%, but the underestimation of discharge can reach up to 75% for peak discharge periods. Therefore, APLIS application is not recommended during peak discharge events, but preferentially for average periods.

Water availability at differenet scales

The comparison of recharge rates assessed at the scale of study sites with the results published on the MEDKAM, based on the model proposed by HARTMANN et al. (2021), reveals in teresting bias and uncertainties, moving from recharge assessment at the catchment scale up to the Mediterranean scale. The recharge at local scale is usually higher than the one calculated at continental scale, causing a possible underestimation of real recharge in karst aquifers. This bias can be due to factors, as: i) impossibility to consider local altitude effects at the wider scale; ii) discarding of additional allogenic components due to the karst features at the local scale; iii) seasonal effects, due to the regional conditions, where temperature is a relevant driver in influencing the duration and the entity of summer droughts. A future validation of the recharge evaluation method is expected and it is recommended to take into account the above-mentioned factors emerged by local scale evaluations.

In terms of availability trends, the performed analysis at the Mediterranean scale is based on the groundwater storage calculated from GRACE satellite data (Xanke and Liesch, 2022): slight to severe lowering in groundwater storage has been found in 75% of Mediterranean countries, with a maximum rate of -25 mm/year. In some cases, the groundwater trend is increasing, up to 15 mm/year, with major effects on the southern boundary of the Mediterranean.

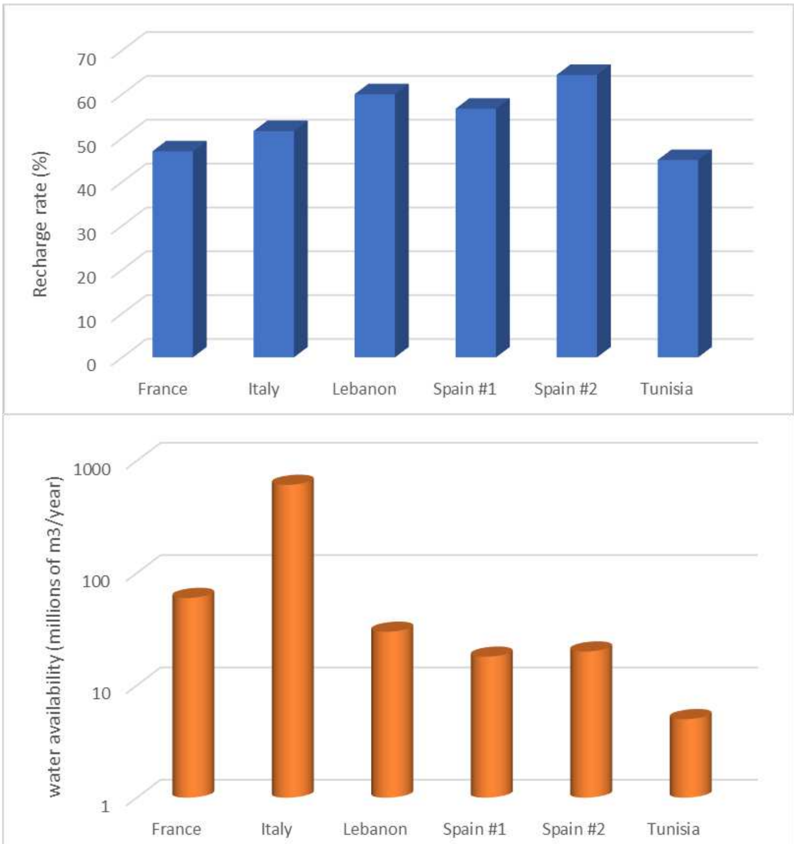

Figure 2: Recharge rate evaluated by APLIS method (above, in blue) and water availability (below, in orange) calculated for each study area.

References and further Reading

- Andreo, B., Vias, J., Duran, J., Jimenez, P., Lopez-Geta, J.A., Carrasco, F., 2008. Methodology for groundwater recharge assessment in carbonate aquifers: application to pilot sites in southern Spain. Hydrogeol. J. 16, 911–925. https://doi.org/10.1007/s10040-008-0274-5.
- Hartmann, A.; Liu, Y.; Olarinoye, T.; Berthelin, R.; Marx, V., 2021. Integrating field work and large-scale modeling to improve assessment of karst water resources. Hydrogeol. J. 29, 315–329.
- Xanke, J., Liesch, T. Quantification and possible causes of declining groundwater resources in the Euro-Mediterranean region from 2003 to 2020. Hydrogeol J (2022). https://doi.org/10.1007/s10040-021-02448-3.

