Mapping steady-state groundwater levels in the Mediterranean region: The Iberian Peninsula as a benchmark

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Abstract

Groundwater is a strategic freshwater resource in the Mediterranean region. Excessive reliance on this vital resource, mainly for agricultural uses, has caused severe groundwater depletion in many aquifers. Uncertainties in groundwater availability are further exacerbated by climate change and its associated impacts. To address these challenges and ensure the longevity of this resource, sustainable groundwater management is essential. Unfortunately, our knowledge of groundwater status at the regional Mediterranean scale is limited due to the lack of consistent in-situ monitoring and data sharing. Groundwater modelling at the global scale offers a tool to evaluate the status of data-scarce regions. This study aims to assess steady-state water table depth in the Mediterranean region and its uncertainty by examining the simulations of three global gradient-based groundwater models. To examine these models' agreement with observed data, we focused for demonstration purposes on the Iberian Peninsula for its climatic diversity similar to that of the Mediterranean region and for its relatively high density of in-situ data. Results showed that the models represented reasonably well the observed groundwater heads of the Iberian Peninsula (R^2 = 0.70-0.74). The models performed better at low elevations than in mountainous areas. To overcome the limitations of the regional models, a geostatistical approach is proposed to downscale the average of the three models for different subsets of the observed data (i.e., 10, 30, 50, and 70%). Results revealed that when the average simulated groundwater depth was conditioned with at least 50% of observations (equivalent to about three wells per 1000 km^2), the spatial groundwater patterns in the Iberian Peninsula were well reproduced ($R^2 \geq 0.65$). Overall, this study shows that despite their underlying assumptions, global models can be used to map regional groundwater resources as long as they are conditioned on observed data.

Keywords

Large-scale modelling, Model performance, geostatistics, Groundwater observations, Iberian Peninsula.

Highlights

- Global groundwater models predicted consistent heads for the Mediterranean basin.
- Models performed better at low elevations than in mountainous areas.
- Global models reproduced well the observed head trends in the Iberian Peninsula.
- A geostatistical approach conditioning global models on observations is proposed.
- Model conditioning with observations density of 3/1000 km^2 or more is recommended.

1. Introduction

Groundwater systems are vast freshwater reserves that are integral components of the hydrologic cycle, comprising about 97% of the accessible global freshwater resources (Gleeson et al., 2016). They represent natural storage systems essential for sustaining domestic, industrial, and agricultural water demands especially during the dry season. Groundwater resources are often the primary source of freshwater or are required to supplement scarce surface-water sources. They also play a fundamental role in alimenting surface water bodies such as rivers, wetlands, and coastal lagoons, ensuring their related ecosystem services, (e.g., Erostate et al. (2020)). Groundwater systems are much more effective for long-term water storage than surface water systems due to the lower evaporative losses from the subsurface. This is particularly relevant for the Mediterranean basin, where potential evaporation rates are generally much higher than precipitation rates (Boulet et al., 2020).

The Mediterranean region's water resources are often fragile, scarce, and unevenly distributed in space and time, particularly in the southern and eastern parts (MedECC, 2020). Groundwater accounts for more than 50% of the available water resources in the Mediterranean region and is essentially the only water resource in the Saharan area. Even though groundwater represents a strategic freshwater reserve in the Mediterranean region (Heggy, 2018) that can mitigate human-induced and climate-related pressures, its status is increasingly uncertain. Furthermore, most Mediterranean countries are expected to face enormous challenges in meeting future higher water demands in almost all sectors with dwindling freshwater resources. The problem is accentuated further due to socio-economic development, such as mass Mediterranean tourism and fast population growth (Cudennec et al., 2007; García-Ruiz et al., 2011). The total population of the states bordering the Mediterranean Sea in 2018 was about 512 million (UN DESA, 2019), representing 6.7% of the world population. On the northern shores, the population has been stagnant since 1980. However, significant increase in population was observed in the south and east of the Mediterranean Sea basin, where the population has more than doubled between 1980 and 2018 from 153 to 314 million. Recognizing that the increase in irrigated areas is proportional to population growth, Shen et al. (2008) estimated a 1-10 km^3/year rise in total water withdrawals in all Mediterranean catchments. Water scarcity is expected to increase further due to climate change and the increasing demand for irrigated agriculture to maintain crop yields and ensure food security (Albiac, 2013; Iglesias et al., 2012).

In addition to the climatic and hydrological factors, the socio-economic characteristics, legal differences among Mediterranean countries, and the absence of constructive policy decisions have amplified the stressed water conditions. For instance, while northern Mediterranean countries have adopted regulations for the protection of groundwater resources, such as the Water Framework Directive in 2000 and the Groundwater Directive in 2006, water regulations in the south Mediterranean region remain complex and fragmented. Furthermore, the lack of systematic monitoring, data-sharing policy and complex water policies in some areas limit the quantitative assessment of this vital resource (Jomaa et al., 2021).

The Iberian Peninsula, located in the north-western corner of the Mediterranean basin, faces many of the water stresses and challenges discussed above (Bukowski, 2017). The rising demand of freshwater from different sectors, together with the increasing occurrence of droughts, led to severe overexploitation of groundwater resource in the recent decades. For instance, Spain has experienced in the last four decades three prolonged and four shorter intense drought episodes (Lorenzo, 2022). Despite the relatively well-developed water resources management in the Iberian Peninsula through national and European directives, decline in summer soil moisture due to more frequent heat waves has been observed (Kurnik et al., 2015). This situation has led to significant changes in agricultural practices with irrigated lands persistently expanded to secure food production for the Iberian Peninsula and beyond (Romero Fresneda et al., 2020). The Iberian Peninsula represents a major agricultural land-use-dominated region, with agriculture accounting for about 75% of water use. This figure is comparable to that of the entire Mediterranean region, where agriculture consumes about 65% of total withdrawals (Blinda, 2008). In recent years, there has been a shift from traditional dry crops to irrigated crops in the Iberian Peninsula and to crops with high water demand. The newly introduced crops on the irrigated land such as alfalfa, maize, berries and fresh vegetableshave higher water demands compared to the traditional Mediterranean crops (olives, grapes, and winter cereal crops), prompting overuse of groundwater resources and the agricultural landscape (Fraga et al. 2018, De Stefano et al. 2015, García-Ruiz et al., 2011; Giannakopoulos et al., 2009; Tanrivermis, 2003). Factors like irrigation technology advancements, market demands and high-crop profitability drive this change. While these changes improve agricultural yield, they challenge water management and sustainability. Long-term sustainable practices and integrated planning are essential to balance water demand with environmental preservation. Additionally, the high water demand for irrigation will continue due to the anticipated increasing occurrence of drought conditions (Fader et al., 2016). Due to climate change, irrigation demand is projected to increase between 4% and 18% by the end of the century (for 2°C and 5°C warming, respectively) (Fader et al., 2016). In addition, many human-induced processes are increasing the stress on water resources (Sivapalan et al., 2014; Wagener et al., 2010).

In recent decades, groundwater modelling has been increasingly used as an efficient tool for groundwater management worldwide. Studying groundwater systems and resources across different scales (from global to regional) is essential for several reasons, namely: for quantifying and understanding groundwater-surface water bodies' interactions, supporting governance and management of large aquifer systems, and providing opportunities to systematically analyse problems and propose solutions for transboundary aquifers systems. All these objectives necessitate accurate tools for modelling groundwater resources at the continental and global scales (Gleeson et al., 2020b; Reinecke et al., 2021).

Fan et al. (2013) were the first to provide a global, high-resolution steady-state water table depth map. Other approaches followed, focusing on integrating gradient-based groundwater models into global hydrological models to better simulate groundwater-surface water interactions (e.g., de Graaf et al. (2015), (Reinecke et al., 2019). These modelling studies were conducted to investigate large-scale patterns of water table depth relate to aquifer properties (de Graaf et al., 2015; Sutanudjaja et al., 2011), or topography (e.g., for the entire USA (Condon et al., 2015; Condon and Maxwell, 2015)), and quantify global anthropogenic impacts on river discharge and groundwater depletion (de Graaf et al., 2019; de Graaf et al., 2017). Similar large-scale groundwater models were developed for other regions such as (Trichakis et al., 2017) for Europe and Westerhoff et al. (2018) for New Zealand. Martinsen et al. (2022) recently used detailed national-scale estimates of groundwater recharge from seven EU countries, combined with a machine learning approach and satellite remote sensing data, to generate a consistent Pan-European long-term average potential groundwater recharge map.

Although advanced numerical local groundwater flow models are beneficial in understanding the flow field of a particular groundwater system. they are site-specific, computationally intensive, and require extensive input data at a finer resolution. As a result, hydrogeological modelling studies are often associated with high degrees of uncertainty. This is due to the underlying assumptions of these models, lack of detailed hydrogeological data to represent the heterogeneous complex subsurface system, and lack of adequate measured data for model calibration. Such modelling studies are particularly challenging in many areas of the world where detailed hydrogeological field investigations are lacking. This is also true for global modelling studies, where models must rely on various aquifer system simplifications. Here we demonstrate that improved estimates of groundwater level can be achieved through regional frameworks that jointly incorporate the results of different global groundwater models and observations of groundwater levels. This combined approach can overcome the limitations of in-situ data (e.g., spatial distribution and availability) with the strength of the models' capabilities in terms of spatial coverage and future predictions. There is an increasing number of studies that have attempted to combine hydrological models with in-situ data. For instance, Westerhoff et al. (2018) developed an improved groundwater model for New Zealand by feeding a global model with detailed national-wide terrain, geology, and recharge. Ghiggi et al. (2019) used global in-situ streamflow observations to train a machine learning algorithm that predicts monthly runoff rates based on climate parameters and other explanatory variables. Jones et al. (2022) developed a global grid-based surface water quality model at a daily time step combining extensive and high-resolution explanatory variables with global observations. These three examples demonstrate how the limitations of global models can be overcome by incorporating local detailed information and increasingly available in-situ data to yield more representative model outputs.

