MedWater Conclusions and Perspectives on Mediterranean Karst Aquifers under Global Change

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Problem setting

The Mediterranean region, already affected by water shortage and water stress, is strongly impacted by climate change, showing a trend of warming that is above the global average (Figure 1). By 2040, temperatures could increase by 2.2 °C compared to pre-industrial times, while increased evapotranspiration and reduced precipitation could decrease water availability by 2-15% (Cramer et al., 2019). These developments will have significant impacts on food and water availability, energy consumption, human health, tourism, economics, and ecosystems. Moreover, the total population of the Mediterranean region is expected to increase by 90 million people in the next 30 years, reaching 611 million in 2050 (Ambrosetti, 2020). Vörösmarty et al. (2000) showed that population increase and the resulting growth in water demand will in many regions of the world have a much greater impact on the availability of water resources than climate change.

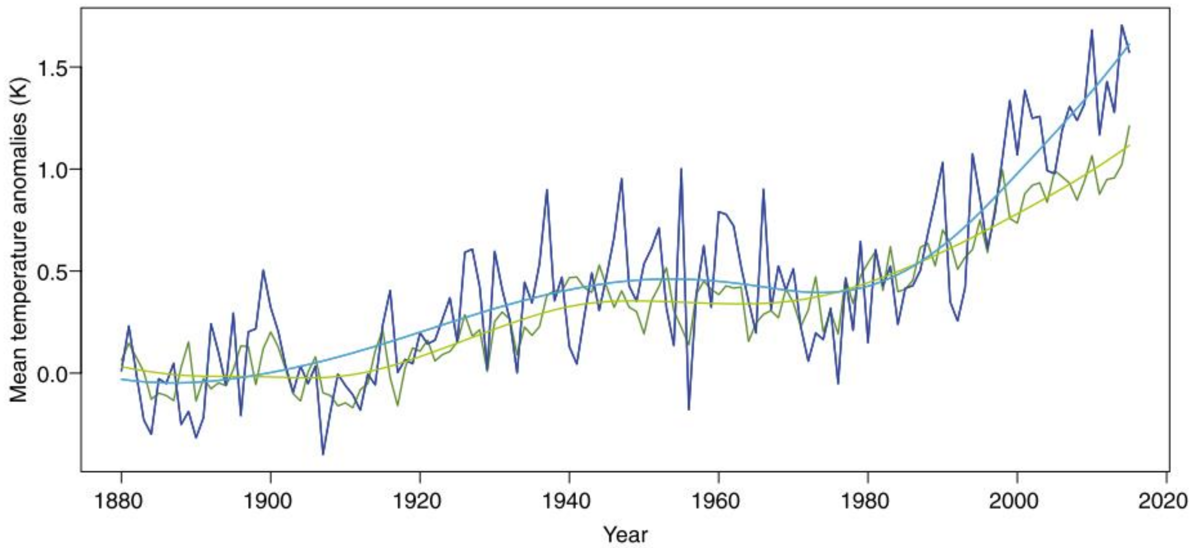

Figure 1: Temperature anomalies in the Mediterranean (blue lines) and worldwide (green lines) compared to the reference period 1880-1899. **Source and copyright: Cramer et al. (2019)**

In their 17 Sustainable Development Goals (SDGs), the United Nations call for an optimized management of available water resources (SDG 6). In the coming decades, the strategic value of groundwater is likely to increase. Compared to surface reservoirs, underground water storage is significantly less affected by evaporation loss, a factor becoming more decisive with rising temperatures, especially in semi-arid regions (McCartney & Smakhtin, 2010).

