PAPER

Quantification and possible causes of declining groundwater resources in the Euro-Mediterranean region from 2003 to 2020

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Abstract

Groundwater resources in Euro-Mediterranean countries provide a large part of the population's water supply and are affected to varying degrees by anthropogenic use and climatic impacts. In many places, significant groundwater-level declines have already been observed, indicating an imbalance between natural groundwater recharge and groundwater abstraction. The extent of changes in groundwater storage (GWS) in the period 2003–2020 is quantified for the Euro-Mediterranean region using the latest data from the Gravity Recovery and Climate Experiment (GRACE/GRACE-FO) satellite mission and recently reanalyzed ERA5-Land climate data from the European Centre for Medium-Range Weather Forecasts. The results are set in relation to the prevailing climate, the regional hydrogeological setting, and annual groundwater recharge and abstractions on country level. Analysis of the mean annual trends over the study period shows significant decreases in GWS in many countries of Europe, Northern Africa and the entire Arabian Peninsula. Overall, there are significantly negative trends in about 70% of the study region. The mean of the trends across the Euro-Mediterranean region is –2.1 mm/year. The strongest negative trends in GWS per country are observed in Iraq and Syria (–8.8 and –6.0 mm/year, respectively), but also countries in central and eastern Europe are affected by depleting aquifers. The results are a clear indicator of the already medium-term groundwater stress in the Euro-Mediterranean region, which is expected to increase in the future, and demonstrate the need for adapted strategies for sustainable groundwater management on a transregional scale in the context of climate change and population growth.

Keywords GRACE · ERA5 · Groundwater storage · Aquifer depletion · Mediterranean · Europe

Introduction

The natural occurrence of groundwater is largely controlled by processes and factors of the prevailing climate, the (hydro)geological environment and the geomorphological characteristics (Mukherjee et al. 2021), and therefore varies in its spatiotemporal availability. Groundwater contribution to spring discharge and baseflow of rivers is important, especially during dry seasons, for enabling continuous domestic, agricultural, and industrial water supplies, while also preserving groundwater-dependent ecosystems. The extent of groundwater contribution to water supply depends in many regions on the available amount of groundwater and its natural recharge, as well as the availability of other freshwater sources, such as surface water. The proportion of groundwater within total freshwater use is much lower in the temperate to cold climates of western, central, and eastern Europe (Treidel et al. 2011) than in the semiarid to arid countries of North Africa and the Middle East, which often depend entirely on groundwater (Hamed et al. 2018; Lezzaik and Milewski 2018). Nevertheless, even in more water-rich regions, groundwater plays an important role in drinking-water supply and agricultural irrigation and is also used to meet growing water demands. Sustainable use of groundwater resources is essential to secure future water supplies, but also to maintain groundwater-dependent ecosystems and a biodiverse landscape, and thus contributes to economic prosperity and development, especially in the context of climate change and demographic growth.

Scientists agree that the Mediterranean region was strongly affected by global warming during the late twentieth century, more than other parts of the world, and will

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experience a further increase in average temperatures and a decrease in precipitation in the twenty-first century, particularly noticeable in the summer months (Pal et al. 2004; Giorgi and Lionello 2008; Mariotti et al. 2015; Lionello and Scarascia 2018; Zittis et al. 2019). Europe has already experienced a particularly high number of heat-waves between 2003 and 2019, more than in a comparable period between 1980 and 1997 (Zhang et al. 2020; Twardosz and Kossowska-Cezak 2021). As a consequence, groundwater recharge has decreased in the past two decades, for example in southern Germany by ~15–26%, compared to a three-decade reference period from 1971 to 2000 (Fliß et al. 2021). A further decrease in groundwater recharge will particularly affect areas that already suffer from water scarcity and where groundwater is often the main source of fresh water (Schilling et al. 2020). The situation is further exacerbated by population growth and the associated increase in demand for fresh water for agricultural, industrial and domestic uses (Le Page et al. 2021). In such areas, the opposing trends of decreasing groundwater recharge and increasing abstraction will further lead to dropping groundwater levels. This effect is even more noticeable in deep aquifers that experience very little or no recharge and are therefore considered as nonrenewable, fossil groundwater resources, as for example in a few aquifers in Jordan (Charalambous 2016), Saudi Arabia or Libya (Gonçalvès et al. 2020; Khater et al. 2003). This means that sufficient availability of groundwater for future generations is at risk.

Local and regional groundwater conditions are usually investigated by in situ measurements of groundwater levels or spring discharges, or estimates of the natural water balance. However, comprehensive data are usually not available at larger scales or, if available, only as estimations and for individual countries, often omitting transboundary aquifer systems. This large-scale information gap has been addressed in recent years through the use of remote sensing data from the Gravity Recovery and Climate Experiment and its follow-on (GRACE/GRACE-FO) satellite mission. Since its launch in 2003, numerous studies have been conducted worldwide by correlating the change in groundwater storage (GWS) derived from GRACE data with groundwater level measurements (Sarkar et al. 2020; Shamsudduha and Taylor 2020; Opie et al. 2020). Also, local and regional studies in the Mediterranean area confirm the suitability of the GRACE data for groundwater assessment such as from Portugal (Neves et al. 2020), Spain (Naranjo-Fernández et al. 2020), France (Biancamaria et al. 2019), Greece (Gemitzi and Lakshmi 2018), the Levant (Quba'a et al. 2018), Jordan (Liesch and Ohmer 2016), Libya, Egypt (Mohamed 2019, 2020; Chao et al. 2018) or Tunisia, Algeria and Morocco (Frappart 2020). The GRACE satellites measure the spatiotemporal changes of the Earth's gravity field caused by changes in the total water storage (TWS), which comprises

the total vertically integrated water content of groundwater, water in the unsaturated zone including soil moisture, surface water and eventually snow water equivalent, and water stored in biomass (canopy storage). With the help of auxiliary data on terrestrial water storage components, it is possible to derive the groundwater component from the TWS. The GRACE data are processed and released in different solutions by the Center for Space Research (CSR) at the University of Austin/Texas, the NASA Jet Propulsion Laboratory (JPL) and the German Research Centre for Geosciences (GFZ).

This study assesses changes in GWS in the Euro-Mediterranean region for the period from 2003 to 2020 based on GRACE data. The study region covers parts of geographic Europe, including Turkey, as well as North Africa and the Middle East (MENA region). The main objectives of this study are:

1. Assessment of the GRACE-derived GWS trends for the entire region, based on recent GRACE and GRACE-FO RL06 Mascon solutions of the CSR, as well as new auxiliary ERA5-Land data from the European Centre for Medium-Range Weather Forecasts (ECMWF)
2. Analysis of changes in GWS for different climatic regions, aquifer productivities and individual countries
3. Assessment of possible causes of the observed trends, like nonsustainable groundwater use or climatic variability
4. Investigation of the suitability of different recharge and abstraction data for the determination of a sustainable use of groundwater resources
5. In-depth studies of selected regions, taking spatially distributed data of additional factors like aquifer properties, agricultural land use and population density into account

Geographical setting

To facilitate the description of the study region in this paper, a recognized nomenclature for specific regions is applied. Northern Europe refers to the Baltic states and Denmark, while Central and Eastern Europe includes the Balkan region, all countries east of Germany and Turkey for practical reasons. Western Europe comprises Belgium, Luxembourg, Netherlands, Germany, Switzerland, Austria and France. Southern Europe covers Portugal, Spain, Italy and Greece, while Northern Africa includes Morocco, Algeria, Tunisia, Libya and Egypt. The Arabian Peninsula includes Iraq, Syria, Jordan, Kuwait, Saudi Arabia, Israel, Qatar, Lebanon, Oman, Yemen and the United Arab Emirates. Northern Africa together with the Arabian Peninsula, also known as the Middle East, forms the MENA region (Fig. 1). Countries not included in the evaluation, due to their small
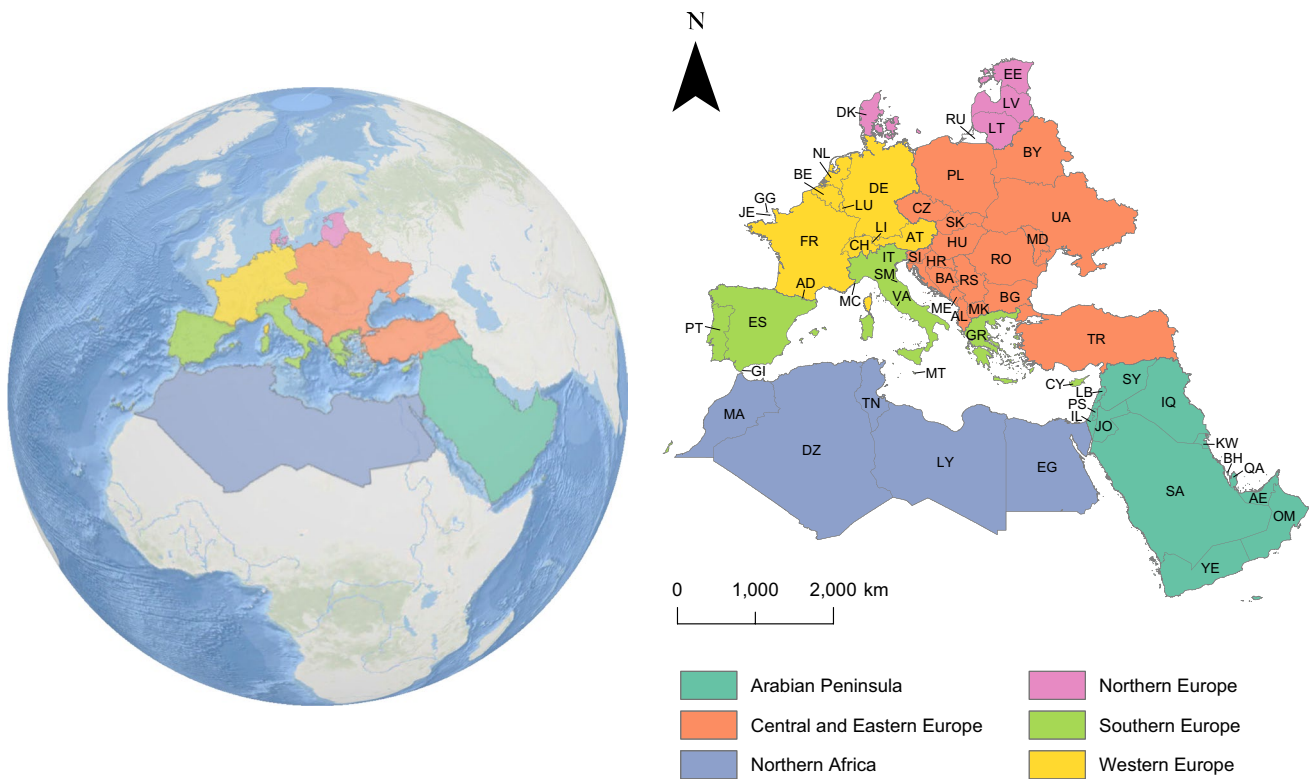
Fig. 1 Location of the study area, which includes most of Europe, North Africa and the Arabian Peninsula. Countries not included in the evaluation but located in the study area are: Andorra (AD), Bahrain (BH), Cyprus (CY), Gibraltar (GI), Guernsey (GG), Jersey (JY), Lichtenstein (LI), Luxembourg (LU), Malta (MT), Monaco (MC), Palestine (PS), San Marino (SM), Vatican City State (VA)

size, but located in the study area are: Andorra (AD), Bahrain (BH), Cyprus (CY), Gibraltar (GI), Guernsey (GG), Jersey (JY), Lichtenstein (LI), Luxembourg (LU), Malta (MT), Monaco (MC), Palestine (PS), San Marino (SM), Vatican City State (VA).

