



Sustainable management of
politically and economically
relevant water resources in
highly dynamic carbonate
aquifers of the Mediterranean

FINAL REPORT

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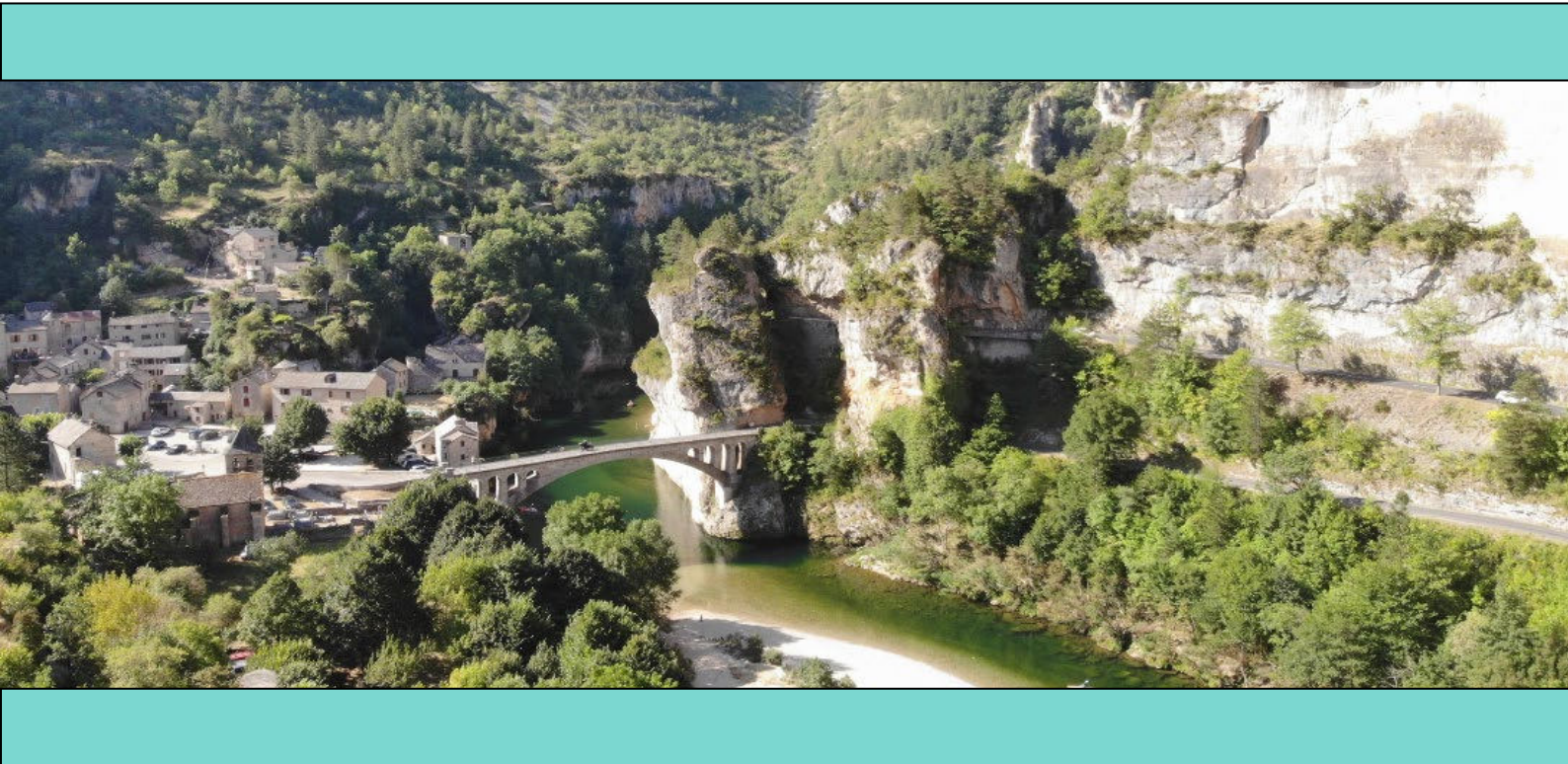
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Motivation

Etwa 10 % der Weltbevölkerung sind auf Grundwasserressourcen aus Karstgrundwasserleitern angewiesen¹. Sie sind insbesondere im Mittelmeerraum weit verbreitet. Während ihre Infiltrationskapazitäten hoch sind, wird langfristig häufig nicht viel Grundwasser gespeichert. Ausgefeilte Bewirtschaftungskonzepte sind erforderlich, da Karstaquifere in Bezug auf Quantität und Qualität zunehmend gefährdet sind. Bis 2040 könnte die Temperatur im Mittelmeerraum im Vergleich zur vorindustriellen Zeit um 2,2 °C ansteigen, während die erhöhte Evapotranspiration und die verringerten Niederschläge die Wasserverfügbarkeit um 2-15 % verringern könnten². Darüber hinaus erleben viele Regionen (z.B. Nordafrika und der Nahe Osten) einen starken Bevölkerungszuwachs, was den Druck auf die Wasserressourcen weiter erhöht.

Ziele

MedWater untersucht das Verhalten von Karstaquiferen, erforscht die Auswirkungen des Klimawandels und des steigenden Wasserbedarfs auf die Grundwasserressourcen und entwickelt Strategien und Werkzeuge für ein nachhaltiges Management. Das primäre Untersuchungsgebiet ist der stark verkars-tete Western Mountain Aquifer (WMA) in Israel und den Palästinensischen Autonomiegebieten. Die Ergebnisse werden auf vergleichbare Aquifere in Italien und Frankreich übertragen. Auf globaler Ebene entwickeln wir verallgemeinerte Modelle für Karstaquifere mit mediterranem Klima und schätzen deren Gefährdung durch Grundwasserstress und den Klimawandel ab. Unsere Arbeit leistet einen Beitrag zur Erreichung der Nachhaltigkeitsziele der UN, insbesondere SDG 6 – universaler und gerechter Zugang zu sauberem Wasser.

In MedWater simulieren wir die Grundwasserneubildung und den Grundwasserfluss, entwickeln einen multikriteriellen Optimierungsalgorithmus für das Grundwassermanagement, quantifizieren grundwasserabhängige Ökosystemleistungen und berech-

nen virtuelle Wasserimporte und -exporte. Ein benutzerfreundliches Entscheidungsunterstützungssystem verarbeitet die Modellierungsergebnisse für den WMA unter Einbeziehung von Klimaprojektionen und Szenarioanalysen. Durch die Kopplung von numerischer Modellierung mit benutzerfreundlichen Werkzeugen liefern wir eine solide Wissensbasis für die Entscheidungsfindung im Grundwassermanagement.



Der Western Mountain Aquifer in Israel und den Palästinensischen Autonomiegebieten

Zentrale Ergebnisse

MedWater untersuchte verschiedene Methoden zur Berechnung der räumlichen und zeitlichen Verteilung der Grundwasserneubildung in Karstgrundwasserleitern. Mit dem Soil & Water Assessment Tool (SWAT) ermittelten wir für den WMA eine langfristige durchschnittliche Neubildung von 199 mm/a

¹ 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>

² 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

(1979-2019). Die Neubildungszone spielt eine wichtige Rolle für Ökosystemleistungen und sorgt für eine hohe Regulierung der Oberflächen- und Grundwasserressourcen, für die Regulierung der Wasserqualität und für den Schutz von Böden und Sedimenten. Klimaveränderungen werden sowohl die Grundwasserressourcen als auch die Ökosystemleistungen beeinflussen. Hochaufgelöste (3 km) Klimaprojektionen zeigen für die Neubildungszone des WMA bis 2070 einen Anstieg der Temperatur um 2,1°C im Winter und Herbst, während die Niederschläge im Herbst um bis zu 59% abnehmen werden. Aufgrund von Klimaverschiebungen könnte die mittlere jährliche Grundwasserneubildung zwischen 16 % und 25 % abnehmen (1980-2000 vs. 2050-2070).

Die Identifizierung des Karströhrennetzwerks wurde mit Hilfe des an der Universität Neuchâtel entwickelten Stochastic Karst Simulators (SKS)³ ermöglicht, der Karststrukturen auf der Grundlage paläoklimatischer Rekonstruktionen des Meeresspiegels und des Klimas im Mittelmeerraum während der letzten 6 Millionen Jahre berechnet. Die Simulationen zeigen, dass die Geometrie eines Karstnetzwerks in hohem Maße von der Lage vergangener Karstquellen gesteuert wird. Diese "soft" Informationen über die Karstentwicklung erlauben es, ein fundiertes hydraulisches Parameterfeld zu generieren.

Mit einem Multi-Kontinuum-Modell (HydroGeoSphere) simulierten wir die Dynamik der vadosen Zone zusammen mit dem Grundwasserströmungssystem. Szenarioanalysen untersuchten die Auswirkungen einer Anpassung der Pumprate und zeigen ein durchschnittliches Absinken des Grundwasserspiegels unter einem ressourcenintensiven Szenario um 7,8 Meter in den nächsten 25 Jahren. In einem Naturschutzszenario hingegen könnte der Grundwasserspiegel bis 2050 um 3,3 Meter ansteigen.

Die landwirtschaftliche Lebensmittelproduktion ist mit Abstand der größte Wasserverbraucher in Israel. Im Jahr 2005 wurden 1.806 Millionen m³ virtuelles blaues Wasser für die in Israel konsumierten Feldfrüchte verwendet. Israel exportierte 132 Millionen

m³ an virtuellem blauem Wasser. Dies entsprach 11,3 % des gesamten blauen Wassers, das für Israels landwirtschaftliche Produktion verwendet wurde. Für den lokalen Verbrauch von blauem Wasser sind Weizen, Äpfel, Oliven und Pfirsiche die größten Wasserverbraucher, während Kartoffeln, Datteln, Trauben und Oliven im Hinblick auf den Export am wasserintensivsten sind.

Ein Decision Support System (DSS) für den WMA beinhaltet Ergebnisse des Grundwassermodells, der Neubildungsberechnung, der Klimaprojektionen und der Szenarioanalysen. Unter Verwendung analytischer Funktionen simuliert das DSS die Reaktion des Grundwasserleiters auf Änderungen von Parametern oder Pumpraten. Ein Framework für die multikriterielle Optimierung (MOO) ermöglicht es Wassernutzern, Strategien zur Grundwasserbewirtschaftung zu testen: Grundwasserentnahme und Wassereinspeisung werden in Bezug auf den Bedarf (z.B. Landwirtschaft, Städte) und die Wasserquellen (z.B. Entsalzung, aufbereitetes Abwasser) optimiert.

Auf der globalen Skala haben wir verallgemeinerte Modelle für verschiedene Typen von mediterranen Karstgrundwasserleitern erstellt. Weiterhin kombiniert ein Grundwasserstress Index u.a. Informationen über Grundwasserneubildung, Entnahmeraten und grundwasserabhängige Ökosysteme. Die Analyse von 133 Grundwasserleitern weltweit zeigte einen erhöhten Grundwasserstress in Südspanien und Nordwestafrika, in Teilen Griechenlands und im Nahen Osten. Wir erwarten, dass mediterrane Karstaquifere sehr vulnerabel gegenüber Klimaveränderungen sind, da unterschiedliche Aquifertypen ähnliche Trends höherer Grundwasserstressindizes bei höheren Temperaturen und geringeren Niederschlägen zeigten.

Unsere Ergebnisse sind in **21 Technical Notes dokumentiert, die in diesem Bericht zusammengestellt sind**. Jedes Technical Note kann auch einzeln als PDF auf der MedWater-Homepage unter <http://grow-medwater.de/home/index.php/products/?lang=de> heruntergeladen werden.

³ Borghi, A., Renard, P., & Jenni, S. (2012). A pseudo-genetic stochastic model to generate karstic networks. *Journal of Hydrology*, 414-415, 516-529. <https://doi.org/10.1016/j.jhydrol.2011.11.032>

Consortium

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- TU Berlin
- University of Göttingen
- University of Bayreuth
- University of Würzburg
- VisDat GmbH
- BAH Berlin

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- Israel Hydrological Service (IL)
- Mekorot Water Company Ltd. (IL)
- Ben-Gurion University of the Negev (IL)
- Hebrew University of Jerusalem (IL)
- Ariel University / Eastern R&D Center (IL)
- Palestinian Water Authority (PS)

Motivation

Around 10% of the world's population relies on groundwater resources from karst aquifers¹. They are particularly common in the Mediterranean area. While their infiltration capacities are high, not much groundwater is stored in the long-term. Sophisticated management concepts are needed, as karst aquifers are becoming increasingly vulnerable with respect to quantity and quality. By 2040, temperatures in the Mediterranean region could increase by 2.2 °C compared to pre-industrial times, while increased evapotranspiration and reduced precipitation could decrease water availability by 2-15%². In addition, many Mediterranean regions (e.g., North Africa and Middle East) are experiencing a large population increase, further increasing the pressure on freshwater resources.

Objectives

MedWater studies the behavior of karst aquifers, investigates the impact of climate change and rising freshwater demands on groundwater resources, and develops strategies and tools for sustainable management. The primary study site is the highly karstified Western Mountain Aquifer (WMA) in Israel and the Palestinian Territories. Results are transferred to similar aquifers in Italy and France. On the global scale, we develop generalized models for karst aquifers with Mediterranean climates and estimate their exposure to groundwater stress and vulnerability to climate change. Our work contributes to achieving the UN's Sustainable Development Goals, particularly SDG 6 – universal and equitable access to clean water.

In MedWater, we simulate groundwater recharge and groundwater flow, develop a multi-objective optimization algorithm for groundwater management, quantify groundwater-dependent ecosystem services, and calculate virtual water imports and exports. A user-friendly Decision Support System processes modeling results for the WMA, incorporating climate projections and scenario analyses. By coupling numerical modeling with user-friendly tools,

we provide a solid knowledge base for decision-making in groundwater management.



The Western Mountain Aquifer in Israel and the Palestinian Territories

Key results

MedWater investigated various methods of calculating the spatial and temporal distribution of groundwater recharge in karst aquifers. With the Soil & Water Assessment Tool (SWAT), we determined a long-term average recharge for the WMA of 199 mm/a (1979-2019). The recharge zone plays an important role for ecosystem services and provides high surface water and groundwater regulation, water quality regulation, and protection of soils and sediments. Shifts in climate will affect both groundwater resources and ecosystem services. High-resolution (3km) climate projections show for the WMA's recharge zone until 2070 an increase of temperature

¹ 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>

² 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

by 2.1°C in winter and fall, while precipitation will decrease by up to 59% in the fall. Due to shifts in climate, mean annual groundwater recharge may decrease between 16% and 25% (1980-2000 vs. 2050-2070).

Identification of the karst conduit network was enabled using the Stochastic Karst Simulator (SKS)³ developed at the University of Neuchâtel, which computes karst structures based on paleoclimatic reconstructions of the Mediterranean Sea level and climate over the last 6 million years. Simulations show that the geometry of a karst network is highly controlled by the position of past karst springs. This “soft” information on karst development allows for the generation of a sound hydraulic parameter field.

With a multi-continuum model (HydroGeoSphere), we simulated the vadose zone dynamics together with the groundwater flow system. Scenario analyses explored the impact of pumping rate adaption and indicate an average groundwater level decline under a resource-intensive scenario by 7.8 meters over the next 25 years. However, a nature-conservation scenario suggests that groundwater levels could increase by 3.3 meters until 2050.

Agricultural food production is by far the highest water user in Israel. 1,806 million m³ of virtual blue water was used for crops consumed in Israel in 2005. Israel exported 132 million m³ of virtual blue water. This represented 11.3% of the total blue water used for Israel’s agricultural production. For local blue water consumption, wheat, apples, olives, and peaches are the highest water users, while potatoes, dates,

grapes, and olives are most water-intensive with respect to exports.

A Decision Support System (DSS) for the WMA includes results of the groundwater model, recharge estimates, climate projections, and scenario analyses. Employing analytical functions, the DSS simulates the aquifer response to changes of parameter sets or pumping rates. A multi-objective optimization (MOO) framework allows water users to test groundwater management strategies: Groundwater extraction and water injection wells are optimized with respect to demands (e.g., agricultural, municipal) and water sources (e.g., desalination, treated wastewater).

On the global scale, we created generalized models for different types of Mediterranean karst aquifers. Furthermore, a Groundwater Stress Index combines information about groundwater recharge and abstraction rates, as well as groundwater-dependent ecosystems, among other indicators. Analyzing 133 aquifers worldwide showed increased groundwater stress in Southern Spain and northwest Africa, parts of Greece, and the Middle East. We expect Mediterranean karst aquifers to be very vulnerable to climate change, as different aquifer types showed similar trends of higher Groundwater Stress Indices with higher temperatures and lower precipitation.

Our results are documented in **21 Technical Notes that are compiled in this report**. Each Technical Note can also be downloaded individually as a PDF on the MedWater homepage at <http://grow-med-water.de/home/index.php/products/>.

³ Borghi, A., Renard, P., & Jenni, S. (2012). A pseudo-genetic stochastic model to generate karstic networks. *Journal of Hydrology*, 414-415, 516-529. <https://doi.org/10.1016/j.jhydrol.2011.11.032>

Technical notes

GROUNDWATER RECHARGE

Groundwater recharge estimation for the Western Mountain Aquifer with the Soil & Water Assessment Tool Hydro-Pedo-Transfer Functions (HPTFs) for prediction of groundwater recharge in karst aquifers under Mediterranean climate

Development of a neural network to calculate groundwater recharge in karstified aquifers

Comparison of methods to calculate groundwater recharge for the karstic Western Mountain Aquifer

GROUNDWATER FLOW

A Karst Conduit Probability Map for the Western Mountain Aquifer using a stochastic modeling approach

Single-continuum MODFLOW model of the Western Mountain Aquifer

Variably saturated dual-continuum flow modeling to assess distributed infiltration and storage in the vadose zone

Comparison of modeling approaches for the simulation of surface and subsurface flow dynamics in complex fractured-porous karst aquifers

ECOSYSTEM SERVICES

Current and future ecosystem services provided by the Western Aquifer Basin

Quantification of ecosystem services flows to Israel

VIRTUAL WATER

Quantification of Israel's virtual water fluxes

Energy and carbon balance of Israel's domestic and imported virtual water supply

WATER MANAGEMENT

Comparison of 3km and 8km-resolution climate simulations with COSMO-CLM for the recharge zone of the Western Mountain Aquifer until 2070

Scenario analysis for the prediction of future groundwater resources in the Western Mountain Aquifer

Mooflow: A generalized framework for basin-scale multi-objective simulation-optimization with MODFLOW

Concept of a web-based Decision Support System and live-processing tool

GLOBAL APPLICATION

Characterization of the Mount Soprano-Vesole-Chianello karst aquifer in southern Italy for modeling groundwater recharge and flow

Impact of climate change on a Mediterranean karst aquifer under active management: the example of the Lez spring in southern France

Creating high-resolution land use and soil moisture maps from remote sensing data

Development of a classification scheme for carbonate aquifers in the Mediterranean region

Calculating groundwater stress of Mediterranean karst aquifers and estimating their vulnerability to climate change on a global scale



Groundwater recharge estimation for the Western Mountain Aquifer with the Soil & Water Assessment Tool

Key findings

- We applied the Soil & Water Assessment Tool (SWAT), which was originally developed for porous medium, to perform high-resolution recharge calculations for the karstified Western Mountain Aquifer (WMA).
- The WMA shows great spatial differences in groundwater recharge. The northern and western parts of the recharge area contribute most to total recharge.
- About 34% of annual precipitation enters the WMA as recharge.
- According to two climate projection models, groundwater recharge may decrease between 16% and 25%.

Motivation

Groundwater recharge is an essential component of groundwater simulations that serve as important assisting tools for management decisions. The accurate estimation of recharge is critical for sustainable water use on a catchment scale. Recharge calculations for the Western Mountain Aquifer (WMA) in Israel and the

West Bank have so far solely been based on empirical equations and therefore are limited in their spatial and temporal resolutions. Empirical equations calculate recharge of the entire aquifer by using monthly or annual means of precipitation data. With the Soil & Water Assessment Tool (SWAT; Arnold et al., 1998), we calculate the entire water balance for the WMA on a daily basis with a particular interest in determining groundwater recharge. The goal is to create an accurate model that shows the spatial and temporal distribution of recharge and is able to simulate the effects of extreme weather events.

Methodology

SWAT is a hydraulic-hydrological model that is based on empirical equations calculating the water cycle within a defined system. It can be used to assess water quantity and quality. Furthermore, SWAT can simulate the influence of different land use types on the hydrological cycle. For these calculations, SWAT requires specific information about soil properties, topography, vegetation, and land use in a watershed. This information serves to create Hydraulic Response Units (HRUs) in each sub-catchment. The characteristics of each HRU are combined with daily climate data (precipitation, max-/min- temperature, relative humidity,

solar radiation, wind) to calculate the water balance on HRU scale with empirical equations. SWAT calculates the actual evapotranspiration, surface and subsurface runoff as well as recharge to the deep aquifer. In addition to creating models on a large spatial extent, SWAT works over long periods of time with available climate data. Therefore, it is able to simulate long-term climate developments as well as single extreme weather events on the watershed, sub-basin, or HRU level.

Soil & Water Assessment Tool (SWAT)

The Soil & Water Assessment Tool (SWAT) calculates the water balance on a daily basis with spatial information about land use, soil properties, and topography, which form unique Hydrological Response Units (HRUs), and time-dependent climate data. The calculations are based on empirical equations and provide accurate data with high temporal and spatial resolutions. The SWAT model can be calibrated with any observed data such as surface runoff or actual evapotranspiration and adjusts sensitive parameters such as transmission loss.