Due to their wide geographic distribution, generally large catchment areas, and drainage towards individual springs, karst aquifers have great potential for exploitation. About 9.2% of the global population depend on groundwater from karst aquifers (Stevanović, 2019). Accordingly, it is essential that they are managed in a smart way. This is especially relevant for the Mediterranean where conduits, factures, and caves have developed at great depths below the present sea level due to the specific recent geological history of this area. At the same time, karst aquifers require dedicated management concepts due to their high dynamics, fast response times to precipitation events, and low storage capacity. Another characteristic of areas with low precipitation rates and high evaporation is the extreme temporal and spatial variability of groundwater recharge. Thus, karst aquifers within Mediterranean climates require a sustainable groundwater management based on flexible, event-based "real-time" management concepts.

In the MedWater project (July 2017-June 2021), an interdisciplinary team focused on the development of new tools and strategies to support decision-makers with managing groundwater resources in karst aquifers in a more sustainable way considering also the impact of shifts in climate in the short- and long-term. The key study site was in Israel, with transfer sites in Italy and France. The project concluded with six key challenges and recommendations.

Six key challenges for karst aquifer management in the Mediterranean

1. Quantification of spatial and temporal variability of groundwater recharge
2. Identification of regional water governance and strategies
3. Quantification of virtual water fluxes, energy, and emissions based on food production and consumption
4. Managing the impact on ecosystem services and biodiversity regionally and globally
5. Identification of methods for regional and global transfer methods
6. Potential and limitations of remote sensing information in regions with high data scarcity

Challenge 1: Quantification of spatial and temporal variability of groundwater recharge

Currently applied methods to estimate recharge in karst aquifers often employ regionalized precipitation and temperature, neglecting the highly variable precipitation pattern and the physics of the infiltration process. In karst aquifers, groundwater recharge consists of a slow and a rapid component. Both recharge components show a specific spatial and temporal pattern and are strongly affected by the thickness of the unsaturated zone, which determines the infiltration flow path and velocity. A semi-arid climate region with a pronounced seasonality of precipitation and intense short-duration rainfall, such as the Mediterranean, accentuates the complex dynamics of dual-domain infiltration and partitioning of the precipitation input signal via localized overland flow processes along Wadi channels. We analyzed a set of methods to calculate recharge for the Western Mountain Aquifer in Israel and the West Bank: (1) water balance calculations using the Soil & Water Assessment Tool (SWAT) which provides a daily water balance for sub-catchments, (2) a soil water balance model (SWBM) which calculates the daily percolation at the zero-flux plane, and (3) Hydro-pedotransfer functions (HPTFs) that calculate recharge on an annual basis.

The data-intensive SWAT model accurately simulates the hydro-/geological cycle of a karst aquifer. It simulates the fast flow component of recharge along the wadis and the slow flow component across the highly heterogeneous terrain. For the Western Mountain Aquifer, overall recharge decreases from West to East and North to South. The high spatial and temporal resolution of the model is unmet by any other published approach. HPTFs can calculate recharge on a small spatial scale but disregard the rapid flow component, which is essential for recharge under high evaporation rates. The SWBM calculates high spatial and temporal resolution recharge with a strong signal after precipitation events. The annual percolation of the SWBM corresponds to the SWAT recharge. The SWBM is not as data-intensive as the SWAT model and therefore does not consider regional differences in detail.

Challenge 2: Identification of regional water governance and strategies

Sustainable water management practices require predictive modeling of large-scale groundwater reservoirs based on accurate estimation of short- and long-term recharge rates and a solid understanding of flow processes. MedWater employed the finite element, distributed, multi-continuum flow simulator HydroGeoSphere to simulate water fluxes in the unsaturated and saturated zone as well as the interaction with the atmosphere considering the impact of climate change on meteorological variables. HydroGeoSphere predicts flow and storage dynamics within the phreatic and the vadose zone and therefore the spatial and temporal distribution of stored groundwater volumes, which forms the basis for water resources management plans. For the Western Mountain Aquifer, we provided projections of future availability of freshwater resources based on three management scenarios: Regional Resource-Intensive (RRI), Baseline, and Regional Nature Conservation (RNC). Simulation results indicate that discharge of the Taninim spring, one of the two main outlets of the aquifer, may substantially drop below the critical red line threshold in the RRI and Baseline scenarios, whereas only the RNC scenario will ensure sustainability of groundwater resources usage (Figure 2). Furthermore, MedWater provides local water authorities with predictions of recharge quantities under the RCP 4.5 climate change scenario, suggesting a recharge decrease. In this context, the applied model allows optimizing pumping well locations to provide water during high demand periods (summer and fall) replenished during winter by recharge (overpumping), and to design abstraction schemes that avoid the intrusion of saltwater into the aquifer. These adapted exploitation strategies can be implemented to face water scarcity due to population increase and climate change.