Climate and land use

Regional climate is generally strongly influenced by the latitude and geomorphological characteristics; thus, regional differences in temperature and precipitation can be observed yearly as well as seasonally. The climate classification according to Koeppen (1936) is still widely used among researchers and was updated by Peel et al. (2007) using a global data set of long-term monthly precipitation and temperature and also used in this study. The classification addresses the relationships between climatic elements (temperature and precipitation) and vegetation, considering the transition from one zone to another as gradual and not as a rigid boundary (Fig. 2a).

Four climate zones are identified in Europe and around the Mediterranean region: arid, temperate, cold, and polar. These zones are further divided into several climate types and subtypes—see Table S1 of the electronic supplementary material (ESM). In central and eastern Europe, a cold climate without a dry season but warm summers is prevailing, which turns to a more temperate climate towards central and western Europe, also with warm summers. Exceptions are the mountainous region of the Alps, the Massif Central in France, the Pyrenees in Spain and the Rhodopes in Bulgaria, which reveal a cold and polar climate at high altitudes. Towards southern Europe and Turkey, a temperate climate with dry summers and partly also dry winters is prevailing and even reaches already arid conditions in the south of Spain. In the MENA region, climate turns into arid conditions, and only the coastal areas and the highlands of the Atlas Mountains reveal a temperate climate with dry summers (Fig. 2a). Figure 2b shows the mean annual groundwater recharge distribution from 2003 to 2020 in the study region, computed based on ERA5-Land data (see section 'Data and methodology' for details). High precipitation rates of over 1,300 mm/year can be found in the European mountain regions and the lowest values below 50 mm/year (or even negative) in the deserts and steppes of the MENA region.

The regional climate is also reflected in land use and settlement structure; thus, in the temperate and cold regions of Europe, land use and settlement density are relatively
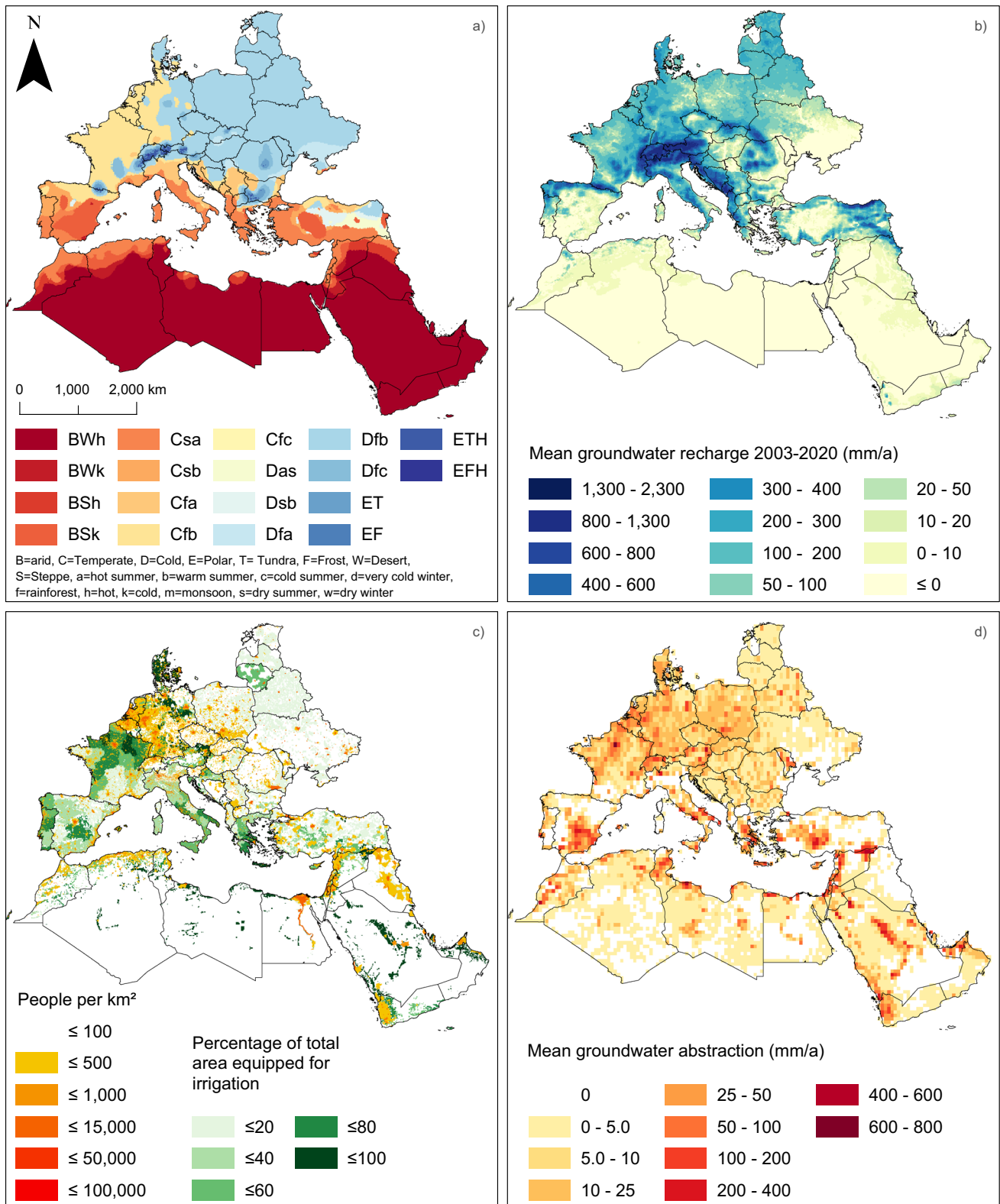
Fig. 2 **a** Climatic zones in the Euro-Mediterranean region (after Koeppen 1936, revised by Peel et al. 2007), **b** mean annual groundwater recharge from 2003 to 2020 (computed based on ERA5-Land data), **c** areas equipped for irrigation (FAO 2021) and population density (CIESIN 2018), **d** mean annual net groundwater abstraction (WaterGAP; Müller Schmied et al. 2021)

homogeneously distributed, with the exception of urban agglomerations. In the MENA region, which is characterized by a mostly arid climate, the density of settlement near the coast is much higher than in the inland areas (Fig. 2c).

Irrigated agriculture is by far the largest water consumer in most countries in the Euro-Mediterranean region (Wriedt et al. 2009; Fader et al. 2016) but the information on the source of irrigation water is rare and has been estimated by Siebert et al. (2010). Agricultural land, which is largely irrigated with groundwater, is found in large parts of Western Europe and Southern Europe (Fig. 2c). These include in particular eastern Germany, Denmark, eastern Austria, large parts of central France and the Aquitaine region, and large parts of Portugal and central Spain, as well as central and southern Italy and southern Greece. In contrast, agriculture in Eastern Europe is much less irrigated with groundwater. Agriculture in the MENA region is mainly practiced in coastal areas, with some exceptions in the inland regions, which are then almost 100% irrigated with groundwater. Figure 2d shows the mean groundwater abstraction, which correlates well with irrigated areas and high population densities.

Hydrogeology

The geological structure of the Euro-Mediterranean region is dominated by a system of connected fold and thrust belts and the associated foreland and back-arc basins, which results from diverse tectonic events since Triassic age. Today's landscape is predominantly shaped by the collision orogeny (Alpine orogeny) of the Eurasian and African-Arabian plates during the late Mesozoic, comprising the closure of various oceanic basins (Cavazza and Wezel 2003). This formed multiple mountain ranges extending from the Iberian Peninsula and North Africa, over Europe, the Balkan region and the Caucasus to central Asia. Most prominent in the Mediterranean area are the Atlas, the Pyrenees, the Alps, the Apennine Mountains, the Dinaric Alps, the Carpathians, the Balkan Mountains, the Taurus, the Caucasus and the Alborz and Zagros belt. In addition to these mountainous regions dominated by metamorphic and igneous rocks, there are a large number of consolidated and unconsolidated sedimentary basins in the Mediterranean region.

The natural genesis of the different types of rocks also affects their hydraulic properties; thus, igneous and metamorphic rocks generally have a very low intergranular permeability but promote groundwater flow through secondary fracturing. The situation is similar with consolidated sedimentary rocks where formations with a fine-grained matrix often reveal low-to-moderate-intergranular permeability, but fracturing enhances groundwater flow. The exception here is the karst aquifers, which have generally an increased permeability due to carbonate dissolution along fractures (Ford and

Williams 2013; Goldscheider and Drew 2007), and therefore play also a crucial role in water supply (Goldscheider et al. 2020). The permeability of unconsolidated materials depends on the composition of grain sizes; thus, fine-grained clayey and silty formations show lower permeabilities than coarse-grained gravelly and sandy aquifers.

The rock types formed during the aforementioned Alpine orogeny are mainly assigned to the category 'practically nonaquifer rocks, porous or fissured' and include mainly igneous and metamorphic rocks. They can be found across the entire European mountain belt, at the Arabian Shield and a few areas in the South of Algeria and Libya (Fig. 3). Low-productive aquifers dominated by intergranular and fracture-flow water are associated with consolidated sediments such as mudstone, fine sandstone or flysch sediments. This type of rock is widespread and can be found, for example, in the extended areas of tectonically influenced regions such as in Spain and Portugal, north of the Alps and the Carpathians, or in large parts of the Arabian Peninsula. Probably the largest group comprises the consolidated sediments of moderate and high productivity. These rock types can be characterized both by intergranular and fracture flow, but also comprise the group of karstified rocks. They are distributed in all countries and can be found, for example, in central France and Germany, the Balkans, Ukraine, but also in the wide plains of the MENA region. Similarly widespread are unconsolidated sediments, which often form large, coherent aquifer systems dominated by sand and gravel, and are either low or highly productive depending on their porosity. These types of aquifers can be found not only in large areas of the northern parts of Eastern and Central Europe, but also in the south of Germany and France, northern Italy and in Hungary, as well as in large areas of the MENA region, e.g. in Algeria, Tunisia, Egypt (Nile delta) and in the eastern and southern Arabian Peninsula (Fig. 3).