Groundwater recharge estimation for the Western Mountain Aquifer with the Soil & Water Assessment Tool



Results

The problem of modeling a karst instead of a porous aquifer is solved by simulating influent conditions within the wadis. This models the fast flow component of karst aquifers, while the large-scale percolation covers the slow flow component. It was due to this addition that surface runoff after extensive rainfall events was able to decrease rapidly after calibration. The calibrated SWAT model shows high spatial variations of groundwater recharge in the model area, which covers around 80% of the WMA's recharge area (Figure 1). Overall, groundwater recharge shows similar trends as precipitation, which decreases with increasing elevation to the east and south. On average, 34% of precipitation in the recharge area contributes to groundwater recharge, while the rest evaporates or becomes surface runoff. SWAT calculates an annual average recharge of 199 mm. After calibration, we applied the SWAT model to predict future recharge rates based on climate projections with resolutions of 3x3 (unpublished) and 8x8 km (Hochman et al., 2018). In the long-term, as total precipitation decreases, we also observe a negative trend in recharge (Figure 2). According to the 8x8 km grid climate predictions, mean groundwater recharge in 2050-2070 is only 84% of the mean recharge in the period 1980-2000.

References

Arnold, J.G., Srinivasan, R., Muttiah, R.S., & Williams, J.R. (1998). Large area hydrologic modeling and assessment part I: Model development. *Journal of the American Water Resources Association*, 34(1), 73-89. <https://doi.org/10.1111/j.1752-1688.1998.tb05961.x>

Hochman, A., Mercogliano, P., Alpert, P., Saaroni, H., & Bucchignani, E. (2018). High-resolution projection of climate change and extremity over Israel using COSMO-CLM. *International Journal of Climatology*, 38(14), 5095-5106. <https://doi.org/10.1002/joc.5714>

The observed decrease for the 3x3 km grid climate predictions is with 25% even higher.

Application

Calculating recharge in a highly karstified aquifer is challenging but of great importance due to its comparatively lower storage potential. This makes karst aquifers highly vulnerable to potential decreases in precipitation and recharge caused by climate change. With SWAT, we were able to create the first high-resolution recharge map for the WMA. In

the future, the significance of each land use type could be investigated to provide more detailed management recommendations that help store water and slow down the rapid congregation and downstream flow after heavy rainfall events, which will intensify according to the climate models. Awareness of a possible recharge deficit is important to adjust future pumping rates. In addition, alternative freshwater sources should be identified to limit water stress in Israel and the West Bank.

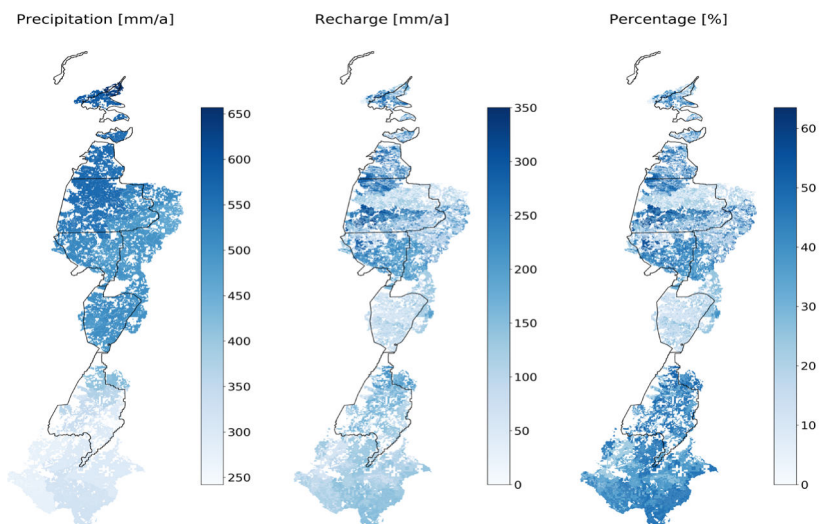


Figure 1: Annual means of precipitation, recharge, and the recharge/precipitation ratio on HRU level for 1990-2018

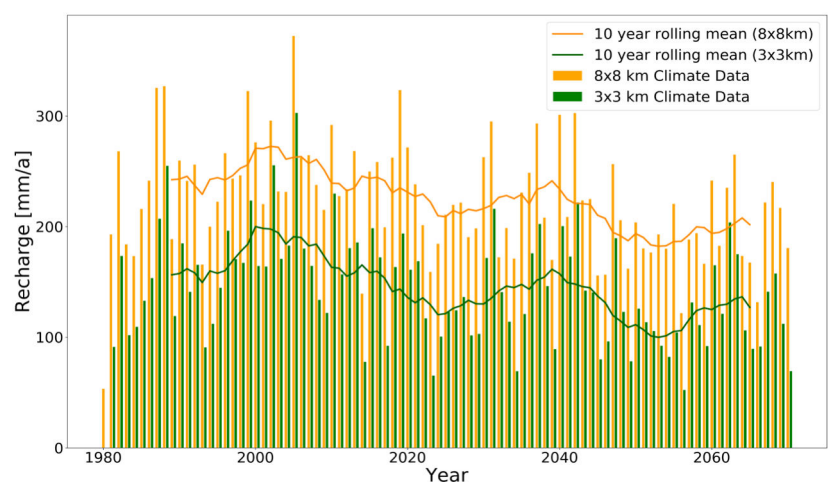


Figure 2: Recharge projections based on 8x8 km and 3x3 km grid climate models. The additional line graphs show the 10 year rolling means.

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Hydro-Pedo-Transfer Functions (HPTFs) for prediction of groundwater recharge in karst aquifers under Mediterranean climate

Key findings

- Mean annual percolation in the study area is primarily dependent on precipitation and potential evapotranspiration and only then determined by land cover and soil properties.
- The application of HPTFs to karst aquifers indicates that the functions cannot capture the rapid flow component of percolation and consequently underestimate recharge.
- However, if this rapid flow component is available from other models, the association with infiltration data from HPTFs yields suitable results for groundwater recharge estimations.

Motivation

Groundwater resources are crucial for the supply of freshwater in the Mediterranean region. Understanding the processes that control groundwater recharge is of vital importance to meet present and future challenges. Especially in karst systems, recharge processes are complex and diverse. This study quantifies groundwater recharge for the Western Mountain Aquifer (WMA) in Israel and the West Bank by extending the application of Hydro-Pedo-Transfer Functions

(HPTFs) to the Mediterranean climate and karst aquifers. So far, their application is limited to the Continental European climate. Mediterranean climate in contrast is characteristic of two distinct seasons: hot, dry summers and mild, rainy winters. In addition, soil cover and vegetation patches on karst surfaces are highly variable. These aspects are expected to have considerable effect on infiltration and the replenishment of karst aquifers. Only limited input data is required when applying HPTFs. Thus, the functions can be used despite possible data scarcity.

Methodology

The recharge area of the WMA is the model area of this study. HPTFs are based on annual calculations of

the water balance in flat topography. The functions depend on the type of land cover and account for annual and seasonal precipitation, potential evapotranspiration, and soil water in the effective root zone. These parameters are correlated within a Geographic Information System (GIS) before applying them to the empirical functions (Table I). Remote sensing and global data sets are being used, which are most feasible for providing temporally and spatially continuous information when working on a regional scale. Precipitation patterns in the Mediterranean climate are subject to a high natural variability, and extreme values of evapotranspiration exceed rainfall during most days. The application of HPTFs to groundwater-recharge estimations in the study

Table I : Applied HPTFs in the study area to predict annual percolation rate (D_a) for four different types of land cover after Wesolek et al. (2008) with P_a : annual precipitation, PET: potential evapotranspiration, W_a : plant-available soil water in the effective root zone, and P_s : precipitation during the vegetation growth period. Capillary rise (Q) is set to zero in the study area due to groundwater tables far below the root zone.

Cropland

$$D_a = P_a - PET (1.45 \log (W_a + Q + P_s) - 3.08) (0.685 \log (1/PET) + 2.865)$$

Grassland

$$D_a = P_a - PET (1.79 \log (W_a + Q + P_s) - 3.89) (0.53 \log (1/PET) + 2.43)$$

Forest

Coniferous:

$$D_a = P_a - PET (1.68 \log (W_a + Q + P_s) - 3.53) (0.865 \log (1/PET) + 3.36)$$

Deciduous:

$$D_a = P_a - 0.9 PET (1.68 \log (W_a + Q + P_s) - 3.53) (0.865 \log (1/PET) + 3.36)$$

Hydro-Pedo-Transfer Functions (HPTFs) for prediction of groundwater recharge in karst aquifers under Mediterranean climate



Hydro-Pedo-Transfer Functions (HPTFs)

Hydro-Pedo-Transfer Functions (HPTFs) were first introduced by Wessolek et al. (2008) following Lin's (2003) "Hydropedology" approach – the integration of methods from soil, plant, and water science. HPTFs predict annual percolation rates on a regional scale under various types of land cover including cropland, grassland, and coniferous and deciduous forests. The empirical functions are based on the water budget equation and account for annual precipitation, potential evapotranspiration, soil properties, and vegetation.

area is limited to the winter months (Dec.-Feb.), when 60 to 90% of annual rainfall occur. The study period is set from 2001 to 2015 due to the availability of consistent datasets. The soil properties for this time are considered unchanging.

Results

The spatial and temporal distribution of percolation in the recharge area of the WMA is calculated for each grid cell (500x500 m resolution) and visualized in annual percolation maps (Figure 1). The functions predict a mean annual percolation of 72 mm, representing on average 19% of the mean rainfall from December to February and 15% of the long-term mean annual rainfall. Previous studies estimate recharge to be 25-35% of the mean annual precipitation for average years. The calculated infiltration values for each cell are summed up over the entire model domain to obtain annual groundwater recharge values. HPTFs assume a spatially uniform replenishment of the aquifer and that all water that passes the root zone reaches the groundwater

reservoir. The resulting estimates are shown in Figure 2. Recharge estimates from given spring discharge and pumping rates are also depicted for validation. Mean annual recharge is estimated at 94 Mm³ compared to 355 Mm³ of spring discharge and pumping rates. It is evident that the total amount of recharge is highly underestimated. High-intensity rainfall events, frequently occurring during the rainy season, may rapidly infiltrate into exposed karst surfaces and induce high recharge. Averaging over longer time periods clearly dampens out these effects.

Application

This study estimates the mean annual percolation in the WMA's recharge area and its spatial distribution using HPTFs. It shows that the functions are not able to capture the rapid flow component, highly relevant for infiltration in karst, and thus underestimate recharge. Field investigations of topographic features such as sinkholes or highly fractured zones might enable the adaptation of the functions in certain areas to

account for rapid flow components of recharge in karst groundwater systems. An accurate estimation of actual evapotranspiration is of key importance. Additionally, the characteristics of Mediterranean climate (distinct dry and wet seasons) challenge an application of HPTFs for long time periods. The feasibility of water budget approaches in semi-arid regions is subject to ongoing research.

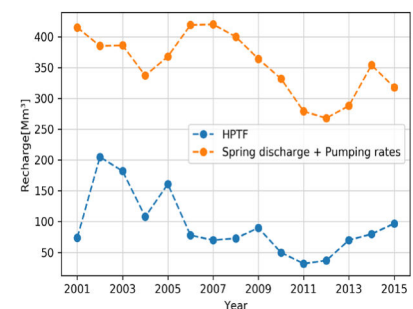


Figure 2: Estimated groundwater recharge for the WMA using HPTFs (mean: 94 Mm³) in comparison to available pumping rates and data on spring discharge (mean: 355 Mm³). Recharge predictions are highly underestimated, indicating that the functions are not able to capture the rapid flow component of infiltration in karst.

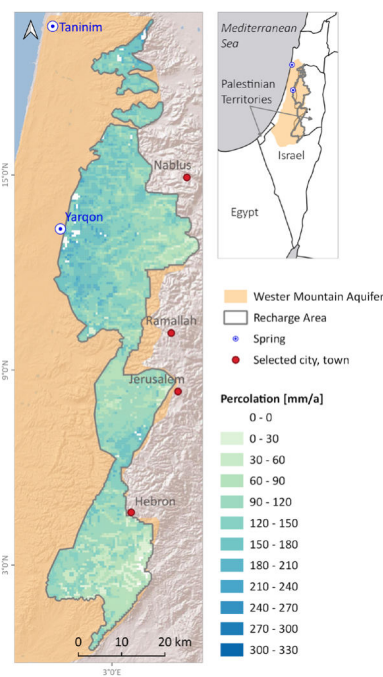


Figure 1: Spatial distribution of mean annual percolation in the WMA's recharge area in 2002. A general north to south trend of decreasing percolation is caused by a strong gradient in precipitation. Zero percolation (white grid cells) is indicated in the urban metropolitan region of Tel Aviv-Yafo. Resolution: 500x500 m.

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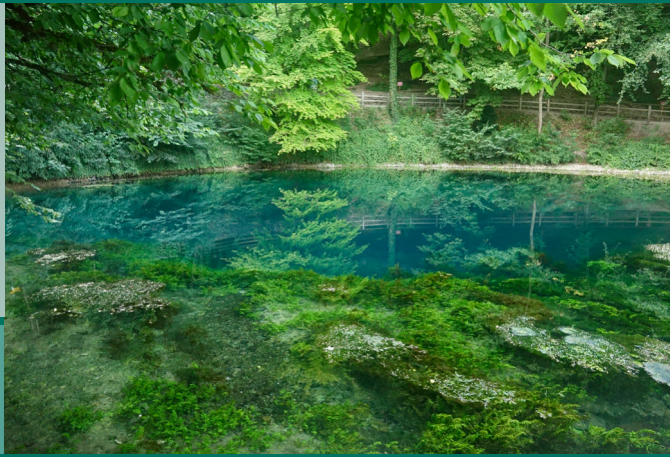
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Development of a neural network to calculate groundwater recharge in karstified aquifers

Key findings

- Neural networks have successfully been applied to model groundwater recharge with satisfactory accuracy despite using no hydrogeological data or knowledge about the karst aquifer.
- Common network architectures were determined that can model the hydraulic behavior of two different karst aquifers (the Lez and Gallusquelle catchments), despite them being vastly different.
- Based on the results, it was possible to make assumptions about some karst characteristics.

only with high uncertainties) due to the lack of data. As neural networks do not need such data or system knowledge, they present a great alternative to numerical modeling approaches. We utilize a machine-learning approach to model the groundwater recharge of karst systems, for which little to no prior information is available, apart from a spring discharge time series, which is used as a proxy for recharge. Two vastly different karst systems were investigated for that purpose: the Lez spring catchment in southern France and the Gallusquelle spring catchment in southern Germany. The goal is to create one neural network that satisfactorily models the spring discharge for both systems.

Methodology

It was decided to only use a bare minimum of data: meteorological data and pumping data. Several different processing techniques, input parameter combinations, and network architectures were investigated to see if they 1) improve the performance and 2) show differences between the two systems, therefore allowing for a characterization of the karst aquifers. Figure 1 shows the conceptual workflow. First, missing or unusable values were dropped, missing parameters (snow accumulation/melt) were

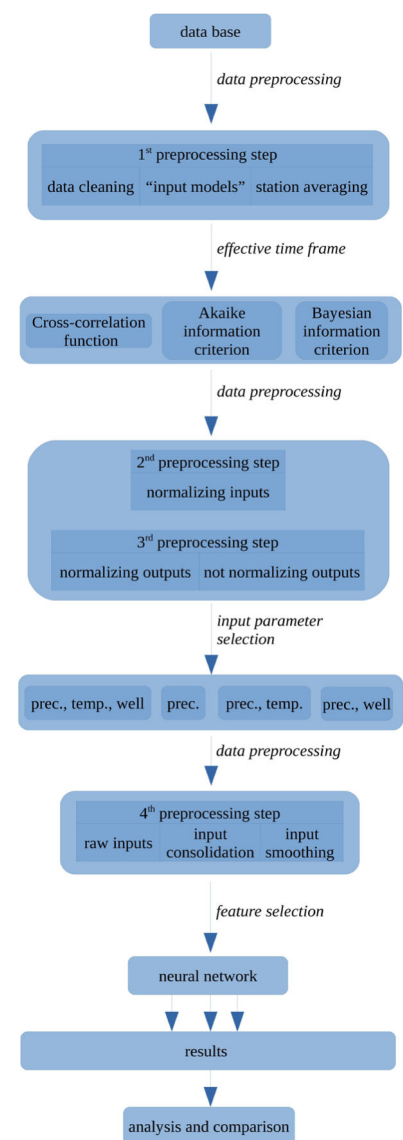


Figure 1: Conceptual depiction of the workflow

Motivation

The two major problems when modeling karst aquifers are the lack of hydrogeological data as well as insufficient knowledge about the system geometry and physics, which are usually more complex for karst aquifers. As the groundwater hydraulics and therefore the recharge depends on data such as hydraulic conductivity, storage, conduit distribution, or conduit apertures, which are all difficult to determine, many models are not applicable (or

Development of a neural network to calculate groundwater recharge in karstified aquifers



modeled, and station measurements were spatially averaged. Then, the effective time frame (i.e., which precipitation events contribute to a single discharge event) was determined using three different approaches (cross-correlation function and Akaike/Bayesian information criterion). After normalizing the inputs/outputs, it was decided which parameters should be used as input (all parameters, only precipitation, etc.). Finally, the inputs were either used as they were or were consolidated or smoothed. These inputs were then fed to neural networks with different architectures. The networks themselves were built using Keras libraries (<https://keras.io/>), which allow for a sequential and therefore easy setup. The results were then analyzed and compared.

Results

The neural networks were able to model spring discharge with satisfactory accuracy, even though no prior knowledge about the systems or any hydrogeological data were integrated in the model. Figure 3 shows the results for the Gallusquelle spring. For the Lez spring, the network had difficulties to reproduce discharge during times of

Neural networks

Neural networks are part of machine-learning and can be seen as complex, nonlinear function fitting tools. Therefore, they need known input/output data pairs to be trained. They consist of several layers (Figure 2), and each layer is composed of neurons. In the input layer, these neurons represent the given inputs. For the following layers, they represent functions. In the end, these functions are combined into one big function, which represents the relationship between inputs and output.

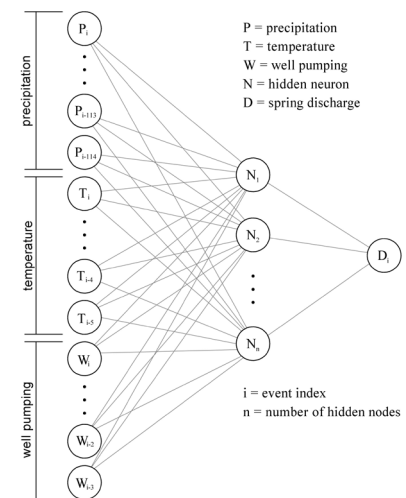


Figure 2: Conceptual neural network for the case that precipitation, temperature, and well pumping are considered as input parameters

storage release and recharge, which is due to the fact that the spring regularly falls dry and is only fed by an artificial, redirected stream from the pumping in these cases. Overall, the relative deviation of the yearly mean discharge rate was +2% for the Lez and -4% for the Gallusquelle spring. It was also possible to determine neural network architectures that are able to reproduce the discharge behavior of both systems in a satisfactory manner, therefore indicating good generalization capa-

bilities and potential for transfer to other karst systems. Based on the intermediate results from the data processing steps and the results of the different network approaches, it was possible to make assumptions about some karst characteristics such as the degree of karstification.

Application

The presented approach can be utilized to model groundwater recharge in karst systems where only little (or even no) prior hydrogeological investigations have been conducted. It is also an effective tool in cases, where data acquisition by field investigations would be economically unfeasible. However, this approach can only be utilized if long time series for spring discharge and meteorological data are available. Furthermore, it is not applicable in cases where forecast conditions vastly differ from the conditions, for which the network was trained. For example, a network that was trained without pumping conditions cannot be used to model the recharge with pumping conditions.

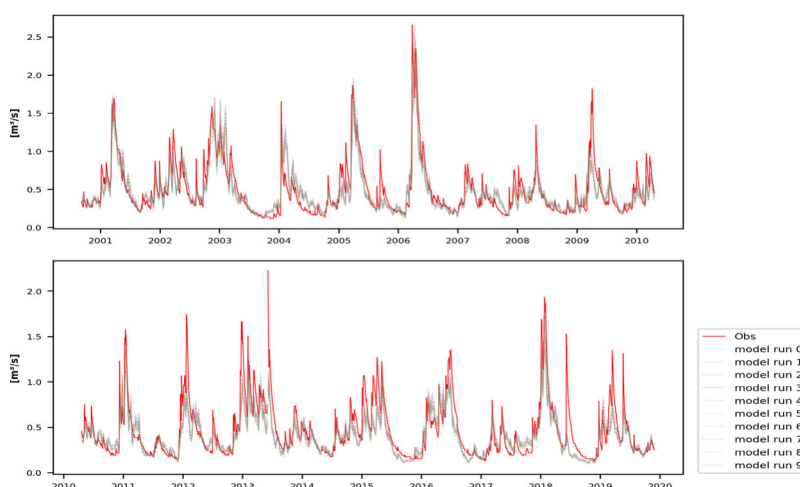


Figure 3: Observed and modeled spring discharges for the Gallusquelle spring

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Comparison of methods to calculate groundwater recharge for the karstic Western Mountain Aquifer

Key findings

- We calculate groundwater recharge for the Western Mountain Aquifer with the Soil & Water Assessment Tool (SWAT) and a soil water balance model (SWBM). The results are compared with two established empirical methods by Zukerman (1999) and Abusaada (2011).
- While Zukerman and the SWBM calculate higher recharge in wet years, Abusaada and the SWAT model calculate higher recharge in years with average to low precipitation.
- The estimated average annual recharge ranges between 30% (SWBM) and 34.7% (Abusaada) of annual precipitation.