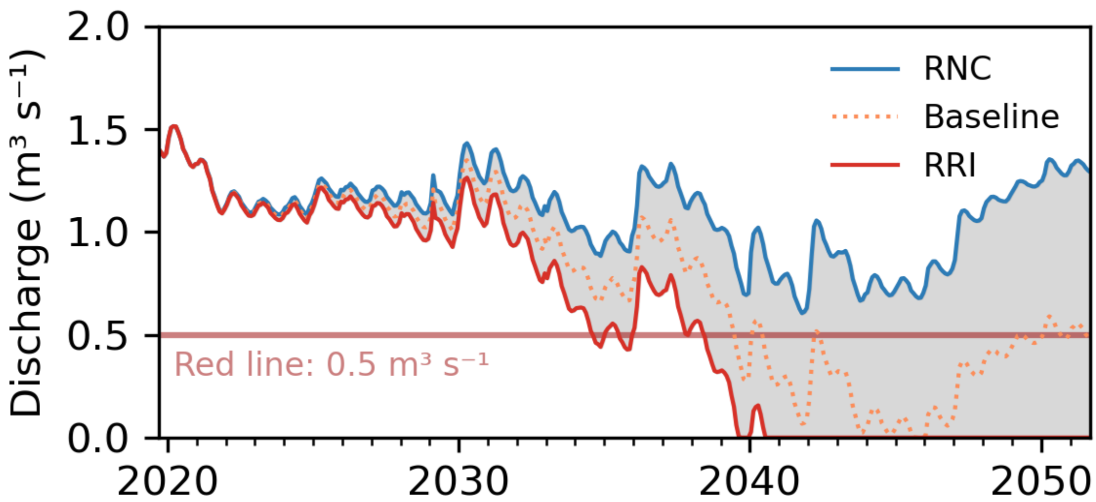

Figure 2: Change in spring discharge of the Taninim/Al Timsah spring in Israel from 2020 to 2050 according to the Regional Resource-Intensive (RRI), Baseline, and Regional Nature Conservation (RNC) scenarios

Challenge 3: Quantification of virtual water fluxes, energy, and emissions based on food production and consumption

Due to Israel's quickly increasing population and limited water resources, the country remains heavily dependent on crop imports to secure food supply. The country has managed to partly deal with water scarcity by technological advancement and highly efficient use of its resources. However, import of virtual water through crops is needed as local production cannot meet the food demand of Israel's population by itself. In the period 2000-2019, according to FAOSTAT, Israel has imported 30 Mio. tons of wheat, while producing only 3 Mio. tons. Israel also imported 23 Mio. tons of maize, while producing only 2 Mio. tons, and imported 9 Mio. tons of soybean, producing none. These data illustrate Israel's dependence on staple crop imports. In total, Israel consumed 1,806 Mio. m^3 of virtual blue water and 6,498 Mio. m^3 of virtual green water in 2005 (Myburgh, 2020). Most of the blue water consumption (1044 Mio. m^3) is used directly in Israel, while 762 Mio. m^3 is imported. However, the imports of virtual green water impressively illustrate the country's dependence on virtual water imports. Wheat was associated with the highest blue water volumes at 405 Mio. m^3, followed by maize at 125 Mio. m^3. Roughly 49% of total energy consumption and 42% of related greenhouse gas (GHG) emissions of Israel's domestic and imported agricultural blue water were embedded in cereals, followed by oil crops (26% energy and 27% GHG) and fruits (11% energy and 16% GHG) (Smolka, 2020). To reduce its reliance on blue water, both domestically and abroad, Israel could stop producing wheat and maize locally due to the extremely high water use per ton of crop and switching to import from regions producing rainfed wheat. To reduce the energy demand and GHG emissions of its imports, Israel could consider importing more from Ukraine, Russia, and Europe rather than North and South America. Besides technological solutions in water management, the import of virtual water will be an important strategy to cope with local water shortages.