Data and methodology

Data on GWS derived from GRACE and ERA5-Land data

Data from GRACE/GRACE-FO RL06 Mascon solutions (Save et al. 2016; Save 2020) from the CSR were used to calculate the changes in GWS for the period from 2003 to 2020. The release RL06 solutions are the latest and up-to-date version of data providing greater accuracy along coastlines by minimizing leakage between land and ocean signals among previous releases (Save et al. 2016; Save 2020). The GWS anomalies are then assessed using a mass balance approach that allows one to separate the GWS signal from the TWS signal. The approach assumes that the change in TWS (ΔTWS) is mainly composed of changes in soil
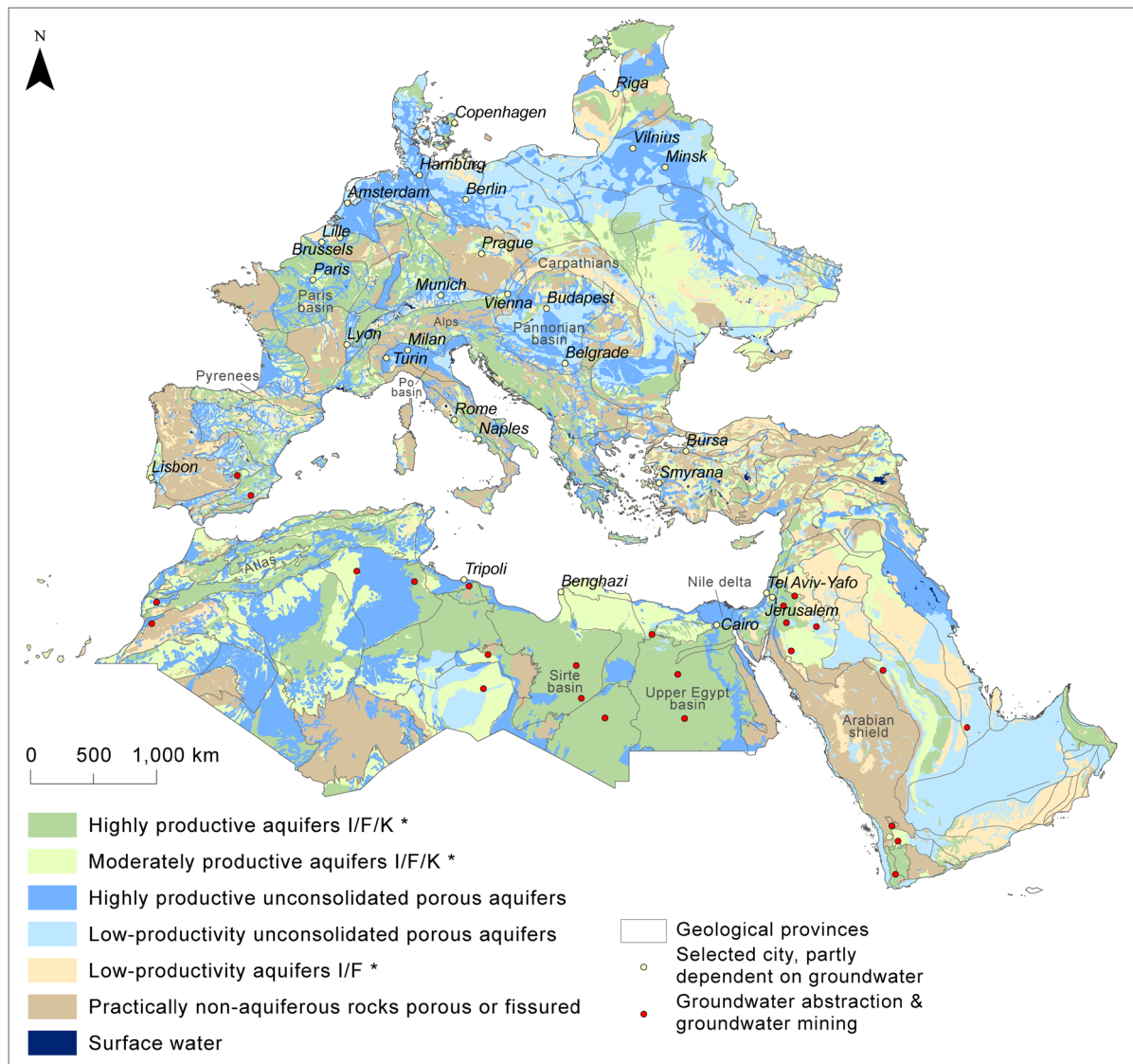
Fig. 3 Hydrogeological setting of the Euro-Mediterranean region showing the adapted aquifer productivity map (see section 'Data and methodology' for details), the geological provinces (Persits et al. 1997; Pollastro et al. 1999; Pawlewicz et al. 2002), selected cities that are partly dependent on groundwater and groundwater abstraction sites. *I* intergranular, *F* fractured, *K* karstified

moisture (ΔSM), snow water equivalent (ΔSWE), surface water (ΔSWA) and groundwater (ΔGW) and is written as (e.g. Richey et al. 2015):

$$\Delta TWS = \Delta SM + \Delta SWE + \Delta SWA + \Delta GW \qquad (1)$$

The change in GWS (ΔGW) is thus computed by subtracting assisting data on soil moisture (ΔSM), snow water equivalent (ΔSWE), and surface water (ΔSWA), all taken from ERA5-Land data (Muñoz Sabater 2019), from the GRACE/GRACE-FO ΔTWS signal. Canopy storage is not considered in this study, since in a nontropical climate, its portion among the water storage components is usually negligible (e.g. Sun et al. 2019). As changes in soil moisture are

typically the largest component of terrestrial water storage variation (e.g. Rodell and Famiglietti 2001), ERA5-Land data were preferred against often-used data from the Global Land Data Assimilation System (GLDAS, Rodell et al. 2004), since recent studies showed their better accuracy compared to in-situ measurements of soil moisture (Beck et al. 2021). Both datasets are used on a monthly time resolution. The data preparation included a coordinate transformation of both data sets to match them geographically, a spatial resampling of ERA5-Land data from 0.1 to 0.25° (to match with CSR GRACE Mascon data, that have a resolution of 0.25°), a computation of GRACE and ERA5-land data as anomalies relative to a common 2003–2020 mean baseline,

a conversion of all data to a common unit of mm/month, and a linear interpolation of smaller data gaps in GRACE values, which are caused by measurement failures of the original GRACE satellites due to battery management since 2011 (NASA 2021).

Computation of GWS trends

A trend analysis was conducted using the seasonal Mann–Kendall trend test (Hirsch et al. 1982), which is well suited for data sets that are subject to seasonal fluctuations, including outliers. This test allows one to determine the significance of a monotonic trend on the basis of the null hypothesis. The thresholds for significance were defined as very significant (≤ 0.01), significant (≤ 0.05) and not significant (>0.05). The mean trend, along with the upper and lower confidence intervals, was calculated using Sen's slope (Sen 1968). The confidence intervals define the range of values for which there is a 95% confidence that it contains the true mean of the underlying data. For later comparison on country levels, the trends in GWS were converted to an annual increase or decrease in groundwater volume per country (calculated from the mean GWS trend in mm/year by cell-wise multiplication with the cell-area and summed up over each country).

Data on water use and recharge

For comparison with the derived trends in GWS, data on withdrawal from groundwater were taken for each country from the Food and Agriculture Organization of the United Nations Aquastat database (FAO 2021). From the global water resources and water use model WaterGAP v2.2d (Müller Schmied et al. 2021), spatially distributed data of the actual net abstraction from groundwater were used, which take return flows caused by human water use into account (mostly due to irrigation).

Furthermore, data of natural groundwater recharge were taken from both data sets. Total groundwater recharge data from WaterGAP are considered as the sum of diffuse groundwater recharge and groundwater recharge from surface waters, and are provided in a spatial resolution of $0.5 \times 0.5°$ (Müller Schmied et al. 2021). Renewable groundwater resources from FAO (2021) represent the sum of total internal and external renewable groundwater resources. Internal renewable groundwater resources are calculated either by estimating the annual infiltration rate (in arid countries) or by calculating the base flow of rivers (in humid countries, FAO 2021) and are therefore only rough estimates. FAO recharge data refer to a reference period of 1961–1990, while the used WaterGap v2.2d data comprise values from 2003 until 2016.

An additional groundwater recharge estimation was made from ERA5-Land data by the European Centre for Medium-Range Weather Forecasts (ECMWF) by subtracting the actual evapotranspiration, surface runoff and change in soil moisture from total precipitation on a monthly basis (modified after Healy 2010):

$$R = P - AET - Qs - \Delta SM \qquad (2)$$

These data include values for the exact study period of 2003–2020, and were calculated in the resolution of ERA5-Land data ($0.1 \times 0.1°$).

Data on climate zones, hydrogeology, land use, irrigation and population density

The dataset of Peel et al. (2007) was used for GRACE trend evaluations regarding climate zones, which represents an improvement or adaptation of the climate classification according to Koeppen (1936) to include more recent climate data. Population density data were taken from the Center for International Earth Science Information Network (CIESIN 2018). Data on agriculture with an indication of areas irrigated with groundwater (as percentage of total area equipped for irrigation) were taken from FAO (2021).

In order to set the GRACE trends in relation to the prevailing hydrogeology, a simplified aquifer productivity map was created as the synthesis of three similar maps from the Euro-Mediterranean region; a simplified grouping of rock formations in relation to their hydraulic properties and productivity is used in the International Hydrogeological Map of Europe (IHME; BGR and UNESCO 2013) and applied here, in a slightly modified description of the legend to match the description of the quantitative map of groundwater resources in Africa by MacDonald et al. (2012) and the map of aquifer productivity for the Arabian Peninsula by Lee et al. (2018). These two maps show a different labeling and quantitative description of aquifer productivity and therefore, a simplified adaptation to the IHME was made in order to achieve a comparable representation of the rock types and their productivity (Fig. 3). Aquifer productivity in this context should be understood as an economic description of an aquifer and its potential to sustain different levels of groundwater supply, derived from the dominant groundwater flow type (O Dochartaigh et al. 2011).

Quantitative analysis of GWS trend data

A quantitative analysis of the GWS trend data was done (1) for the different climate zones, (2) for individual countries, and (3) for zones of different aquifer productivities, Moreover, semiquantitative analyses of selected individual regions, as well as considerations of land use and population density, were conducted.

Besides the analyses of GWS trends in mm/year and (for countries) volume (million m^3/year and country),

a comparison of trends in GWS with the values of mean groundwater recharge and groundwater abstraction was conducted. At a regional scale, variations in GWS are expected to be equal to recharge (R) minus abstractions (abs), and are related to precipitation (P), evapotranspiration (AET), surface runoff (Qs) and changes in soil moisture (SM) via the water budget equation (e.g. Neves et al. 2020)

$$\Delta GWS = R - abs = P - AET - Qs - \Delta SM - abs \qquad (3)$$

To get hints on possible causes for the found GWS trends such as nonsustainable groundwater abstractions that exceed recharge, or possible trends in recharge that could be attributed to climatic variability, the differences in recharge and abstractions from several datasets were computed and compared with the GWS trends. A dominance analysis approach as applied by Thomas and Famiglietti (2019) for the US to derive the relative influences of climatic parameters (groundwater recharge) and groundwater use could not be realized due to insufficient data for groundwater abstractions.

Because the GRACE data represent the equal-area geodesic grid of size $1 \times 1°$ at the equator, which is the current native resolution of CSR RL06 mascon solutions, it might be inaccurate at relatively small-scale analyses, hence countries with an area smaller than 10,000 km^2 were excluded from the evaluation. Additionally, care should be taken when using these solutions in basins smaller than approximately 200,000 km^2 (Save et al. 2016), which has to be kept in mind when interpreting the results for the remaining smaller countries. Figure 4 gives an overview of the used datasets, the applied workflow and the most important calculation steps of the analyses of GWS trends.