Motivation

Recharge is the most important input factor of groundwater models. It occurs in the outcrops of the karstic Western Mountain Aquifer (WMA) in Israel and the West Bank at different rates due to a dual-type flow system comprising conduit flow (fast flow component) and diffuse infiltration (slow flow component). Recharge is not only determined by surface pro-

perties but also by the distribution of precipitation throughout the year. The Soil & Water Assessment Tool (SWAT) addresses this problem and calculates daily recharge rates on a small spatial scale. A similarly high spatial and temporal resolution can be achieved with the application of a soil and water balance model (SWBM). Standard empirical equations are used traditionally to calculate recharge with one set of equations without considering spatial differences or the influence of extreme weather events. Here, we compare the recharge estimates from a SWAT model and a SWBM to those calculated with two established empirical methods.

Methodology

Recharge estimates from a SWAT model were compared to recharge rates calculated with the empirical methods by Abusaada (2011) and Zukerman (1999). While SWAT calculates the water balance with daily climate data and therefore takes into account the influence of extreme precipitation events and potential over-saturation of the soil, the empirical methods only use monthly (Abusaada) or annual (Zukerman) precipitation amounts. As Abusaada assumes that recharge occurs mostly during the wet months of November – March, he specifically

developed a set of equations for these months. Zukerman on the other hand developed equations for different annual precipitations, assuming the percentage of precipitation resulting in groundwater recharge increases with greater annual precipitation. In addition, we applied a SWBM by Schmidt et al. (2014) to calculate the percolation at the zero-flux plane with soil water balance equations. The method uses the same temporal and spatial distribution as the SWAT model and the same precipitation and potential evapotranspiration data. Recharge is calculated for the hydrological year September – August and based on the same climate data (Israel Meteorological Service (IMS)).

Recharge estimation

Recharge rates for the WMA are estimated with different methods: empirical equations by Zukerman (1999) and Abusaada (2011) as well as a SWAT model and a SWBM. While the empirical methods only use monthly or annual precipitation data averaged over the entire recharge area, SWAT, for example, requires additional information about temperature, solar radiation, relative humidity, and wind velocity as well as soil and topography.

Comparison of methods to calculate groundwater recharge for the karstic Western Mountain Aquifer



Results

The recharge comparison for the period 1979-2019 shows an average annual recharge of 173-201 mm per year (Table 1). The percentage of mean annual precipitation (576 mm) resulting in groundwater recharge is between 30 and 34.7%. The highest recharge is calculated with Abusaada's equation and the SWAT model, while the SWBM calculates the lowest recharge. Figure 1 shows the annual precipitation and recharge calculated with the four methods. During the extremely wet years 1991, 1992, and 1994, Zukerman's equation and the SWBM calculate the highest recharge, while they underestimate recharge during years with average precipitation compared to Abusaada. For wet years, the SWAT model and Abusaada's equations do not calculate the high peaks found in the Zukerman and SWBM results. The extremely dry years of 1999 and 2017 on the other hand resulted in below-average recharge calculated with Abusaada's equation and the SWAT model. Overall, the SWAT model shows the same correlation between annual precipitation and recharge as Abusaada's equation, while the SWBM and Zukerman's equation provide similar results (Figure 2).

Application

Calculating recharge in a highly karstified aquifer is challenging but of great importance due to its comparatively lower storage potential. This makes karst aquifers highly vulnerable to potential decreases in precipitation and recharge caused by climate change. Identifying and applying the most accurate method for recharge estimation is very important for future management of the Western Mountain Aquifer and to better assess the volume of stored water. All compared methods

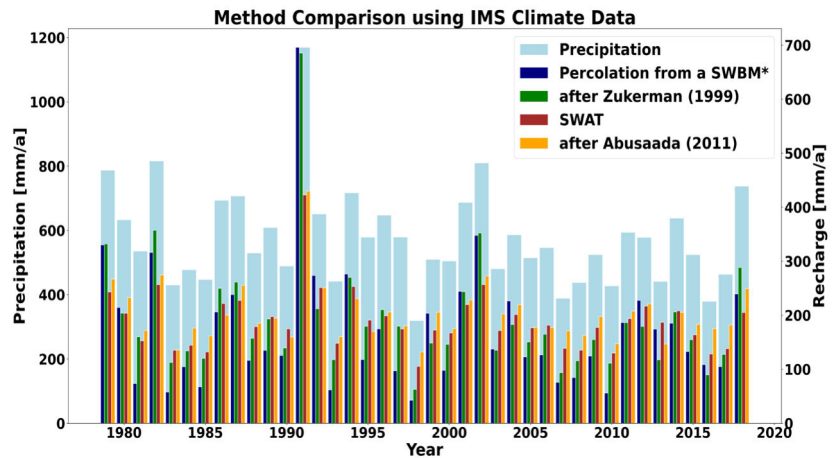


Figure 1: Precipitation and recharge from 1979-2018. *SWBM: soil water balance model.

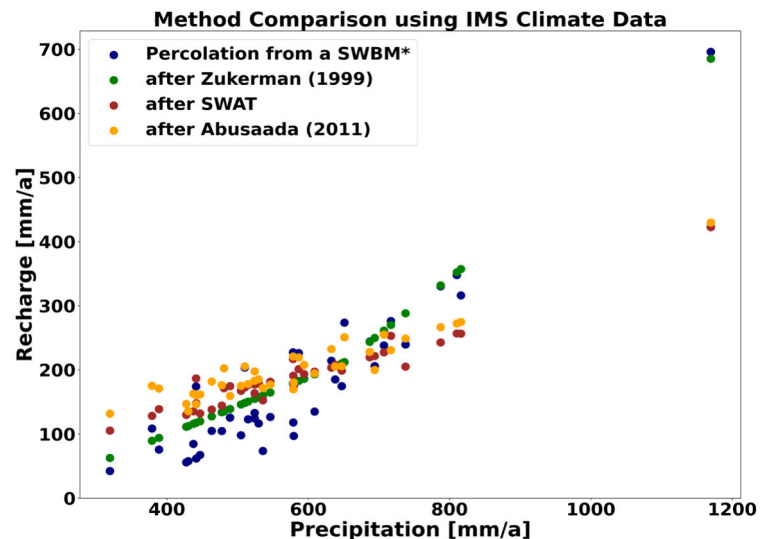


Figure 2: Scatter plot of annual precipitation and recharge. *SWBM: soil water balance model.

Method	mm/a	Mm ³ /a	%
SWAT	199	360	34.5
SWBM	173	314	30,0
Abusaada	201	364	34.7
Zukerman	192	348	33,2

have benefits: While the equations by Zukerman and Abusaada are easy to apply, the spatial and temporal distribution of recharge is only simulated with SWAT and the SWBM. This can be a major benefit for regional management purposes.

Table 1: Average annual recharge in mm/a, Mm³/a, and in % of average annual precipitation

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A Karst Conduit Probability Map for the Western Mountain Aquifer using a stochastic modeling approach

Key findings

- A stochastic approach enables an analysis of the uncertainty of generated karst conduit networks based on a Karst Probability Map.
- Simulations based on a conceptual model of aquifer genesis show that the geometry of conduit networks is highly controlled not only by the position of present karst springs but also by spring locations during past geological ages.
- Soft information on karst development allow for the generation of a sound hydraulic parameter field, which can be implemented in numerical groundwater models.

Motivation

Most of the groundwater flow in carbonate rock occurs in conduits. Due to the complex structure of these conduit networks, the prediction of groundwater flow in carbonate aquifers is challenging. Yet, covering extended areas of Earth's continental surface, they host major groundwater resources and call for sustainable aquifer management strategies. Hence, understanding the governing hydrological processes is of vital importance.

Simulator (SKS) is a stochastic model to generate karst conduit networks. This study generates multiple runs of the SKS to create a Karst Probability Map for the Western Mountain Aquifer (WMA), a highly karstified and exploited carbonate aquifer in Israel and the West Bank. The method is numerically efficient, and its inputs can be easily adjusted. This makes the SKS algorithm a useful tool to rapidly test and adapt different hypotheses of karst aquifer genesis. The resulting Karst Probability Map can be input to hydrological numerical groundwater models, which require a sound representation of the governing processes in karst systems.

Methodology

Application of the SKS algorithm requires the development of a conceptual model of the aquifer's karst genesis. Soft information from this conceptual model, such as karstifiable formations or identified present or past inlet (dolines or swallow holes) and outlet (springs) locations, are used as input to the SKS. The method itself is based on four main steps, as summarized in the Box. Multiple runs of the SKS are applied to create a 2D Karst Probability Map. In each run, the location of inlets for the WMA is determined randomly within the aquifer's recharge zone due to the lack of field infor-

mation about individual inlets. Outlet locations are equally randomly generated within given bounds based on the karst genesis model and its different phases of karstification.

Results

Figure 1 presents the conceptual model of the WMA's karst genesis. Three different phases of karstification are identified. During phase 1, a paleo-discharge zone exists, located close to the present-day coastline of Israel. In phase 2, which represents a period of extremely low sea levels during the Messinian Age

Stochastic Karst Simulator (SKS)

The "Stochastic Karst Simulator" (SKS) developed by Borghi et al. (2012) is a stochastic modeling approach to generate 3D karst conduit networks. The SKS approach consists of the following steps: (1) building a three-dimensional conceptual geological model focused on the main hydro-stratigraphic units, (2) adding information about structural elements (faults and fractures), (3) identifying the location of possible recharge and discharge locations in recent times and past geological ages, and (4) simulating the karst conduits.

A Karst Conduit Probability Map for the Western Mountain Aquifer using a stochastic modeling approach

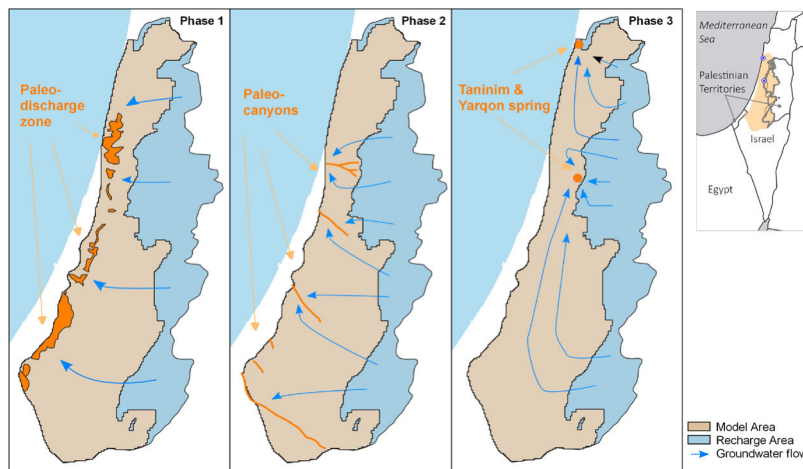


Figure 1: Conceptual model of the WMA's karst development. Identified phases of karstification: 1 - Paleo-discharge zone, 2 - Paleo-canyons, and 3 - Modern-day conditions.

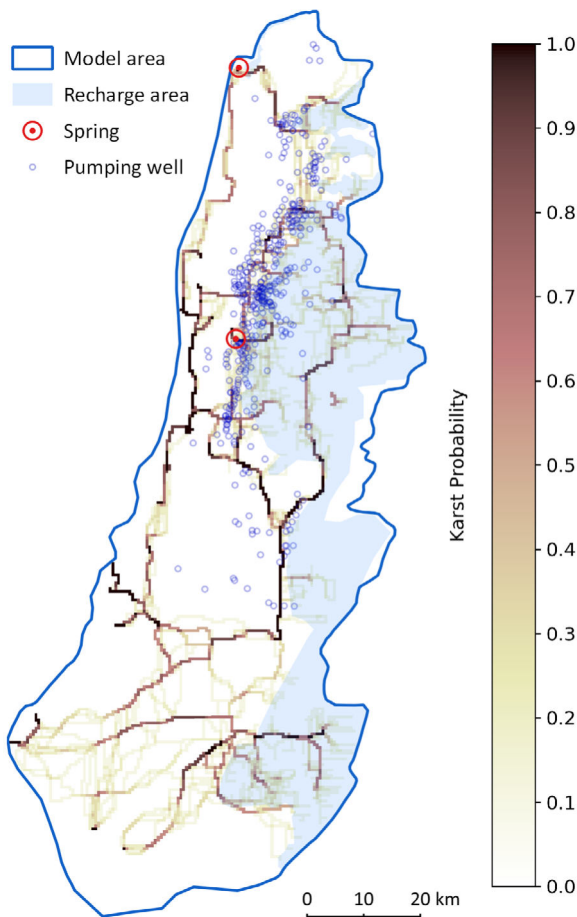


Figure 2: Resulting Karst Probability Map of the WMA, showing the spatial distribution and probability of the generated conduit networks in the model area

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(around 5 million years before present), paleo-canyons formed along this coastline, providing discharge points for the WMA. Phase 3 shows the modern-day outlets of the aquifer: the Yarkon and Taninim springs. The resulting Karst Probability Map for the WMA, composed of multiple runs of the SKS, is presented in Figure 2. The location of the most productive pumping wells in the region are also depicted, assuming high yield due to high karstification in these areas. Two apparent trends in the orientation of the network itself are identified: 1) conduits extending east to west, from the recharge area to the present-day coastline of Israel, and 2) conduits extending south to north towards the present-day spring locations. Many of the S-N trending conduits branch off from pre-existing E-W trending conduits. The iterative approach of the SKS algorithm allows to account for these trends in agreement with the 3-phase karst development in the WMA.

Application

The SKS algorithm is a useful tool to test different hypotheses of karst genesis and to understand the evolution of karst network geometries. Otherwise unavailable spatial information about the geometry and distribution of karst conduit networks, especially in areas the size of the WMA model area (ca. 6000 km²), is made accessible with the presented simulations. The stochastic approach also enables users to investigate the uncertainty of generated networks in the form of a Karst Probability Map. It allows for the generation of a hydraulic parameter field after expanding the map into 3D, which can then be implemented into a numerical groundwater model.

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Single-continuum MODFLOW model of the Western Mountain Aquifer

Key findings

- The complex geological system of the karstified Western Mountain Aquifer (WMA) was simplified in a single-continuum MODFLOW model.
- The model accurately simulates the extensive exploitation of the WMA and the drying out of the historically most productive Yarkon spring.
- Due to great spatial differences in hydraulic conductivity, areas with a higher/lower density of conduits can be isolated.
- The model shows quick responses of the aquifer to external factors such as seasonal differences in recharge.

Motivation

The Western Mountain Aquifer (WMA) is Israel's most important groundwater source and has been heavily exploited since the early 1950s. The aquifer experiences significant changes in the pressure head throughout the seasons and long-term changes caused by wet or dry years. These quick responses of the aquifer to climatic changes can cause water shortages if not addressed early on. Sustainable aquifer management can be supported by hydrogeological modeling. We crea-

ted a fully calibrated MODFLOW model (Harbaugh, 2005) that can simulate groundwater flow in the WMA. In addition, the model simulates possible future water stress by integrating the results of high-resolution projections of climate and groundwater recharge until 2070. A good management plan can adjust groundwater extraction, i.e. pumping rates, before shortages even appear.

Methodology

The necessary files for the MODFLOW model were prepared in python scripts, where the geometry of four georeferenced layers forms two confined aquifers divided by a semi-conductive aquitard. Each formation has specific initial hydraulic properties within defined zones that stretch mostly from north to south. These zones were defined with regard to the great drop of hydraulic head around faults and the mountains of the recharge area as well as increased transmissivities measured in boreholes. After the geometry of the model was set up, the boundary conditions of pumping wells, springs, groundwater recharge in the outcrops of the WMA, and the saline intrusion near the Taninim spring were added to account for temporal changes in the system. The model implements the recharge calculations by a SWAT-model from 1979-2019,

MODFLOW

MODFLOW is a finite difference model (Harbaugh, 2005) that is able to simulate the groundwater flow process through an aquifer. It was developed and has been updated since the 1980s by the United States Geological Survey (USGS). It is a single-continuum model that is suitable for applications to karst aquifers.

previous years are simulated with recharge rates calculated by Abusaada (2011). The groundwater model can run in the steady-state and transient mode. Calibration of the model was done with PEST, an object-oriented parameter estimation code.

Results

The complex karst aquifer can be modeled as a single continuum in MODFLOW if enough zones are delineated. The fast flow component of karst aquifers occurring in conduits cannot be accurately simulated due to the limitations of the software, but high transmissivities can be achieved well. The calibrated pressure head shows the same trends and water table as the observed values. Figure 1 compares the observed and simulated head at selected observation wells across the confined upper aquifer for the period 1970-2019. From 1990 to 1995, the selected observation wells

Single-continuum MODFLOW model of the Western Mountain Aquifer



show an increase of pressure head due to the extremely wet year 1992. The seasonal change on the other hand is visible in the fluctuation of the pressure head, which is the strongest in the confined area of the north-west lowlands and an indicator of the storage capacity and temporal differences in groundwater recharge. In recent years, simulated and observed observation wells show different trends. The increase in simulated pressure head is caused by the Israeli pumping rate reduction of $\sim 100 \text{ Mm}^3/\text{a}$. Assuming the groundwater recharge is simulated correctly as before, additional water must be extracted that is currently unaccounted for.

Application

The MODFLOW model will help to make educated management decisions to reduce water stress by avoiding overexploitation and preparing for future changes caused by less annual precipitation and therefore reduced groundwater recharge. Figure 2 shows a nature conservative scenario with a reduction of pumping rates to 80% of the 5 year mean recharge, which would guarantee that groundwater levels stay above the red lines. The model can also help to find unnoticed water abstractions as shown above. A Karst Probability Map developed with the Stochastic Karst Simulator can be implemented in the model to increase the accuracy and provide information about the karst network and its state. This additional information will help to simulate the aquifer's fast flow component. The calibrated MODFLOW model is used as the basis for a Multi-Objective Optimization framework and a Decision Support System for the WMA.

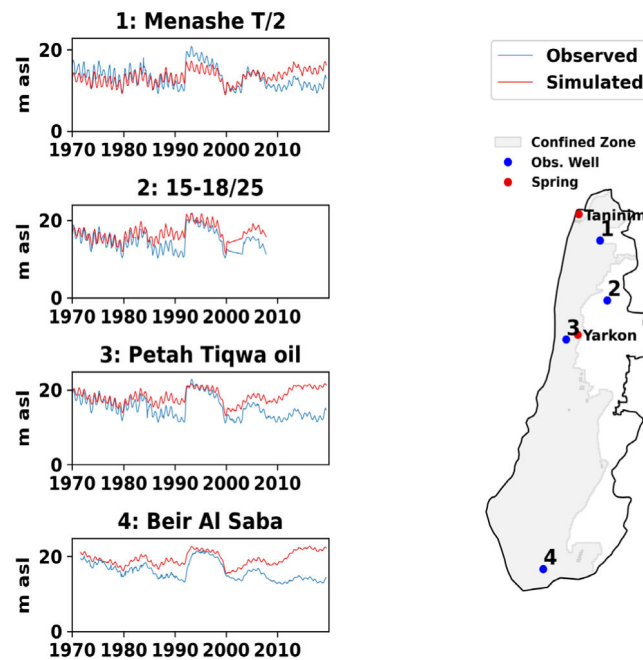


Figure 1: Comparison of the simulated and observed pressure head at selected observation wells across the confined upper aquifer

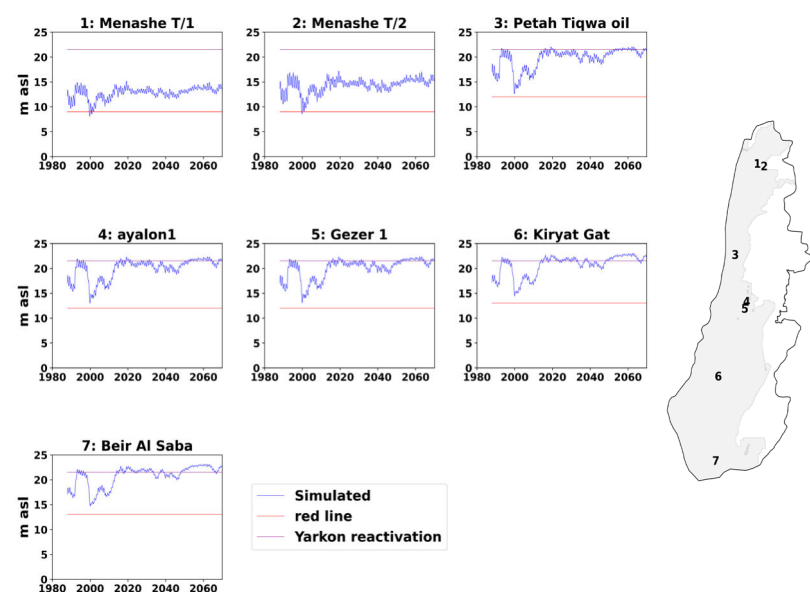


Figure 2: Selected simulated observation wells until 2070, compared with the Hydrological Service's corresponding red lines for maximum pumping

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Variably saturated dual-continuum flow modeling to assess distributed infiltration and storage in the vadose zone

Key findings

- We simulate flow in the variably saturated fractured-porous subsurface, accounting for the storage capacity of a several hundred meters thick vadose zone and the duality of karstic flow in the vadose and phreatic zone.
- The model demonstrates that altered precipitation patterns due to climate change require careful adaptation of water management practices to account for the complex interaction between rapid infiltration and long-term groundwater storage patterns.
- Modeling spatially distributed dynamics at sufficiently high temporal resolution and in the context of climate change simulations on a catchment scale requires substantial computational power and a parallelized computing environment.

Motivation

Climate change is expected to significantly impact water resources in Mediterranean karst aquifers due to the expected overall decrease in average precipitation depth, while the intensity and frequency of short-duration extreme rainfall might increase. The reduced total

annual precipitation may not necessarily decrease recharge since karst features, such as dolines and dissolution shafts, provide high infiltration capacities, reducing the total volume of water exposed to evapotranspiration. With its expected large variability in recharge and its complex geometric structure and hydraulic properties, the management of the Western Mountain Aquifer (WMA) in Israel and the West Bank requires appropriate management strategies and therefore adapted groundwater modeling tools. The main objective of this subproject is to simulate the temporal and spatial discharge dynamics of the WMA taking into account the storage properties of the phreatic and vadose zones as well as the geometric and hy-

draulic characteristics of the karst system, composed of a draining conduit network and the adjacent porous matrix storage system.