In this study, we evaluated three global-gradient groundwater models (de Graaf et al., 2015; Fan et al., 2013; Reinecke et al., 2019) and combined them with in-situ data to better represent regional groundwater levels in the Mediterranean context, focusing on the Iberian Peninsula. The latter was used for demonstration purposes to test how the models' results can be integrated with in-situ observed head data for better groundwater resource assessment. For this purpose, observation data from 3822 wells across the Iberian Peninsula were compiled and utilised for downscaling. The Iberian Peninsula was selected because of its readily accessible dense in-situ data and wide range of climates, and because it faces water stresses representative of the entire Mediterranean basin. We examine how predictions developed from distinct global models can be combined with in-situ data to better evaluate and ultimately manage available groundwater resources. But, how many in-situ data are necessary to substantially improve the downscaled global models? To this end, the analysis is repeated, assuming different subsets (10, 30, 50, and 70%) of the 3822 data are available with the aim of identifying a minimum amount of in-situ data for acceptable estimates. Specifically, the objectives of this study are to (i) assess the groundwater resources in the Mediterranean region using the outputs of three global groundwater models, (ii) evaluate the performances of the models against in-situ data for the Iberian Peninsula, and (iii) map the steady-state water table depth using the models' results conditioned with different subsets of the observations from the Iberian Peninsula. Developing a comprehensive understanding of the groundwater resources at a regional scale even in steady-state conditions are relevant for long-term management and identification of policy needs. An important output of this study is to provide guidance on the optimum observation wells density required for accurate mapping of groundwater level at a regional scale.

2. Materials and methods

2.1. Research area

2.1.1. The Mediterranean region

The Mediterranean Sea Basin, located in the middle of the Ecumene between Europe, Africa, and Asia, covers terrestrial parts of 22 countries with a total Mediterranean coastline of 46,000 km. According to Koppen's climate classification (Rubel, 2017), many areas of the Mediterranean region are characterized by dry and hot summers with seasonal droughts and humid winters with intense rainfall events and wide spatiotemporal precipitation patterns. The annual precipitation is less than 400 mm in several southern Mediterranean region countries (less than 255 mm in parts of North Africa) and more than 1000 mm for the northern shores (with precipitation exceeding 2540 mm near Dalmatia in Croatia). Potential evapotranspiration is mostly above 1200 mm, indicating a high water deficit in many areas (EC, 2012). The topography of the region shows that most of the Mediterranean basin is surrounded by high mountains: the Pyrenees in southwestern Europe, the Alps in southern France and north-western Italy, and the Atlas Mountains in northern Africa. The Mediterranean basin is also characterized by semi-arid steppes and coastal wetlands. The prevalence of limestone rocks means that karstic catchments are common in the region. The abundant karstic resources across the Mediterranean are unequally exploitable and subject to conservation restrictions. Hartmann and Moosdorf (2012) showed that the Mediterranean region's lithologic structure and physical properties are 85% sedimentary rocks, of which one-third are carbonate rocks. The Mediterranean land cover map shows that cultivated lands, managed shrubs, and trees are the three largest land types covering 31%, 23%, and 20% of the land, respectively (Bartholomé and Belward, 2005). In terms of land use, agriculture historically dominated the coastal plains. This pattern is partly due to past human activities but is now being disrupted by the intense urbanization of the Mediterranean coastal plains and the replacement of some agricultural terraces in favour of Mediterranean forests, particularly in Europe (Morán-Tejeda et al., 2010).

2.1.2. The Iberian Peninsula

The Iberian Peninsula, located in the southwestern corner of Europe, has a complex orography with high plains in the interior surrounded by mountain ranges that occasionally reach the coastline. The Iberian Peninsula has a typical Mediterranean climate with an extended dry season, where evapotranspiration depends mainly on water availability. It is witnessing a rising precipitation seasonality and land-atmosphere coupling (Rios-Entenza and Miguez-Macho, 2014). The Cantabrian Mountains, with 700 mm/year of precipitation (Font-Tullot, 2000), separate the humid northwest from the rest of the Peninsula. The northwest highlands record a mean annual precipitation value above 2800 mm, representing one of the wettest regions in Europe (Cardoso et al., 2013). However, the driest regions are located in the southeast, where precipitation is the absolute minimum in Europe, with less than 200 mm/year (Font-Tullot, 2000). The semi-arid climates extend over large areas in the east and centre of the Iberian Peninsula (Gimeno et al., 2010; Martin-Vide, 2001). The annual precipitation distribution shows large differences between the northwest and the Mediterranean coastal area. Along the Mediterranean coast, high precipitation occurs in autumn (Millan et al., 2005). In contrast, inland, which lacks maritime influence, is characterised by high spring precipitation, an important period for agriculture and plant ecology. The summer is often dry. Over the last decades, groundwater use for irrigation has intensified significantly in almost all arid and semi-arid areas of Spain, similar to many other regions of the Mediterranean basin. Irrigation is mainly carried out by farmers without enough control and planning from water authorities (Garrido et al., 2006).

2.2. Description of the global models

Three global process-based groundwater models were considered in this study (de Graaf et al., 2015; Fan et al., 2013; Reinecke et al., 2019). These models have been described in detail in their original publications; thus, only a brief summary is given here. Table 1 presents the main characteristics of each model.

Table 1. Main features of the global steady-state models (modified from (Reinecke et al., 2020)).

Input data	**de Graaf et al. (2015)**	**Reinecke et al. (2019)**	**Fan et al. (2013)**
Spatial resolution	6′ (~10 km)	5′ (~9 km)	30″ (~1 km)

Timescale	Steady-state and transient	Steady-state and transient	Steady-state
Surface elevation	5’ avg. of 30” DEM from HydroSHEDS	5’ avg. of 30” DEM	Modified 30” DEM
Conductivity data	GLHYMPS 1.0 (Gleeson et al., 2014)	GLHYMPS 2.0 (Huscroft et al., 2018)	Global lithology (Hartmann and Moosdorf, 2012)
Aquifer thickness	Calibrated	200 m	Infinite
Layers	1 (vertically integrated)	2	1 (vertically integrated)
Groundwater recharge for steady-state	Simulated long-term averages PCR-GLOBWB (1960-2010)	WaterGAP mean (1901-2013)	Simulated mean of annual recharge multiple GHMs (1961-1990)
Surface waterbody location	In almost every cell	In every cell	No surface water
Calibrated	Manual	No	Manual
Software	MODFLOW	G³M-f	Fan and Miguez-Macho model (2011)

*GHMs: Global Hydrological Models

2.2.1. Fan et al. (2013) model

The “Equilibrium Water Table” (EWT) model by Fan et al. (2013) is a steady-state groundwater model that was the first to simulate a high-resolution global groundwater table depth map at 30′′ (arc-seconds). A variety of global data, including both satellite data and ground-based observations, were used to calculate water table depths (WTD) for each cell (Fan et al., 2013; Fan and Miguez-Macho, 2011; Miguez-Macho et al., 2007). This model provides a long-term average of the WTD without pumping or irrigation. The EWT method uses estimates of hydraulic conductivity from a global soil database (Reynolds et al., 2000) for the top 1 m of soil. Below this depth, the hydraulic conductivity is assumed to decrease exponentially with depth. Also, this model ignores the hydraulic interrelation between rivers and groundwater. Moreover, this model requires calibration to head observations (de Graaf et al., 2015) and does not simulate surface water runoff; if the groundwater table is estimated to be above the ground surface, the model simply removes that volume of water from the system (Reinecke et al., 2019, Fan et al., 2013). The calculation of the groundwater table and the long-term equilibrium between vertical and horizontal groundwater flows is based on mass balance and Darcy's law (e.g., Dingman, 2002; Hendriks, 2010). This model uses elevation data from global topography models at 30" resolution (Smith and Sandwell, 2003). The net recharge to groundwater is defined, at a resolution of 30", equal to the mean annual estimates of Döll and Fiedler (2008). The hydraulic conductivity was calibrated on a continental scale (Fan et al., 2013) using ground-observed groundwater level data.

2.2.2. de Graaf et al. (2015) model

The model by de Graaf et al. (2015) represents a global-scale groundwater model (excluding Greenland and Antarctica) at 6' spatial resolution (approximately, 10 x 10 km at the equator) over the period 1960-2010. The model defines the global aquifer system as a single-layer unconfined aquifer. The model provides a first-order estimate of the spatial variability of groundwater table elevation in its natural state as a function of geology and climate, i.e., ignoring groundwater extraction. The head distribution is controlled by groundwater recharge and river discharge with outputs from the global hydrological model PCR-GLOBWB (van Beek et al., 2011). The model consists of two components: (1) the hydrological model PCR-GLOBWB used to calculate the initial annual net recharge and channel discharge, and (2) a groundwater model using MODFLOW (Harbaugh et al., 2000). The high-resolution global lithological maps (GLiM) (Hartmann and Moosdorf, 2012) and permeability databases (Gleeson et al., 2011) were initially used for the parameterization of the aquifer properties. It is worth mentioning that there is an updated version of de Graaf et al. (2015) model that improved the assumption and parameterization of the model, considering both confined and unconfined layers of groundwater systems (de Graaf et al., 2017).