## Results and discussion

Trends in groundwater storage

Figure 5 shows the computed trends in GWS for the Euro-Mediterranean region from 2003–2020. The trend analysis of GWS provides an indication of an increase or decrease of GWS in a certain area over the period under consideration. The trend in GWS is given here as an annual mean over the entire time span from 2003–2020 and can therefore vary over shorter periods. A negative trend over the specified time period is equivalent to a decrease in groundwater resources, while positive trends indicate an increase. It should be noted that GRACE-derived data always refer to the entire vertical groundwater column and thus represent the sum of GWS changes in multilayered aquifer systems, where present, and observed groundwater level records of individual aquifers may therefore differ. Negative trends in GWS may either be the result of a decrease in groundwater recharge or indicate that groundwater abstraction exceeds groundwater recharge in the long-term. Positive trends in turn indicate either an increase in groundwater recharge and/or reduction in groundwater use and hence a recovery of groundwater resources.

Fig. 4 Data sources, workflow and most important calculation steps of the analyses of GWS trends
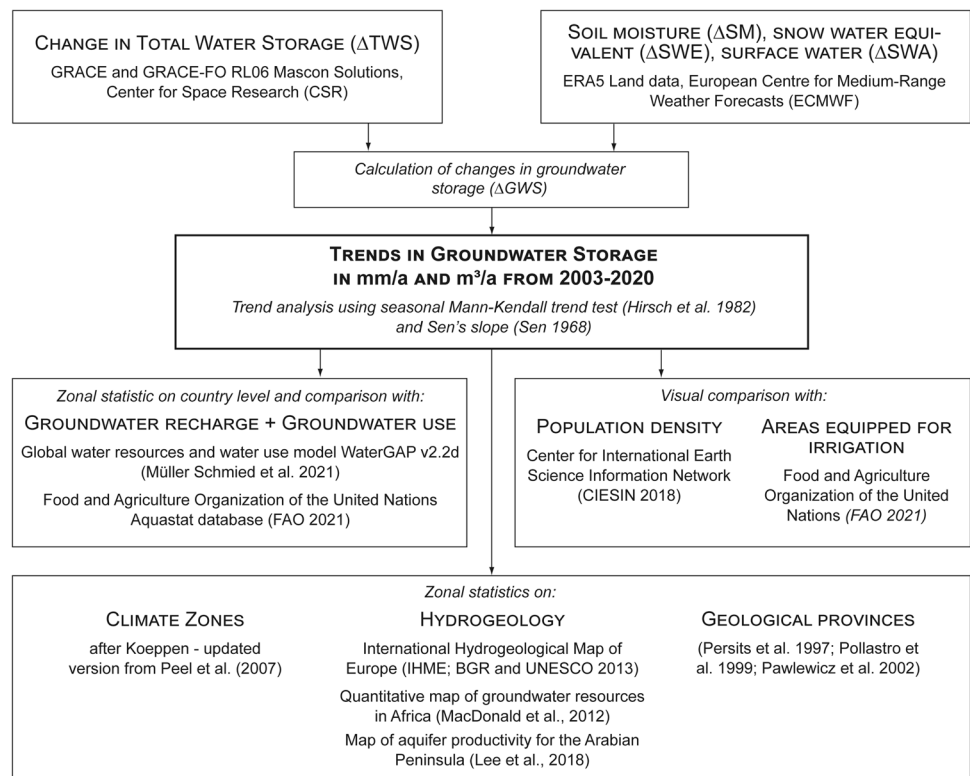
Fig. 5 Mean annual trend of GRACE-derived GWS in the Euro-Mediterranean region for the period of 2003–2020
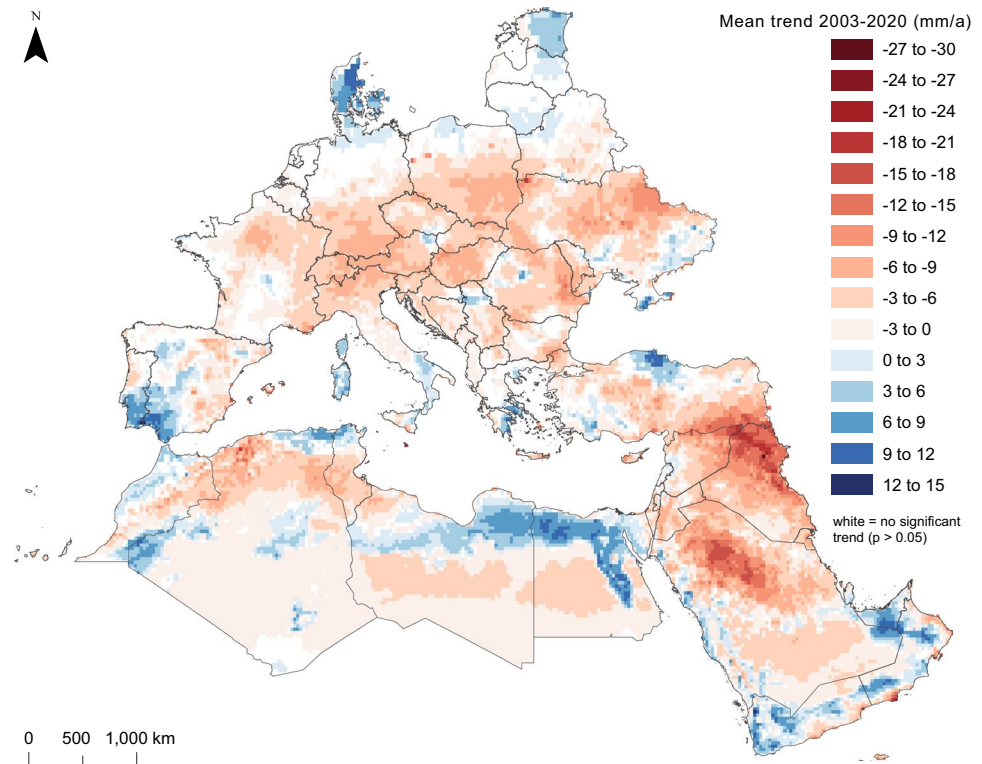
A very significant trend in GWS ($p \leq 0.01$) can be observed in about 82% of the study area, while 5% is still significant ($p \leq 0.05$). No significant trends ($p > 0.05$) are found in 13% of the study area, e.g. in larger parts of northern Germany and south-western France, or scattered in smaller areas of North Africa, Spain, Italy or Turkey (Fig. 5). About 80% of the area with significant trends reveal negative values and about 20% positive values. The actual values of the not-significant trends (most of which are very small with average absolute values at around –0.6 mm/year for negative trends and 0.5 mm/year for positive trends) were still included in the computation of spatially averaged trends (for countries, climate zones, etc.).

Trends in GWS in different climate zones

Based on the distribution of trends in GWS over the study area, it can be seen that positive and negative trends occur in all major climate zones (Figs. 2a and 5; Table 1). However, the average of each major climate zone is negative and ranges from –1.5 to –4.4 mm/year. The strongest negative trends of subclimate zones are found in the arid hot steppe of the MENA region, with an average value of –7.2 mm/year and in the cold region with hot and dry summers in Eastern Europe with an average trend of –5.7 mm/year. However, these zones represent less than 3% of the total investigated area. Similarly, the few polar regions with high altitudes and tundra-dominated landscapes are also subject to strong

negative trends with values ranging from –2.8 to –5.9 mm/year, though representing less than 1% of the area. This can be observed, for example, in the Alps, the Balkans, and the Carpathians. The cold regions with warm summers and without a dry season, which cover about 19% of the study area, show a mean annual trend of –2.9 mm/year. The hot arid desert-like regions, which account for almost 51% of the study area and are present mainly in the MENA region, show an average negative trend of –1.7 mm/year, and most temperate regions of central and western Europe (about 19% of the study area) show average negative trends between –0.7 and –2.5 mm/year. It appears that negative trends on average extend across all climate zones, with a slight tendency towards more negative trends in polar (–4.4 mm/year), arid (–3.8 mm/year) and cold regions (–3.4 mm/year) compared to temperate regions (–1.5 mm/year), though also great differences in distribution within the regions can be observed.

Trends in GWS for individual countries

The average annual trends in GWS in mm/year for the major regions are given in Table 2. Those for each country, including the lower and upper confidence intervals, are given in Table 3 and are also presented in Fig. 6. The results of the GWS trend analysis show that an average negative trend is observed in 36 of the 47 countries, while 11 countries show a positive average trend (Fig. 6; Table 3). In 33 countries,

Table 1 Computed mean annual trend of groundwater storage (GWS) from 2003 to 2020 in relation to climate zones (after Koeppen 1936) and their percentage distribution in the Euro-Mediterranean region

Climate classification after Koeppen (1936)	Climate zone in % of the total Euro-Mediterranean region	Mean annual trend in GWS (2003–2020) [mm]
Arid–desert–hot	51.3	–1.7
Arid–desert–cold	1.1	–3.6
Arid–steppe–hot	1.6	–7.2
Arid–steppe–cold	3.8	–2.6
Arid regions	57.8 (sum)	–3.8 (mean)
Temperate–dry and hot summer	7.9	–1.5
Temperate–dry and warm summer	1.6	–0.7
Temperate–without dry season–hot summer	2.3	–2.5
Temperate–without dry season–warm summer	7.2	–2.0
Temperate–without dry season–cold summer	0.01	–0.8
Temperate regions	18.9 (sum)	–1.5 (mean)
Cold–dry summer–hot summer	0.7	–5.7
Cold–dry summer–warm summer	0.7	–2.7
Cold–without dry season–hot summer	1.2	–2.2
Cold–without dry season–warm summer	18.7	–2.9
Cold–without dry season–cold summer	1.2	–3.3
Cold regions	22.5 (sum)	–3.4 (mean)
Polar–tundra	0.5	–3.8
Polar–frost	0.01	–2.8
Polar–tundra–high elevation	0.3	–4.8
Polar–frost–high elevation	0.01	–5.9
Polar regions	0.8 (sum)	–4.4 (mean)

also the upper confidence level is in the negative range, which means that there is a 95% certainty of a decrease in GWS. Only for five countries (Yemen, Portugal, Estonia, the United Arab Emirates and Denmark) are also the lower confidence levels positive (Table 3), indicating a 95% certainty of positive trend in GWS. The overall mean of the trends across the Euro-Mediterranean region is –2.1 mm/ year, which corresponds to a loss of water volume of about 29,500 million m^3/year, with the Arabian Peninsula showing the largest annual loss of about 12,000 million m^3, Northern Europe experiencing a small annual gain in groundwater of about 440 million m^3 (Table 3).