Methodology

We employ the parallelized flow simulator HydroGeoSphere (HGS) on a high-performance-computing platform to simulate transient, variably saturated water flows on the catchment scale. A double-continuum approach based on the volume-effective Richards equation with Van-Genuchten parameters is applied to simulate flow in the variably saturated fractured/karstic-porous subsurface (Figure 1b), accounting for the duality of karstic flow, both in the vadose and phreatic zones, with rapid flow

a) Soil water balance model:

b) Subsurface model:

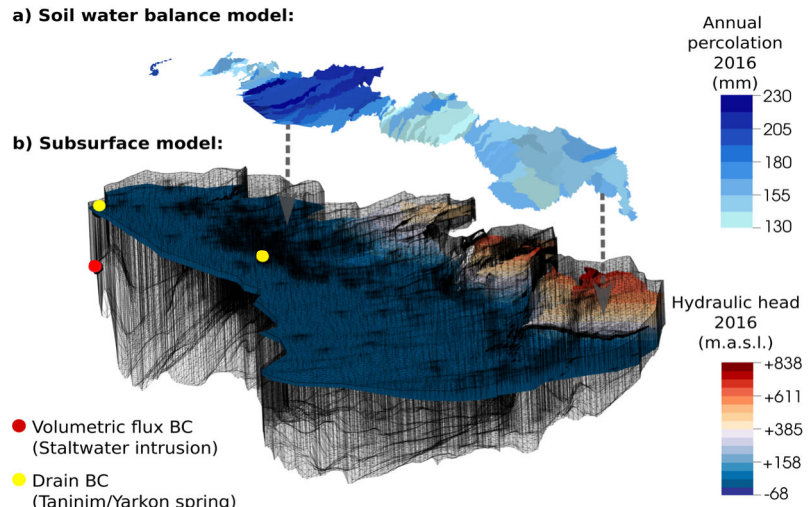


Figure 1: Spatial discretization and simulation results for the year 2016

Variably saturated dual-continuum flow modeling to assess distributed infiltration and storage in the vadose zone



HydroGeoSphere (HGS)

HydroGeoSphere (Aquanty Inc., 2019) is a three-dimensional, physics-based, integrated surface-subsurface, multi-continuum flow simulator that can be run on parallelized high-performance-computing platforms, facilitating the computation of large-scale complex representations of catchments. It simultaneously solves the 2D overland flow and 3D subsurface equations, allowing rainfall to partition into overland flow and dual-continuum infiltration naturally.

through conduits and slow flow through the rock matrix. We apply optimized unstructured triangular meshes with refinement near wells, streams, and springs to deal with the high computational demand and potential numerical convergence issues. We compute daily infiltration at the level of the Zero-Flux-Plane as input a priori by a semi-distributed water balance model (Schmidt et al., 2014). This model considers separate soil moisture balances for two types of “soils”, actual soil and bare carbonate rock, with the relative areal proportions controlling the relative contributions to overall infiltration input. We calibrated the soil moisture balance model spatially distributed on sub-basin level.

Results

With the ability to simulate rapid infiltration, the change in storage in the vadose and the phreatic zone, and the characteristics of the karst system dynamics, the constructed flow model has considerable advantages compared to currently available models, providing Israeli stakeholders with the option of predicting spatiotemporally distributed groundwater recharge, i.e., the available groundwater for sustainable abstraction. The non-linear response of groundwater recharge to transient climatic inputs requires a daily resolution for the analysis. The recharge area comprises a thin cover of soil and bare karstified carbonate rock, providing fast, direct infiltration pathways along karst features (e.g., sinkholes and dolines). In the hilly regions towards the East, the vadose zone displays a thickness of several hundred meters, emphasizing the importance of variably saturated flow and the evaluation of spatiotemporally distributed recharge to quantify the impact of climate change on groundwater resources. Lastly, the flow model provides insight into the infiltration dynamics at the catchment scale, i.e., mean residence times in the vadose zone characterized by a potential-dependent exchange between slow/diffuse and fast flow system, hence the ability to control the long-term release of water.

Application

The flow model exhibits a new level of detail with respect to modeled processes and spatial information, increasing predictive power considerably. The tool will assist the local water authority in adopting strategies to plan abstraction within a 5-year window accounting for changed recharge dynamics following climate change effects on precipitation patterns. However, due to its nonlinear constitutive relationship, the Richards equation only applies on specific spatial length scales, and since the process described is capillary driven, it neglects gravity-driven infiltration. The developed model allows for a number of follow-up studies, such as the prediction of flood routing, flood-runoff forecasts in wadis, the quantification of the relevance of channel infiltration along the wadi courses, i.e., direct groundwater recharge, the quantification of the relevance of vadose zone storage, or the improvement of process understanding for Managed Aquifer Recharge applications.

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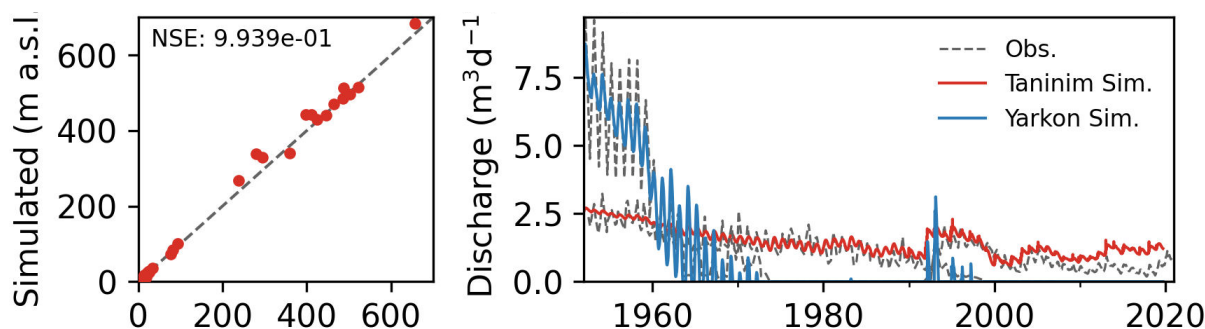


Figure 2: Calibration of the a) steady-state and b) transient, variably saturated dual-continuum flow model

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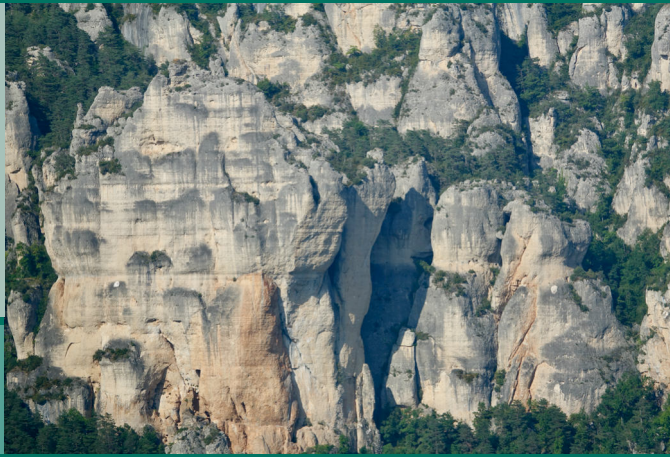
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Comparison of modeling approaches for the simulation of surface and subsurface flow dynamics in complex fractured-porous karst aquifers

Key findings

- We compare two numerical flow models for the computation of groundwater storage dynamics to assess their ability to resolve the complex process spectrum and hence their specific predictive power with respect to available water resources.
- All numerical models are subject to a trade-off between predictive power and efforts to reduce parametric ambiguity and structural uncertainty.
- The appropriate level of model complexity is determined by the availability of field data and the type of problem to be solved, demanding different degrees of representation of hydro(geo)logical processes.
- In karst systems with thick vadose zones, it is important to include the flow processes in this compartment, since it can be an important resource particularly during drought periods.

Motivation

Flow dynamics in karst aquifers are subject to highly heterogeneous flow processes in all compartments, i.e., the surface, vadose, and phreatic

zone (Figure 1). The heterogeneous distribution in hydraulic properties (e.g., hydraulic conductivity, storage) within these compartments affect the local and global routing dynamics and hence the magnitude and dissipation of the hydraulic signal between source (precipitation) and spring outlet (Jeannin & Sauter, 1998; Smart & Hobbs, 1986). Numerical models for the prediction of recharge and dynamics of groundwater resources are subject to a trade-off between predictive power and efforts to reduce parametric ambiguity and structural uncertainty. Here we compare two modeling approaches – a saturated single-continuum and a variably saturated dual-continuum flow model developed for the Western Mountain Aquifer in Israel and the West Bank – with respect to their fields of applications and their respective predictive power.

Methodology

The single-continuum model computes saturated flow based on the Darcy equation parameterized by volume and system (conduit / matrix) integrating hydraulic conductivities (Table 1), representing both the conduit and matrix flow compartment by a single parameter. The Upper and Lower Judaeen Aquifer are discretized respectively by single-node layers, and the separating aquitard Moza/Beit-

Meir is indirectly accounted for by pronounced anisotropic hydraulic conductivities in both sub-aquifers. The dual-continuum flow model for variably saturated water flows uses the Richards' equation for both continua with a vertically discretized vadose and phreatic zone. Both models utilize daily infiltration as an input computed a priori via a dual-medium water balance model representing recharge dynamics at the zero-flux plane below the soil zone. In the single-continuum model, infiltration is either computed by a soil water balance approach or as monthly recharge by a SWAT model. The single-continuum model directly routes the estimated infiltration to the phreatic zone, while the dual-continuum model computes variably saturated infiltration dynamics for both the matrix and karst conduits.

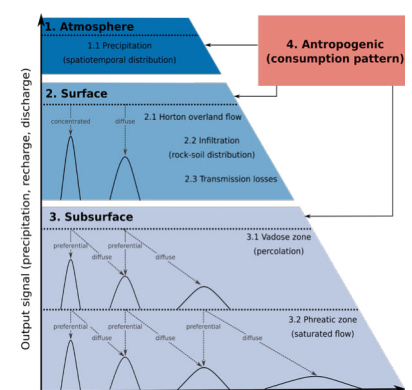


Figure 1: Overview of the flow compartments that affect local and global flow processes and provide storage

Comparison of modeling approaches for the simulation of surface and subsurface flow dynamics in complex fractured-porous karst aquifers



Table 1: Comparison of the numerical models' physical representation and discretization

	Modflow (Single-Continuum)	HydroGeoSphere (Dual-Continuum)
	Physical process representation	
Surface routing	Coupled to a SWAT model with semi-distributed representation of infiltration excess based on Soil Conservation Service Curve Number (SCS-CN)	Distributed overland flow with depth-integrated Saint-Venant equations*
Vadose zone (soil)		Soil water balance model including evapotranspiration dynamics
Vadose zone (consolidated)	Infiltration lag indirectly modelled via anisotropic hydraulic conductivity	Coupled dual-continuum system governed by the Richards' equation (Van Genuchten parametrization)
Phreatic zone	Darcy equation in a single-continuum setting	Coupled dual-continuum system governed by the Richards' equation (Van Genuchten parametrization)
	Discretization	
Temporal	Daily	Adaptive (daily-subdaily)
Spatial (vertical)	No vertical discretization, lumped representation of Upper and Lower Aquifer	Vertical discretization with adaptive resolution, sub-meter spacing close to surface, coarser resolution within the phreatic zone
Spatial (horizontal)	Quadrilateral mesh (total number of $\sim 5 \cdot 10^4$ cells)	Delaunay mesh with partially refined spacing (total number of $24 \cdot 10^4$ cells)
	Computational aspects	
Computational Effort	Low (~ 1 h for a 20a simulation period)	High (~ 1.5 d for a 20a simulation period)
Parallelization	-	OpenMP
	License and support	
Costs	Free	$\sim 2000\text{€}$ (single-node license + technical support)
Support	No official support, rather large user community and forums	Technical support team of Aqunty, smaller user community

* not yet realized for the WMA model

Results

The models vary in terms of complexity and are subject to different degrees of uncertainty with respect to process representation and parametrization. Both models accurately simulate groundwater levels and spring discharge time series (i.e., the drying up of Yarkon spring desiccation) within the calibration period. However, each model has its distinct fields of applications and potential advantages and shortcomings. The single-continuum flow model runs much faster and requires far less computational resources. Due to the reduced number of processes involved and lumped representation of the vertical aquifer layer structure, the model is less vulnerable to parametric ambiguity. Therefore, it can quickly provide simulation results and can be embedded within a responsive decision support system to test the long-term effects of various pumping scenarios. However, the single-continuum model is subject to higher uncertainty (e.g., caused by the non-physical representation of the infiltration process) compared to the double-continuum model and therefore more likely prone to parameter degeneration

(i.e., non-physical values). The unsaturated dual-domain storage capacity may vary significantly with time and space for aquifers with several-hundred-meters thick vadose zones. The superposition of rapid recharge via fractures and dissolution features (dolines, shafts) and long-term diffuse infiltration via the matrix domain must be considered, particularly in the light of the imminent changing precipitation patterns due to climate change. Further, the double-continuum model provides more realistic estimates of the global hydraulic parameters due to the lower structural uncertainty (at the expense of computational time). In contrast, the single-continuum model applies parameters with lumped physical representation (i.e., the low vertical hydraulic conductivity represents the Moza/Beit-Meir aquitard and the vadose zone).

Application

Due to their different strengths, both models have different fields of application. The single-continuum flow model finds its application in testing scenarios for groundwater flow on longer, i.e., monthly or annual time intervals, where mainly long-

term storage processes are relevant. Should, however, short-term, event-based flow and flood problems be addressed, as well as transport problems for which flow velocities need to be better represented, single-continuum models are not the appropriate tool. In contrast, the double-continuum model can be applied to investigate the effect of the change in precipitation patterns concomitant with climate change and the role of the vadose zone for its storage dynamics. The double-continuum model can be expanded by integrating a surface flow continuum to account for Horton overland flow, improving the model's predictability regarding the partitioning of rainfall into infiltration and floods.

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Current and future ecosystem services provided by the Western Aquifer Basin

Key findings

- The Western Aquifer Basin provides high surface water and groundwater regulation services. We expect them to decrease under future climate change conditions.
- Water quality regulation is high due to low nitrate pollution.
- The ecosystem services index for soil protection is also high.
- The ecosystems responsible for food production provide a relatively low percentage of the total food demand. Food production reliant on groundwater resources is expected to decrease with climate change.

Motivation

Karst aquifers play a vital role in the regional management of ecosystem services, especially the provisioning of potable water and irrigation water for agriculture (thus safeguarding drinking water and food security), but also erosion regulation. They are vulnerable to human impact and are difficult to manage, especially in the Mediterranean climate where groundwater recharge and flow dynamics are extremely variable. The Western Aquifer Basin (WAB) in Israel and the West Bank faces additional water

stress due to rapid climate change and a high population growth rate. The high domestic and agricultural water demand increases the pressure on groundwater resources, while projected climate change could reduce groundwater recharge due to decreasing precipitation and increasing evapotranspiration. In this study, we quantify the impact of climate change (i.e., altered precipitation and temperature) on ecosystem services in the WAB.

Methodology

To predict plausible future changes in ecosystem services, we applied the Soil & Water Assessment Tool (SWAT). The model area is split into a recharge zone with mountainous karstic features and a non-recharge zone. The precipitation varies from 150 mm in the South to 500 mm in the North. To capture the different catchment properties well, two separate SWAT models were developed with the data sets listed in Table 1. The models were calibrated with monthly stream discharge data. Due to karstic and non-karstic zones

and multiple rivers in the watershed, multi-sites model calibrations were performed. The model outputs of monthly river discharge, yearly groundwater recharge, monthly nitrate concentration, yearly sediment yield, and yearly biomass and crop yield were used to analyze different ecosystem services. They were determined by i) the index for regulation of surface water quantity, location, and timing (IRSWQLT) from the estimated river discharge (cum) and observed flow, ii) the index for regulation of groundwater quantity, location, and timing (IRGWQLT) from the estimated deep aquifer recharge, well abstraction, and spring discharge (MCM), iii) the index for regulation of water quality (IRWQ) from estimated and allowable nitrate concentration (mg/L), iv) the index for protection of soils and sediments (IPSS) from estimated and allowable sediment yields (ton/ha), and v) the index for food and feed (IFF) from crop biomass (ton), crop yield (ton/ha), and maximum crop yield. These ecosystem services indices were analyzed

Table 1: Data sets used for SWAT model development

Data	Spatial Resolution	Source
DEM	30 m	SRTM
Land-use map	30 m	UBAY based on Hamaraag and IMA
Soil map	250 m	Ravikovitch (1970)
Soil profile		The Soils of Israel by Singer (2007)
Crop management		FAO
Weather	daily	IMS, NCEP

SRTM = Shuttle Radar Topography Mission, IMA: Israel Ministry of Agriculture, FAO = Food and Agriculture Organization, IMS: Israel Meteorological Services, NCEP: National Centre for Environmental Prediction

Current and future ecosystem services provided by the Western Aquifer Basin



Ecosystem services

Humans depend on Earth's ecosystems and the services they provide. They include food, water, sediment regulation, nutrient regulation, and hazard regulation. In this study, ecosystem services are quantified with the Soil & Water Assessment Tool (SWAT; Arnold et al., 1998) using the 'Index' approach (Logsdon & Chaubey, 2013). All indices have unitless values between 0 and 1, where ecosystem services are lowest at 0 and highest at 1.

for the period 2003-2015 on the watershed and subbasin level, both for the recharge and non-recharge zone. The ecosystem services indices under future climate change conditions were analyzed until 2070 under climate change scenario RCP4.5.

Results

The current indices for different ecosystem services (Figure 1) are compared with the indices of ecosystem services under future climate change conditions (Figure 2) for the recharge and non-recharge zone. The IRSWQLT is 0.83 for the

recharge zone and 0.95 for the non-recharge zone. This means that river discharge meets environmental flow requirements 83% and 95% of the time. The IRGWQLT of 0.84 means that groundwater recharge provides 84% of the sum of groundwater abstractions and spring discharge. For both regions, the nitrate concentration is very low, which results in very high water quality regulation indices. Both regions have high relative areas of barren (19%) and urban land (17%), and only 35% of the agricultural area includes field crops, vegetables, and significant areas of orchards. Therefore, the index for food and feed is very low in both regions. The index for protection of soils and sediments is also moderate to high, which means soils are well protected. Under future climate change conditions, the indices for regulation of surface water and groundwater quantity, location, and timing decrease alarmingly because of the reduced precipitation and increase in temperature. While the indices for regulation of water quality and protection of soils and sediments remain high, the index for food and feed drops significantly. This indicates that more food may need to be imported in the future.

Application

The results of this study can assist policy-makers with a better understanding and management of the region's natural ecosystems and food supply reliant on groundwater resources. The scenario analysis, estimating the impacts of future climate change, raises a concerning issue about the region's freshwater and food supply. It must be noted that the model has not yet been calibrated with nitrate concentration and sediment yield because of the lack of observed data, which reduces the prediction reliability of IRWQ and IPSS. The model will be further developed and used to also investigate the effects of land use changes on ecosystem services until 2070.

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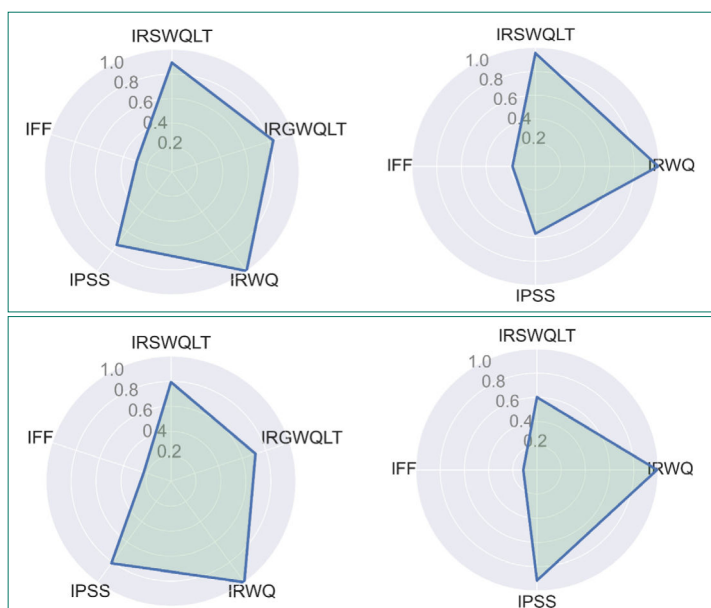


Figure 1: Current indices for different ecosystem services provided by the recharge zone (left) and the non-recharge zone (right). The IRGWQLT is absent on the right, because the non-recharge zone does not contribute to groundwater recharge of the Western Mountain Aquifer. (IRSWQLT: Index for regulation of surface water quantity, location, and timing, IRGWQLT: Index for groundwater quantity, location, and timing, IRWQ: Index for regulation of water quality, IPSS: Index for protection of soils and sediments, and IFF: Index for food and feed).

Figure 2: Indices for different ecosystem services under climate change conditions for the recharge zone (left) and non-recharge zone (right).

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Quantification of ecosystem services flows to Israel

Key findings

- This study compares three watersheds in Iowa, Kansas, and the Ukraine with respect to three ecosystem services (ES) using indices to quantify the trade-offs in ES flows to Israel.
- All three watersheds have a relatively high freshwater provisioning service. The Iowa watershed has a slightly lower erosion regulation service, and the USA watersheds are clearly superior in food provisioning compared to the Ukraine watershed.
- We use normalized ES indices which are unitless values between 0 and 1, enabling us to compare watersheds of different sizes and streamflow quantities.