2.2.3. Reinecke et al. (2019) model (G^3M)

Reinecke et al. (2019) developed the G^3M model (referred as Reinecke et al. (2019) model in this study), a global process-based groundwater model that was targeted to be integrated into the global hydrological model WaterGAP 2 (Döll et al., 2014; Müller Schmied et al., 2014). The model, with a grid size of about 9 km x 9 km at the Equator, computes lateral and vertical groundwater flows, groundwater storage changes, and exchanges with surface-water bodies for all land areas. The model is based on the groundwater modelling framework G^3M-f (open source and available at https://globalgroundwatermodel.org/, last accessed 22 February 2023), which relies on the groundwater flow equations and processes described in the MODFLOW code (Harbaugh, 2005). In this study, only the steady-state variant of the model is used without considering groundwater pumping. The hydraulic conductivity used in G^3M was derived from GLHYMPS 2.0 (Huscroft et al., 2018) using the GLiM high-resolution global lithology map (Hartmann and Moosdorf, 2012). The hydraulic conductivity of the deeper layer was determined assuming that conductivity decreases exponentially with depth. Ocean boundary heads were set globally to 0 m. Groundwater recharge is based on mean annual groundwater recharge (Döll et al., 2014) for the period 1901–2013 computed by WaterGAP 2.2c (Müller Schmied et al., 2014). At each cell, the 30th percentile of the 30" land surface elevation from Fan et al. (2013) is used as the surface water body elevation. The 30th percentile was selected because it represents an average or typical elevation within a region, capturing surface water spatial distribution and variability (Reinecke et al. 2019).

2.3. Comparison of simulated hydraulic heads with observations in the Iberian Peninsula

Several types of data were used in the analysis of this study, including WTD, hydraulic head, and topographic elevation (DEM). Groundwater level observations were collected for the whole Iberian Peninsula in the form of WTD and hydraulic head. For Spain, groundwater level data from 2883 wells were downloaded from (https://sig.mapama.gob.es/geoportal/, last accessed 22 September 2021) for the period 1965-2017. The data are maintained by the Ministry of Agriculture and Fisheries, Food and

Environment and the Ministry for Ecological Transition through the Monitoring Network Information System Portal. For Portugal, a total of 939 wells were downloaded from the national groundwater database (https://snirh.apambiente.pt/, last accessed 22 September 2021). The data are maintained by the Portuguese Environmental Agency through The National Water Resources Information System (SNIRH). Thus, a total of 3822 groundwater level time series were used, spanning 25 years on average. Such a large number of wells provides a unique opportunity to evaluate the predictions of the different global models. Also, and as described below, the in-situ data were combined with the model results to obtain improved estimates of the WTD spatial variation over the Iberian Peninsula. To compare global steady-state flow models to transient WTD and head observations, transient groundwater data is aggregated by averaging values over the period from 1965 to 2017. This results in single WTD for each monitoring well, a long-term average of the whole time series data representative of steady-state conditions.

2.4. Evaluation of model predictions against observed heads

The observed data were compated to each model individually as well as the arithmetic average of the three models. The three models were evaluated after aggregating each model's simulated heads on a regular 4.4 km x 4.4 km grid covering the Iberian Peninsula. This grid is finer than those used by (Reinecke et al., 2019) and (de Graaf et al., 2015); however, it is coarser than the grid of (Fan et al., 2013) (Table 1).

To facilitate the comparison of the gridded model results and the irregularly distributed data from the observation wells, the observed data were interpolated onto the same uniform 4.4 km x 4.4 km grid. Yang et al. (2004) showed that there is no absolute best interpolation method and that the optimal choice is rather case-dependent. In addition, Yang et al. (2004) stated that the interpolation results should be critically evaluated based on what we know about the interpolated surface. In this study, the areal interpolation method, geostatistical ktiging-nased interpolation method, was utilized for the estimation of the data on the grid. The method estimates values and standard errors for an entire geographic area based on data available for a different polygon system. It redistributes values from a given polygon system onto another polygon system considering their spatial relationships (Mennis, 2003). Since the density of observation data is quite large, with observed data in all regions of the Iberian Peninsula, the interpolated and observed heads are not significantly different. Commonly, the simulated and the interpolated observed groundwater heads are compared instead of the WTD because the head represents the energy per unit weight that drives flow and is consequently physically more meaningful (Gleeson et al., 2020a). It also avoids the need for an accurate surface elevation at the monitoring well.

The agreement between the models results and the interpolated observations were evaluated by computing the coefficient of determination (R^2) and residual maps. Residuals were computed as simulated minus interpolated heads. To further explore the consistency of the three models with the observed data, we compare the residual heads of the three models, defined as the average simulated head minus the interpolated observed heads grouped under five land surface elevation categories.

2.5. Mapping of WTD by combining model predictions and observations

In this study, we present a mapping approach that combines models predictions and in-situ data to estimate WTD across the Iberian Peninsula. This process allows for a comprehensive spatial distribution and variability of steady-state WTD that combines both sets of the data: the model results as well as the irregularly spaced in-situ measurements. The model results are derived from a process-based numerical model providing complete spatial coverage. However, simulated values are subject to some degree of uncertainty due to the assumptions inherent in any model. In contrast, observed WTD data are direct measurements deemed more accurate but reflect local conditions. Combining both sets of data benefits from the strength of each data type: direct measurements, which are more accurate but typically limited in number versus the exhaustive coverage that the model results provide, which relies on solving the governing groundwater flow equation using various hydrogeological data such as hydraulic conductivity, land use, recharge and imposed boundary conditions.

The model conditioning process involves interpolating the residuals of WTD data and then adding it to the average simulated WTD of the three models. The interpolation of the residuals allows for adjusting the model outputs to match the observed WTD data more accurately. The equation of the conditioning process is expressed as follows:

$$WTD(x,y) = WTD_s(x,y) + \sum_i^N \omega_i [WTD_{o,i} - WTD_{s,i}],$$

where $WTD(x,y)$ is a weighted depth to water table at location (x,y), $WTD_s(x,y)$ is the simulated depth to water table at location (x,y) equal to the average of the WTD simulated by the three models, $WTD_{o,i} - WTD_{s,i}$ are the residuals between the observed and simulated depths at observation locations, ω_i are weights determined from kriging and N *is* the number of nearby observation points used in conditioning.

It should be mentioned that the model conditioning can be viewed as an interpolation of the in-situ data using kriging with a spatially varying mean that is defined to be equal to spatial distributed average of the global models.

This study includes a large number of observation data covering the Iberian Peninsula, which is not common in most modelling studies. In typical studies, often a much smaller number of such measurements are generally available. Considering the estimated map combining the three global models and all the available data as reference, an exercise is performed by developing WTD maps by randomly retaining subsets of the data (10%, 30%, 50% and 70% of all data), with the objective of determining a threshold number of observations to obtain good estimates.

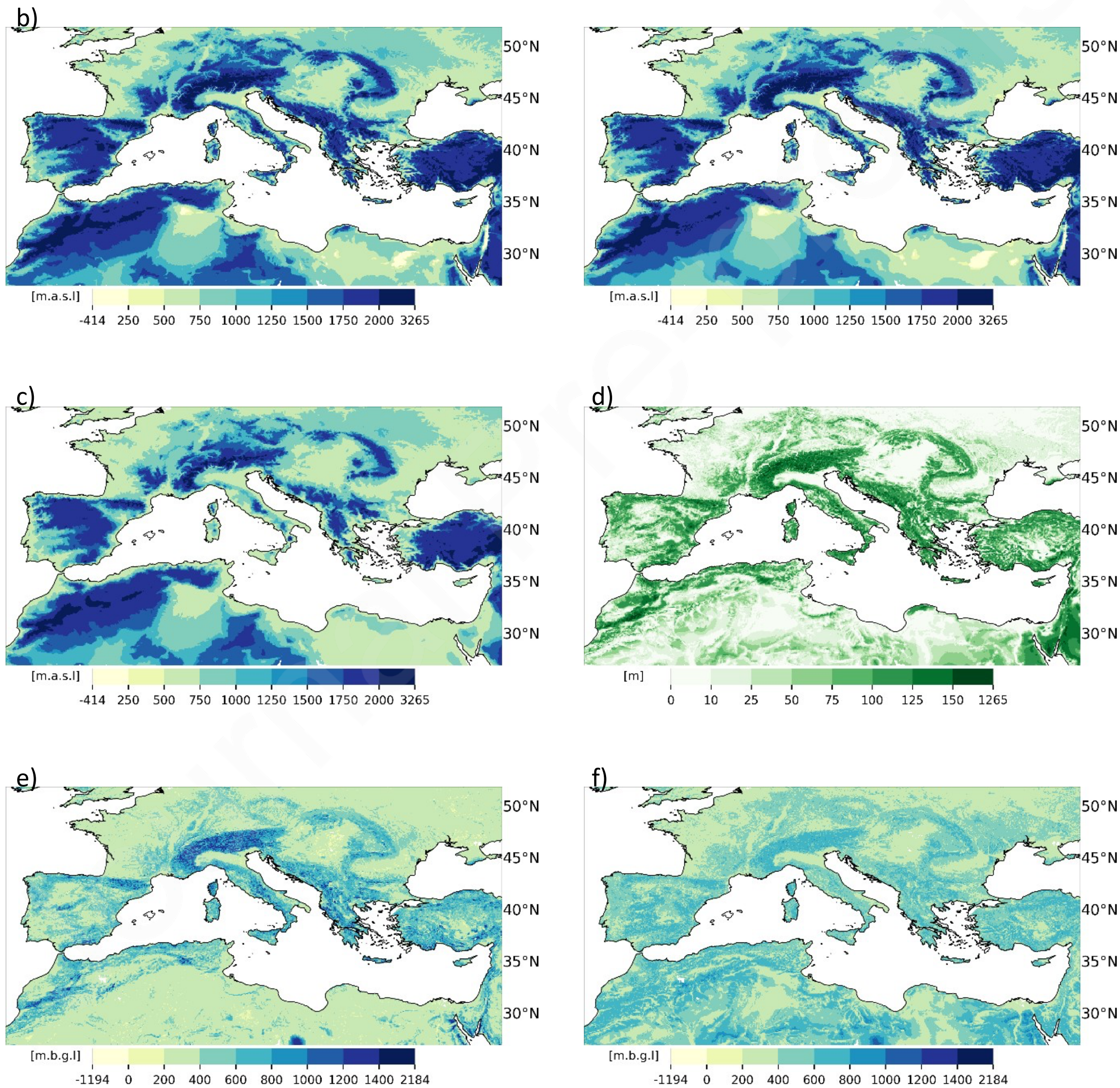
3. Results

3.1. Regional hydraulic head distribution under natural steady-state conditions

Figs. 1a-c show the simulated steady-state groundwater levels obtained by the three global models under natural conditions (without abstractions) in meters above sea level (m.a.s.l). These maps illustrate the general pattern of hydraulic heads in the Mediterranean region. For Fan et al. (2013), the heads were calculated by subtracting the WTD from the land surface elevation. However, for the other models, the steady-state hydraulic head was directly reported.