The strongest negative average trends can be observed for Iraq (–8.8 mm/year) and Syria (–6.0 mm/year), but

also other countries of the Arabian Peninsula show clear negative trends, as for example Kuwait (–5.7 mm/year), Jordan (–4.3 mm/year) and Saudi-Arabia (–3.9 mm/year). However, countries in Western, Central and Eastern Europe are also affected from negative average trends in GWS, with Switzerland being the most affected (–5.7 mm/ year), followed by Hungary (–5.7 mm/year) and Austria (–5.1 mm/year). The countries of the Balkan region also show average negative trends, ranging from very strong trends in Slovenia (–4.7 mm/year) to less strong trends in North Macedonia (–1.9 mm/year). In Southern Europe, the situation is ambivalent, with strong negative trends in Italy (–2.0 mm/year) and weak negative trends in Spain (–0.3 mm/year) and Greece (–0.1 mm/year), while

Table 2 Mean annual trend of GWS from 2003 to 2020, expressed in mm/year and million m^3/year, of the different regions and their percentage portion on the total investigated area

Region	Percentage of total study area	Mean trend 2003–2020 (mm/year)	Mean trend 2003–2020 (Million m^3/year)
Arabian Peninsula	22.3	–2.9	–12,098
Central and Eastern Europe	23.1	–1.5	–9,284
Northern Africa	35.5	–0.4	–5,059
Northern Europe	2.2	1.0	437
Southern Europe	7.6	–0.3	–599
Western Europe	9.4	–1.3	–2,908
Total region	100	–2.1 (mean)	–29,511 (sum)

Table 3 Statistical country values of the calculated mean annual trends in GWS from the GRACE and ERA5 data, including confidence intervals. Data on groundwater recharge and ground-water abstraction from the FAO (2021), WaterGAP (Müller Schmied et al. 2021) and ERA5-Land datasets (Muñoz Sabater 2019), as well as the differences calculated from the data sets of the FAO (2021), WaterGAP and ERA5. n.d. no data

Country	Continent	Area	Mean trend from GRACE and ERA5-Land data	Mean trend: lower confidence interval	Mean trend: upper confidence interval	Mean trend from GRACE and ERA5-Land data	Mean trend: lower confidence interval	Mean trend: upper confidence interval	With-drawal from groundwater (FAO)	Net groundwater abstraction (anag) (WaterGAP)	Total renewable groundwater (FAO)	Annual groundwater recharge (gr) (WaterGAP)	Mean annual groundwater recharge ERA5-Land	Recharge–abstraction (FAO)	Recharge–abstraction (WaterGAP)	Recharge (WaterGap)–abstraction (FAO)	Recharge (ERA5-Land)–abstraction (FAO)
		km²	mm/year			Million m³/year											
Albania	Europe	28,486	-1.8	-3.2	-0.3	-49	-91	-8	107	26	6,200	5,444	10,359	6,093	5,418	5,337	10,252
Austria		83,964	-5.1	-6.4	-3.7	-414	-521	-304	1,061	1,660	6,000	11,131	47,127	4,939	9,471	10,070	46,066
Belarus		207,605	-1.5	-2.6	-0.4	-328	-562	-98	811	1,205	15,900	23,229	23,863	15,089	22,024	22,418	23,052
Belgium		30,671	-1.5	-2.7	-0.2	-45	-84	-8	632	565	900	6,615	6,151	268	6,050	5,983	5,519
Bosnia and Herzegovina		50,993	-2.7	-4.1	-1.3	-133	-202	-66	294	44	11,570	9,635	23,582	11,276	9,591	9,341	23,289
Bulgaria		111,300	-2.6	-4.0	-1.1	-286	-446	-122	582	346	6,400	7,663	9,233	5,818	7,317	7,081	8,651
Croatia		56,377	-2.9	-4.3	-1.5	-164	-245	-82	425	233	11,000	11,924	15,285	10,575	11,691	11,499	14,861
Czech Republic		78,888	-3.7	-4.9	-2.5	-296	-394	-200	369	525	1,430	5,961	11,871	1,061	5,436	5,592	11,502
Denmark		44,441	6.0	4.5	7.6	228	170	287	672	517	4,300	10,632	8,870	3,629	10,115	9,961	8,199
Estonia		45,438	2.7	1.3	4.1	120	58	182	247	70	4,000	5,769	8,436	3,753	5,699	5,522	8,189
France		548,780	-2.4	-3.6	-1.1	-1,274	-1,981	-573	5,506	4,578	120,000	83,426	108,414	114,494	78,848	77,920	102,908
Germany		357,242	-2.5	-3.9	-1.1	-927	-1,413	-445	5,963	3,946	45,700	58,205	76,347	39,737	54,259	52,242	70,384
Greece		132,559	-0.1	-1.5	1.2	-16	-182	147	6,854	1,713	10,300	10,604	13,003	3,446	8,891	3,750	6,149
Hungary		93,119	-5.7	-7.1	-4.3	-519	-648	-391	583	320	6,000	6,544	3,545	5,417	6,224	5,961	2,962
Italy		301,631	-2.0	-3.6	-0.5	-561	-1,011	-118	n.d.	549	43,000	40,848	85,192	n.d.	40,299	n.d.	n.d.
Latvia		64,563	0.6	-0.7	1.9	37	-47	117	84	82	4,700	8,639	12,098	4,617	8,557	8,556	12,014
Lithuania		64,945	0.8	-0.4	2.0	53	-26	127	140	120	1,100	10,812	10,833	960	10,692	10,672	10,692
Montenegro		13,780	-2.6	-4.2	-1.0	-34	-55	-13	n.d.	3	n.d.	4,017	2,803	n.d.	4,014	n.d.	n.d.
Netherlands		34,968	-0.4	-1.8	0.9	-13	-55	27	983	490	4,500	7,456	9,672	3,517	6,966	6,473	8,689
North Macedonia		25,424	-1.9	-3.1	-0.8	-47	-75	-19	162	-361	n.d.	2,011	2,833	n.d.	2,372	1,849	2,671
Poland		311,947	-3.6	-4.8	-2.5	-1,133	-1,483	-793	1,673	2,600	12,500	40,024	634	10,827	37,424	38,351	-1,039
Portugal		91,978	2.1	0.4	3.9	189	41	340	4,794	39	4,000	10,078	37,312	-794	10,039	5,284	32,518
Republic of Moldova		34,060	-3.8	-5.0	-2.7	-139	-182	-97	127	498	1,300	3,206	0	1,173	2,708	3,079	-127
Romania		237,980	-4.2	-5.6	-2.8	-999	-1,338	-661	647	896	8,460	31,726	33,737	7,813	30,830	31,079	33,090
Serbia		88,478	-2.3	-3.6	-0.9	-208	-327	-87	460	292	n.d.	8,781	10,380	n.d.	8,489	8,321	9,920
Slovakia		49,029	-4.9	-6.2	-3.6	-248	-314	-183	312	332	1,730	7,330	9,441	1,418	6,998	7,018	9,129
Slovenia		20,683	-4.7	-6.1	-3.3	-96	-125	-67	190	91	13,500	4,348	10,537	13,310	4,257	4,158	10,347
Spain		505,752	-0.3	-1.6	0.9	-143	-768	486	6,394	1,601	29,900	34,337	33,592	23,506	32,736	27,943	27,198
Switzerland		41,262	-5.7	-7.3	-4.0	-223	-286	-158	869	827	2,500	6,927	33,376	1,631	6,100	6,058	32,507
Turkey		781,152	-3.0	-4.4	-1.7	-2,378	-3,439	-1,307	15,460	-337	67,800	56,802	89,256	52,340	57,139	41,342	73,796
Ukraine		600,353	-3.8	-5.2	-2.4	-2,220	-3,029	-1,409	1,178	88	22,000	46,079	26,605	20,822	45,992	44,901	25,427

Table 3 (continued)

Country	Continent	Area	Mean trend from GRACE and ERA5-Land data	Mean trend: lower confidence interval	Mean trend: upper confidence interval	Mean trend from GRACE and ERA5-Land data	Mean trend: lower confidence interval	Mean trend: upper confidence interval	Withdrawal from groundwater (FAO)	Net groundwater abstraction (anag) (WaterGAP)	Total renewable groundwater (FAO)	Annual groundwater recharge (gr) (WaterGAP)	Mean annual groundwater recharge ERA5-Land)	Recharge–abstraction (FAO)	Recharge–abstraction (WaterGAP)	Recharge (WaterGap)–abstraction (FAO)	Recharge (ERA5-Land)–abstraction (FAO)
Algeria	North Africa	2,316,559	−1.3	−1.6	−0.9	−2,821	−3,721	−1,935	8,103	1,488	1,517	23,059	3,107	−6,586	21,571	14,956	−4,996
Egypt		982,443	0.2	−0.2	0.6	123	−291	533	6,500	−12,825	1,500	22,172	3	−5,000	34,997	15,672	−6,497
Libya		1,616,873	−0.9	−1.2	−0.6	−1,501	−1,989	−1,017	5,550	3,017	600	9,006	171	−4,950	5,989	3,456	−5,379
Morocco		406,318	−1.0	−1.8	−0.1	−393	−722	−57	2,322	1,103	10,000	7,836	9	7,678	6,733	5,514	−2,313
Tunisia		155,177	−2.9	−3.6	−2.3	−466	−570	−366	3,062	1,538	1,595	6,436	202	−1,467	4,898	3,374	−2,860
Iraq	Arabian Peninsula	437,114	−8.8	−10.1	−7.6	−3,809	−4,356	−3,268	n.d.	−11,450	3,280	42,271	9,773	n.d.	53,721	n.d.	n.d.
Israel		21,981	−3.2	−3.8	−2.6	−65	−77	−53	840	406	1,225	3,229	154	385	2,823	2,389	−686
Jordan		89,066	−4.3	−4.9	−3.8	−388	−435	−342	615	556	540	1,321	3	−75	765	706	−612
Kuwait		17,323	−5.7	−6.3	−5.2	−100	−110	−92	770	28	20	141	139	−750	113	−629	−631
Lebanon		10,133	0.2	−1.1	1.6	2	−11	15	1,157	140	3,200	979	500	2,043	839	−178	−657
Oman		307,991	0.5	−0.1	1.1	152	−26	324	1,532	379	1,300	2,075	5,683	−232	1,696	543	4,151
Qatar		11,367	0.2	−0.4	0.7	2	−4	8	251	36	58	64	6,626	−193	28	−187	6,376
Saudi Arabia		1,959,676	−3.9	−4.3	−3.4	−7,469	−8,369	−6,594	21,010	8,510	2,200	15,499	825	−18,810	6,989	−5,511	−20,185
Syria		185,757	−6.0	−7.1	−4.9	−1,097	−1,297	−902	n.d.	2,958	6,174	8,277	1,095	n.d.	5,319	n.d.	n.d.
United Arab Emirates		70,904	4.2	3.8	4.7	288	260	317	2,562	1,253	120	3,860	5	−2,442	2,607	1,298	−2,557
Yemen		419,900	1.0	0.4	1.6	406	151	651	2,525	1,541	1,500	777	2,420	−1,025	−764	−1,748	−105

