communications earth & environment

Article

https://doi.org/10.1038/s43247-024-01554-w

Multi-decadal groundwater observations reveal surprisingly stable levels in southwestern Europe

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Climate change and human activity are leading to water scarcity in southwestern Europe. Groundwater use is thought to be unsustainable in the region, yet regional assessments using measured data are missing. Here, we evaluate long-term trends and drivers of groundwater levels and found a more complex situation. Historical data (1960–2020) from 12,398 wells in Portugal, Spain, France, and Italy showed 20% with rising groundwater levels, 68% were stable, and only 12% were declining. Rising wells in temperate climates were due to increased precipitation. Recovering wells in semi-arid regions were attributed to improved groundwater management. Stable wells are concentrated in temperate climates with year-round high precipitation. Declining wells in semi-arid regions are primarily located near agricultural areas and experience prolonged summer soil moisture loss, whereas in temperate regions, the decline is associated with large urban areas. Systematic groundwater monitoring and data sharing are essential for sustainable and science-based water resources management.

Heat-induced dry conditions, accompanied by changes in precipitation patterns, are becoming more frequent and widespread throughout Europe[1,2]. This study focuses on Portugal, Spain, France, and Italy, four Mediterranean countries in southwestern Europe that are responsible for a large share of the European Union's fruit, vegetable and cereal production[3,4]. These countries[5–7] rely heavily on groundwater, which provides 30–50% of irrigation and 28–75% of drinking water supplies[5,6,8,9]. The study area already faces escalating droughts, reduced streamflow and soil moisture[10–13], highlighting the increased role of groundwater as a buffer to mitigate water stress. Predicted warming rates will surpass global averages by 20%[14]. A 2 °C temperature rise is predicted to lead to frequent heatwaves[15], with a 15–30% summer precipitation decline[16,17], affecting freshwater availability, crop productivity, and leading to increased summer irrigation, energy demand, and forest fire risks[15,18].

Despite the critical importance of groundwater in southwestern Europe, there are no detailed regional-scale investigations of its responses to natural and anthropogenic drivers. A recent study using coarse-scale GRACE satellite data indicates a declining trend in groundwater levels in eastern Spain, northern France, and northern Italy[19]. However, the limited resolution of satellite observations hinders the identification of specific physical drivers underlying groundwater level changes. On the other hand, aquifer-scale investigations highlight important local declines in groundwater levels within the region, often associated with irrigation[20–22]. Yet, these spatially-limited studies do not provide a comprehensive and comparative regional picture of the status of this vital water resource.

To address this knowledge gap, this study assesses multi-decadal groundwater level trends using multiple data sources, including an extensive historical dataset from 12,398 wells in Portugal, Spain, France, and Italy,

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collected between 1960 and 2020. These datasets allow us to bridge the gap between local, regional and large-scale (satellite) perspectives and better assess the factors contributing to observed patterns in groundwater levels. These factors include climate variables, such as precipitation, and anthropogenic influences, such as proximity to urban and irrigated areas. These four countries provide a unique opportunity to investigate regional groundwater changes and their drivers across diverse climates, benefiting from the availability of long-term monitoring data, and well-established international governance. This regional study can serve as a benchmark for other regions worldwide facing similar challenges.

The specific objectives of this study are (i) to identify trends in groundwater levels, (ii) to cluster multi-decadal groundwater level trends spatially, and (iii) to disentangle climatic and anthropogenic drivers of these trends. The results enhance understanding of changes in groundwater levels in southwestern Europe and insights that can support informed decision-making for sustainable groundwater management in the face of changing climatic conditions and increasing water demands.

Results

Contrasting temporal trends in groundwater level changes

Figure 1a shows the number and measurement frequency of observation wells in each country since 1960. Most wells (58%) have more than ten years of groundwater level measurements, with only 8% having 30 years or more. For wells with more than a decade of measurements, the frequency varied between daily (23%), weekly (19%), monthly (18%), and bimonthly (40%). Wells with the most weekly and daily measurements are located in France. In Portugal and Spain, 90% of observations were collected at monthly or bimonthly frequencies. Figure 1a superimposes key national water policy instruments over the number of wells. Generally, the implementation of national water laws increased monitoring efforts, which were possibly further accelerated after 2000 due to mandatory groundwater monitoring and reporting requirements of the Water Framework Directive[23].