Motivation

Global trade in crop commodities enables countries with limited water and land resources to maintain food security, but it also makes them reliant on ecosystems abroad. The term ecosystem services (ES) represents the benefits people obtain from ecosystems. ES include food provisioning, freshwater

provisioning, and erosion regulation, among others. This study focuses on these three services that are considered key to maintaining food and water security. It looks at Israel as a case study, focusing on the staple crops wheat, maize, and soybean that are imported to Israel from the USA and Ukraine. Similar to the concept of virtual water or the water footprint, we view ES as virtually imported or the importing country having an ES footprint in the exporting country. The provision of ES varies in different countries and within countries, and some regions can be considered more suitable for the production of certain crops than others. This study looks at crop production within specific watersheds and compares them using a set of ES indices.

Methodology

Over the last few decades, Israel has imported significant quantities of wheat, corn, and soybean from the USA and Ukraine. We compare three watersheds in terms of the ES provided and the global flows of virtual ES to Israel (Koellner et al., 2019). We modeled two watersheds in Iowa and Kansas (USA) and one in Ukraine using the Soil and Water Assessment Tool (SWAT). These watersheds represent a range of production systems, from a relatively low precipitation

climate with wheat and irrigated corn production in western Kansas, to rainfed corn and soybean production in Iowa, and rainfed corn, soybean, and wheat production in Ukraine. The monthly streamflow is used to calculate a freshwater provisioning index based on an environmental flow requirement of 30% of long-term flow. The biomass and yield of the relevant crops are used to calculate the food provisioning index based on the maximum yield across all watersheds. The sediment yield is used to calculate the erosion regulation index based on a maximum tolerable soil loss rate of 5 t/ha per year.

Quantification approach

The Soil and Water Assessment Tool (SWAT; Arnold et al., 1998) is a watershed-scale hydrological model capable of producing outputs that can be used to quantify a large variety of ecosystem services. For this analysis, we used the outputs on streamflow (freshwater provisioning), crop and biomass yield (food provisioning), and sediment yield (erosion regulation) to compare the different watersheds. Each index is normalized to a value of 0 to 1 to enable a direct comparison of the watersheds.

Quantification of ecosystem services flows to Israel



Results

When comparing the three watersheds in terms of freshwater provisioning (Figure 1a), the index is relatively high for all three cases, meaning that in each individual month the streamflow is rarely below the 30% threshold. Figure 1b shows the erosion regulation index, indicating a slight differentiation between the watersheds with Iowa having a slightly lower index. This is likely due to higher precipitation and having only corn-soybean rotation. When we look at the food provisioning index (Figure 1c), Iowa and Kansas stand out significantly over the Ukrainian watershed. This is primarily driven by the lower yields in Ukraine, which means that the USA watersheds are more efficient food producers. Based on

the results for these three services it appears that crop production in the USA is more efficient when all ES are taken into account than in Ukraine. An additional watershed from Brazil will further be included in the analysis, as well as indices for additional ES. A more comprehensive analysis of the trade-offs can also be made by including calculations of energy demand and emissions associated with Israel's crop imports.

Application

An analysis of ES flows will enable policy-makers to identify countries and watersheds that have high ES indices and from which they could import crops while reducing environmental impacts. The concept of virtual ES provides an ad-

ditional lens through which to investigate the reliance of importing countries on ecosystems abroad and identify non-linear trade-offs. Rather than using a simple indicator such as tons per hectare or cubic meters per second, we opted to use an index which is a normalized unitless value between 0 and 1. This enables us to compare watersheds of different sizes and streamflow quantities. On the other hand, indices introduce an extra layer of complexity and therefore uncertainty.

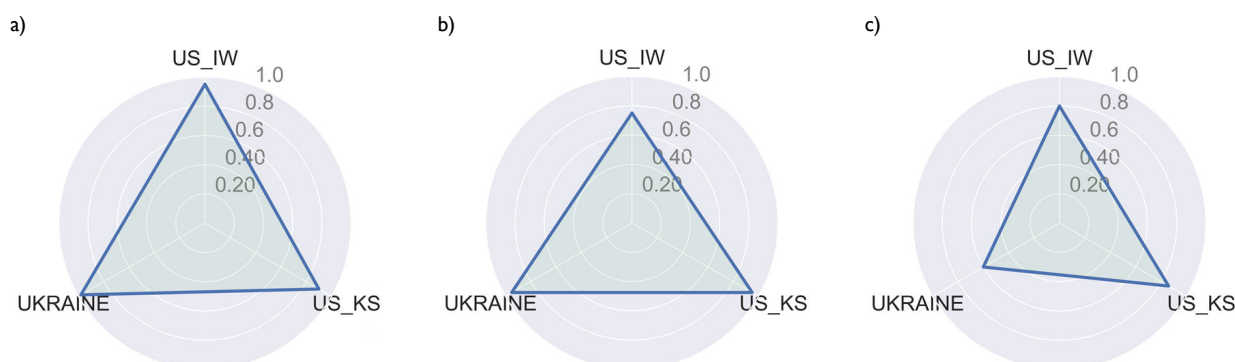


Figure 1: Comparison of a) Freshwater provisioning service, b) Erosion regulation service, c) Food provisioning service for the watersheds in Iowa and Kansas (USA) and Ukraine

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Quantification of Israel's virtual water fluxes

Key findings

- 1,806 MCM of virtual blue water and 6,498 MCM of virtual green water were used in the production of 100 crops consumed in Israel in 2005.
- From total blue water consumption, 1,044 MCM originated from Israel's domestic production.
- Israel exported 132 MCM of virtual blue water. This represented 11.3% of the total blue water used for Israel's agricultural production.
- For domestic consumption, wheat had the highest virtual water volume, followed by maize. Regarding exports, potatoes and dates were highest.

Motivation

This study focuses on Israel's crop water use. It takes into account crop imports as well as Israel's domestic crop production in quantifying green and blue water use in a spatially explicit manner. Different crops are associated with varying rates of water use. Spatial variation is introduced by factors such as climate, soil type, yields, irrigation techniques, and water sources.

There are multiple public databases containing water volumes consumed per ton of crop on country and watershed levels. This study primarily uses the watershed-scale Pfister and Bayer (2014) data (PB). We compare it to Mekonnen and Hoekstra (2011) Water Footprint Network (WFN) data to illustrate the differences between the two databases. Israel is a particularly interesting case study due to its relatively high blue water use per capita, while also importing virtual water to maintain water and food security. Analysis is also carried out at finer spatial scales (grid cell and watershed levels) to identify hotspots of water use within countries as well as individual crops that are heavily represented in the overall virtual water budget.

Methodology

We analyzed the virtual water use of 1) imports and domestic crop production for consumption in Israel and 2) Israel's crop production for export. In the first step, global data on water use (Million Cubic Meters (MCM) of green and blue water per ton of primary crop equivalent) was applied to production data (in tons) to derive blue and green water use by crop. The primary crop production dataset is from 2005 and consists of bilateral trade and

production data relating to 142 crops, as defined by the Food and Agriculture Organization of the United Nations (FAO), and 239 processed products. The dataset producers (Fridman & Kissinger, 2018) used an origin-tracing algorithm to assign import flows to the original countries of production. We combined the trade data with the PB database on water use at the watershed level to calculate water volumes in MCM. The main analysis is limited to some of the 'thirstiest' countries and crops. Data processing was mainly done with ArcGIS and Microsoft Excel.

Virtual water content

"The water footprint of a product (alternatively known as 'virtual water content') expressed in water volume per unit of product (usually m³/ton) is the sum of the water footprints of the process steps taken to produce the product" (Mekonnen & Hoekstra, 2011). In this study, we take into account global data on green (precipitation) and blue water (surface and groundwater) in Million Cubic Meters per ton of primary crop equivalent.

Quantification of Israel's virtual water fluxes



Results

1,806 MCM of virtual blue water and 6,498 MCM of virtual green water were used in the production of all crops consumed in Israel in 2005. From total blue water consumption, 1,044 MCM originated from Israel's domestic production. At the country level, Israel's production for domestic consumption accounts for approximately 58% of blue water volume across all crops while it only covers 36% in terms of crop production tonnes. Wheat was the dominant crop with 22% of the total volume of Israel's blue water consumption. Maize was second at 7%, followed by apples, olives, soybeans, and sunflower seeds. In 2005, Israel exported 132 MCM of virtual blue water. This represented 11.3% of the total blue water used in Israel's agricultural production. Potatoes, dates, grapes, and olives were particularly relevant. The two data-

sets resulted in largely different water volumes: For wheat, the PB data resulted in 405 MCM, the WFN data in only 63 MCM of blue water. Overall, the WFN data yielded lower blue water volumes (1,083 MCM compared to 1,806 MCM), while the opposite was true with respect to green water (9,161 MCM compared to 6,498 MCM).

Application

These analyses produce data with which Israel can refine a strategy of regional optimization, decreasing its dependence on blue water, minimizing groundwater depletion, and avoiding imports from blue water hotspots. The approach demonstrated here is applicable to any other country in the world. However, there is high uncertainty with respect to water volumes data due to low temporal and spatial resolutions. Including green water

demonstrates the degree to which watersheds from which crops are imported to Israel rely on blue water as a share of total water use. This information provides useful insights for regional optimization, including choosing alternative suppliers from other watersheds or

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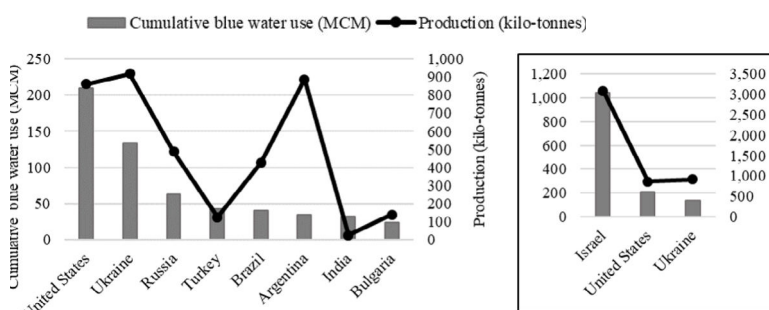


Figure 1: a) Blue water use in million cubic meters and crop production in kilo-tonnes for countries exporting to Israel and b) Comparison of Israel, United States and Ukraine

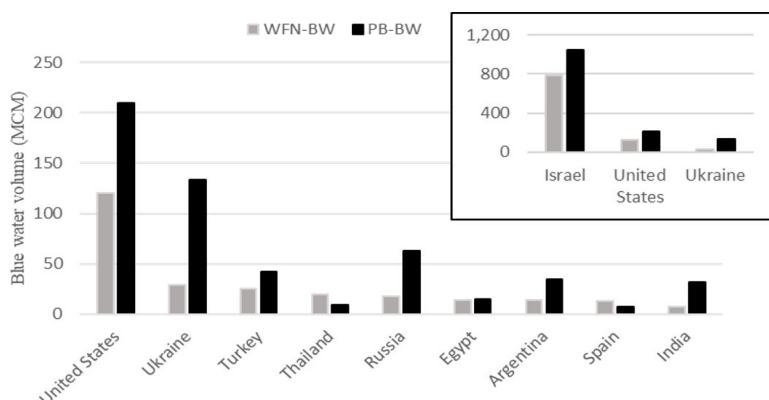


Figure 2: Comparison of blue water volumes in million cubic meters as calculated with the Water Footprint Network (WFN) and Pfister & Bayer (BP) datasets

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Energy and carbon balance of Israel's domestic and imported virtual water supply

Key findings

- The total energy use and emissions of Israel's domestic crop production (563 GWh/431 kt CO₂e) are much lower than the energy and emissions embedded in crop imports (1,796 GWh/749 kt CO₂e).
- Domestic energy use and emissions were mainly attributable to irrigation with water from alternative sources, while transport accounted for 72% and 57% of imported energy and emissions, respectively.
- Despite the transport, average greenhouse gas (GHG) emissions (CO₂e per ton of crop) of imports were significantly lower for several crops compared to domestic production.

Motivation

Every food product “embeds” a certain volume of water consumed or polluted during its production process. This has been referred to as its “virtual water” content or Water Footprint. Natural recharge from rainfall in Israel cannot meet the current water demand. One approach of dealing with (seasonally) limited precipitation is crop irrigation. Depending on the water source, water supply for irrigation can be particularly energy-intensive.

The second approach many countries rely on is the import of crops. According to the Food and Agriculture Organization of the United Nations, agriculture is responsible for 69% of global freshwater withdrawals. This makes the global trade in crops of paramount importance in managing scarce water resources while reducing the impact on the climate. This study investigates the energy requirements and associated emissions of Israel's domestic crop production and imports. It seeks to contribute to Sustainable Development Goals 6 concerning better water management and Goal 12 relating to sustainable consumption and production patterns. We particularly focus on the energy used for abstraction, treatment, distribution, and reuse of water, termed “energy for water”, as well as the impact transport has on emissions related to crop trade.

Methodology

Since the 2000s, Israel has increasingly relied on desalinated water with its associated high energy requirements and emissions. At the same time, Israel is heavily reliant on imports of staple crops with significant emissions due to transport. The process of calculating the energy demand and associated emissions of Israel's crop consumption requires the combination of multiple datasets. In

Data requirements

The shapefile and dataset of watershed-level blue water consumption was obtained from Pfister and Bayer (2014). Crop production for Israeli consumption (Fridman & Kissinger, 2018) was provided in form of 5-arc-minute-resolution rasters. Data on the national irrigation mix was taken from Leão et al. (2018). The calculation of transport distances was based on the port location shapefile of the World Port Index. All calculations were performed in R Studio.

the first step, crop- and watershed-specific total blue water use of Israel's national crop consumption was quantified for the year 2010. The quantification was based on existing spatially explicit datasets of blue water consumption rate (in m³/t) and crop production (in t) for Israeli consumption as well as irrigation efficiency factors. Total blue water use was subsequently differentiated by water source according to national irrigation mix data. In a third step, water source-specific “energy for water” and related GHG emissions were calculated. Transport energy and GHG emissions were determined based on crop production data and transport distances.

Energy and carbon balance of Israel's domestic and imported virtual water supply



Results

The total energy demand associated with virtual blue water consumption in Israel amounted to 2,359 GWh (Figure 1). 24% were attributable to domestic production (563 GWh) and 76% to imports (1,796 GWh). The import component was so high mainly due to the energy consumption related to transport (72%), compared to 28% “energy for water”. Artificial water sources – desalinated sea water (49%) and domestic wastewater (33%) – were responsible for most of the domestic “energy for water”. The total GHG emissions of 1,180 kt CO₂e split into 37% (431 kt CO₂e) associated with domestic consumption and 63% (749 kt CO₂e) with imports. The main difference compared to energy consumption was the lower relative importance of import transport. Ca. 49% of total energy consumption and 42% of related GHG emissions of Israeli domestic and imported agricultural blue water were embedded in cereals (Figure 2), followed by oil crops (26% energy and 27% GHG) and fruits (11% energy and 16% GHG). Wheat produced in Israel had a domestic weighted

average of 524 kWh/t (energy) and 401 kg CO₂e/t (emissions). Imported wheat from Ukraine, Romania, and Turkey was only around 60-285 kWh/t and 23-230 kg CO₂e/t.

Application

Analyses of energy requirements and emissions related to virtual water imports as well as domestic crop production are of interest to policy makers aiming to strike a balance between locally produced crops and those that are imported. The trade-off analysis enabled by using this approach allows stakeholders to better address the challenges of

reducing emissions while maintaining food security. Considering the increasing global importance and feasibility of energy-intensive alternative water sources, our results highlight the importance of including the energy consumption and GHG emissions related to water supply for agricultural irrigation into environmental assessments. The use of publicly available global datasets makes the approach easily replicable. However, these data often come with high uncertainty, which is the main challenge that needs to be addressed in future work.

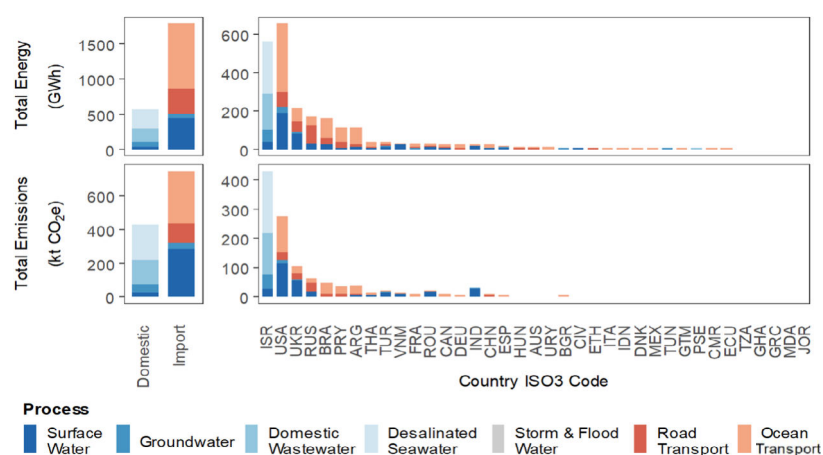


Figure 1: a) Total energy consumption (GWh) and b) total GHG emissions (kt CO₂e) of domestic and imported virtual blue water for Israel's consumption and the corresponding source of emissions

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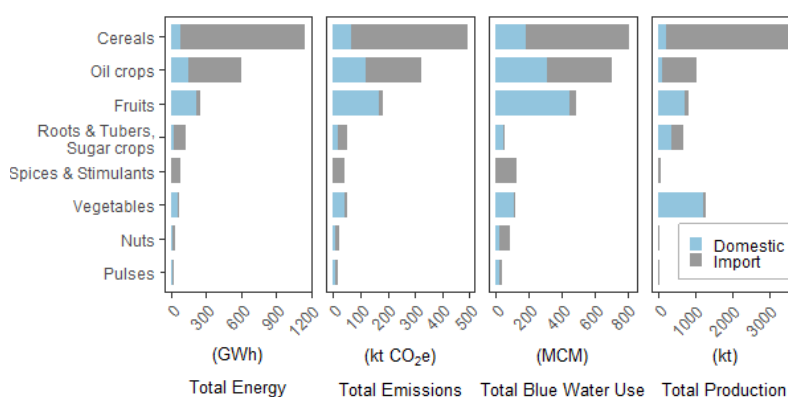


Figure 2: Total energy consumption, emissions, blue water use, and production differentiated by crop groups

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Comparison of 3km and 8km-resolution climate simulations with COSMO-CLM for the recharge zone of the Western Mountain Aquifer until 2070

Key findings

- Seasonal temperature changes (increase of up to 2.2 °C in winter and fall) show minimal differences in distribution and magnitude between the ISR3 and ISR8 data.
- Projected seasonal changes in precipitation show up to 59% (ISR3) and 42% less precipitation (ISR8) in fall.
- The extreme indicators for temperature show similar distribution patterns for ISR3 and ISR8 with more apparent changes in the ISR3 data.
- The extreme indicators for maximum and mean precipitation show strongly divergent distribution patterns between the ISR3 and ISR8 data.

Motivation

The Western Mountain Aquifer (WMA) is one of the most important groundwater resources for Israel and the West Bank. It has been intensively used for decades due to continuous population growth, industrial progress, and extensive agricultural production. The WMA's recharge zone is spatially restricted to the eastern part of the aquifer area along the north-south striking mountain ranges. The climate is characterized by extremely low

precipitation in the hot summer months and a highly variable geographical distribution of precipitation, with 700 mm per year in the north and 200-300 mm in the south. Investigations of potential climatic changes in the recharge zone could provide indications of the long-term recharge capacity of the WMA. High-resolution climate projections for Israel have been published by Hochman et al. (2018). These showed an increase in temperature of up to 2.5°C in winter and a decrease in seasonal precipitation for the northern and central regions of up to 40% in fall. In addition to these initial studies, higher-resolution climate projections were prepared as part of the MedWater project specifically for the recharge zone of the WMA.

Methodology

To evaluate future climatic conditions of the WMA's recharge zone, two sets of daily climate data (1981-2070, IPCC RCP4.5) with resolutions of 0.0025° (about 3km) (ISR3) and 0.0715° (about 8km) (ISR8) were provided by the Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC). The data are based on the Coordinated Regional Downscaling Experiment Middle East North Africa (MENA-CORDEX) (Bucchignani et al., 2018) and have been produced by the regional climate model COSMO-CLM (Rockel et al., 2008). For the period 2041-2070, several

COSMO-CLM

The COSMO-CLM (Consortium for Small-scale Modelling model in Climate Mode) is a unified model system for numerical weather prediction (NWP) and regional climate modeling (RCM) used by various national weather services. It is employed at a spatial resolution between 1 and 50km. The model was originally developed by the German Meteorological Service (DWD) and the COSMO consortium. Later, a climate mode (CLM) with the extensions necessary for climatological applications was provided by the CLM community.

indicators of seasonal climate change and extreme events (Table I) were determined for the ISR3 and ISR8 data and compared to a 1981-2010 hindcast period. The calculation was based on the Expert Team on Climate Change Detection and Indices (ETCCDI) indicators. The parameters used for calculating the indicators were average (T_{2m}), minimum (T_{min}), and maximum (T_{max}) temperature 2m above the surface, and precipitation (P). Data was processed with the programming language Python. The generated raster files were evaluated for the recharge zone using the Zonal Statistics Tool in QGIS.