Fig. 6 Mean annual trends in GWS from 2003 to 2020 for each country with the lower and upper confidence interval, in million m³/year
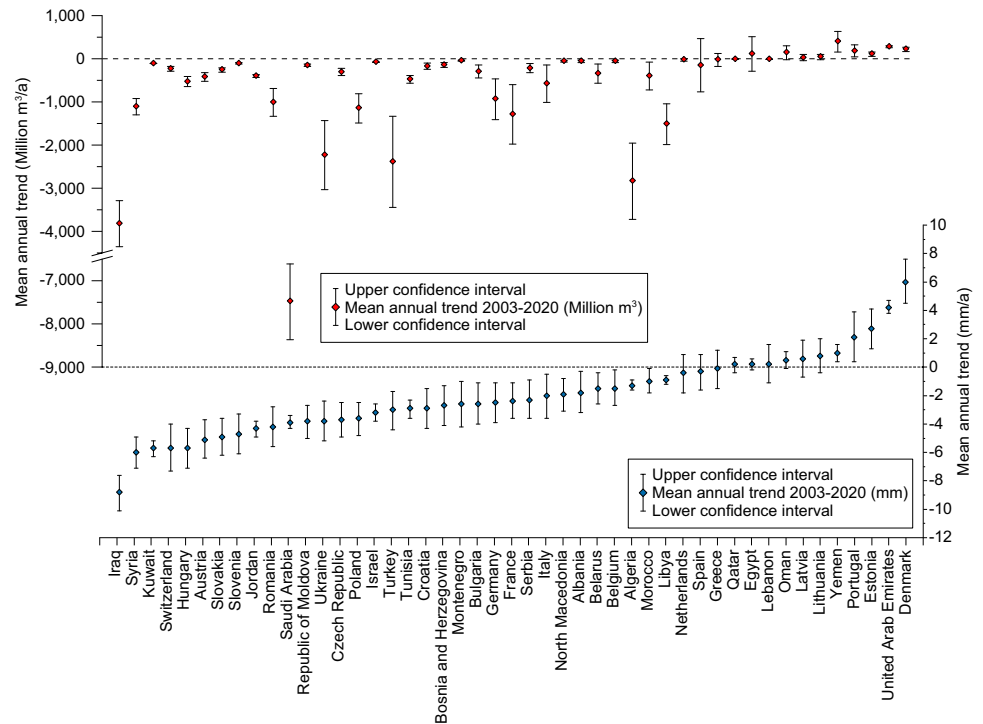
Portugal reveals a positive trend (2.1 mm/year). Average positive trends of GWS per country are mostly found in Northern Europe such as in Latvia, Lithuania, Estonia and Denmark with values between 0.6 and 6.0 mm/year. North African countries reveal weak to strong negative trends for Libya, Algeria, Tunisia, and Morocco (–0.9 to –2.9 mm/year), while Egypt shows a slightly positive trend (0.2 mm/year; Table 3).

It should be noted, however, that the mean value is often not representative for the entire area of a country, as the trend in many countries varies greatly from region to region. This is particularly noticeable in the countries of Northern Africa, for example, as well as in Spain and Turkey.

Comparison of trend in GWS with recharge and abstractions on country level

The sustainable use of groundwater resources is usually derived from the comparison of the amount of natural groundwater recharge and groundwater abstractions (Fig. 7; Table 3). This can give hints for possible causes of negative trends, which can be attributed to regions where abstractions exceed natural recharge. For a comparison, the GRACE derived trends in GWS were converted to an annual increase or decrease in GWS volume per country (calculated from the mean GWS trend in mm/year by cellwise multiplication with the cell-area and summed up over each country).

At the country level, the recharge values from the FAO, the WaterGAP model, and computed based on ERA5-Land data, reveal partly large differences (Fig. 7), which is either caused by the different calculation methods and/or by different periods under consideration. The FAO groundwater recharge data are long-term annual averages of the reference period of 1961–1990 (FAO 2021), generated either by estimating annual infiltration rate of precipitation (in arid countries) or by computing river base flow (in humid countries, FAO 2021). The WaterGap data include diffuse groundwater recharge and groundwater recharge from surface-water bodies, which are in turn the results of an elaborate modelling procedure (Müller Schmied et al. 2021), but refer to the period of 2003–2016 only. The computations based on ERA5-Land data are the result of a simpler water balance approach, but therefore refer to the exact study period of 2003–2020.

The groundwater abstraction data of the FAO comprise the annual gross amount of water extracted from aquifers, including withdrawal of renewable groundwater, as well as water from overabstraction of renewable groundwater or withdrawal from fossil groundwater (FAO 2021). Values are taken from 2017 (newest available values) to make them comparable across countries, since for many countries, earlier values are patchy, which leads to errors especially in countries where abstraction rates have strongly increased or decreased over the study period. The WaterGap net abstraction from groundwater data refers to 2003–2016, but,

Fig. 7 Range of mean annual groundwater recharge from FAO data for the period 1961 to 1990 (FAO 2021), from WaterGAP data for the period 2003–2016 (Müller Schmied et al. 2021) and from ERA5 data for the period from 2003 to 2020 (Muñoz Sabater 2019), as well as mean annual groundwater abstraction data from the FOA from 2017 and from WaterGAP data for the period 2003–2016 for each country in the Euro-Mediterranean region
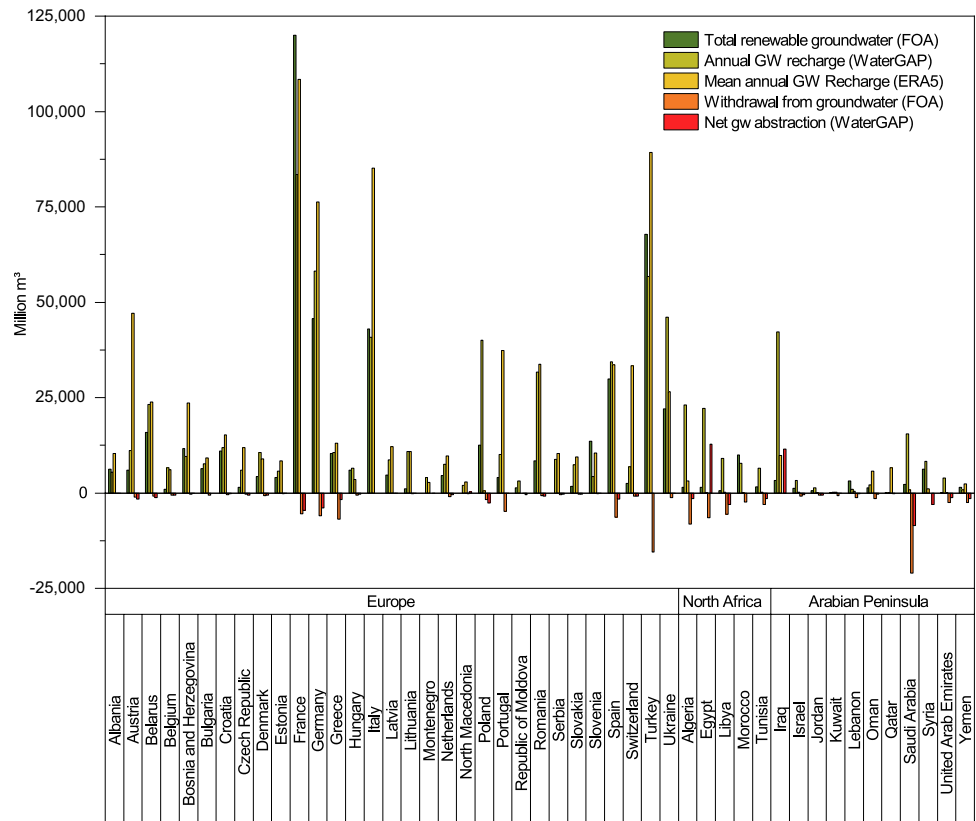
contrary to the FAO data, includes return flows caused by human water use (mostly due to irrigation). Moreover, the GRACE, WaterGAP and ERA5-data all come at different spatial solutions, which can lead to inaccuracies especially when calculating volumes for smaller countries. Overall, for the mentioned differences, a direct comparison of GWS trends with average values of groundwater abstraction and groundwater recharge data on country level is only meaningful to a certain degree, i.e. in a semiquantitative way (Fig. 7). Table 3 shows the differences of recharge and abstraction for the FAO data, the WaterGap data, and the recharge from WaterGap and ERA5-Land data minus abstraction from FAO. These data already exhibit a strong variability.

The differences of annual recharge and net abstraction from the WaterGap data are positive for all countries except Yemen, which seems somehow unrealistic compared to other studies. It can only be assumed that the net abstraction values are probably underestimated, which might be a result of the overestimation of return flows by human water use or overestimation of the annual recharge rates. Strongly declining groundwater levels, e.g. on the Arabian Peninsula, could otherwise not be explained.

The differences of groundwater recharge and abstractions from FAO data show a more diverse picture. Unfortunately, Iraq and Syria, the two countries with the strongest negative trends in GRACE GWS, lack FAO abstraction data. The data

exhibit nonsustainable abstractions for most countries on the Arabian Peninsula and also for Northern Africa (Algeria, Libya, Tunisia, Egypt). In Europe, negative net balances from FAO data are only given for Portugal. The results are widely consistent with losses in groundwater volume from GRACE-derived GWS data for the Arabian Peninsula and Northern Africa, apart from Qatar and United Arab Emirates, which exhibit even a gain in GWS. On the other hand, countries with high losses in GWS from GRACE data in Europe, like France, Poland, Germany and Hungary, do not exhibit unsustainable use of groundwater from FAO data. Since the FAO abstraction data seem rather up to date and reliable (apart from possibly unrecorded illegal withdrawals), the recharge data refer to the period of 1961–1990. A possible explanation is that the observed decline in groundwater resources in these regions is the result of a climatic decline in recharge in the period of 2003–2020 (considered for the GWS trend) compared to the earlier reference period, as stated, e.g. by Fliß et al. (2021) for southern Germany.

In order to investigate this possible influence, WaterGap recharge values as well as recharge values for 2003–2020, calculated based on a simple water balance approach from ERA5-Land data, were used instead of FAO recharge for computation of sustainable use along with the FAO abstractions. The results from the WaterGap recharge and FAO abstraction data are still somehow unrealistic for most

countries, with loss values only for five countries on the Arabian Peninsula, leading to the assumption that also the WaterGap recharge values could be overestimated. Though there are still some contradictions, the computed results based on ERA5-Land recharge and FAO abstractions show the most correspondences with changes in groundwater volumes from GRACE GWS data. This is the case for most countries of the Arabian Peninsula and Northern Africa, which show partly high losses in GWS volumes and at the same time a nonsustainable groundwater use. Most countries with gains in GWS (except United Arab Emirates, Egypt, Lebanon, and Yemen) now show a recharge surplus over abstraction. However, still there are many countries, especially in Europe (e.g. Romania, France or Germany) that show partly high losses in groundwater volume from GRACE-derived GWS, but have a high recharge surplus over abstraction at the same time. Again, a possible explanation could be the different time periods considered: while GRACE GWS and ERA5-Land recharge data include low recharge values in the extremely dry summers in central Europe in 2018–2020, the FAO abstraction data from 2017 do not include presumably increased abstractions in the same period, leading to a distorted balance. Though it must be admitted that the differences are partly that large (e.g. for Germany and France), this probably can not be the only reason.

As mentioned, the comparisons are only possible in a semiquantitative way and a direct comparison of GWS gain or loss volumes with volume differences in recharge and abstractions are not meaningful due to different calculation methods and reference periods. On the other hand, the comparisons here show that the traditional approach of using recharge and abstraction data, which are subject to great uncertainties, are often not suitable for the determination of a sustainable use of groundwater resources.

Comparison of trends in GWS with trends in natural groundwater recharge

To analyse possible climatic influences on the GWS, a trend analysis (seasonal Mann–Kendall Test and Sen's Slope) for the monthly recharge values computed from ERA5-Land data from 2003–2020 was carried out. Apart from smaller regions on the Arabian Peninsula and Northern Africa, the trends were not significant over most of the study region, especially in Europe (results not shown). However, several studies found that groundwater recharge decreased in the past two decades, compared to a three-decade reference period from 1971 to 2000 such as the study by Fliß et al. (2021) for southern Germany, which could play a role in some regions, even if the (monotonic) trends within the study period are mainly not significant. In any case, it can be assumed that groundwater withdrawals (which can be partly

also influenced by climate variability especially regarding abstractions for irrigation) play a dominant role, especially when downward trends in GWS are large.