It is observed that the simulated steady-state hydraulic head generally follows the land surface elevation (Fig. 1). However, as expected, the head varies within a smaller range than surface elevations, and, hence, the hydraulic gradient departs from the surface elevation slope. For example, higher heads are observed for all models in the Alps, in southern France and north-western Italy, and the Atlas Mountains in northern Africa, whereas lower heads are observed along the coast. Fig. 1d depicts a map of the standard deviation of the heads simulated by the three models. It is observed that the discrepancies between the three models can be quite large. This difference is attributed to the global nature of the three models, which necessarily involves a number of assumptions, the relatively coarse discretization of the model, and differences in the model input data. The highest standard deviations in excess of 1000 m, are observed in the mountainous regions.

Figs. 1e-1g illustrate the spatial patterns of simulated WTD as obtained from the three models,. Fig. 1h presents the standard deviation of WTD of the three models. Compared to the hydraulic heads, high discrepancy between the three models is observed in different regions, especially in the mountainous regions. For instance, de Graaf et al. (2015) model shows greater WTD estimates compared to the other models. The slight differences between the standard deviations of hydraulic heads and WTDs (Figs. 1d and 1h) are due to the use of distinct spatial resolutions for land surface elevation.



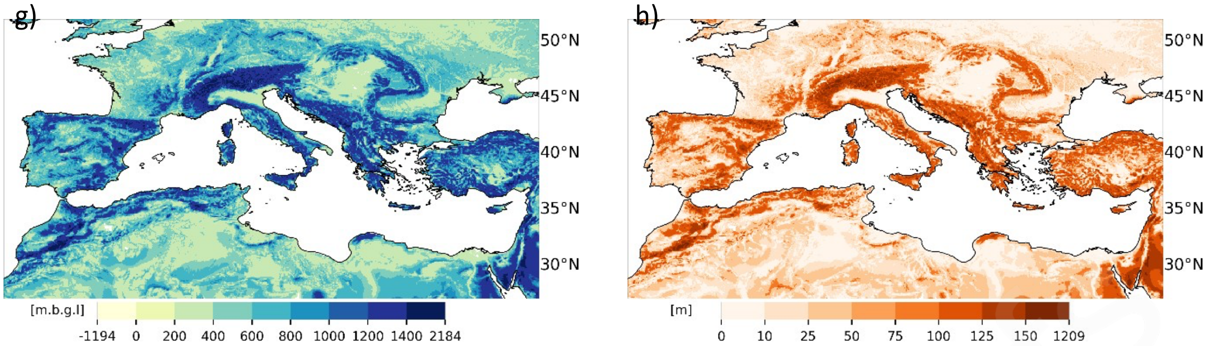
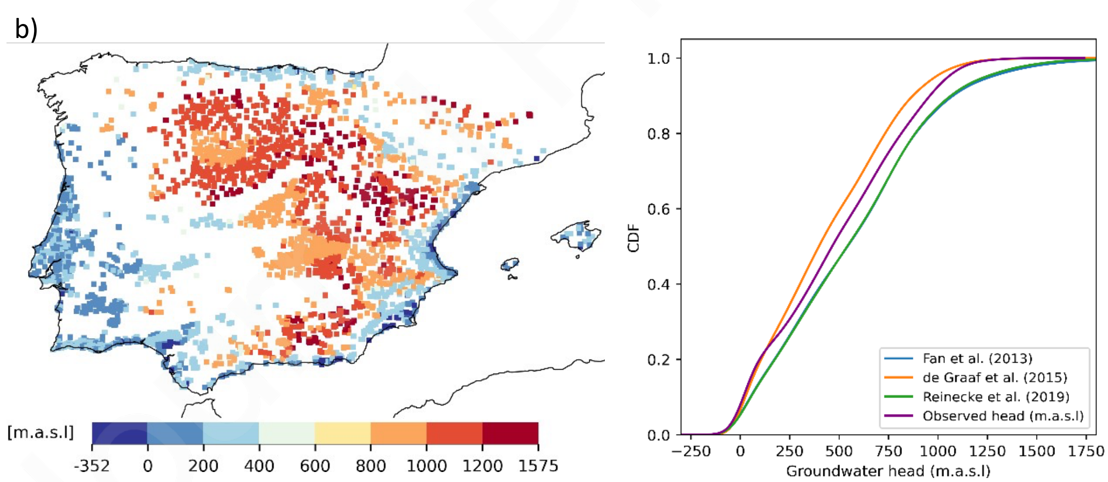


Fig. 1. Steady-state simulated groundwater head (m.a.s.l) as obtained from the three models in the Mediterranean. (a) Reinecke et al. (2019), (b) Fan et al. (2013), (c) de Graaf et al. (2015), and (d) standard deviation of steady-state simulated groundwater head (m) as obtained from the three models. Figs. (e)-(g) represent the steady-state water table depth (m.b.g.l) from the three models, and (h) is the corresponding standard deviation (m).

3.2. Comparison to groundwater well observations in the Iberian Peninsula

The spatial patterns of observed steady-state head and WTD over the Iberian Peninsula are given in Figs. 2a and 2c, respectively. The corresponding cumulative distribution functions (CDF) of the simulated and observed heads and WTD are shown in Figs. 2b and 2d, respectively.



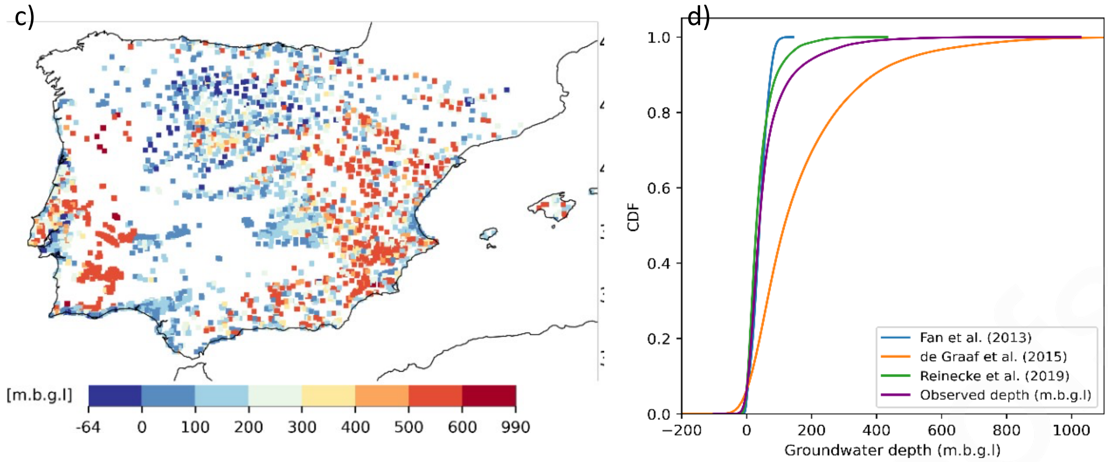


Fig. 2. (a) Spatial distribution of observed groundwater heads in the Iberian Peninsula, (b) cumulative distribution function (CDF) of the simulated and observed heads, (c) spatial pattern of observed WTD in the Iberian Peninsula, and (d) CDF of the simulated and observed WTD.

Observed heads are better reproduced than WTDs by the three models, as also seen from the maps shown in Fig. 1. To further examine the three models, the observed data were interpolated on the same grid as the mode results. The interpolated heads and the arithmetic average of the three models over the entire Iberian Peninsula are shown in Figs. 3a and 3b, respectively. Fig. 3c shows the spatial distribution of the residuals defined as the difference between the average of the three models and the interpolated heads. Based on visual inspection, the simulated heads mimic the same spatial patterns in the map obtained from the observed data. The interpolated head values vary from mean sea level at the coast to a maximum of about 1500 m (Fig. 3a). However, the difference map (Fig. 3c) shows that the simulated heads are seen to overestimate the observed heads (such as in the Pyrenees). The underestimation of hydraulic heads occurs especially for higher elevated areas (as shown in Figs. 3c-d). This underestimation is to be expected because shallow water tables are most likely present in higher elevated regions that the three models do not capture due to the coarse grid resolution. Overestimation of heads is also evident at lower elevations (approx. 0-500 m). On the other hand, the model heads across Spain and Portugal border seems to overestimate the observed values. This could be explained by the possible bias of in-situ data monitored separately by the two countries, resulting in a discontinuity in the interpolated data (Fig. 3a). This points to the need to develop international standardized protocols for data collections and reporting.