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The KARMA Project


Photo: Jaime Ortega

Early Warning System for karst groundwater contamination

Key findings

KARMA test sites found comparable water quality issues dealing with turbidity and fecal contamination and applied fluorescence-based methodologies for quick water quality assessment.

Specific Early-Warning Systems were designed and implemented in Lez and Ubrique systems considering turbidity and complementary easy-to-measure parameters.

A complete EWS, including continuous record of rainfall and water parameters, data transmission and deployment of warning levels for the water managers was achieved at Ubrique test site.

Introduction

In the last decades, the availability of drinking water worldwide has been constrained due to quality issues. This situation is especially noticeable in the Mediterranean area, where karst aquifers have traditionally been exploited as a reliable source for drinking water supply and constitutes one of the most vulnerable regions to climate change (Hartmann et al., 2014). In some karst systems, the presence of a well-developed network of fractures and conduits provokes that contaminants and pathogenic microorganisms may be rapidly transferred from the surface to the groundwater capture points during recharge events. The hydroclimatic and geological features result in a high vulnerability to contamination of certain springs or boreholes intended for drinking purposes. Hence, an adequate management during such high-risk periods is essential to avoid public health issues. Nowadays, the implementation of monitoring networks for continuous recording of physical-chemical water parameters, as well as real-time data transmission, constitute strategic tools to forecast and rapidly detect contamination episodes.

EWS strategies

Within this context, the concept of Early Warning System (EWS) comprises a set of techniques designed to optimize groundwater catchment in terms of water quality (Grayman et al., 2001). In the frame of KARMA project, EWS strategies were tested at Lez (France) and Ubrique (Spain) karst systems, which are intended for drinking water supply. The karst area of Hochifen-Gottesacker (Austria) was included as a complementary test site focused on the development of EWS techniques. The EWS implementation procedure was realized according to three steps described by Marín et al., (2021) and mainly consisted in (1) continuous records of natural responses to generate a sufficiently large and representative database to perform (2) the statistical analysis for the identification of the optimal EWS parameters (those which allow a quickly, reliable and economical detection of the arrival of polluted groundwater at any supply point) and workflow development. The final step (3) entails the system launching with operational perspective.

The existence of previous investigations at these study areas exposed that the main water quality issues were related with high turbidity periods and associated fecal contamination after intense rain events that impede groundwater use for water supply population. Thus, in KARMA test sites, spring discharge as well as hydroclimatic and physical-chemical parameters of water (electrical conductivity, temperature and turbidity) were continuously monitored. Furthermore, fluorescence-based techniques and microbiological culture-based methods (i.e. *E. Coli*) were commonly used to detect organic and bacteriological contamination. According to the features of each system, specific techniques were applied at each test site to better identify groundwater origins and contaminant transport processes: Cl^- and Dissolved Oxygen (DO) in Lez system, Particle Size Distribution (PSD) and bacterial enzymatic activity (β-d-glucuronidase) in Hochifen-Gottesacker and PSD, trace elements and Rn^{222} in Ubrique test site.

Figure 1: Algarrobal spring at Ubrique test site during a contamination event with high turbidity.

Water quality issues and Early-Warning parameters

During KARMA period, several flooding events with associated turbidity were registered at the three test sites. Maximum turbidity records varied between ≈15 NTU at Lez spring (France) and ≈340 NTU at Algarrobal spring (Ubrique test site, Spain, Fig. 1). The maximum activity of E. coli measured during KARMA period apparently showed proportional values with turbidity between test sites: ≈480 CFU/100mL at Lez spring and ≈2970 CFU/100mL at Algarrobal spring (Ubrique test site, Spain). The statistical analysis allowed to determine the main correlations between water parameters and fecal contamination indicators. In Lez and Ubrique systems, those resulted to be turbidity and protein-like fluorescence. In the Austrian test site, an apparently good correlation between particle size distribution and turbidity together with β-d-glucuronidase was found. Hence, a common stage was achieved at the three test sites: the identification of (1) potential hazardous substances for human health and (2) "Early Warning" parameters. More refined protocols were developed facing the implementation of individual EWS (France and Spain test sites) with the definition of the EWS workflow (Fig. 2) and specific thresholds that activate the warning alerts adapted to hydrogeological features, contamination type and operational characteristics of the drinking water distribution system.