Challenge 4: Managing the impact on ecosystem services and biodiversity regionally and globally

Ecosystem services in the Western Aquifer Basin are under pressure because of agricultural land use and climate change. An index-based method was applied to quantify five ecosystem services: regulation of surface water quantity, regulation of groundwater quantity, regulation of freshwater quality, food provisioning, and protection of soils and sediments. SWAT calculates as input for this index-based method ecosystem services for four scenarios (2021 – 2050), with one climate scenario (RCP 4.5) and three land use scenarios: Baseline, Regional Nature Conservation (RNC), and Regional Resource-Intensive (RRI). These are compared to index values in the period 2000-2015. Whereas surface water and groundwater provisioning have been high in the past, our investigation predicts that these two services will decrease in the future due to lower precipitation rates. In contrast, erosion regulation will increase, because precipitation-related erosion is reduced. Our study does not find any change in the future for water quality regulation services. The food provisioning services remain stable except for a marginal reduction in the RNC scenario, which assumes that large areas of agricultural land are converted to forest land. Our research also found that the crop yield (tons per ha) for irrigated cropland would increase compared to rain-fed cropland. This would lead to an increasing water demand in the agricultural sector. The increasing demand for irrigation water would need to be fulfilled through non-conventional water sources, such as desalinated seawater and brackish water and treated wastewater. In addition, the reduction of the surface water provisioning index indicates a concerning situation for river ecosystems. Non-conventional water sources would be an alternative solution to restore natural river ecosystems. Therefore, there may be a trade-off between more production of water-intensive crops and a better protection of river ecosystems.

With respect to the impact on ecosystem services in regions exporting to Israel such as USA and Ukraine, food production services in the "exporting" watersheds are relatively high, while freshwater provisioning and erosion regulation are maintained at satisfactory levels. This is largely due to these regions having well established agricultural production systems where efficient management practices are in place. It is worth noting though that production yields in the USA are larger than in the Ukraine, meaning less land is required for production. In terms of aquatic biodiversity impacts related to freshwater extraction based on global datasets, the largest fractions of potential species lost are in the USA and Israel (Myburgh, 2020). This creates a trade-off between more efficient production per unit of land in the USA with higher impacts on aquatic biodiversity, compared to Ukraine where land requirements are larger, while aquatic biodiversity impacts are smaller.

Challenge 5: Identification of methods for regional and global transfer methods

Opportunities for global-scale assessments of karst groundwater resources have increased with recent publications, most notably the World Karst Aquifer Map (Chen et al., 2017) and the World Karst Spring hydrograph database (Olarinoye et al., 2020). Together with remote sensing (e.g., MODIS NDVI time series of vegetation cover), global meteorological data (e.g., ERA5) and global hydrological models (GHMs; e.g., WaterGAP or PCR-GLOBWB), they allow the application of analytical techniques, especially with GHMs improving their resolutions from 0.5° (ca. 55 km) to 0,0833° (ca. 9 km). MedWater offers first ideas of how these new techniques can provide critical insights on aquifer management: Based on seven indicators of quantitative groundwater stress, we determined a high Groundwater Stress Index (GSI) for aquifers in southern Spain and northwest Africa, parts of Greece, the Middle East, and on islands like Malta, Crete, or Chios. Relatively less stressed were karst aquifers along the European Mediterranean coast in France and Italy. We expect Mediterranean karst aquifers to be vulnerable to climate change, as, within our analyzed dataset of 133 aquifers, higher GSI values clearly correlate with a higher annual temperature and lower annual precipitation, providing an estimate of how climate change could impact these critical water resources. The magnitude of these increases in groundwater stress, however, differs depending on the aquifer type (e.g., depending on parameters such as terrain and land cover). Thus, some aquifers are more threatened than others, and this information can prioritize management decisions as well as guide successful monitoring. A generally high vulnerability to climate change in the Mediterranean region is corroborated by predicted climate zone shifts until 2100 by Beck et al. (2018). However, while global analyses can broadly point towards hotspots and emerging trends, optimal groundwater management remains site-specific and requires sophisticated modeling tools that rely on abundant input data to forecast future resource availability.