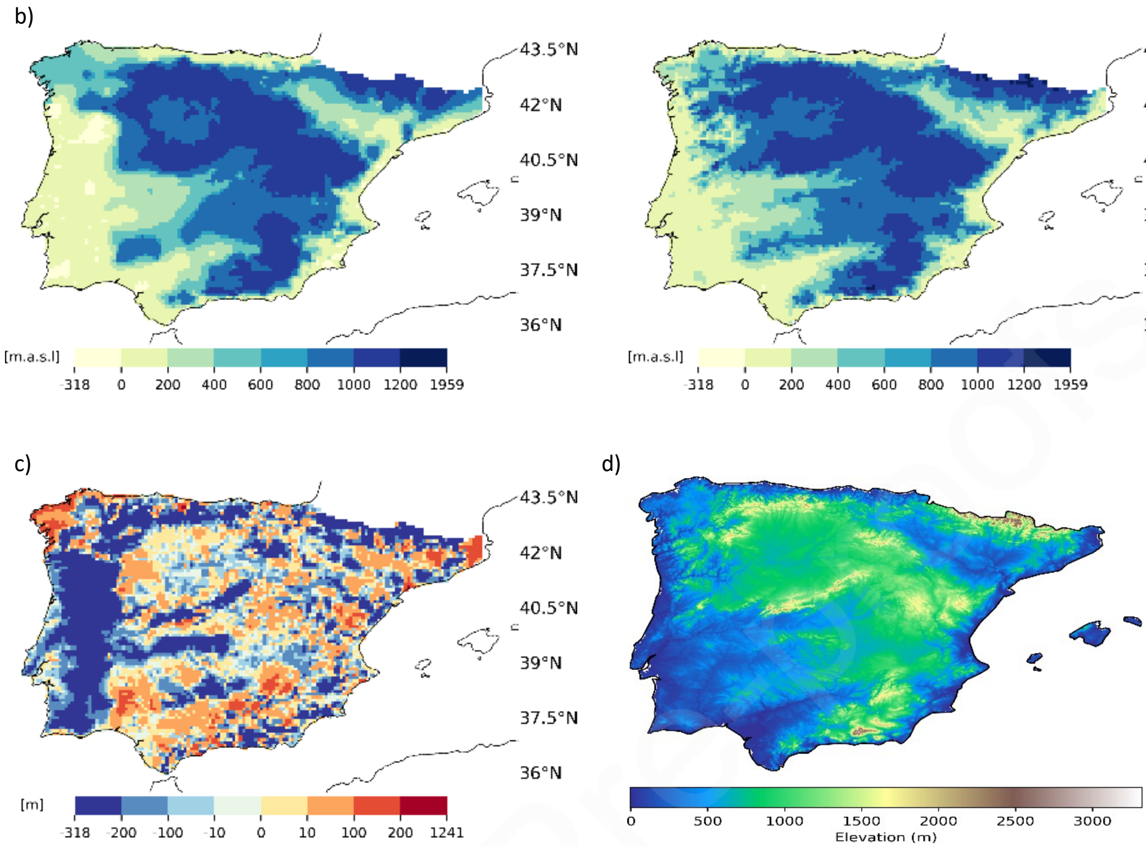


Fig. 3. (a) Steady-state groundwater head in the Iberian Peninsula obtained by interpolating the observed values, (b) mean of steady-state simulated groundwater head (m) as obtained from the three models, and (c) difference between (a) and (b) (blue reflects the model overestimation, while the red shows the underestimation). (d) Digital elevation model for the Iberian Peninsula (m) obtained from HydroSHEDS.

3.3. Evaluation of the simulated heads in the Iberian Peninsula

The performance of the three groundwater models was further analysed by examining scatter plots and probability density functions of the simulated and observed (interpolated onto the 4.4 km by 4.4 km) heads. Fig. 4a displays a scatterplot of simulated vs. interpolated heads and (as an inset) a scatterplot of residuals vs. interpolated heads. Fig. 4b shows the density distributions of the interpolated and simulated head data using a Kernel Density Estimate (KDE). Data shown in Fig. 4a are the simulated heads at the centre of each grid compared to the average of all heads falling within that particular grid.

Fig. 4 shows more outliers in both Reinecke et al. (2019) and Fan et al. (2013) models than in de Graaf et al. (2015) model, especially at high head values close to 1000 m (Fig. 4a)suggesting that the simulated steady-state hydraulic heads of de Graaf et al. (2015) better matches the interpolated heads in the Iberian Peninsula. The overall correlation of the interpolated and simulated hydraulic heads is quite good for all three models (R^2 = 0.7-0.74, Fig. 4a) but has important local differences. The univariate head distribution (KDE plot) of the de Graaf et al. (2015) model, shown in Fig. 4b, is remarkably close to the observed data (shaded in purple) with the highest coefficient of correlation (R^2 = 0.74). Reinecke et al. (2019) and Fan et al. (2013) models appear to have the same distribution, especially for extreme values (e.g., above 1000 m likely due to the use of the same source of land surface elevation from HydroSHEDS (5’ averaged DEM, Table 1).

Because the steady-state models cannot account for the effects of groundwater abstraction, the computed hydraulic head values are lower than the interpolated values in the groundwater depletion areas. As mentioned above, this difference can be attributed to the global nature of these three models and the relatively limited local data used for their calibration.

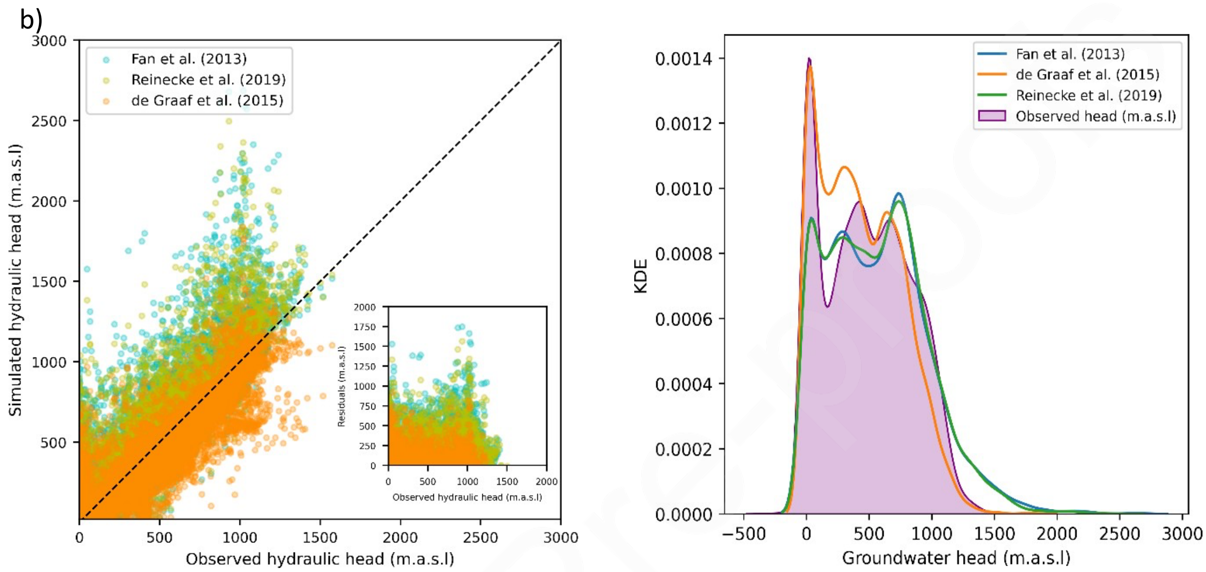


Fig. 4. (a) Scatter plots and residuals of interpolated versus simulated groundwater head values in the Iberian Peninsula and (b) comparison of Kernel Density Estimate (KDE) plots of the three models with the interpolated values of groundwater head in the Iberian Peninsula.

Fig. 5 shows the head residuals. Results indicate that the residuals are getting higher and more widely dispersed as the surface elevation increases. This is evident for the average values of the three models (Fig. 5) as well as for each of the three models individually (Fig. 4a), indicating that the models' performance is affected by the topography, especially when the elevation is greater than 500 m.

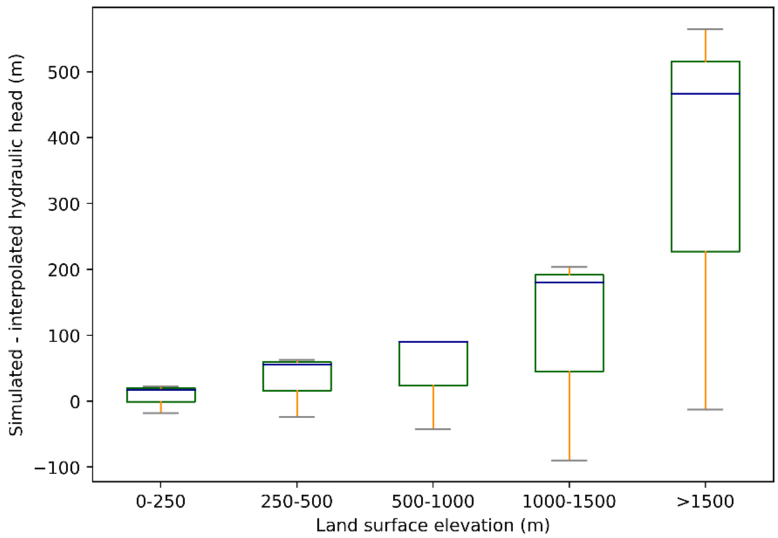


Fig. 5. Boxplots of residuals (simulated average of the three models - interpolated observed head) vs. land surface elevation categories.

3.4. Conditioning the simulated WTD on available in-situ data

. While the hydraulic head is the quantity that appears in the groundwater flow equation and is computed by the models, WTD is often of more interest from an exploitation point of view. For this reason, this section focuses on WTD and aims at obtaining the improved estimate by combining both model results (from different models) and ground observations. Using a geostatistical approach, we build a model for the spatial variability of WTD in which the average of the three models represents a non-stationary mean value about which the true WTD oscillates. Interpolating the observed WTD data using this model should give a better map than any of the simulated model maps or the interpolation of the observations with a stationary mean. In this section, we analyse how much we can reduce the amount of observed data and still obtain a reliable interpolated map. For this purpose, the interpolated map using all data (and the mean of the models as the mean of our geostatistical model) is used as the reference, and this map is compared with new interpolated maps computed using a fraction of the original data. In this case, the analysis was performed by randomly retaining subsets of the original data.

Fig. 6 shows the averaged simulated steady-state WTD as derived from the three models conditioned on the observed WTD data for the Iberian Peninsula. For comparison, the maps corresponding to the 10, 50 and 100% (reference map) of the observed data are shown in Figs. 6a-c, respectively. These maps combine the information from model outputs and observed data. For locations without direct observations, the weighted WTD estimate is close to the simulated WTD computed from the global groundwater model outputs. At locations close to observations, the conditioned WTD approaches the measurements. As more data are included, the simulated maps become more consistent with the observed data (Fig. 2c).