Regional GWS trends, related land use and population density

The regional distribution of the GWS trend within and across countries can look different depending on many factors, including population density and land use—for example, the European region with some densely populated urban centres is much more homogeneously used for agriculture and settlement, while the population density in the MENA region is mainly limited to coastal regions or isolated urban or agricultural areas inland (Fig. 2c). It can be seen throughout the study region that areas with high groundwater abstractions are often more affected by negative trends than other areas (Fig. 2d). Moreover, these regions widely coincide spatially with those in which there are either agricultural areas irrigated with groundwater (e.g. in central Saudi-Arabia, parts of Italy and France) or higher population densities (e.g. eastern Iraq, the Po valley in Italy and the Île-de-France region around Paris; Fig. 2c). This suggests that the negative trends in GWS can at least partly be attributed to nonsustainable groundwater abstractions, though there are also exceptions, for example in parts of south-western Spain, where not significant or even positive trends prevail in spite of high groundwater abstractions. This may result either from the fact that the spatially distributed data of net groundwater abstraction include irrigation return flow, which might mitigate negative trends in GWS due to abstraction for agriculture, or, in some arid zones, abstractions may not always be directly spatially connected to land use or population density, as groundwater is sometimes abstracted from more remote areas (e.g. in southern Libya).

Trends in GWS for zones of different aquifer productivities

The extent to which groundwater can be explored generally depends on the productivity of the aquifers and their accessibility. Highly productive, shallow aquifers are generally easier to explore than deep and less productive ones; however, their surface exposure also plays an important role in groundwater recharge, as they generally respond more strongly to precipitation events than deep and covered aquifers. Much less productive and deep aquifers are tapped more frequently when water demand is high and water from other sources is not available. From the results of the trend analysis in GWS, there is no clear indication that certain types of aquifers are particularly affected by positive or negative trends when considering the entire region; however, a clearer picture emerges when specific regions or single geological

provinces are considered. The complete analysis of all geological provinces can be found in Table S2 of the ESM.

A negative trend in GWS can be observed for all types of aquifers in Europe and Turkey, with average trends ranging between –1.9 and –3.5 mm/year. However, the highly productive intergranular, fractured and karst aquifers show somewhat stronger negative trends, on average with –3.5 mm/year, than the moderately productive aquifers (with –2.5 mm/year) and the high to low productivity unconsolidated porous aquifers (with –2.0 and –2.5 mm/year, respectively). Low-productivity intergranular and fractured aquifers as well as practically nonaquifer rocks show also slightly less negative trends of –2.2 and –1.9 mm/year on average, respectively. Since they are usually hardly used for water supply, this could be an indication of climatic causes.

The aquifers in North Africa show a slightly lower negative trend than in Europe with average values between –0.3 and –2.0 mm/year, whereas the low-productivity unconsolidated porous aquifers even show positive trends of 0.6 mm/year. However, the latter are only found in about 2% of the region. The strongest negative trend is shown by the low-productivity unconsolidated porous aquifers, with –2.0 mm/year.

In the Arabian Peninsula, generally many more negative trends can be observed, as already mentioned previously. The highly productive unconsolidated porous aquifers stand out in particular, with an average trend of –10.1 mm/year, which is certainly due to their generally easier accessibility. The moderately productive intergranular, fractured and karst aquifers are also heavily stressed, with a mean value of –6.4 mm/year. The other aquifer types, including the low-productivity ones, also show negative trends between –2.5 and –3.3 mm/year (Table 4).

Selected regional examples of GWS trends

In the following, selected regions or countries in western and southern Europe, the Arabian Peninsula and Northern Africa (Fig. 8) are discussed in more detail. With an annual groundwater consumption of about 4,800 million m^3 and an annual groundwater recharge of between 4,000 and 37,000 million m^3, Portugal shows sustainable use of groundwater, which is also reflected in a slight gain in GWS of 189 million m^3/year. Spain also seems to run a sustainable groundwater management strategy with an annual groundwater consumption of about 6,400 million m^3 and an estimated amount of renewable groundwater of about 34,000 million m^3. However, it recorded a slight mean annual loss in GWS of about 143 million m^3/year. Positive trends in GWS are especially observed in the southern Iberian Massif, which consists of intergranular and fractured sediments and magmatic and metamorphic rocks of low productivity. A moderately negative trend in GWS prevails in the Iberian Cordillera, where a complex sequence of intergranular, fractured, and karstified formations of moderate to high productivity is exposed, alongside unconsolidated sedimentary formations of low to high productivity (Fig. 8a,b).

France experiences a mean annual groundwater loss of about 1,270 million m^3, corresponding to 23% of the total groundwater abstraction of about 5,500 million m^3. With an estimated amount of renewable groundwater recharge between around 83,000 and 120,000 million m^3/year, the GRACE-derived country-wide loss in GWS cannot be explained from averaged nonsustainable extractions. On the other hand, it is limited to some regions in central and eastern France; thus, the Anglo-Paris basin reveals a mean annual loss of 576 million m^3, the Trans Graben basin of 127 million m^3, the Massif Central of 159 million m^3, and the Lion-Camargue basin of about 208 million m^3 (Fig. 8a and b), together accounting to already 72% of total groundwater loss. These areas are already known for declining groundwater levels, as described by Maréchal and Rouillard (2020).

For Italy, a mean annual groundwater loss of about 561 million m^3/year was calculated, while the mean annual renewable groundwater volume is reported to be between about 40,000 and 85,000 million m^3. Data on groundwater use are not available for Italy. A negative trend is observed in

Table 4 Mean annual trends of GWS changes from 2003 to 2020 in relation to different types of aquifer productivity in Europe, North Africa and the Arabian Peninsula

Aquifer productivity	Europe + Turkey		North Africa		Arabian Peninsula	
	Trend (mm)	Total area %	Trend (mm)	Total area %	Trend (mm)	Total area %
Highly productive aquifers I/F/K[a]	–2.5	12	–1.1	38	–3.2	7
Moderately productive aquifers I/F/K[a]	–3.5	14	–0.3	24	–6.4	9
Highly productive unconsolidated porous aquifers	–2.0	14	–1.5	21	–10.1	5
Low-productivity unconsolidated porous aquifers	–2.6	21	–2.0	3	–2.5	34
Low-productivity aquifers I/F[a]	–2.2	19	0.6	2	–3.1	28
Practically nonaquifer rocks, porous or fissured	–1.9	20	–0.8	12	–3.3	17

[a] *I* intergranular, *F* fractured, *K* karstified

Fig. 8 **a** Hydrogeological map of Portugal, Spain, France and Italy with **b** the mean annual trends in GWS. **c** Hydrogeological map of Algeria, Tunisia and Libya with **d** the mean annual trends in GWS. **e** Hydrogeological map of the Arabian Peninsula with **f** the mean annual trends in GWS. Bahrain (BH), Andorra (AD), Vatican City State (VA), Monaco (MC), Palestine (PS), and San Marino (SM) are not evaluated
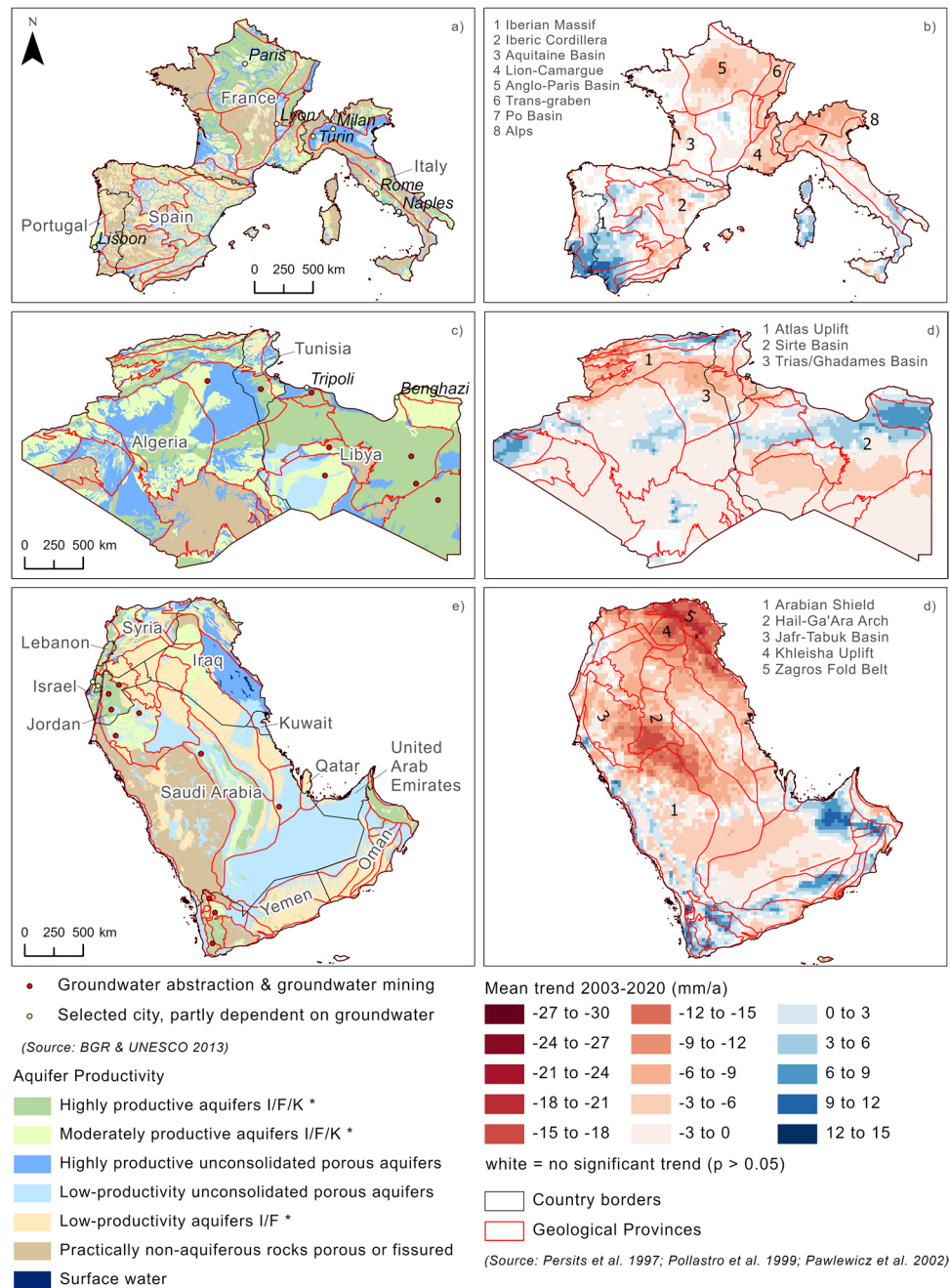
many coastal areas, but is mainly attributed to the northern and central parts of Italy, especially the central mountainous regions of the Apennines and the Po Valley (Fig. 8b). The latter consists of a highly productive unconsolidated porous aquifer and reveals a mean annual loss of 249 million m^3, while the Apennines consists of nonwater-bearing rocks and highly productive fractured and karstified aquifers (Fig. 8a). A decrease in precipitation in Italy due to climate change was already observed before the 2000s (Polemio and Casarano 2008; Ducci and Tranfaglia 2008) and also groundwater overuse (Lancia et al. 2020), which both can be the

causes for negative trends in GWS. The results correspond to some regional observations of groundwater depletion, e.g. in coastal aquifers (Sappa and Vitale 2001) and large parts of the mountainous regions in central Italy, as evidenced by declining groundwater levels and spring discharges (Fiorillo et al. 2015; Lancia et al. 2020). However, other studies have not identified declining spring discharges in the northern Apennines or the piedmont (Cervi et al. 2018; Bastiancich et al. 2021).