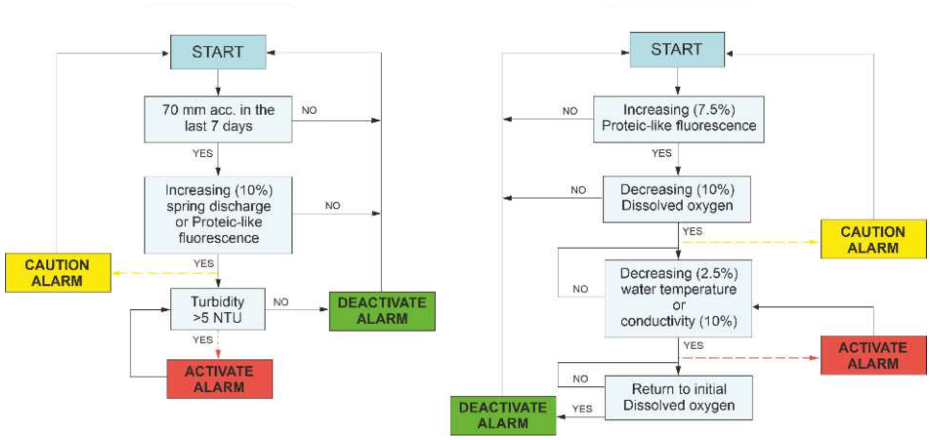

Figure 2: Architecture of Early-Warning workflows developed for Ubrique and Lez karst systems.

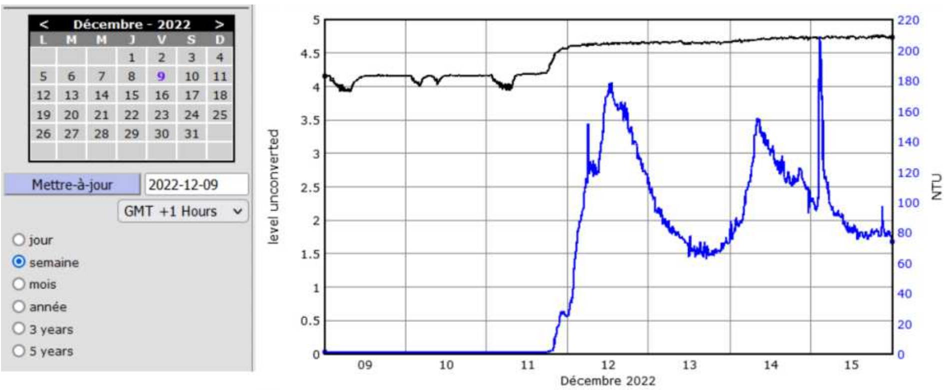

Figure 3: Online visualization of real time data during a flooding event in Algarrobal spring in December 2022.

Implementation and validation

The remote data gathering via telemetry systems and its integration with smart algorithms for deployment of warning messages is currently being developed and tested only in Ubrique test site (Spain). The launch of an online platform allowed to visualize in near (15 min) real time the measured values of rainfall, spring discharge, temperature, electrical conductivity, turbidity, protein-like fluorescence and battery load of the installed devices. As an example, Figure 3 shows the time series of rainfall in the recharge area and turbidity at Algarrobal spring in the online platform during the first test at the end of 2022. The ongoing step of the implementation consists on the validation phase, which is continously updated with newly acquired data and consist on the evaluation of system efficiency by analyzing key performance indicators (KPI) such as the rate of false warnings (positive or negative). The full implementation of the EWS in Ubrique test site can help decision makers to take the appropriate actions through the telemetry system and warnings sent by SMS to the municipal water company managers.

References and further Reading

- Grayman, W.M.; Deininger, R.A.; & Males, R.M., 2001. Design of Early Warning and Predictive Source-water Monitoring Systems. AWWA Res. Fdn, Denver.
- Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., Weiler, M., 2014. Karst water resources in a changing world: Review of hydrological modeling approaches. Rev. Geophys. 52 (3), 218–242.
- Marín, A.I., Martín Rodríguez, J.F., Barberá, J.A., Fernández-Ortega, J., Mudarra, M., Sánchez, D., Andreo, B. 2021. Groundwater vulnerability to pollution in karst aquifers, considering key challenges and considerations: application to the Ubrique springs in southern Spain, Hydrogeol J, p. 29.