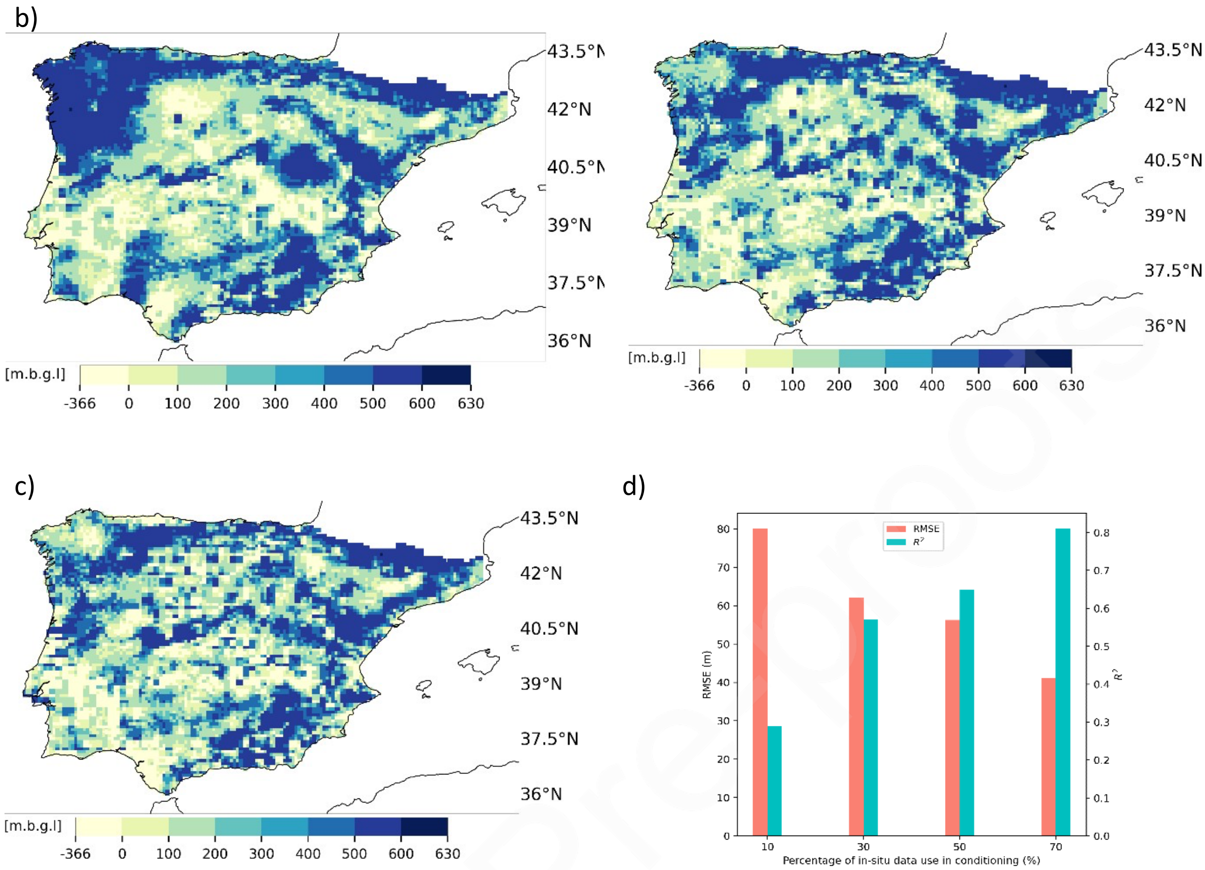


Fig. 6. Mean of steady-state simulated water table depth (WTD) (m) as obtained from the three models conditioned on (a) 10, (b) 50% of observed data, (100%) reference map (c), and (d) performance metrics for the 10, 30, 50 and 70 subsets in terms of RMSE and R^2.

Results show that when at least 50% of observed data (equivalent to about three observations per 1000 km^2) are incorporated in conditioning, the general patterns of WTD are well represented (with $R^2 > 0.5$). This includes the WTD in the mountainous regions such as the Pyrenees, which were not well represented in the global models. The effect of conditioning is clearly seen in the North West of the Iberian Peninsula, where the models predict deep water table compared to observations. Visual inspection also shows WTD values in the Central and West of the Iberian Peninsula tend to be in the low to medium range, while the WTD in the North and East seem to be in the medium to high range of WTD values. Increasing the percentages of conditioning data from 10 to 70% of the available observational data resulted in a significant improvement in performance compared to the reference data set (100% of data), as evidenced by a decrease in RMSE from 80 m to 41 m and an increase of R^2 from 0.29 to 0.81 (Fig. 6d).

4. Discussion

4.1. Sources of uncertainty

The results presented in this study for the Mediterranean region demonstrate the major advantage of using global models, namely: their wide spatial coverage, which helps in assessing groundwater resources and its interaction with surface water bodies (e.g., Fan and Miguez-Macho, 2011, Birkens et al. 2015, Gleeson et al., 2021). For instance, with more than 592 transboundary aquifers worldwide, (UNESCO, 2021), global models could be particularly useful for the management of shared water resources. Furthermore, the model can be used in vulnerability analysis, climate change impact assessment and as initial conditions in integrated transient analyses. However, due to the nature of global groundwater models and their coarse resolution, these models are associated with high levels of uncertainty..

In this study, the results of three recently developed global steady-state groundwater models covering the Iberian Peninsula are examined.Several factors contribute to the uncertainties of global model simulations. Our investigation suggests that head residuals of the three models significantly increase as surface elevations increase, indicating that the performance of the models is strongly affected by recharge and topography. Simulated groundwater heads are most consistent with each other and with interpolated data for lower elevation regions. It is worth to mention that groundwater observations are biased toward lower land surface elevations areas where most wells are located such as coastal areas which are characterized by lower land surface elevations and shallow groundwater systems, biasing the observations. In contrast, in mountainous regions the variability within the models exceeds several hundred meters in some locations. This could be attributed to the approximate surface elevation used with coarse model grids. As mentioned above, another key parameter that influences groundwater levels is the recharge rate. The recharge rate, which is highly variable in space and time, is difficult to estimate because it is impacted by numerous meteorological, land use and hydrogeological factors, especially at high elevations (Ajami, 2021). The definition of this parameter is particularly challenging at the global scale and for the coarse grids utilized by the global groundwater models. he use of steady-state recharge values in the models is another source of uncertainty as it does not represent the actual recharge processes. Moreover, differences in surface water bodies elevation assumed in the three models can contribute to the uncertainty of the simulated heads. (Reinecke et al., 2019) reported that simulated heads were found to be significantly affected by assumptions about water exchange with surface water bodies.

4.2. Future recommendations

Because of their original purposes, which is to simulate groundwater flow at global scale, these models lack details such as topographical variation and aquifer properties (Richey et al., 2015). To enhance the regional accuracy of regional models, these models require detailed input data (e.g., climate forcing data, recharge rates, hydraulic conductivity, karstic features and groundwater abstraction rates), as well as further downscaling benefiting from local high-resolution data.

Optimal predictions of WTD were reached in this study by combining the average of the three model results with direct in-situ data. This framework benefitted from the models' spatial exhaustiveness while at the same time overcoming the limitations of these models with the strengths of reliable in-situ data. Our analysis suggests that the average steady-state WTD of the three models for the Iberian Peninsula conditioned on about three measurements per 1000 km^2 could reproduce reasonably well (with $R^2 > 0.65$) the WTD spatial patterns of the Iberian Peninsula (Fig. 6).

It is important to mention that the groundwater level observations are measured at a specific point in time, while the simulated groundwater heads represent the steady-state average. Discrepancies between the scales make comparison between model results and point-in-time observations from the WTD difficult. The locations of the observations are often biased toward coastal regions, river valleys, and areas with productive aquifers occur. Since the current study only presents a natural steady-state model, comparison with observations provides only the primary indicator of where the model and the performance metrics need to be improved through further investigation. In the interim, the proposed geostatistical combination framework is arguably the optimal alternative to provide a better assessment of groundwater resources over the Iberian Peninsula and could possibly be upscaled to the whole Mediterranean region. An alternative approach is to embed finer spatial details within the global groundwater model, such as the study of (Westerhoff et al., 2018) that was used to more accurately simulate groundwater levels in New Zealand. Their improved results were attributed to a combination of several factors, such as the finer spatial resolution of the model, enhanced calibration, and the use of high-resolution conductivity data. Although more computationally demanding, the use of finer grids is particularly critical for improved model simulations. Coarser grids risk mixing different groundwater systems, resulting in the misrepresentation of hydrogeological features and diminished agreement with observed data. This is particularly true for highly heterogeneous aquifer systems and multilayer aquifer systems that abound in the complex geology of the Mediterranean basin and elsewhere (William and Forese Carlo, 2003).

To date, global models have not been adequately tested or evaluated in regions known as a hotspot of groundwater importance and data scarcity, such as the Mediterranean region. Overall, we have a limited understanding of the capabilities of different modelling approaches to characterize groundwater at large scales (Neuman, 2002, Sutanudjaja et al., 2011, Condon et al., 2021). Yet, it is crucial to assess the capabilities and performance of large-scale models given their modelling aim of addressing large-scale processes and to overcome limitations in data availability. Large-scale modelling has particular relevance in developing countries where basin models are not yet available or are poorly constrained due to the lack of local data; in these contexts, basic information about water resources obtained from global-scale models would be a great advantage if it is locally relevant (Bierkens, 2015).

The ensemble WTD distribution combining simulated WTD from global models and conditioned on locally observed data could be useful for modelling studies that assess large-scale anthropogenic impacts, such as the impact of climate change on groundwater. Groundwater availability maps produced from these models have several advantages. These maps help governmental agencies to develop appropriate policies related to water resource management, urban and rural planning, agricultural activities and industry establishment. Such up-to-date maps enable decision-makers to develop effective groundwater monitoring and management strategies and hence are potentially useful for land use planning and groundwater quantity monitoring.