Comparison of 3km and 8km-resolution climate simulations with COSMO-CLM for the recharge zone of the Western Mountain Aquifer until 2070



Table 1: List of ETCCDI indicators calculated with precipitation and temperature data

Indicator	Description	Units
Precipitation		
R10	Number of days with precipitation ≥ 10 mm/day	days/year
R20	Number of days with precipitation ≥ 20 mm/day	days/year
CDD	Maximum number of consecutive dry days (< 1 mm)	days/year
CWD	Maximum number of consecutive wet days (> 1 mm)	days/year
Rx1day	Maximum of daily precipitation	mm/day
SDII	Mean precipitation on wet days (> 1 mm)	mm/wet day
Temperature		
SU	Summer days—annual count of days when the daily $T_{\max} > 25^{\circ}\text{C}$	days/year
TR	Tropical nights—annual count of days when the daily $T_{\min} > 20^{\circ}\text{C}$	days/year
TNn	Annual minimum value of daily T_{\min}	$^{\circ}\text{C}$
TXx	Annual maximum value of daily T_{\max}	$^{\circ}\text{C}$

Results

The following results represent a selection of seasonal parameters and indicators that provide important information on climate change in the WMA's recharge area. The ISR3 and ISR8 data show significant differences in the distribution and magnitude of calculated indicator values. Evaluation of the average seasonal temperatures shows for both the ISR3 and ISR8 data a general temperature increase of up to 2.2°C in winter and fall (Figure 1a). For the average seasonal precipitation, the ISR3 projection shows a significant precipitation decrease of up to 59% in the fall compared to 42% in

the ISR8 projection (Figure 1b). Deviations are seen in the maximum number of TR with 58 days per year (ISR3) as opposed to 45 days (ISR8) in the northern part (Figure 1c). The CDD in winter is on average 1 day higher in the ISR3 data than in the ISR8 data. Large deviations between the ISR3 and ISR8 data occur for the Rx1Day. Figure 1d shows a projected change in the maximum value for Rx1Day of 55 mm/day as opposed to 0.5 mm/day (ISR8) and in the minimum value of -31 mm/day as opposed to -14 mm/day (ISR8). The SDII for the ISR3 data shows projected changes in the maximum value of up to 2mm/wet day, whe-

reas no positive change is predicted for the ISR8 data, and projected changes in the minimum value with -3.6 mm/wet day (ISR3) as opposed to -1.6 (ISR8).

Application

The high-resolution ISR3 projection shows an even more accurate trend of climate change for extreme indicators of temperature and precipitation and predict extreme precipitation events not simulated in the ISR8 data. The changing future precipitation patterns, longer dry spells, and higher temperatures in the precipitation-rich months, with consequently higher evaporation rates, demonstrate the need for action. With the incorporation of ISR3 data into the groundwater models developed in MedWater, accurate recharge rates can be projected in the long-term. In addition, groundwater pumping can be adjusted in scenario analyses to show the response of the WMA with respect to changes in groundwater levels and thus develop long-term management strategies.

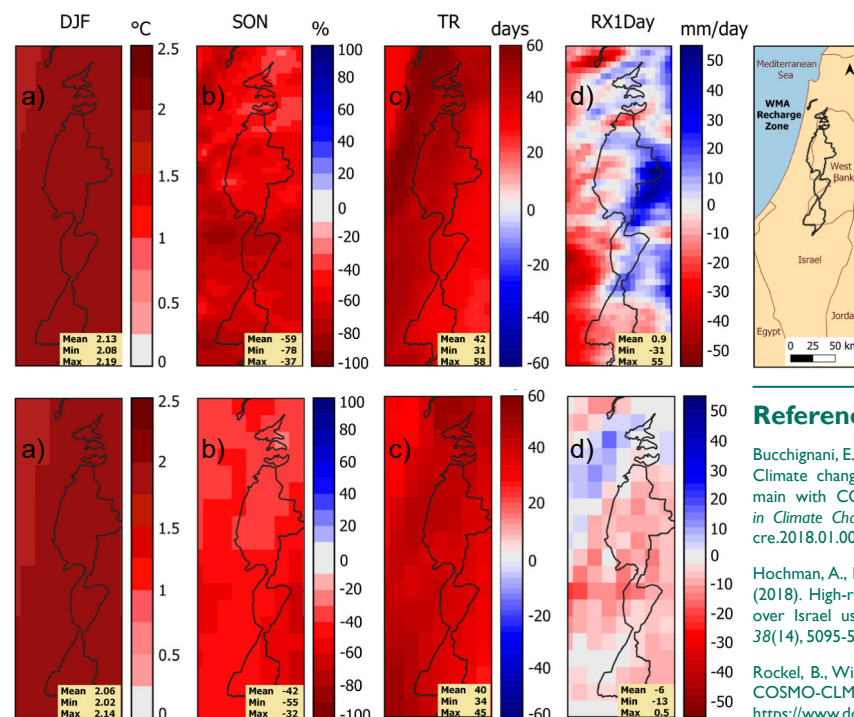
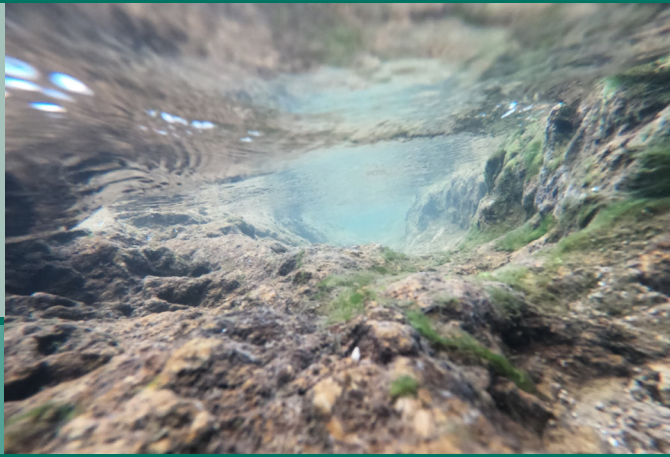


Figure 1: ISR3 (upper row) and ISR8 (lower row) projections for change in seasonal mean temperature and precipitation and extreme indicators, 2041–2070 minus 1981–2010. a) shows the average temperature change in winter (Dec-Jan-Feb), b) the average precipitation change in fall (Sep-Oct-Nov), c) the number of tropical nights (TR), and d) the maximum of daily precipitation (Rx1Day).

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Scenario analysis for the prediction of future groundwater resources in the Western Mountain Aquifer

Key findings

- Three groundwater management scenarios – Regional Nature Conservation (RNC), Baseline (B) and Regional Resource Intensive (RRI) – are investigated with regards to their respective impact on groundwater resources.
- The RCP4.5 climate change scenario is the basis for all management scenarios.
- The results indicate an average groundwater level decline under the RRI scenario by 7.8 meters over the next 25 years, while the RNC scenario suggests that groundwater levels increase by 3.3 meters until 2050.

Motivation

Groundwater resources in the Mediterranean region are vulnerable to drought because of specific climatic conditions (i.e., temperature, seasonality in precipitation, and specific groundwater recharge patterns) and increasing water consumption due to economic and population growth. Scenario analysis is a valuable tool to reveal the impact of external developments and support stakeholders in decision-making by showing the impact of different types of management options.

For the Western Mountain Aquifer (WMA) in Israel and the West Bank, early water management practices from 1950 until 1970 consisted solely of utilizing groundwater and the rapid construction of local and regional water supply facilities to satisfy increasing demand. However, heavy abstraction led to a drop in groundwater levels and the drying up of the Yarkon/Ras Al Ain spring in the 1960s, highlighting the importance of adequate groundwater management. Here, we assess the impact of groundwater management options and climate change on groundwater resources.

Methodology

We employ a downscaled RCP4.5 COSMO-CLM climate model

(Hochman et al., 2018) with a spatial resolution of 3 km for the CORDEX-MENA region. This climate change scenario is considered uniformly across all management scenarios as an external driving force. With precipitation and reference evapotranspiration from the COSMO-CLM climate model as input to a dual-continuum soil water balance model, daily infiltration was calculated at the level of the zero-flux-plane (Figure 1a). Three groundwater management scenarios – Regional Nature Conservation (RNC), Baseline (B), and Regional Resources Intensive (RRI) – are assessed, each associated with different abstraction rates from the WMA (Figure 1b). The abstraction rates for the Baseline scenario are

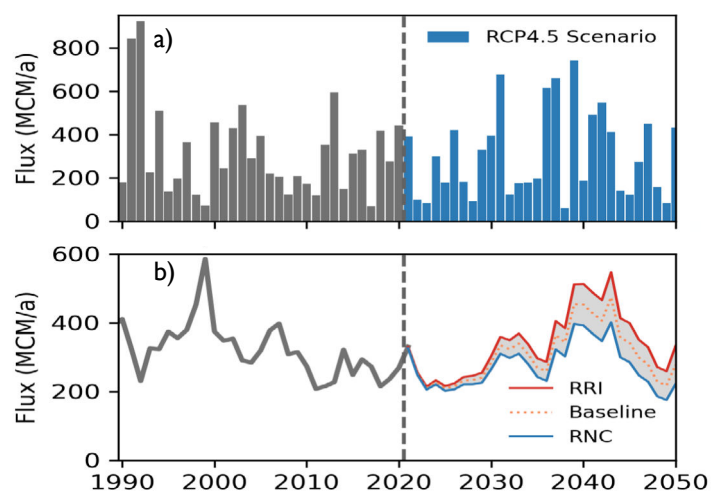


Figure 1: Model input for a) infiltration at the level of the Zero-Flux-Plane under the RCP4.5 climate scenario and b) annual groundwater abstractions under the RNC, B, and RRI scenarios

Scenario analysis for the prediction of future groundwater resources in the Western Mountain Aquifer



defined based on the current management plan of the Israeli water authority that currently limits groundwater abstractions to the 5-year moving average of recharge. In contrast, the RNC and RRI scenarios assume respectively a 20% decrease and increase from the Baseline scenario. We implemented the groundwater abstraction scenarios for a total of 506 wells presently operating. The distribution of pumping rates is assumed to be proportional to the present distribution. The impact of climate change and management scenarios on groundwater resources is subsequently simulated by a variably saturated dual-continuum flow model (HydroGeoSphere), computing the time-dependent storage of a several hundred meters thick vadose zone and the duality of karst groundwater flow dynamics in the vadose and phreatic zones.

Results

The high-resolution regional climate projection indicates a median increase in temperature by up to 2.5 °C and an increase in consecutive dry days until 2070. Furthermore, the climate model projects a more pronounced inter-annual variability of precipitation, resulting in a more pronounced variability of recharge. The numerical simulations of dual-

domain infiltration and groundwater flow indicate an average groundwater level decline under the RRI scenario by 7.8 meters during the next 25 years. The RNC scenario suggests that groundwater levels increase on average by 3.3 meters by 2050. Figure 2a shows simulated groundwater levels at the observation well "Petah Tikva 01", located in the east of Tel-Aviv, which serves as a reference well representative of the central part of the WMA. Simulations suggest that groundwater levels and spring discharge may drop substantially below the red line under the Baseline and RRI scenarios (Figure 2a & b).

Application

The analysis of individual scenarios may be complemented in the future by detailed spatial pumping scenarios, i.e., optimizing locations of pumping wells to avoid intrusion of saltwater into the aquifer in the North-West. In addition, the potential of the WMA as strategic storage of reclaimed water may be further investigated. Managed Aquifer Recharge may allow to effectively store water within suitable locations of the aquifer and provide groundwater resources for exceptionally dry periods under consideration of the aquifer's complex infiltration and flow dynamics. Suitable

Scenario analysis

A scenario is a hypothetical description of the future development of the groundwater system, based on expected changes in recharge and water demand. The acquired information provides insight into the outcome of specific management decisions and external developments. They also serve as a communication tool to figuratively draw public attention to the implications of political decisions and unravel the latitude of potential trends. Normative scenarios assimilate interests and values with the aim of guiding the decision-making process, whereas explorative scenarios investigate possible trends independent of their desirability and with limited measures of interference.

locations are defined by extended mean residence times characteristics. Additionally, the regional model can be scaled down to the recharge area or specific karst features (i.e., dolines), allowing further detailed studies on the infiltration dynamics. Local authorities repeatedly stated their interest in a spatiotemporally distributed recharge assessment that provides higher accuracy for planning purposes.

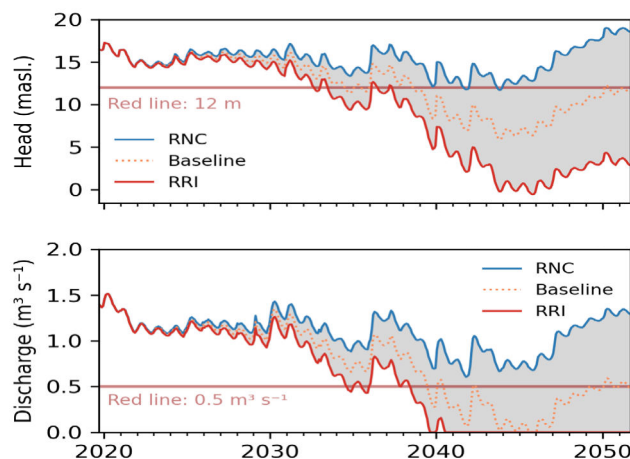


Figure 2: Change in a) hydraulic head in the observation well "Petah Tikva 01" and b) spring discharge at the "Taninim/Al Timsah" spring from 2020 to 2050 according to the RNC, B, and RRI scenarios

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Mooflow: A generalized framework for basin-scale multi-objective simulation-optimization with MODFLOW

Key findings

- We introduce the software package Mooflow for Python to set up and perform generalized multi-objective simulation-optimization of groundwater management.
- Mooflow couples the groundwater model MODFLOW with the water distribution network model Pywr and parallelized heuristic optimization algorithms.
- Application of the framework is demonstrated on a fictional water resource system for the Western Mountain Aquifer.
- The software will be made publicly available as open source at https://bitbucket.org/BAH_Berlin/mooflow.

Motivation

Sustainable water resources management (WRM) in arid regions is often subject to conflicting interests. A typical problem in groundwater-related WRM is the optimization of groundwater extraction rates. The objectives to maximize sustainability or other ecological aspects conflict with the minimization of pumping costs or shortages. Multi-objective simulation-optimization (MOSO) provides water

managers with a diverse set of best possible (Pareto-optimal) compromise solutions regarding these conflicting interests. In MOSO, a heuristic optimization algorithm is coupled to a groundwater model to evaluate the aquifer response. Additionally, for basin-wide optimization tasks and conjunctive use management, the integration of a superordinate branching water distribution system can be beneficial for modeling. Currently, no software is available to provide a generalized framework to help users set up and run a MOSO with MODFLOW (Harbaugh, 2005). Therefore, we introduce Mooflow for the Python programming language to integrate MODFLOW with the Pywr water distribution model (Tomlinson et al., 2020) and state-of-the-art heuristic optimization algorithms.

Methodology

Basin-wide optimization can comprise many wells and a substantial number of decision variables. To reduce optimization complexity, Mooflow features methods to minimize the number of decision variables by grouping wells and sharing decision variables. Because the computing time of basin-wide groundwater models can be extensive, parallelization may be necessary. The Python package DEAP (Fortin et al., 2012) provides powerful multi-objective algorithms and parallelization.

Mooflow uses an object-oriented design to be general, modular, and expandable. A variety of classes and functions are provided for a step-by-step setup of a MOSO:

1. An optimization algorithm varies extraction or recharge rates and evaluates the aquifer response.
2. Groundwater levels, drainage, and extractions are read from MODFLOW. Total extractions and recharge are assigned to groundwater source nodes or recharge nodes in the Pywr-model.
3. Pywr is executed to distribute the water available in the system for each time step or as a total balance.
4. Fitness function values are computed and returned to the optimization algorithm.

Mooflow

Setting up a simulation-optimization requires the development of code to modify configuration of models, run models, read model outputs, and compute fitness functions. A generalized framework provides functionality to solve these complicated tasks for a variety of problems with a few lines of code. Mooflow leverages Python, an easy-to-use high-level programming language, hugely popular in science and engineering. It adds to an already extensive library of Python packages.

Mooflow: A generalized framework for basin-scale multi-objective simulation-optimization with MODFLOW



Results

Mooflow is applied to the Western Mountain Aquifer (WMA) in Israel and the West Bank for a scenario in the year 2040 with a 17% mean reduction in groundwater recharge. A total of 513 extraction wells and 32 recharge wells with seasonal extraction/recharge patterns are integrated in a MODFLOW model of the WMA. The seasonal extraction/recharge patterns are scaled up or down using ten decision variables that are subject to optimization. Figure 1 shows the superordinate fictional branched water distribution network that is simulated with Pywr. All wells are assigned to different management parcels and provide water to, or receive water from, the respective GW_nodes in the water distribution network. Each parcel further contains additional demand and source nodes. Three fitness functions describe the management goals of increasing sustainability, decreasing provision costs, and reducing overall shortages in water supply until 2040. Figure 2 shows the approximated Pareto-Front after

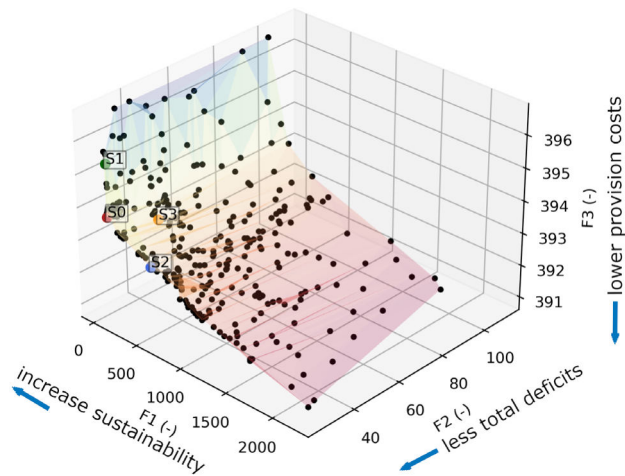


Figure 2: Pareto-Front with four selected solutions S0 to S3

2000 model evaluations. Solution S0 provides a sustainable management, cutting back slightly on groundwater extraction and allowing for minor shortages in water supply. The water footprint of imported crops increases as fewer crops are produced in the WMA, because less irrigation water from groundwater sources is available. The increase in imports and supplied water from other sources result in rising costs.

Application

The software package Mooflow for Python enables users to set up and perform multi-objective simulation-optimization of groundwater management with MODFLOW. The integration of the Pywr water distribution model allows to integrate the flexibility of the superordinate water network to distribute water from different sources to demands and can prevent limitations in the design space of the optimization. Further development will extend the capabilities by integrating the LAK3 model for better conjunctive use management modeling.

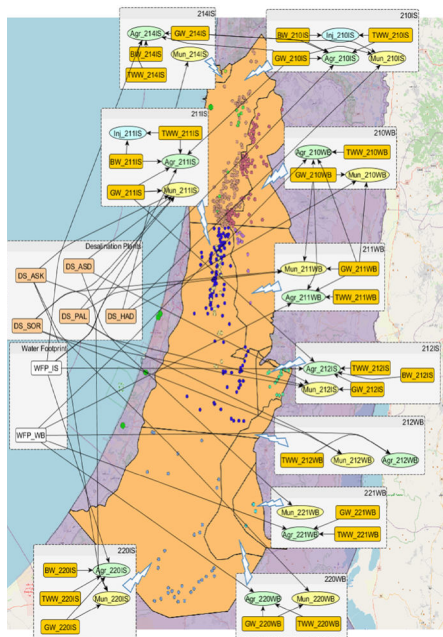


Figure 1: Water distribution system with 10 management sections. Source nodes are TWW – treated wastewater, GW – groundwater, BW – brackish water, DS – desalination plants, and WFP – water footprint of imports. Demand nodes are Munmunicipal/industrial and Agricultural. Arrows show flow directions. Points depict the extraction wells, except green in 210IS and light brown in 211IS, which are recharge wells.

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Concept of a web-based Decision Support System and live-processing tool

Key findings

- The Decision Support System enables stakeholders to make efficient use of limited groundwater resources in the Western Mountain Aquifer.
- The tool illustrates climate and land use changes in the form of interactive maps.
- The results from a numerical MODFLOW model are analyzed and visualized in a graphical user interface (GUI) and post-processed in a live routine for dynamic queries and responses.
- Data storage and processing is mainly based on raster formats (netCDF, hdf5, vrt) to ensure high-performance computing.

Motivation

For the implementation of a sustainable water resources management, web-based information systems are used as an interface between science and practice. Groundwater resources in Mediterranean carbonate aquifers are limited and might decrease in the future due to the effects of climate change. Tools and user interfaces are necessary that enable both professionals and technical authorities, as well as direct users of water resources,

to make the most efficient use of these limited groundwater resources. Therefore, there is a high demand for user-friendly, applied, and interactive Decision Support Systems (DSS) that illustrate process dependencies and predicted system states, and allow the user to generate dynamic queries and corresponding system responses. To fulfill these requirements for the Western Mountain Aquifer in Israel and the West Bank, a web-based DSS is needed that combines results from numerical modeling with a live-processing tool. It is based on an analytical approach that can be effectively used by stakeholders to test-run their own individual scenarios and develop proposals for solutions.

Methodology

The DSS was developed and continuously adjusted based on close cooperation with the Hydrological Service of Israel (HSI). It consists of three interlinked components: an import routine to convert numerical modeling results into the DSS data environment, a control environment to change the configuration of a selected model and perform live-processing, and a graphical user interface (GUI) to visualize the results (Figure 1). Thematically, the DSS is divided into the modules „Base data“, „Statistics“, and „Groundwater modelling“. The „Base data“ module helps with a deeper understanding of regional runoff and groundwater recharge. The underlying numerical

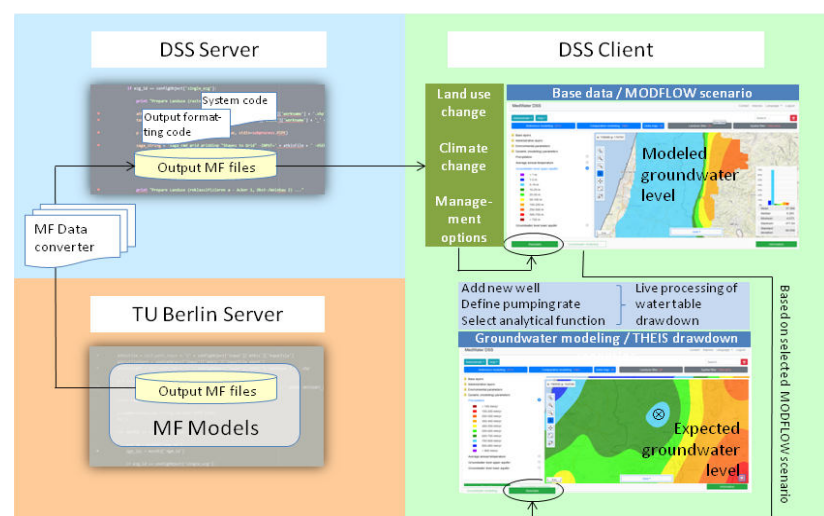


Figure 1: Conceptual design and workflow of the web-based Decision Support System

Concept of a web-based Decision Support System and live-processing tool



MODFLOW model developed at the TU Berlin considers aspects of land use, climate, and management change from 1951 to 2070. All data were transferred into the DSS and can be visualized (GUI) and evaluated ("Statistics" module). In the "Groundwater" module, the user can apply existing models and actively adapt selected elements (set new wells, change pumping rates) to generate dynamic queries and corresponding system responses. For this purpose, a user administration was established.