For long-term trend analysis, we employed 7155 wells with over a decade of data—covering 44% of the groundwater bodies within the study region. Areas with at least one well per 500 km^2, aligning with France's National Quantitative Monitoring Network for Groundwater density[24], were evaluated for spatial coverage (Fig. 1b). Among these wells, 15% exhibited a rising trend, 65% were stable, and 20% showed declines. Figure 1b portrays inconsistent trends in neighbouring wells; a deeper examination reveals varying trends at nearby locations due to differing measurement durations, suggesting a multi-decadal temporal behaviour. For instance, wells in Spain's Murcia and Castilla y Leon regions, monitored for over 20 years, display a declining trend, contrasting with neighbouring wells with shorter records of 10–20 years of data showing a rising trend. These dynamics, comprising of prolonged decline followed by a recent level stabilization or recovery, are likely driven by climatic variability or water management modifications.

Multi-decadal clustering reveals long-term groundwater changes

For a detailed examination of long-term groundwater trends, we focused on 1038 wells, ensuring that annual means would be available for at least 6 out of 10 years for each decade between 1985 and 2014. Notably, the threshold was surpassed in the majority of cases, 80% of the wells had complete datasets for the three decades. Based on the trend results of each decade (Fig. S1), a multi-decadal clustering analysis was performed, from which nine clusters were identified based on water table depth (WTD) evolution: rising, stable, and declining water levels (Fig. 2a–c). Among these clusters, 20% displayed rising, 68% stable, and 12% declining water levels. These statistical results obtained from clustering and multi-decadal analysis are slightly different to those reported in the previous section, as the number of wells and investigation periods are different (see Methods for further details).

Rising groundwater level clusters (Clusters 1–3, Fig. 2b) are defined as having rising trends in at least one of the three decades. Cluster 1 includes recovering wells that exhibited declining trends in the first decade, followed by stabilization and rising (i.e., recovering) levels in the subsequent decades. Despite the overall rising trend in the last decade, the wells within Cluster 1 experienced an average decadal decline of 2 m, calculated as the arithmetic mean of the differences in the median WTD between the third (2005–2014) and first decade (1985–1994) across all wells in the cluster. Conversely, Clusters 2 and 3 consistently exhibited rising level trends throughout the study period (1985–2014), with average decadal increases of approximately 3–4 m (Fig. 2c).

Wells in Clusters 4–6 exhibited near-stable levels, with slight variations observed in Clusters 5 and 6 during the first and third periods, respectively, while wells in Cluster 4 exhibited no significant trends (Fig. 2b). In contrast to other clusters, the average decadal level changes in this group are minimal, measuring less than 1 m (Fig. 2c).

In the clusters showing declining levels (Clusters 7–9), all wells exhibited significant declining trends during at least one of the three decades. The steepest decline in Cluster 7 wells was observed during the third decade, while Cluster 8 wells exhibited a decline in the second decade (1995–2004). Wells in Cluster 9 show a continuous depletion across the entire period (1985–2014). The decadal groundwater level change was the highest in this group, with Cluster 9 wells exhibiting an average decadal decline of 11 m, while Clusters 7 and 8 wells had decadal declines of 3 and 5 m, respectively. A notable portion of wells with declining trends are in well-known confined aquifers, which show more pronounced and lasting groundwater level changes than unconfined aquifers. However, the lack of comprehensive data for all wells prevented a clear distinction between aquifer types in this analysis.