Challenge 6: Potential and limitations of remote sensing information in regions with data scarcity

In MedWater, remote sensing was assessed to be one alternative input for simulation of the hydrological cycle and the water balance. With the advent of operational synthetic aperture radar (SAR) systems such as Sentinel-1, downscaling of global soil moisture products such as the soil water index (SWI) derived from Advanced SCATterometer (ASCAT) data is possible (Paulik et al., 2014). However, this approach requires dense in situ observation networks for calibration to a specific aquifer of interest. In addition, the frequent situation of vegetation-free outcrops and soil pockets in elevated locations of Mediterranean karst aquifers must be considered when modeling vadose zone processes. In MedWater, unmanned aerial vehicles (UAVs) have shown great potential to distinguish these landscape elements that regulate run-off and infiltration processes on topographically exposed surfaces of karst aquifers. The use of UAV on the other hand limits operational application and spatial transfer. In the future, this relevant separation may be implemented using very high-resolution optical satellite data, which, however, is not free-of-charge available outside the scientific community.

Overall perspectives of the MedWater project

Management of karst aquifers requires the improvement of their resilience to short-term (month) or medium-term (decades) changes in meteorological variables, accommodating for expected shifts in climate and reducing vulnerability. For a better management of these systems, suitable methods are the analysis of spring discharge and water table time series, which serve as calibration data for our models. Besides hydrological and meteorological data, further data needed to design powerful models are information about the system geometry and its hydrogeological characteristics. In the future, new approaches to quantify groundwater recharge should be developed addressing especially the impact of climate change.

If water shortage increases, observed deficits cannot in all cases be compensated completely by classical aquifer management operations such as lowering water demand, more efficient water usage, prioritization of water users, or reducing local agricultural production. New methods are needed that allow usage of new water resources such as treated wastewater. Thus, in Israel, 80% of treated wastewater is currently used for crop irrigation. Furthermore, 10 years ago, Israel started to invest in freshwater production from desalinated seawater. Currently, 30% of freshwater demand is supplied with desalinated seawater. In addition, a combination of blue, green, and grey infrastructures in urban areas is a promising method to reduce water loss and to increase water storage. Only a combination of these strategies will allow to protect groundwater resources in the future and to increase resilience to expected shifts in climate.

Large regional aquifers can also act as temporal water storage systems and therefore as major components in overall management concepts. Based on the modeling tools developed in MedWater, karst aquifers can be managed with a smart pumping scheme. For example, management could include:

- Overpumping strategies, i.e., the generation of storage volume (cones of depression) within the karst aquifer during dry periods, to be replenished by recharge water following heavy rain events in the winter seasons. This allows to pump groundwater resources located in deep karst cavities developed in the Mediterranean area.
- Employing the karst aquifer as a storage buffer for excess desalinated sea water.
- Considering the internal storage dynamics of the phreatic and vadose zone: Groundwater hydrographs as well as spring discharge records demonstrate a multiannual storage capacity of the phreatic and the thick vadose zone. Following very wet winters, spring discharge and well hydrographs have showed very gradual recessions over periods of several years.