Results

The entire process chain „Configuration - Control - Visualization“ is mapped based on groundwater recharge. The user can apply an existing model and actively adapt (configure) selected elements (e.g., setting new wells with infiltration or abstraction rates). After appropriate configuration and subsequent post-processing, the recalculation of depression funnels and groundwater hydrographs is done by applying the analytical THEIS well function (Figure 2). Thus, regional, grid-related statements about changing groundwater levels can be made in a temporally

and spatially differentiated manner within the framework of a live-processing routine. Technical adaptations by the HSI as well as data exchange are no longer necessary. A delay in obtaining the results caused by long computing times is also eliminated. This increases the suitability of the system for groundwater management in the sense of decision support. Access to the DSS and its graphical user interface is designed in a way that even stakeholders who were not actively involved in the MedWater project can use it effectively and perform their own scenarios analyses. For data processing, fast formats (hdf5, NetCDF) and effective raster data processing is used. The web-based DSS has a responsive design, so that it can also be used on mobile devices.

Application

The innovative and exploitative potential of the developed DSS can be seen in the coupling of numerical modeling with user-friendly, analytical live-processing tools. However, it must be pointed out that the results do not have the depth of a complete numerical model. The DSS can be used directly by the Israeli partners

Open-source tools & data

Open-source tools (e.g., Mapserver, Mapproxy, GDAL, Python, NumPy) are used to minimize investments and maintenance costs for stakeholders working with the DSS. A web server with configured geospatial software and backup system is used as a technological basis. The development of the graphical user interface (GUI) is browser-based. For this, the frameworks of Bootstrap, jQuery, and OpenLayers are used. Data storage and processing is mainly based on raster formats (netCDF, hdf5, virtual raster technology) to ensure high-performance computing.

or easily be transferred to an Israeli web server and then used in conjunction with the HSI's own models. The HSI has already expressed interest in the possibility of integrating saltwater intrusion into the MODFLOW model and thus the DSS. Adjustments and extensions of the system as well as transfer to other regions are easily possible if required data are available.

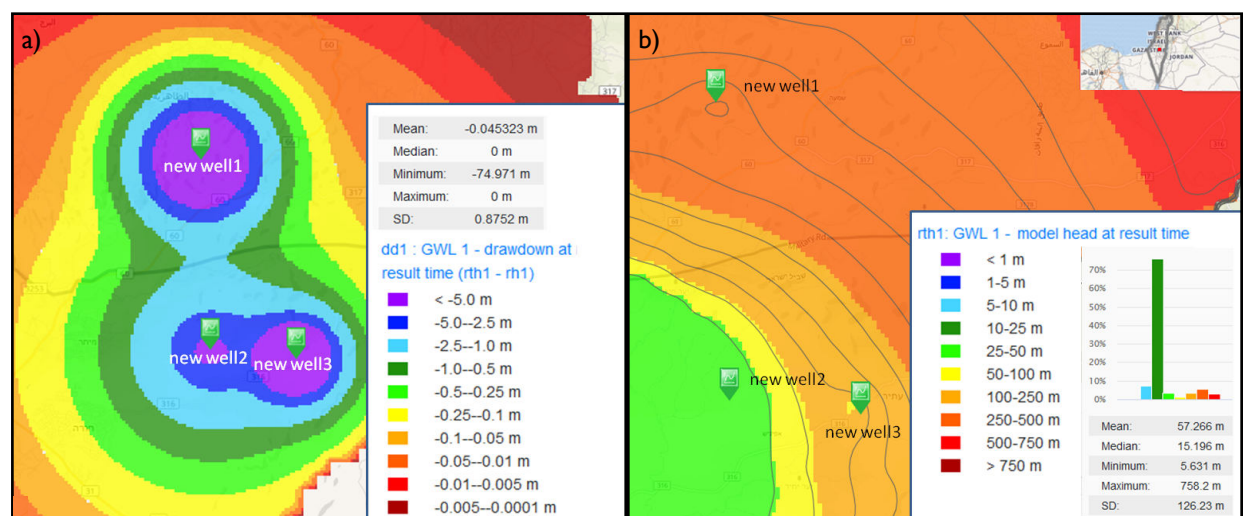


Figure 2: a) Recalculated drawdown by the THEIS well function and b) groundwater level simulated by the MODFLOW model combined with the analytical calculation.





Characterization of the Mount Soprano-Vesole-Chianello karst aquifer in southern Italy for modeling groundwater recharge and flow

Key findings

- The integration of updated stratigraphic/structural data and their spatial modeling is key for the reconstruction of a 3D hydrogeological model of the karst aquifer.
- Monitoring discharge of the Capodifiume spring shows a constant groundwater regime.
- The spatial distribution of the soil thickness can be estimated by field measurements and correlation with land use types.
- The influence of soil covering on groundwater recharge can be assessed by the characterization of soil's hydrological properties and field monitoring of water content.

Motivation

In southern Italy, 40 karst aquifers with autonomous groundwater circulation have been identified (De Vita et al., 2018). These aquifers are formed by Mesozoic carbonate series whose involvement in the Apennine compressive tectonic phases (Miocene) has led to their hydrogeological confinement with adjoining low-permeability basins and flysch series. This geo-structural

feature controls groundwater circulation, which is mainly oriented towards large basal springs (with a mean yearly discharge of up to 3.8 m³/s), favoring their tapping for feeding principal aqueduct systems. Notwithstanding the strategic relevance of karst aquifers for the social and economic development of southern Italy, current knowledge of groundwater recharge and storage/flow has not yet advanced far enough to support modeling and management under the effects of climate variability. A deeper characterization of the aquifers and understanding of processes leading to groundwater recharge and storage/flow are

considered key aspects for setting up empirical or numerical models aimed at forecasting possible scenarios of groundwater availability.

Methodology

The strategy described here was applied to the Mount Soprano-Vesole-Chianello karst aquifer in Italy's southern Campania region. To advance the characterization of the karst aquifer, aspects which have been studied and the applied methods/tools are: i) reconstruction of a 3D hydrogeological model of the karst aquifer through the integration of new stratigraphic/structural data and their spatial modeling with GemPy

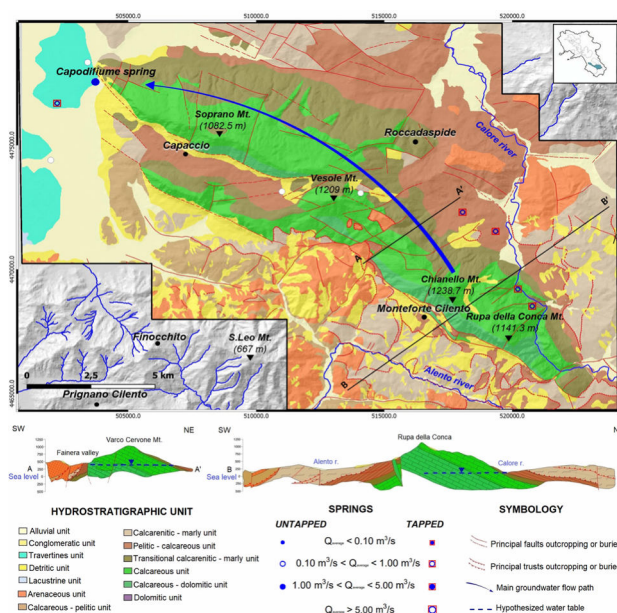


Figure 1: Hydrogeological map and cross-sections of the Mount Soprano-Vesole-Chianello karst aquifer

Characterization of the Mount Soprano-Vesole-Chianello karst aquifer in southern Italy for modeling groundwater recharge and flow



GemPy

GemPy (De La Varga et al., 2019) is an open-source tool for generating 3D structural geological models in Python, which allows to create complex combinations of stratigraphical and structural features such as folds, faults, and unconformities. It was designed to consider probabilistic modeling by managing uncertainties of geological data.

(De La Varga et al., 2019) and the algorithm of the Stochastic Karst Generator (SKS; Borghi et al., 2012); ii) assessment of the groundwater regime by coupled measurements of spring discharge and monitoring the nearby water table; iii) assessment of the spatial distribution of the thickness of soils covering the carbonate bedrock, based on field measurements and spatial modeling, carried out by a supervised classification of Google Earth images; iv) assessment of the hydrological influence of soil covering on groundwater recharge by characterization of Soil Water Retention Curves and field monitoring of water content.

Results

We reconstructed the physical model of the karst aquifer by a series of activities and results:

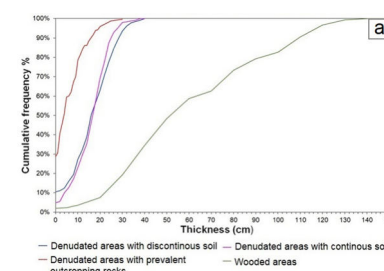
creating new hydrostratigraphic maps (CARG Project) (Figure 1), spatial modeling of their geometry with GemPy, and stochastic modeling of karst conduits with the SKS algorithm. In addition, by monitoring spring discharge, we identified a constant groundwater regime, with discharge values varying from 2.79 to 3.45 m³/s (2019-2020) (Figure 2). Moreover, we tested a procedure for the spatial modeling of soil covering the carbonate bedrock. The method was based on the measurement of soil thickness (by driving a steel rod down to the bedrock) and assessing its variability in different land use conditions. We estimated lower values of soil thickness in denudated areas (median around 0.12 m) and greater values in wooded areas (median around 0.50 m) (Figure 3a). Afterwards, we carried out the spatial modeling of soil thickness by its correlation with land use types across the whole aquifer. Finally, by the laboratory characterization of Soil Water Retention Curves (Figure 3b), we assessed and mapped the available water depth, which we used for estimating the water budget and groundwater recharge.

Application

The approaches applied in this sub-project advance the characterization of karst aquifers in southern Italy

and can be used for reconstructing empirical or numerical models, simulating scenarios of climate change, and setting up a resilient management of groundwater resources. The most important lesson learnt is the not negligible role of soil coverings in groundwater recharge. This aspect, which concerns the field study of the so-called Earth's Critical Zone, is usually not analyzed in detail in hydrogeological studies. The principal limitations of this study are related to the lack of long-term time series of spring discharge and measurements of the karst aquifer's water table, which are prevented by the aquifer's high depth.

Frequency of soil thickness



Soil Water Retention Curves

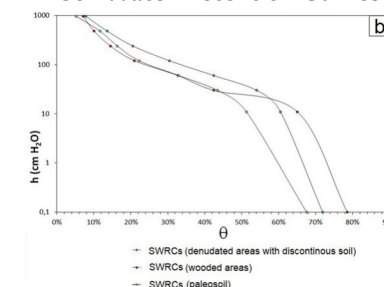


Figure 3: a) Frequency of soil thickness and b) Soil Water Retention Curves (SWRCs) in different land use types

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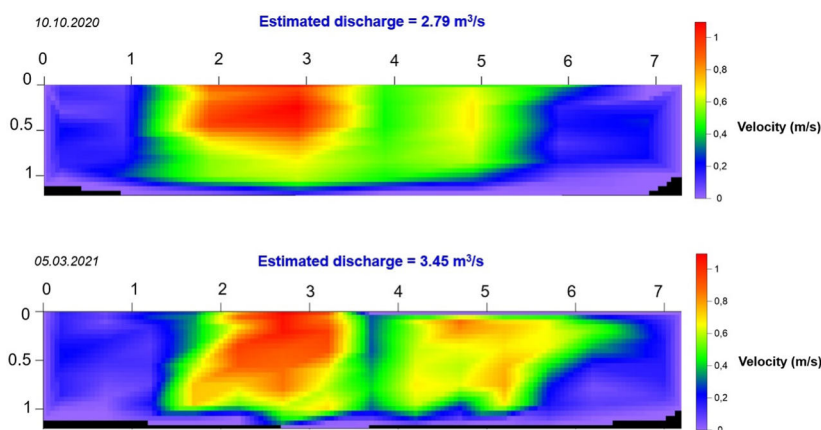


Figure 2: Flow velocity maps of two extreme discharge values, measured at the channel downstream the Capodifiume spring

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Impact of climate change on a Mediterranean karst aquifer under active management: the example of the Lez spring in southern France

Key findings

- The Lez karst aquifer is under active management for supplying drinking water to Montpellier city – it is subject to the highest groundwater pumping in the world.
- The karst aquifer is highly complex with two different compartments and an impact of pumping at the regional scale.
- A new semi-distributed global modeling approach has been developed to simulate water levels in the different parts of the aquifer and the discharge rate at the spring.

Motivation

The Lez spring has been supplying the city of Montpellier since 1854. Prior to 1968, the resource was exploited through gravity abstraction varying between 25 and 600 l/s. In 1982, deep wells were drilled into the main karst drain upstream of the spring (Figure 1) to obtain a maximum yield of 2000 l/s. Today, the mean pumping flow rate is about 1050 l/s, which represents the highest pumping rate from a single point in the world. This kind of exploitation is called “active management”, with a controlled water level

depletion of the karst aquifer. Groundwater is abstracted at a higher rate than the natural discharge rate at the spring during summer. This creates storage capacities for infiltrating water during fall which usually comes with high rainfalls. During summer, a part of the abstracted water is diverted into the Lez river to ensure a minimum discharge rate for aquatic ecosystems. The main objective of our study is to develop a modeling tool that can simulate the complex hydrodynamics of the karst aquifer in order to compute the future impact of climate change and a potential increase of pumping rates on water levels and discharge.

Methodology

The developed hydrogeological model is based on our state of knowledge of the Lez karst system, which consists of two main compartments with very different hydrogeological characteristics: The western part is unconfined and constitutes the infiltration area of the aquifer while the eastern part is confined (Figure 2). The modeling was done using transfer methods implemented with TEMPO software (Pinault et al., 2001). This methodological approach, called inverse modeling, enables us to characterize the regime of complex hydrosystems that are found in karst as well as of

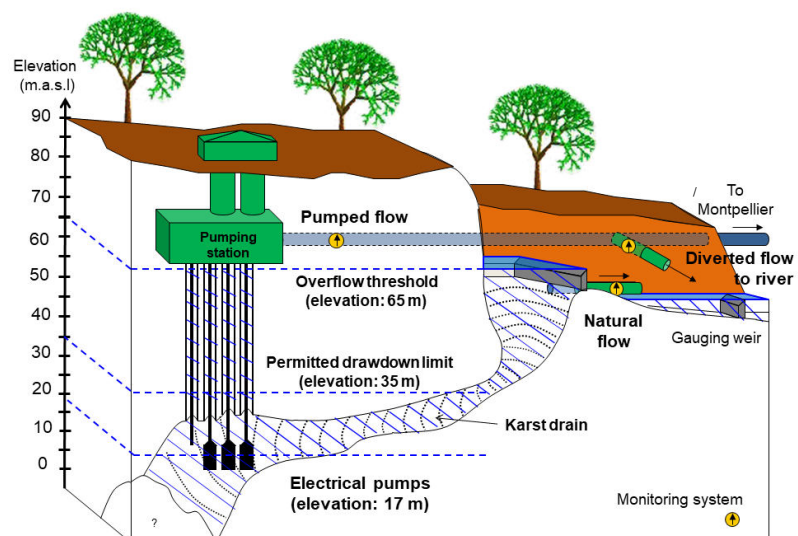


Figure 1: Pumping configuration at the Lez spring

Impact of climate change on a Mediterranean karst aquifer under active management: the example of the Lez spring in southern France



TEMPO software

TEMPO is an inverse model that calculates unit hydrographs as well as the impulse response of fluxes from rainfall data, the purpose of which is hydrograph separation. Inverse modeling makes it possible to characterize the dynamic processes from which the properties of karst systems can be identified. The relationship between inputs and outputs is based on normalized impulse response functions, whose parameters are obtained through the inverse method. The mathematical development is based on the work by Pinault et al. (2001).

more homogeneous porous media. The transfer model we used is composed of four sub-models (or modules) to reproduce the hydrodynamic regime of a complex karst aquifer made up of two compartments and subject to an active management through pumping.

Results

Climate change scenarios from the Intergovernmental Panel on Climate Change have been downscaled at the karst catchment scale in order to produce temperature and precipitation time series for the period 2045-2065. The semi-distributed model was first calibrated and validated on past data time series of water levels and discharge measured for the karst aquifer

(Ladouche et al., 2014). Then, the model was used to simulate the impact of climate and pumping change scenarios on water levels and discharge rates at the outlet of the karst aquifer. Figure 3 shows the simulated and observed water levels at the spring for the reference case (in blue) and the future case (climate change plus an increase of pumping by 20 %). These results are compared to two important levels: the present authorized drawdown limit into the karst drain and the elevation of the pumps. This provides a first idea about the sustainability of the aquifer's active management in the future. The simulations show that the Lez karst aquifer will be impacted by climate

change and pumping increase in a way than can still be supported by the groundwater resource.

Application

The model shows that climate change would induce a decline of groundwater recharge, a water level decrease of 4 to 5 meters, and a decrease of 250 to 400 l/s of discharge rates during low flow conditions. The pumping system could even allow an increase of abstraction in the future, but a pumping test in real conditions is necessary to investigate the hydrodynamic properties of the aquifer in such likely lower level conditions. More generally, these results show that the karst aquifer's active management could constitute one of the solutions for an adaptation to global change. They also show that, given their hydrogeological characteristics and the likely deep development of karstification, Mediterranean karst aquifers could constitute a promising water resource in the future.

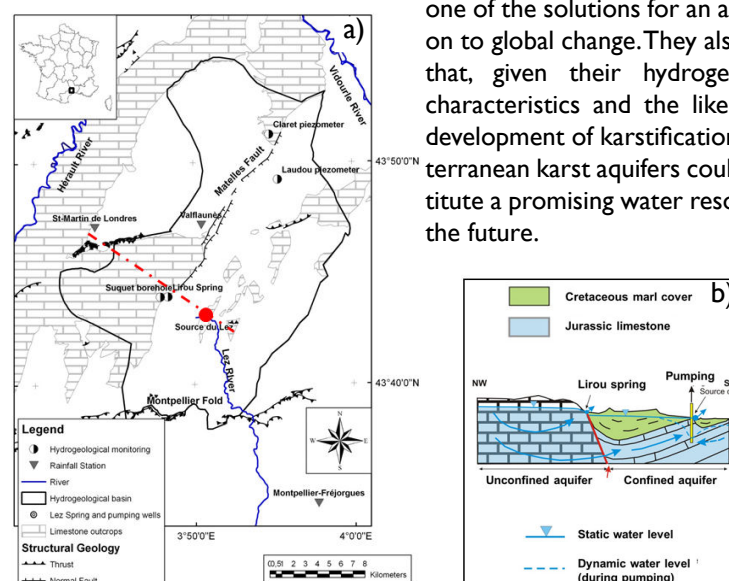


Figure 2: a) Hydrogeological map and b) cross section of the Lez karst aquifer (modified after Ladouche et al. (2014))

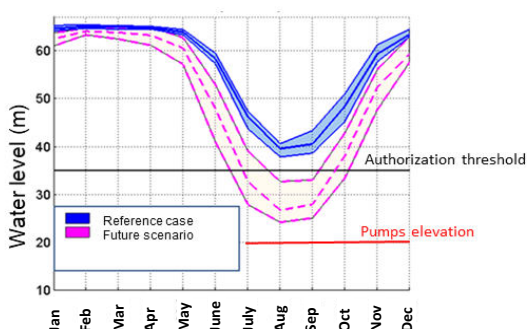


Figure 3: Observed and simulated monthly average water levels at the Lez spring (blue: reference case with present climate and exploitation rate; red: scenario with climate change and exploitation rate increase)

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Creating high-resolution land use and soil moisture maps from remote sensing data

Key findings

- Optical Sentinel-2 systems provide high-resolution land use/land cover maps that can be improved at higher levels of detail (crop maps) by the integration of SAR-systems such as Sentinel-1.
- A procedure for downscaling the global Soil Water Index from ESA-CCI using Sentinel-1 data is developed.
- Geodata integration and machine-learning workflows can improve the quality of remote sensing-based results, which can serve as additional information for applications in data-scarce regions.

Motivation

Today, land use information and soil and vegetation parameters such as soil moisture or vegetation density are widely used for hydrological modeling or ecosystem services assessments. Particularly in data scarce-regions, remote sensing has become an essential data source (Sheffield et al., 2018). For land cover classifications and the derivation of vegetation parameters, mainly data from the Landsat sensors with a spatial resolution of 30 m have been used. Radar-based analyses have proven essential for

accurate estimates of near-surface soil moisture; however, global products are based on coarse resolutions (12.5 km - 25 km pixel size; Peng et al., 2017). Recently, the European Sentinel-1 and 2 systems have provided high-resolution time series which have already demonstrated their potential for new developments in these fields. In MedWater, different remote sensing data was explored to create and provide accurate high-resolution (10 m - 20 m) land use and near-surface soil moisture maps using GIS and machine-learning methods. These maps were developed for the Western Mountain Aquifer (WMA) in Israel and the West Bank, the project's main study site.