Figure 2a shows that the identified clusters are distributed across the four countries spanning various climate and hydrological conditions. To provide context, we illustrate some selected areas from the different clusters in the Supplementary Information (Fig. S2 and Table S1). An example of rising/recovering groundwater levels in a semi-arid climate is in La Mancha Oriental, an aquifer in the Jucar River basin of eastern Spain (Fig. S2). The recovery in groundwater level reflects management changes implemented in the last two decades after a period of severe groundwater depletion. The capacity of the farmers' water users association to adopt measures for more sustainable use was an essential component of these changes[25]. Ravenna (Po River basin, Italy), an area with dense urban and agricultural lands, has rising groundwater levels. Most wells in this area belong to Cluster 3, characterized by a steep rise of groundwater levels in the first decade, followed by near-stable levels. In contrast to La Mancha Oriental, rising levels in Ravenna are related to natural and anthropogenic land subsidence[26,27].

Regions experiencing declining clusters include Béziers in southern France, where drinking water accounts for 75% of groundwater abstractions, with half of the water allocation dedicated to serving the summer tourism demand[28]. Another declining area is Bordeaux, which has growing urban areas. Since the 1960s, groundwater level drops have been reported in this area, with domestic use accounting for most of the withdrawals[29,30].

Climatic and anthropogenic drivers controlling groundwater level changes

Besides extractions, long-term groundwater fluctuations are also influenced by changes in precipitation patterns[31], land use[32–34] and, if hydraulically connected, surface water[35,36]. We analysed the influence of several variables (Supplementary Tables S2, S3) related to climatic, hydrogeological and anthropogenic factors (Figs. S3, S4) on the observed clustered WTD evolutions. The impacts of these factors are discussed below. Note that the groundwater level's response to these drivers is partly mediated by characteristics such as well depth, flow conditions (confined/unconfined), and flow system position; however, due to the lack of comprehensive data for these parameters across all wells, further analysis is infeasible.

Climatic and hydrological drivers

Distinct rising, stable, and declining patterns were observed across the different climate regions. Specifically, stable wells are more prevalent in temperate climates (72%) compared to semi-arid regions (46%) (Fig. 2a).