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Photo: Jaime Ortega

Groundwater vulnerability mapping to pollution in Mediterranean karst sites

Key findings

This study assesses the groundwater vulnerability to pollution of Mediterranean karst aquifers by the application of COP method, which complies with the conceptual approach of the European COST Action 620.

The Mediterranean karst aquifers studied in KARMA present high spatial heterogeneity regarding vulnerability to pollution, where the most vulnerable areas correspond to highly karstified limestones and thin/bare soils or also drainage areas of sinking rivers and endorreic areas, which natural drainage occurs through swallow holes hydrologically connected to shafts and other endokarst features.

The reliability of the vulnerability maps has been validated by different techniques. This reinforces the viability of these maps as a tool to support decision-making in spatial planning and the progress toward the achievement of the Sustainable Development Goal 6 (SDG6) of the United Nations in order to ensure availability and sustainable management of water and sanitation for all.

Introduction

The water supply of many countries around the world depends -to a large extent- on groundwater. However, the use of groundwater as drinking water depends on its availability and quality. The karst aquifers are especially vulnerable to pollution due their hydrologic behaviour derived from karstification. In this kind of aquifers, contaminants may easily reach the saturated zone and then be rapidly transported through karst conduits over large distances (Figure 1).

Under the current climate change context, the increase of extreme drought frequency is expected in the Mediterranean region. Hence, groundwater quality constitutes a key issue to ensure the water security in karst regions. Groundwater vulnerability assessment methods have been developed to provide the necessary basis for implementing preventive measures facing groundwater protection, considering the delimitation of protection zones one of the most relevant techniques. Therefore, they have are effective tool in the protection of water resources.

The groundwater vulnerability of Unica springs catchment (Slovenia), the Lez spring catchment (France), Ubrique test site (Spain) and Qachqouch spring catchment (Lebanon) have been assessed under KARMA project by COP and COP+K methods (Vias et al., 2006, Andreo et al., 2009) that comply with the conceptual approach of the worldwide applied COST Action 620 (Zwahlen, 2004).

The resulting maps of the KARMA test sites present a high variability of the vulnerability degree due to the complexity and heterogeneity of geological and structural features among the investigated aquifers.

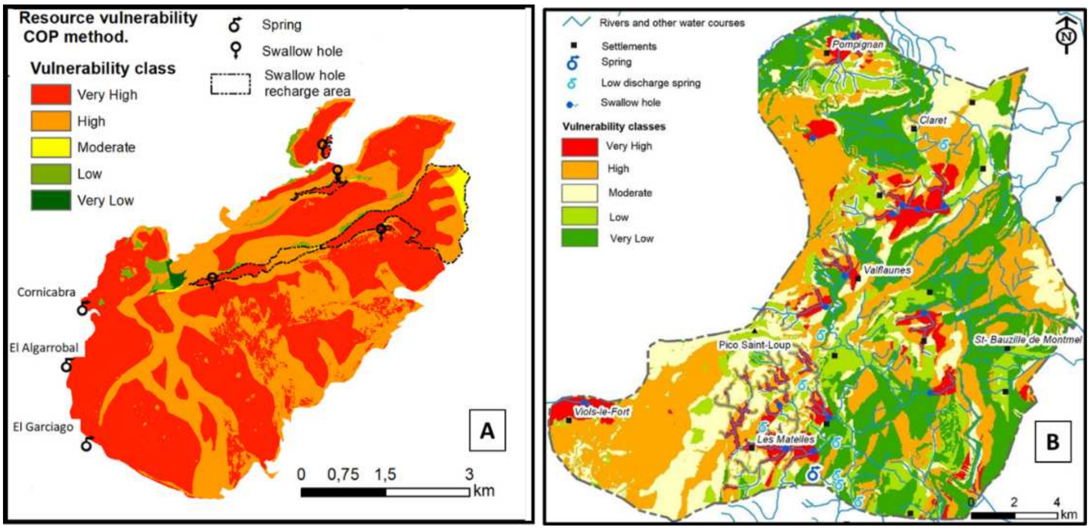

Figure 1: Maps of resource vulnerability to contamination of two KARMA test sites:
(A) Ubrique aquifer, Spain, (B) Lez spring catchment area, France