Methodology

High-resolution land use mapping relied on multi-temporal data from

Sentinel-2 and Sentinel-1 (2016-2018). Google Earth provided training data to distinguish between basic land use classes (e.g., settlement, water, forest, desert, cropland). Crop data was obtained from the Israeli Ministry of Agriculture and Rural Development. Sentinel-2 data was processed with the open source software Sen2Cor. Machine-learning was applied for classification optimization. For the creation of detailed crop distribution maps, Sentinel-1 backscatter was included, as it comprises information on the vegetation structure. The downscaling procedure to estimate near-surface soil moisture integrates different indicators that influence the signal from Sentinel-1. These include terrain parameters, NDVI time series comprising information about vegetation dynamics, and NDWI time series of the vegetation water con-

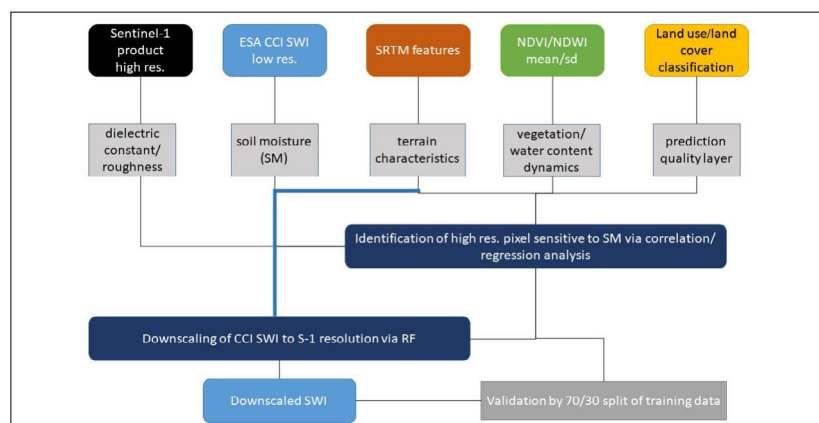


Figure 1: Workflow of the downscaling approach

Creating high-resolution land use and soil moisture maps from remote sensing data



tent. It is assumed that constantly increased vegetation water content indicates high soil moisture. Random forest (RF) was used as a machine-learning algorithm to downscale the 12.5 km Soil Water Index (SWI) to a resolution of 20 m. The procedure is described in Figure 1.

Results

Key results are high-resolution land use maps (Figure 2) and downscaled SWI time series (Figure 3). The classification accuracy was almost 70% for the major land cover classes and achieved 65% for the detailed maps. The complexity of land cover in dry climate conditions such as Mediterranean karst areas introduced high spectral confusion between soil and settlement bodies, water and foil cover of fields, and different vegetation classes. Sentinel-1 data enormously improved the quality of the detailed crop maps. The aggregated land use map was directly integrated in the approach to downscale the SWI. The internal validation of the SWI approach resulted in an average coefficient of determination (R^2) of 0.96 and a mean square of variation (RMSE) of 1.5%. Analysis of the resulting time series indicates spatial variations of soil moisture in the study area. However, for some

land use classes, prediction quality can be assessed to be reduced, e.g., in the case that water bodies or impervious areas characterize the SWI pixel under consideration. Agricultural use or sparse vegetation that is typical in arid climates, as well as bare soils allow for comparatively good predictions.

Application

In data-scarce regions, remote sensing can contribute valuable data sets such as high-resolution land use and soil moisture maps. They can serve as input to different models and are useful for management purposes, e.g., if integrated in information systems. Land use classifications benefit from SAR data, as they contribute a higher thematic level of detail. In MedWater, land use and soil moisture were relevant information for hydrological analyses and ecosystem services assessments. Difficulties are the SAR-based soil moisture assessment under vegetation cover and validation. Hence, future work should aim for in-situ validation. International activities, such as JECAM (Joint Experiment for Crop Assessment and Monitoring) that includes the German TEREENO site DEMMIN, are promising starting points.

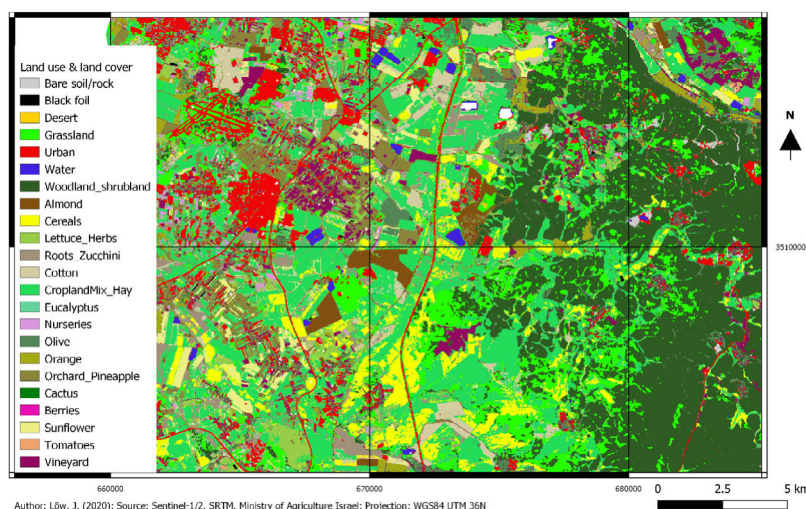
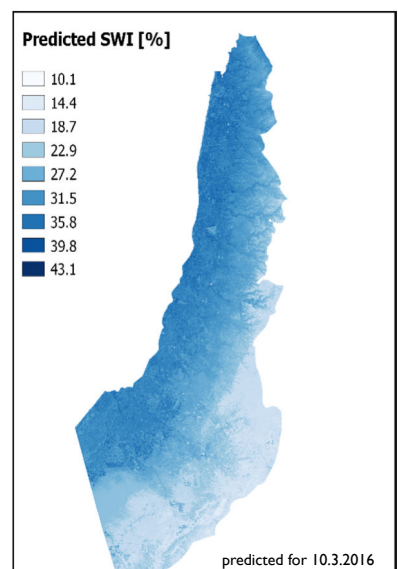


Figure 2: Map of land cover in the study area showing classification information on overview and high-detail levels (2016)

Soil Water Index (SWI)

The Soil Water Index approximates the percentage of soil water in relation to the soil water holding capacity in different soil depths (here the top 1 m). Water holding capacities of soils differ mainly with soil structure and are also affected by organic matter. In the ESA-CCI SWI product, remote sensing methods contribute the near-surface soil moisture to a two-layer water balance model. More information about the SWI are provided by Paulik et al. (2014).



Author: L  w (2020)
Source: ESA CCI SWI, SRTM, Sentinel-1/2
Projection: WGS84 UTM 36N

Figure 3: Soil Water Index (SWI) at a pixel resolution of 20 m based on Sentinel-1/2, SRTM, and ESA CCI SWI data

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Development of a classification scheme for carbonate aquifers in the Mediterranean region

Key findings

- A classification scheme for karst springs has been developed to cluster carbonate aquifers according to hydraulic characteristics of the vadose and phreatic zones.
- The classification scheme can be employed to assess storage and flow characteristics of karst aquifers based on geometry and spring discharge patterns.
- The approach provides an efficient generalization tool for the management of karst aquifers in Mediterranean climates.

Motivation

Spring hydrographs contain integral information about the hydrogeological characteristics (e.g., maturity of karst, storage) of an aquifer and are largely influenced by temporal and spatial precipitation patterns. The surface topography and characteristics, as well as the geometry and hydraulic properties of vadose and phreatic zone compartments transform the original input signal according to their individual flow characteristics (e.g., storage and transmissivity). Flow processes in the individual compartments contribute to the superimposed bulk hydrograph signal at the spring

(Jeannin & Sauter, 1998; Smart & Hobbs, 1986) and reveal certain aquifer properties. However, the superposition of the effects of the individual compartments makes it highly challenging to derive functional relationships. Here, we develop a method to characterize carbonate aquifers in Mediterranean climates based on their discharge signal and easily accessible aquifer characteristics. Our approach provides a valuable tool for the evaluation of aquifers in terms of their potential to provide freshwater, even under climate change conditions.

Methodology

By overlaying Mediterranean climate zones after Köppen-Geiger with a global database of carbonate rock

aquifers (WOKAM), we identified 79 associated spring discharge time series from the World Karst Spring hydrograph (WoKaS) database

Spring hydrograph recession coefficient

The spring hydrograph recession coefficient is computed from the slope of the hydrograph recession curve and is composed of three typical stages (conduit, intermediate, baseflow). It is a characteristic parameter of an aquifer, which is a result of its phreatic hydrodynamic properties (Rorabaugh, 1964), such as hydraulic conductivity, storage coefficient, and aquifer geometry.

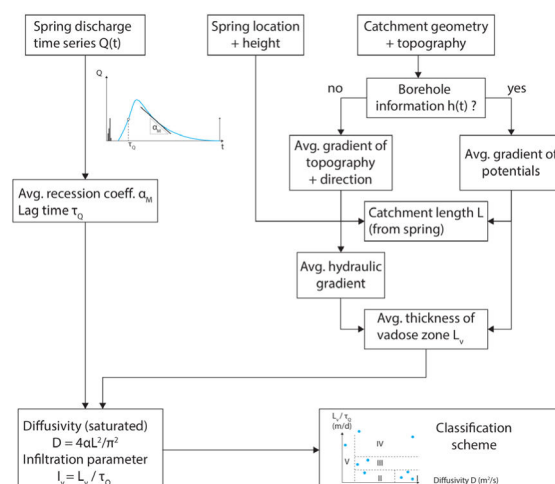


Figure 1: Workflow for the classification of carbonate aquifers located in Mediterranean climate zones

Development of a classification scheme for carbonate aquifers in the Mediterranean region



for 65 Mediterranean carbonate rock aquifers. Rorabaugh (1964) has shown that the hydraulic diffusivity of an aquifer system can be characterized based on a spring recession curve:

$$D = \frac{T}{S} = \frac{4\alpha L^2}{\pi^2}$$

where α is the recession coefficient determined by regression analysis, and L is the average catchment length. Here, we apply this relation to provide insights into karst maturity. The infiltration parameter (I_v) can be defined as

$$I_v = \frac{L_v}{\tau_q}$$

where L_v is the average depth of the vadose zone and τ_q is the time lag between the peak time of the precipitation event and the first inflection of the spring discharge or water table fluctuation in a borehole. This parameter primarily characterizes the influence of the vadose zone, i.e., infiltration on the spring discharge signal and therefore the storage potential of the vadose zone. All available spring discharge time series of the natural aquifers are characterized in terms of these parameters and grouped into clusters.

Results

We extracted 11 hydrographs suitable for recession analysis from the dataset of 79 Mediterranean karst springs. The remaining spring hydro-

graphs were not suitable for further analysis due to the coarse temporal resolution of the discharge time series or lack of spatial information. To evaluate the parameter space not represented by the data of existing natural karst aquifers, we applied a 2-dimensional numerical surrogate model to investigate the full spectrum of the parameter space. For each natural spring, we constructed a dual-continuum surrogate model based on average geometric properties (i.e., average length to the groundwater divide, median vadose zone thickness) and calibrated the hydraulic properties to fit the observed spring recessions. Subsequently, we altered the vadose zone thickness and the hydraulic conductivity of the conduit continuum to derive functional relationships between aquifer properties and the recession behavior. In Figure 2, the dashed vertical lines illustrate the two distinct linear scaling regimes of the vadose zone thickness and the infiltration parameter. The color represents the hydraulic conductivity of the conduit continuum. The synthetic data demonstrates the applicability of the derived parameters (i.e., unambiguity of the

parameters), the infiltration parameter I_v and diffusivity D , controlled respectively by the vadose zone thickness and the hydraulic conductivity of the conduit continuum.

Application

The presented classification allows to assess carbonate aquifers in terms of their vulnerability and adequacy for groundwater abstraction without a priori detailed knowledge about the subsurface characteristics of an aquifer. Carbonate aquifers with a higher infiltration parameter and lower diffusivity are more resilient to droughts. However, high infiltration parameters may indicate a high risk of contamination. Therefore, from a groundwater management perspective the most suitable carbonate aquifers exhibit medium to high infiltration parameters and low diffusivity values. The classification may be further improved by installing automatic measuring devices in currently not monitored spring types and by including carbonate aquifers adjacent to the current Mediterranean climate zone, since it is projected to shift with climate change.

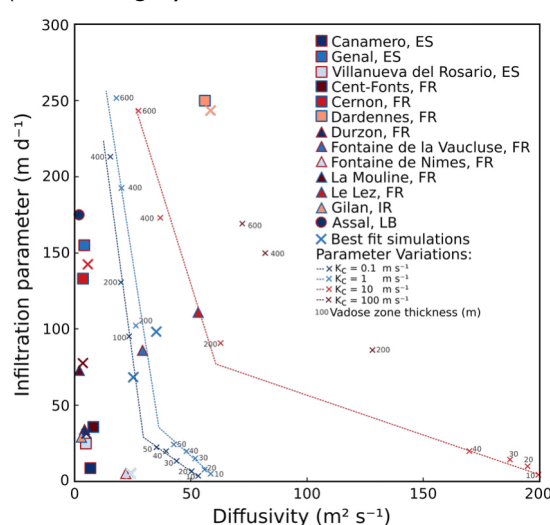


Figure 2: Classification of spring discharge time series in terms of diffusivity and infiltration characteristics. The simulated data is outlined via a cross marker, where the color indicates the hydraulic parameter of the conduit continuum and the label indicates the respective vadose zone thickness.

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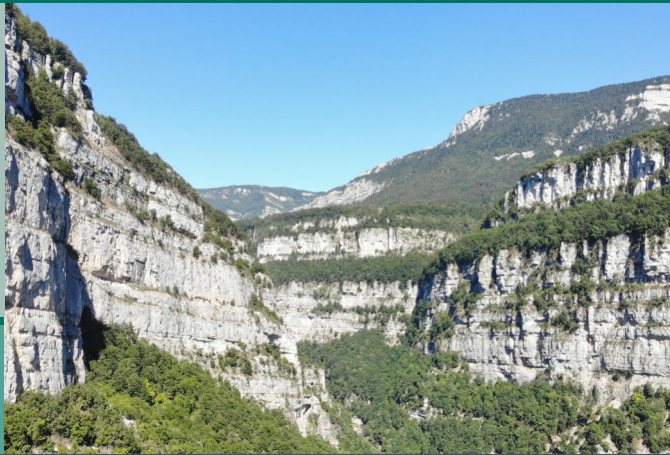
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Calculating groundwater stress of Mediterranean karst aquifers and estimating their vulnerability to climate change on a global scale

Key findings

- We calculate a Groundwater Stress Index (GSI) for 133 karst aquifers with Mediterranean climates and assess their vulnerability to climate change.
- The results indicate increased groundwater stress in southern Spain and northwest Africa, parts of Greece, and the Middle East, while many aquifers on the European Mediterranean coast show relatively low stress.
- Different aquifer groups show very similar trends of higher GSI values with temperature increase and precipitation decrease with varying magnitude.

Motivation

Humans and ecosystems around the world rely on groundwater from karst aquifers. They are particularly abundant in the Mediterranean region. Due to complex karst structures, these aquifers have high infiltration capacities as well as high hydraulic conductivities, which makes them vulnerable to pollution and, as their prediction and management are complicated, overexploitation. Currently, many aquifers are under stress due to rising water demands. Available groundwater resources may decline

further, as climate change could strongly decrease natural recharge. To have a quantitative indication of the current and future state of these critical groundwater resources, we assessed the current level of quantitative groundwater stress of karst aquifers with Mediterranean climates and investigated how similar aquifer types differ in terms of groundwater stress with varying temperature and precipitation. The idea is that comparable aquifers with currently higher temperature or less precipitation may serve as a projection for how other aquifers' stress could increase in the future, thus, how vulnerable they are to climate change.

Methodology

For the selection of Mediterranean karst aquifers, we overlaid the World Karst Aquifer Map with

Mediterranean climate zones (Csa, Csb, Csc) after Köppen-Geiger (Beck et al., 2018). To increase the level of detail, the original karst aquifers were subdivided using HydroBASINS-data. Based on the condition that >50% of their area is assigned to any of the three Mediterranean climate types, we identified 179 karst aquifers or sub-areas. For the selected aquifers, we calculated a Groundwater Stress Index (GSI) based on seven indicators. Hydrogeological indicators – groundwater recharge (I1), storage (I2), and abstractions (I3) – were provided by outputs from the global freshwater model WaterGAP (2.2d). We included two hydrological indicators based on ERA5 data: Runoff relative to average precipitation (I4) and the climatic water balance (precipitation minus potential evapotranspiration). I6 measures the area irrigated with

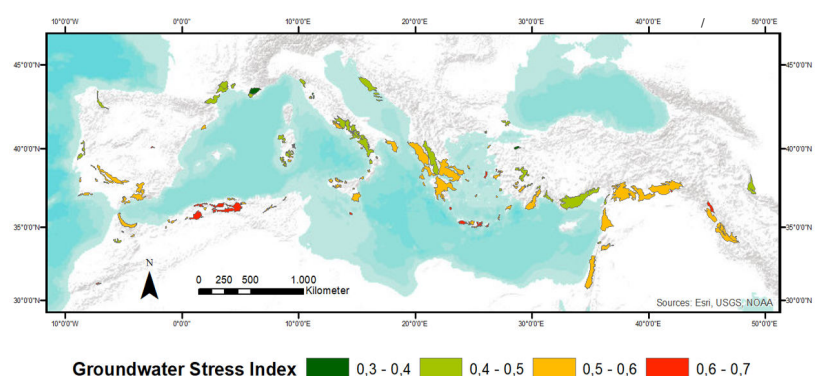


Figure 1: Groundwater Stress Index for 133 Mediterranean karst aquifers (focus on Mediterranean Sea); 0 = no water stress, 1 = extreme water stress

Calculating groundwater stress of Mediterranean karst aquifers and estimating their vulnerability to climate change on a global scale



Groundwater stress

Groundwater stress is commonly interpreted as the imbalance between natural recharge and abstractions for human use. Recent studies (e.g., de Graaf et al., 2019) showed the importance of adding environmental flow requirements to this equation. Exacerbated by population growth and climate change, groundwater resources are under extreme pressure: Gleeson et al. (2012) calculated that the global groundwater footprint ("the area required to sustain groundwater use and groundwater-dependent ecosystems") is 3.5 times the actual area of aquifers.

groundwater expressed as percentage of total area equipped for irrigation (FAO AQUASTAT). Finally, 17 identifies groundwater-dependent ecosystems, based on natural areas that maintain a relatively constant amount of green vegetation (high NDVI; MOD13Q1 data) during dry periods.

Results

Indicator values were spatially and temporally averaged to describe a recent trend on aquifer level and normalized to range between 0 (no water stress) and 1

(extreme water stress). For index composition, we gave each indicator an equal weight, although groundwater storage was excluded because of high correlation with groundwater recharge. Due to incomplete data for individual indicators, we could calculate a Groundwater Stress Index (GSI) for 133 aquifers. The result is shown in Figure 1 for the Mediterranean, indicating increased groundwater stress in southern Spain and northwest Africa, parts of Greece, and the Middle East. In comparison, many aquifers on the European Mediterranean coast show relatively low groundwater stress. The aquifers were afterwards grouped based on similarities in two classification parameters: degree of karstification (terrain was used as a proxy) and land cover. With three classes each, we built 9 aquifer groups. For each group, we plotted calculated GSI values with the aquifers' average annual temperature and precipitation (ERA5 data). We then assessed the difference in groundwater stress accompanied by altered climatic factors (i.e., the vulnerability to climate change). The results are summarized in Figure 2. In general, all 9 groups show very similar trends of higher GSI values with temperature increase and precipitation decrease with varying magnitude.

Application

Our approach mimics the effect of climate change on groundwater stress relying on present-day observed conditions. The methodology's simplicity is its greatest strength and limitation, as information is unavoidably lost through temporal and spatial data aggregation. Furthermore, some of the defined aquifer groups did not have enough members to be a representative sample. This had a strong effect on the identified vulnerability trends, showing the steepest slopes in the groups with the fewest members. This could be mitigated by adding additional climate zones into the analysis, considering that, as shown by Beck et al. (2018), Mediterranean climate zones are likely to expand or shift until the end of the century.

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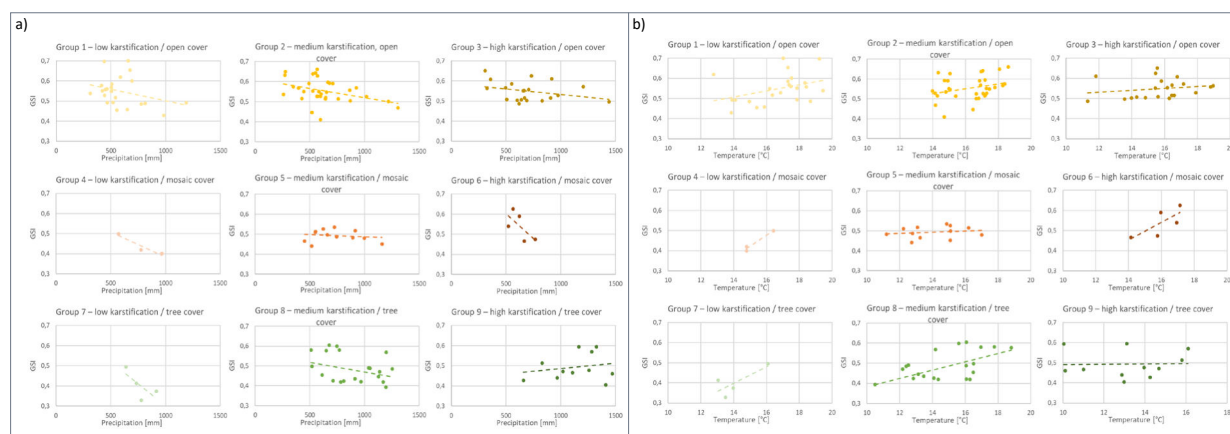


Figure 2: Relationship between groundwater stress (GSI) and a) average sum of annual precipitation (2000-2019) and b) average annual temperature (2000-2019) for 9 aquifer groups, based on similar karstification and land cover

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