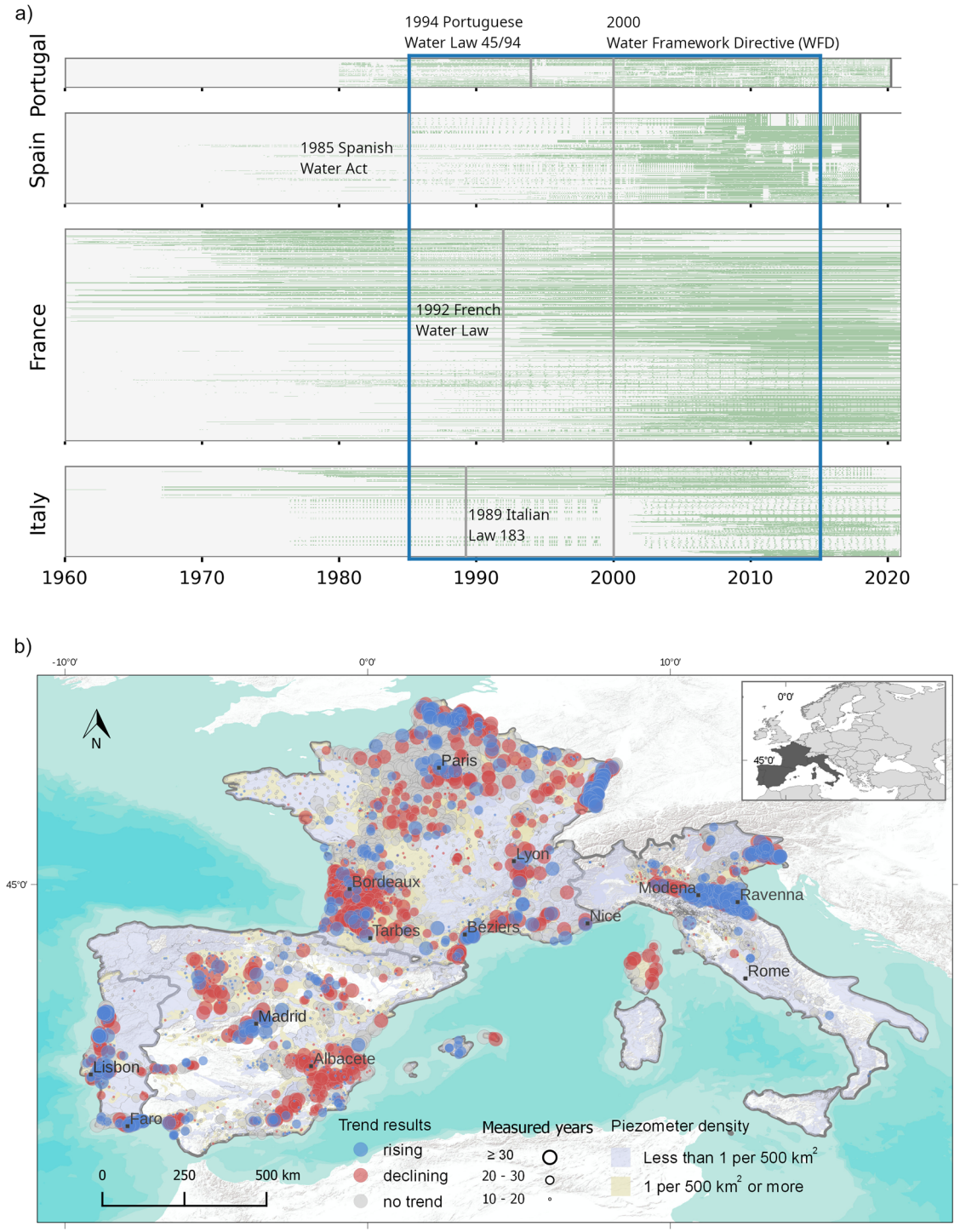


Fig. 1 | Groundwater level measurements and trends from different time frames. **a** Heat maps depicting groundwater level monitoring from 1960 to 2020 and key national and regional water policy instruments for Portugal, Spain, France, and Italy. Each row is an observation well of the respective country; grey and green colours indicate the absence or presence of measurements, respectively. The blue box frames the period used for the multi-decadal trend analysis (1985–2014). **b** Groundwater-level change hotspots determined by trend detection for 7155 wells for the entire 30-year period (more than 10 years of data, blue for rising, red for declining, grey for stable levels). Years measured in each well are reflected in the circle size. In brown, groundwater bodies with a well density of at least 1 per 500 km^2. Background imagery from https://www.arcgis.com/home/item.html?id=c61ad8ab017d49e1a82f580ee1298931.

Conversely, wells with declining/rising levels are 12–14% more abundant in semi-arid regions compared to temperate climates.

Correlations between WTD and annual precipitation revealed that wells in stable clusters (Clusters 4–6) exhibited a markedly stronger negative correlation (−0.41 to −0.51) (Fig. 2d). In comparison, for declining and rising clusters (Clusters 1–3, and 7–9), the correlation ranged from −0.13 to −0.33. Notably, the correlation was weakest for declining-level Cluster 9, with an average value of −0.13. These results suggest that factors other than precipitation, primarily anthropogenic influences, drive the observed changes. In Cluster 1, where levels stabilized or recovered, the strongest correlation between WTD and annual precipitation was found for wells located in temperate climates (mean correlation of −0.33), while wells in