The overall analysis of the KARMA vulnerability maps shows an elevated spatial heterogeneity. As a general trend, the highest vulnerability areas correspond to highly karstified limestones and thin/bare soils or also sinking streams catchments and endorreic areas, which natural drainage occurs through swallow holes hydrologically connected to shafts and other endokarst features. Aquifer sectors influenced by exokarstic landforms, such as karren field or dolines, tend to be less vulnerable than karst swallow holes although in some systems they can present extreme vulnerability. COP method identifies as Low or Very Low vulnerable areas the sectors where low permeability soils and lithology overlying the aquifer exist.

As an example of the results obtained with the COP method, Figure 1 shows the vulnerability maps of the Ubrique aquifer and the Lez spring catchment area. The differences between these maps can be seen in the range contrast of the obtained vulnerability classes in each area and in their spatial distribution. This shows that the vulnerability of karst aquifers, and therefore, the delimitation of the protection zones drinking water sources, require specific studies for each study area that the hydrogeological particularities of the aquifer.

Since the final goal of any vulnerability map is to support stakeholders for decision-making and to promote a land-use management compatible with the groundwater protection, the accuracy and reliability of the obtained maps is required for its practical applications. A solid understanding of the hydrogeological functioning of the aquifer constitutes a key issue for groundwater vulnerability assessment.

Validation may involve a wide range of methods and techniques such as field tracing experiments, analysis of natural responses of karst springs, study of environmental tracers, numerical modeling, etc. (Marín and Andreo, 2015). The natural and artificial tracers are useful techniques to validate the vulnerability maps that complement each other enhancing the knowledge about infiltration/recharge processes and vulnerability in karst aquifers (Figure 2).

In the framework of KARMA project, the vulnerability maps have been validated thorough the analysis of hydrodynamic and hydrochemical responses of the main springs that drain the aquifer, together with the evolution of natural tracers of infiltration and dye tracer tests (Figure 3). Although there is room for further improvement efforts to reduce certain uncertainties, the good results obtained in the validation of the maps demonstrate their usefulness for groundwater protection and land use planning in the recharge basins of the KARMA test sites.

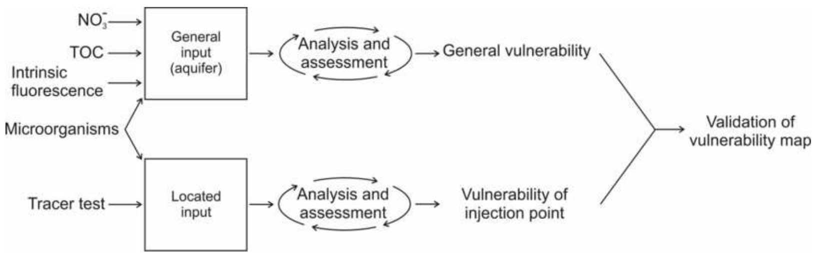

Figure 2: Natural and artificial tracers as techniques for validation of the vulnerability maps (Marín and Andreo, 2015)

Figure 3: Dye tracer test injections (Karst aquifers in Southern Spain)

References and further Reading

- Andreo B, Ravbar N, Vías JM (2009) Source vulnerability mapping in carbonate (karst) aquifers by extension of the COP method: application to pilot sites. Hydrogeol J 17(3):749–758. https://doi.org/10.1007/s10040-008-0391-1
- Marín, A.I., Andreo, B. (2015). Vulnerability to Contamination of Karst Aquifers. In: Stevanović, Z. (eds) Karst Aquifers—Characterization and Engineering. Professional Practice in Earth Sciences. Springer, Cham. https://doi.org/10.1007/978-3-319-12850-4_8
- Vías J, Andreo B, Perles M, Carrasco F, Vadillo I, Jiménez P (2006) Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method. Hydrogeol J 14(6):912–925
- Zwahlen F (ed) (2004) Vulnerability and risk mapping for the protection of carbonate (karst) aquifers. Final report of COST Action 620. European Commission, Directorate-General XII Science, Research and Development, Brussels

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