The evaluation of the three global models for the Iberian Peninsula underlines the need for continued work on regional models by including more detailed data to better reflect hydrogeological conditions. Further analysis could include transient simulations, as recently performed by de Graaf et al. (2019), that take into account groundwater extractions, which are widespread over the Iberian Peninsula (Siebert et al., 2010, 2013). Some of the most critical groundwater pumping areas in the Iberian Peninsula include the Guadalquivir Basin in Andalusia, the Tagus Basin in Portugal and Spain, the Ebro Basin in Catalonia, and the Duero Basin in Spain (Gelati et al., 2020). These areas have experienced significant declines in groundwater levels and increasing salinity in some areas. Sustainable management of these resources is essential to ensure their long-term availability.

The overestimation of simulated hydraulic heads observed in some mountainous regions occurs for two main reasons. The first is that the complex topography of the area is not accurately represented in the model, leading to errors in the estimated water flow and resulting hydraulic heads. The second is that the models use the sea as a boundary conditions, and as we move away from the coast to the mountainous regions, the error becomes large due to inaccurate estimation of groundwater flow. Furthermore, inaccuracies in the topography, geology, and hydrological characteristics, as well as inaccuracies in the data used to calibrate the model, can lead to overestimation or underestimation of simulated groundwater levels.

In parallel, the analysis presented in this paper, especially the conditioning performed for the Iberian Peninsula, demonstrates the importance of establishing regional data repositories that collect and maintain hydrogeological, land use and water level data. These data will be particularly useful for the continued development of regional models and their downscaling to regional and local scales, ultimately helping manage the groundwater resource. This is particularly valid for the Mediterranean basin, where transboundary aquifer systems are common water resources. These are vital for the peoples of the region and where, despite recent efforts, data collection and sharing remains limited and spatially fragmented. When ground truthing data are not shared at the right time, this can result in inadequate water management, especially under the rapidly changing climate and social conditions. This calls for enhanced data sharing policy in the Mediterranean region and elsewhere to support water management plans and meet users' needs.

4. Conclusions

In this study, we examine the steady-state hydraulic heads simulated by three global groundwater models for the Mediterranean region, focusing on the Iberian Peninsula. The three models consistently represent the groundwater flow patterns under steady-state conditions, yet significant differences remain. As such, these models do not always reflect well local hydrogeological conditions. Further conditioning on local data was needed to downscale the global models to the regional scale. To further examine the performance of models simulated hydraulic heads, we focus on the Iberian Peninsula, where data from an extensive network of observation wells (3822 in total) were compiled. The large number of in-situ data provides us with a unique opportunity to assess the models' performances and demonstrate the value of observations in conditioning the models' simulations. This allows us to benefit from the strengths of both approaches i.e., model spatial coverage and high reliability of in-situ data. Because the performance of the three models is comparable and no model was particularly superior to the others, we further assumed the arithmetic average of the three models, referred to as ensemble distribution, to be the optimal representation of the simulated WTD distribution. The three models are overall comparable when examining the entire Iberian Peninsula. However, a local scale, they may differ from each others. The ensemble distribution was further conditioned on the available observation using a kriging scheme. For the Iberian Peninsula case, it is observed that conditioning on the observed data had a significant impact on the WTD in many regions, highlighting the value of observation data and their importance for downscaling the results of global models. Results show that when the average simulated WTD was conditioned with at least about three wells per 1000 km^2 (equivalent to about 50% of the used in-situ data), the spatial WTD distribution in the Iberian Peninsula was reasonably represented ($R^2 \geq 0.65$). Overall, this study reflects the beneficial use of global groundwater models for regional mapping of groundwater resources and demonstrates how improved assessment of this vital resource can be reached when different models' outputs are further conditioned on observed data.

CRediT authorship contribution statement

Nahed Ben-Salem: Conceptualization, Methodology, Data analysis, Visualization, Writing - original draft, Writing - review and editing; **Robert Reinecke:** Conceptualization, Methodology, Discussion, Writing - review and editing; **Nadim K. Copty**: Discussion, Writing - review and editing; **J. Jaime Gómez-Hernández**: Discussion, Writing - review and editing; **Emmanouil Varouchakis**: Discussion, Writing - review and editing; **George P. Karatzas**: Discussion, Writing - review and editing; **Michael Rode**: Discussion, Writing - review and editing; **Seifeddine Jomaa:** Conceptualization, Methodology, Discussion, Writing - review and editing, Supervision.

Declaration of competing interest

The authors declare no competing interests.

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References

Ajami, H., 2021. Geohydrology: Groundwater. In: Alderton D, Elias SA, editors. Encyclopedia of Geology (Second Edition). Academic Press, Oxford, 408-415.

Albiac, J., Esteban, E., Tapia, J., Rivas, E., 2013. Drought in Arid and Semi-Arid Regions: A Multi-Disciplinary and Cross-Country Perspective. 323–339: Springer, Dordrecht.

Bartholomé, E., Belward AS, 2005. GLC2000: a new approach to global land cover mapping from Earth observation data. Int. J. Remote Sens. 26, 1959-1977.

Bierkens, MFP., 2015. Global hydrology: State, trends, and directions. Water Resour. Res. 51, 4923-4947.

Blinda, M., 2008. Resources and Water Demand. Forecasts for the Future of Water in the Mediterranean. IEMed Mediterranean Yearbook, Blue Plan for the Mediterranean, Valbonne.

Boulet, G., Jarlan, L., Olioso, A., Nieto, H., 2020. Chapter 2 - Evapotranspiration in the Mediterranean region. In: Zribi M, Brocca L, Tramblay Y, Molle F, editors. Water Resources in the Mediterranean Region. Elsevier, 23-49.

Bukowski, J., 2017. A “new water culture” on the Iberian Peninsula? Evaluating epistemic community impact on water resources management policy. Environ. Plan C Politics Space. 35(2): 239-264. DOI:10.1177/0263774x16648333.

Cardoso, RM., Soares, PMM., Miranda, PMA., Belo-Pereira, M., 2013. WRF high resolution simulation of Iberian mean and extreme precipitation climate. Int. J. Climatol. 33, 2591-2608.

Condon, LE., Hering, AS., Maxwell, RM., 2015. Quantitative assessment of groundwater controls across major US river basins using a multi-model regression algorithm. Adv Water Resour. 82, 106-123.

Condon, LE., Maxwell, RM., 2015. Evaluating the relationship between topography and groundwater using outputs from a continental-scale integrated hydrology model. Water Resour. Res. 51, 6602-6621.

Condon, L.E., Kollet, S., Bierkens, MFP., et al., 2021. Global Groundwater Modeling and Monitoring Opportunities and Challenges. Water Resour. Res. 57(12): e2020WR029500 DOI:https://doi.org/10.1029/2020WR029500.

Cudennec, C., Leduc, C., Koutsoyiannis, D., 2007. Dryland hydrology in Mediterranean regions—a review. Hydrol Sci J. 52, 1077-1087.

de Graaf, IEM., Gleeson, T., van Beek, LPH., Sutanudjaja, EH., Bierkens, MFP., 2019. Environmental flow limits to global groundwater pumping. Nature. 574, 90-94.

de Graaf, IEM., Sutanudjaja, EH., van Beek, LPH., Bierkens, MFP., 2015. A high-resolution global-scale groundwater model. Hydrol. Earth Syst. Sci. 19, 823-837.

de Graaf, IEM., van Beek, RLPH., Gleeson, T., Moosdorf, N., Schmitz, O., Sutanudjaja, EH., 2017. A global-scale two-layer transient groundwater model: Development and application to groundwaterdepletion. Adv Water Resour. 102, 53-67.

De Stefano, L., Fornés, JM., López-Geta, JA., Villarroya, F., 2015. Groundwater use in Spain: an overview in light of the EU Water Framework Directive. Int. J. Water Resour. Dev. 31, 640-656. DOI:10.1080/07900627.2014.938260.

EC., 2012. Mediterranean groundwater report : Technical report on groundwater management in the Mediterranean and the water framework directive. In: Commission E, editor. Directorate General for the Environment.

Erostate, M., Huneau, F., Garel, E., Ghiotti, S., Vystavna, Y., Garrido, M., 2020. Groundwater dependent ecosystems in coastal Mediterranean regions: Characterization, challenges and management fortheir protection. Water Res. 172, 115461.

Fader, M., Shi, S., von Bloh, W., Bondeau, A., Cramer, W., 2016. Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements. Hydrol. Earth Syst. Sci. 20, 953-973.

Fan, Y., Miguez-Macho, G., 2011. A simple hydrologic framework for simulating wetlands in climate and earth system models. Clim. Dyn. 37(1): 253-278. DOI:10.1007/s00382-010-0829-8.

Fan, Y., Li, H., Miguez-Macho, G., 2013. Global Patterns of Groundwater Table Depth. Science. 339, 940-943.

Fraga, H., García de Cortázar Atauri, I., Santos, J.A., 2018. Viticultural irrigation demands under climate change scenarios in Portugal. Agric. Water Manag. 196: 66-74. DOI:https://doi.org/10.1016/j.agwat.2017.10.023.

García-Ruiz, JM., López-Moreno, JI., Vicente-Serrano, SM., Lasanta–Martínez, T., Beguería, S., 2011. Mediterranean water resources in a global change scenario. Earth Sci Rev. 105, 121-139.

Gelati, E., Zajac, Z., Ceglar, A., Bassu, S., Bisselink, B., Adamovic, M., et al., 2020. Assessing groundwater irrigation sustainability in the Euro-Mediterranean region with an integrated agro-hydrologic model. Adv. Sci. Res. 17: 227-253.

Ghiggi, G., Humphrey, V., Seneviratne, S. I., and Gudmundsson, L., 2019. GRUN: an observation-based global gridded runoff dataset from 1902 to 2014, Earth Syst. Sci. Data. 11, 1655–1674. https://doi.org/10.5194/essd-11-1655-2019, 2019.