Most north African countries show slightly negative trends in GWS, with values ranging from –0.9 to –2.9 mm/

year, and only Egypt shows a slightly positive trend of 0.2 mm/year, mostly visible along the Nile and the northern part of the country (Fig. 8d). The positive trends are also visible in northern Libya, with the exception of a narrow coastal strip where negative trends occur. Other areas with positive trends are found in northern Tunisia and Algeria as well as along the north-western Atlantic coast of Morocco. Large areas with negative trends are present in the inland areas of Egypt, Libya and in large parts of the Atlas Mountains, which stretches from Morocco over Algeria to Tunisia. The different aquifer types in the north African countries are subject to similar variations and trends, with the low productivity intergranular and fractured aquifers even showing slightly positive trends with 0.6 mm/year, but accounting for only about 2% of the area. The moderate and highly productive intergranular, fractured and karstified aquifers reveal weak to moderate negative trends of –0.3 and –1.1 mm/year, respectively, which outcrop in about 62% of the region (Fig. 8c). The trends in north-western Algeria correspond with the depletion of groundwater resources observed by Berhail (2019) and the gradual decline of groundwater levels in the coastal zone in south-western Morocco identified by Malki et al. (2017) and Ouhamdouch et al. (2018).

The region most affected by negative trends in GWS is the Arabian Peninsula. It is characterized by the south-eastern Arabian shield basement complex of low-permeability igneous and metamorphic rocks and the north-eastern stable and mobile shelf of mainly karstified carbonate rocks and consolidated sediments. The latter merges in the north into the collision zone of the Arabian and Eurasian Rift, the Zagros mountain belt (Fig. 8e). In all Arab countries, groundwater plays a crucial role in water supply, but due to natural water scarcity, many aquifers are not sustainably managed, resulting in declining groundwater levels. All countries show a strong negative trend in GWS, with Iraq at –8.8 mm/year and Syria at –6.0 mm/year being the most affected (Fig. 8f). Groundwater abstraction data are not available for these countries, but the region is known for severe groundwater abstraction, as for example the city of Erbil in northern Iraq which is located in the centre of a large depression cone affecting the Khleisha uplift and the Zagros fold belt (Stevanovic and Iurkiewicz 2009; Nanekely et al. 2017; Awadh et al. 2020).

In Jordan, the recorded annual groundwater abstraction is about 615 million m^3, thus already officially exceeding the officially recognized average annual recharge rate of FAO (2021) of 540 million m^3. The rather strong mean annual decline in GWS of –4.3 mm/year corresponds to an average annual storage loss of 388 million m^3, which exceeds the official annual groundwater deficit of about 235 million m^3 in 2017 (MWI 2017). This can probably at least be partly attributed to illegal groundwater abstractions that are not officially counted. Moreover, the FAO estimations of the long-term recharge or renewable groundwater resources

could also be overestimated, as indicated by computations of recharge from 2003–2020 based on ERA5-Land data. Also, the overuse of transboundary aquifers, e.g. by Saudi Arabia, certainly contributes to the computed losses. Saudi Arabia officially withdraws over 21,000 million m^3 groundwater per year, exceeding by far even the most optimistic estimations of natural recharge. This causes an average annual storage loss within the countries' borders of about 7,500 million m^3, which is reflected in a strong cone of depression, affecting the Hail Ga'Ara arc and the Jafr Tabuk basin (Fig. 8f). Other countries such as Kuwait and Israel also show negative trends on average with –5.7 and –3.2 mm/year, respectively. Qatar, Libanon, Oman, Yemen and the United Arab Emirates, however, show even positive mean trends between 0.2 and 4.2 mm/year, which is limited to the central, sparsely populated desert and mountainous areas, with the more densely populated coastal areas and the western and eastern parts showing slightly negative trends. For the eastern part of the United Arab Emirates, this coincides with the regional observation of Yilmaz et al. (2020). It has to be mentioned though, that the results of the GRACE–derived data for the smaller countries of the Arabian Peninsula has to be interpreted with some care.

Regarding aquifer types in the Arabian Peninsula, most are strongly affected by the negative trends in GWS, which could be due to the natural water scarcity in this region and the additional use of low-productivity groundwater systems that contribute less to water supply in water-rich countries. The most affected aquifers are the highly productive unconsolidated porous aquifers with an average trend of –10.1 mm/year, which are generally shallow and easy to develop, followed by moderately productive intergranular and fractured aquifers (including karstified rocks) and practically nonaquifer rocks (porous or fissured) with –6.4 and –3.3 mm/year, respectively. Both aquifer types occur in about 26% of the area (Fig. 8e).

Conclusion

In this study, new data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission and recently reanalyzed ERA5-Land data were used to examine trends in GWS in the Euro-Mediterranean region over the period from 2003 to 2020. The results were related to the regional climate and hydrogeologic setting, as well as to data on renewable groundwater resources and groundwater abstractions for each country.

The main findings are:

- Significant trends in GWS can be observed for most of the Euro-Mediterranean area (87%). Of these, about 80%

are negative trends and only 20% are positive trends, so that there are significantly negative trends in about 70% of the study region. The overall mean of the trends across the Euro-Mediterranean region is –2.1 mm/year.

- The Arabian Peninsula is most affected with average negative trends of –2.9 mm/year, followed by Western, Central and Eastern Europe with –1.5 mm/year, North Africa with –0.9 mm/year and Southern Europe with –0.7 mm/year. Northern Europe experiences a positive trend of 1 mm/year in the period under consideration (but comprises only 2.2% of the study area).

- Negative and positive trends can be observed in all climate zones, with a slight tendency towards more negative trends in polar, arid and cold regions (–4.4, –3.8 and –3.4 mm/year), compared to temperate regions (–1.5 mm/year).

- On individual country level, an average negative trend is observed in 36 of the 47 countries, while 11 countries show a positive average trend. The strongest negative average trends can be observed for Iraq (–8.8 mm/year) and Syria (–6.0 mm/year). However, the mean value is often not representative for the entire area of a country, as the trend in many countries varies greatly from region to region. Moreover, the results should be taken with care for smaller countries due to the native GRACE resolution.

- Comparisons of GRACE-derived GWS trends with recharge and abstraction data show that with regard to the study period, the observed trends in GWS are mainly not related to trends in recharge, whereas groundwater withdrawals probably play a dominant role.

- The traditional approach of using recharge and abstraction data is often not suitable for the determination of a sustainable use of groundwater resources at a country level, since these data are often subject to great uncertainties. GRACE-derived GWS trends can be used to overcome this problem.

The results of this study confirm the observations of earlier studies that have already documented declining groundwater levels in large parts of Europe and the Mediterranean region, and thus show that these trends are still unbroken. As expected, semiarid to arid countries such as Iraq, Syria, Jordan, and Saudi Arabia, which heavily rely on groundwater, are most affected. However, temperate regions in Southern, Western and Central Europe and cold climate regions in Eastern Europe, are also largely affected by groundwater depletion such as large parts between France, Germany, Poland, Italy and Hungary. Moreover, average GWS trends at the country level often do not reflect the actual situation, since densely populated and agricultural areas are usually more affected by negative GWS trends, mostly visible in populated coastal areas around the Mediterranean.

Up to now, declining trends in GWS have been partly attributed to increasing groundwater use as well as climate change and decreasing groundwater recharge rates (EUWI 2007; Aureli et al. 2008). The latter has been attributed particularly over the last two decades to an above-average number of heat waves during the summer months (Zhang et al. 2020; Twardosz and Kossowska-Cezak 2021). While one also cannot certainly quantify the respective shares of climatic and anthropogenic (abstraction) influences, which is probably difficult anyway, due to a lack of reliable data on the one hand and the fact that recharge and abstractions are often highly negatively correlated on the other hand, this study can at least give hints that climatic influences seem to play a minor role in most of the study area, since trends in recharge over the study period are widely not significant. On the other hand, at least for regions with most severe declining trends in groundwater resources, comparisons of recharge and abstraction data on country level show a nonsustainable use, indicating that overextractions are the dominant drivers for groundwater depletion in most regions. Moreover, regions with strongly declining trends are often spatially associated with densely populated areas or areas with known groundwater abstractions for irrigation. This finding is also in accordance with other studies with different modelling approaches, which showed that direct climatic influences on groundwater levels are rather low and account for only a small part of the falling groundwater levels (e.g. Alfaro et al. 2017; Wunsch et al. 2021).

Additionally, this study concludes that trend analyses of GRACE-derived GWS data give a more reliable picture of sustainable groundwater use compared to the traditional approach of renewable groundwater resources (or natural recharge) and abstractions. The reasons are most probably inaccurate data for groundwater recharge, which is difficult to accurately determine (e.g. Moeck et al. 2020), as well as partly unreliable data for abstractions (unrecorded and/or illegal withdrawals). Moreover, the GRACE-derived GWS trends allow for spatially resolved assessments of groundwater resources compared to averaged water budgets at the country level. Further indications for this are the good spatial agreement of regions with declining GWS trends and high population densities or intense agricultural use, as well as high correlation between regional groundwater-level observations and GRACE-derived changes in GWS, which have already been demonstrated by many studies (e.g. Neves et al. 2020; Biancamaria et al. 2019; Liesch and Ohmer 2016; Chao et al. 2018; Frappart 2020).

As a result of negative GWS trends, groundwater resources in Europe and the Mediterranean region are increasingly in a state of stress, which not only has implications for drinking-water availability, but also for river baseflow and groundwater-dependent ecosystems. The results underline the need for adapted sustainable groundwater

management strategies on a transregional scale, including cross-boundary and coastal aquifer systems. Appropriate strategies must not only aim at more efficient groundwater use for drinking-water supply and agriculture by using nonconventional water resources and advanced irrigation techniques, but may also adapt decision criteria such as for water availability, which is often estimated from long-term averages, e.g. of groundwater recharge rates. Furthermore, it should include maintenance of the existing hydraulic infrastructure to reduce water losses and intelligent control systems, e.g. of groundwater drainage systems or new forms of technology such as managed aquifer recharge (Dillon et al. 2019) to counteract declining groundwater levels. However, ecological approaches to increase groundwater recharge rates can also be part of the portfolio of measures such as through forest conversion from conifers to deciduous trees, which have a lower interception rate, as suggested by Hennig and Hilgert (2021) for north-eastern Germany. In most cases, however, a combination of different measures is the most promising approach, also taking socio-economic and political factors into account. This study also showed that there is still a lack of comprehensive, region-wide, long-term hydrogeologic and water-use data series on groundwater recharge and groundwater abstractions, although many of the large-scale models show promising results and more accurate data may be available at individual country level.

Declarations

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