Overall, the MedWater project provides solutions for:

- Spatially and temporally high-resolution calculations of the quantitative state of karst groundwater resources as well as predicted changes due to shifts in climate, with a particular focus on the accurate estimation of groundwater recharge.
- A more integrated assessment of water resources, also considering virtual water fluxes and associated energy demand and carbon emissions, as well as requirements of ecosystems and the services they provide, both regionally and abroad.
- The use of global databases and remote sensing data as well as stochastic methods to increase the level of information in data-scarce regions and to enable global-scale analyses.

- The optimization of groundwater use with respect to competing water demands and trade-offs.
- The creation of an efficient modeling basis for implementation in user-friendly management tools (in particular, a Decision Support System).

All MedWater subprojects are summarized in more than 20 Technical Notes, which are available on the project website www.grow-medwater.de.

References

Ambrosetti, Elena (2020). Demographic challenges in the Mediterranean. In European Institute of the Mediterranean (Ed.), *IEMed Mediterranean Yearbook 2020* (pp. 300-304). https://www.iemed.org/observatori/arees-danalisi/arxius-adjunts/anuari/med.2020/Demography_Mediterranean_Countries_Elena_Ambrosetti_IEMed_YearBook2020.pdf

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., & Wood, E.F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data, 5*(1), 180214. https://doi.org/10.1038/sdata.2018.214

Chen, Z., Goldscheider, N., Auler, A., Bakalowicz, M., Broda, S., Drew, D., Hartmann, J., Jiang, G., Moosdorf, N., Richts, A., Stevanović, Z., Veni, G., Dumont, A., Aureli, A., Clos, P., & Krombholz, M. (2017). *World karst aquifer map (WHYMAP WOKAM)* [Data set]. BGR, IAH, KIT, UNESCO. http://doi.org/10.25928/b2.21_sfkq-r406

Cramer, W., Guiot, J., & Marini, K. (2019). *Risks associated to climate and environmental changes in the Mediterranean region*. Mediterranean Experts on Climate and Environmental Change (MedECC). https://www.medecc.org/wp-content/uploads/2018/12/MedECC-Booklet_EN_WEB.pdf

McCartney, M., & Smakhtin, V. (2010). *Water Storage in an era of climate change: Addressing the challenge of increasing rainfall variability*. International Water Management Institute. http://www.iwmi.cgiar.org/Publications/Blue_Papers/PDF/Blue_Paper_2010-final.pdf

Myburgh, S. (2020). *An integrated biophysical-ecosystem assessment of Israel's trade of agricultural crops with respect to embedded virtual waterflows* [Master's thesis, University of Bayreuth].

Olarinoye, T., Gleeson, T., Marx, V., Seeger, S., Adinehvand, R., Allocca, V., Andreo, B., Apaéstegui, J., Apolit, C., Arfib, B., Auler, A., Barberá, J. A., Batiot-Guilhe, C., Bechtel, T., Binet, S., Bittner, D., Blatnik, M., Bolger, T., Brunet, P., … Hartmann, A. (2020). Global karst springs hydrograph dataset for research and management of the world's fastest-flowing groundwater. *Scientific Data*, *7*(1), 59. https://doi.org/10.1038/s41597-019-0346-5

Paulik, C., Dorigo, W., Wagner, W., & Kidd, R. (2014) Validation of the ASCAT Soil Water Index using in situ data from the International Soil Moisture Network. *International Journal of Applied Earth Observations and Geoinformation, 30*, 1-8. https://doi.org/10.1016/j.jag.2014.01.007

Smolka, G. (2020). *Energy consumption and greenhouse gas emissions of domestic water versus virtual blue water for agricultural production* [Master's thesis, University of Bayreuth].

Stevanović, Z. (2019). Karst waters in potable water supply: A global scale overview. *Environmental Earth Sciences*, *78*(23), 662. https://doi.org/10.1007/s12665-019-8670-9

Vörösmarty, C.J., Green, P., Salisbury, J., & Lammers, R.B. (2000). Global water resources: Vulnerability from climate change and population growth. *Science, 289*(5477), 284-288. https://doi.org/10.1126/science.289.5477.284