Giannakopoulos, C., Le Sager, P., Bindi, M., Moriondo, M., Kostopoulou, E., Goodess, CM., 2009. Climatic hanges and associated impacts in the Mediterranean resulting from a 2 °C global warming. Glob Planet Change. 68, 209-224.

Gleeson, T., Befus, KM., Jasechko, S., Luijendijk, E., Cardenas, MB., 2016. The global volume and distribution of modern groundwater. Nat. Geosci. 9, 161-167.

Gleeson, T., Cuthbert, M., Ferguson, G., Perrone, D., 2020a. Global Groundwater Sustainability, Resources, and Systems in the Anthropocene. Annu Rev Earth Planet Sci. 48, 431-463.

Gleeson, T., Wagener, T., Döll, P., Zipper, SC., West, C., Wada, Y., et al., 2020b. HESS Opinions: Improving the evaluation of groundwater representation in continental to global scale models. Hydrol. Earth Syst. Sci. Discuss. 2020, 1-39.

Gleeson, T., Wagener, T., Döll, P., Zipper, SC., West, C., Wada, Y., et al. 2021. GMD Perspective: the quest to improve the evaluation of groundwater representation in continental to global scale models. Geosci. Model Dev. Discuss. 2021, 1-59.

Hartmann, J., Moosdorf, N., 2012. The new global lithological map database GLiM: A representation of rock properties at the Earth surface. Geochem Geophys. 13.

Heggy, E., 2018. Probing groundwater in arid environments: challenges and opportunities south of the Mediterranean basin. Euro-Mediterranean Journal for Environmental Integration. 3, 42.

Iglesias, A., Quiroga, S., Moneo, M., Garrote, L., 2012. From climate change impacts to the development of adaptation strategies: Challenges for agriculture in Europe. Clim. Change. 112, 143-168.

Jomaa, S., Reinecke., R., Ben-Salem, N., Chavez Garcia Silva, Varouchakis, E., Vasco Silva, J., Cesaracciu., C., et al. 2021. Multidisciplinary joint-force efforts towards science-based management in the Mediterranean region: A particular focus on transboundary aquifers. In: UNESCO, editor. ISARM2021: Transboundary Aquifers Challenges and the Way Forward. UNESCO: The United Nations Educational, Scientific and Cultural Organization, 7, place de Fontenoy, 75352 Paris 07 SP, France, Paris. 250 pages.

Jones, E. R., Bierkens, M. F. P., Wanders, N., Sutanudjaja, E. H., van Beek, L. P. H., and van Vliet, M. T. H., 2022. DynQual v1.0: A high-resolution global surface water quality model. Geosci. Model Dev. Discuss. 2022: 1-24. DOI:10.5194/gmd-2022-222.

Kurnik, B., Kajfez-Bogataj, L., Horion, S., 2015. An assessment of actual evapotranspiration and soil water deficit in agricultural regions in Europe. Int J Climatol. 35(9):2451-2471. doi: 10.1002/joc.4154.

Lorenzo, M.N., Alvarez, I., Taboada, J.J., 2022. Drought evolution in the NW Iberian Peninsula over a 60 year period (1960–2020). J. Hydrol. 610, 127923. DOI:https://doi.org/10.1016/j.jhydrol.2022.127923.

Martinsen, G., He, X., Koch, J., Guo, W., Refsgaard, JC., Stisen, S., 2022. Large-scale hydrological modeling in a multi-objective uncertainty framework – Assessing the potential for managed aquifer recharge in the North China Plain. J. Hydrol. Reg. Stud. 41, 101097.

MedECC., 2020. Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report. In: Cramer W, Guiot, J., Marini, K., editor

Mennis, J., 2003. Generating Surface Models of Population Using Dasymetric Mapping. Prof. Geogr. 55(1): 31-42. DOI:https://doi.org/10.1111/0033-0124.10042.

Morán-Tejeda, E., Ceballos-Barbancho, A., Llorente-Pinto, JM., 2010. Hydrological response of Mediterranean headwaters to climate oscillations and land-cover changes: The mountains of Duero River basin (Central Spain). Glob Planet Change. 72, 39-49.

Müller Schmied, H., Eisner, S., Franz, D., Wattenbach, M., Portmann, FT., Flörke, M., et al. 2014. Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration. Hydrol. Earth Syst. Sci. 18, 3511-3538.

Neuman, SP., 2002. Accounting for conceptual model uncertainty via maximum likelihood bayesian model averaging. Acta Universitatis Carolinae - Geologica. 46, 529--534.

Reinecke, R., Foglia, L., Mehl, S., Trautmann, T., Cáceres, D., Döll, P., 2019. Challenges in developing a global gradient-based groundwater model (G^3M v1.0) for the integration into a global hydrological model. Geosci. Model Dev. 12, 2401-2418.

710 Reinecke, R., Müller Schmied, H., Trautmann, T., Andersen, LS., Burek, P., Flörke, M., et al. 2021. Uncertainty of simulated groundwater recharge at different global warming levels: a global-scale multi-model 712 ensemble study. Hydrol. Earth Syst. Sci. 25, 787-810.

713 Reinecke, R., Wachholz, A., Mehl, S., Foglia, L., Niemann, C., Döll, P., 2020. Importance of Spatial Resolution in Global Groundwater Modeling. Groundwater. 58: 363-376.

Reynolds, CA., Jackson, TJ., Rawls, WJ., 2000. Estimating soil water-holding capacities by linking the Food and Agriculture Organization Soil map of the world with global pedon databases and continuous pedotransfer functions. Water Resour. Res. 36, 3653-3662.

Richey, AS., Thomas, BF., Lo, M-H., Reager, JT., Famiglietti, JS., Voss, K., et al. 2015. Quantifying renewable groundwater stress with GRACE. Water Resour. Res. 51, 5217-5238.

Romero Fresneda, R., Moreno García, J.V., Martínez Núñez, L., Huarte Ituláin, M.T., Rodríguez Ballesteros, C., Botey Fullat, R., 2020. Comportamiento de las precipitaciones en España y periodos de sequía (Periodo 1961-2018), Technical Report 32 of AEMET. DOI:10.31978/666-20-006-0.

Rubel, F., Bruggerm, K., Haslinger, K., Auer, I., 2017. The climate of the European Alps: Shift of very high resolution Koppen-Geiger climate zones 1800/2100. Meteorologische Zeitschrift. 26, 115-125.

Shen, Y., Oki, T., Utsumi, N., Kanae, S., Hanasaki, N., 2008. Projection of future world water resources under SRES scenarios: water withdrawal / Projection des ressources en eau mondiales futures selon les scénarios du RSSE: prélèvement d'eau. Hydrol Sci J. 53, 11-33.

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., and Portmann, F. T., 2010. Groundwater use for irrigation – a global inventory. Hydrol. Earth Syst. Sci. 14, 1863–1880. DOI:10.5194/hess-14-1863-2010.

Siebert, S., Henrich, V., Frenken, K. , Burke, J., 2013. Update of the global map of irrigation areas to version 5. Project report, 170 pp.

Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, CA., et al. 2014. Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. Earth's Future. 2, 225-230.

Sood, A., Smakhtin, V., 2015. Global hydrological models: a review. Hydrol Sci J. 60, 549-565.

Sutanudjaja, EH., van Beek, LPH., de Jong. SM., van Geer, FC., Bierkens, MFP., 2011. Large-scale groundwater modeling using global datasets: a test case for the Rhine-Meuse basin. Hydrol. Earth Syst. Sci. 15, 2913-2935. DOI:10.5194/hess-15-2913-2011.

Tanrivermis, H., 2003. Agricultural land use change and sustainable use of land resources in the mediterranean region of Turkey. J. Arid Environ. 54, 553-564.

Trichakis, I., Burek, P., de Roo, A., Pistocchi, A., 2017. Towards a Pan-European Integrated Groundwater and Surface Water Model: Development and Applications. Environmental processes. 4, 81-93.

UNESCO Ua., 2021. Global Status of SDG Indicator 6.5.2 and Acceleration Needs. United National Publication. UN ISBN 978-92-1-117269-0. UNESCO ISBN 978-92-3-100452-0.

United Nations, Department of Economic and Social Affairs (UN-DESA), Population Division., 2019. World Urbanization. Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations.

Wagener., T., Sivapalan, M., Troch, PA., McGlynn, BL., Harman, CJ., Gupta, HV., et al., 2010. The future of hydrology: An evolving science for a changing world. Water Resour. Res. 46.

Westerhoff, R., White, P., Miguez-Macho, G., 2018. Application of an improved global-scale groundwater model for water table estimation across New Zealand. Hydrol. Earth Syst. Sci. 22, 6449-6472.

William, C., Forese Carlo, W., 2023. The Mediterranean region - a geological primer. IUGS. 2, 160-168.

Highlights

- Global groundwater models predicted consistent heads for the Mediterranean basin.
- Models performed better at low elevations than in mountainous areas.
- Global models reproduced well the observed head trends in the Iberian Peninsula.
- A geostatistical approach conditioning global models on observations is proposed.

- Model conditioning with observations density of 3/1000 km^2 or more is recommended.

CRediT authorship contribution statement

Nahed Ben-Salem: Conceptualization, Methodology, Data analysis, Visualization, Writing - original draft, Writing - review and editing; **Robert Reinecke:** Conceptualization, Methodology, Discussion, Writing - review and editing; **Nadim K. Copty**: Discussion, Writing - review and editing; **J. Jaime Gómez-Hernández**: Discussion, Writing - review and editing; **Emmanouil Varouchakis**: Discussion, Writing - review and editing; **George P. Karatzas**: Discussion, Writing - review and editing; **Michael Rode**: Discussion, Writing - review and editing; **Seifeddine Jomaa:** Conceptualization, Methodology, Discussion, Writing - review and editing, Supervision.