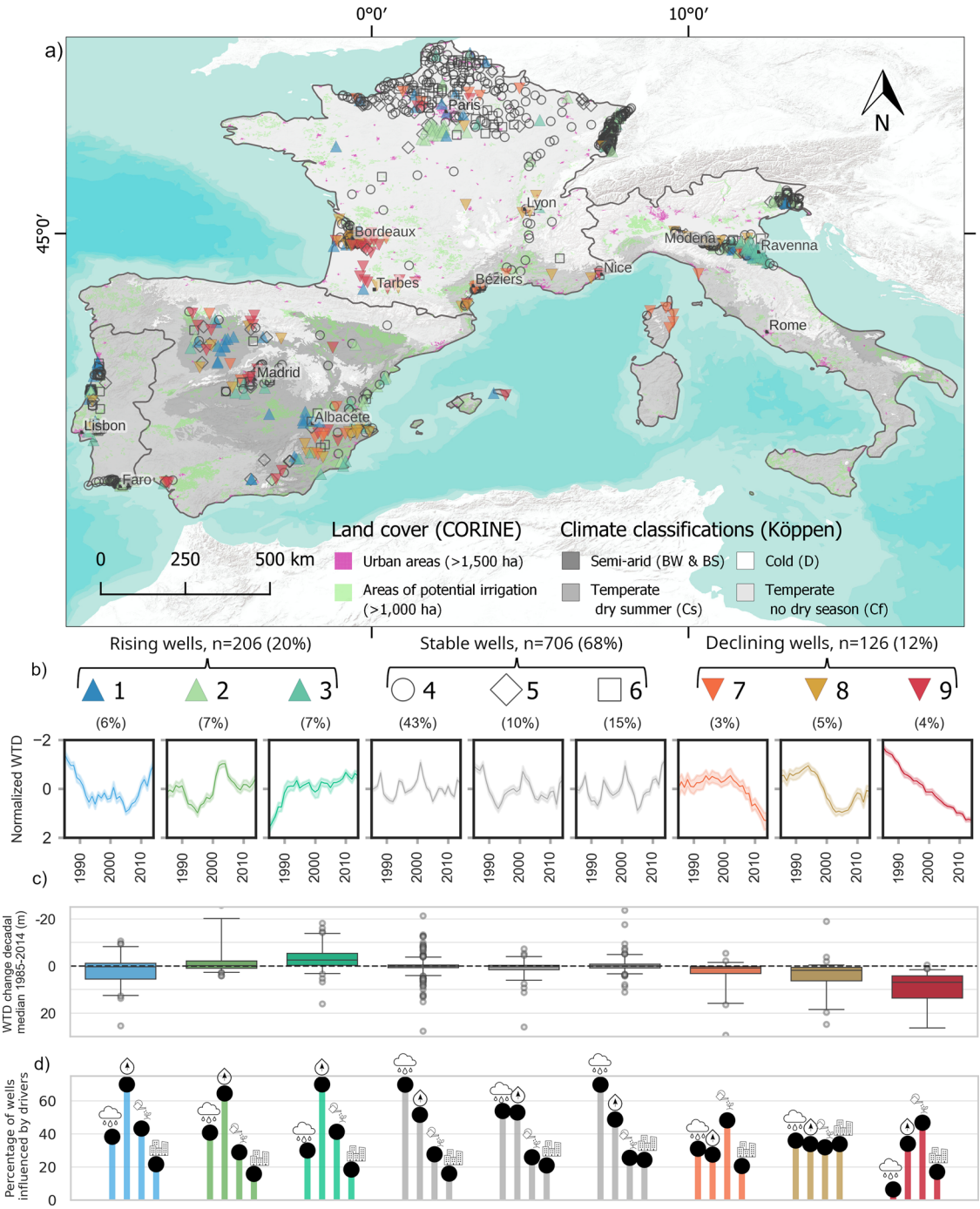


Fig. 2 | Cluster distribution and characterization of water table depth (WTD). **a** Spatial distribution of WTD evolution clusters in climate classifications (symbols defined in **b**). **b** WTD cluster behaviour during 1985–2014 based on the normalized WTD average of the given cluster. **c** Interquartile (IQR) distribution of the median differences in WTD changes between 1985–1994 and 2005–2014, IQR within the box limits and the median as the centre line. Whiskers extend to 1.5 times the IQR, and outliers as dots outside the whiskers. **d** Percentage of observations with strong influence from each driver. Cross-correlation in excess −0.45 between annual precipitation – annual WTD (cloud symbol). Precipitation increases greater than 10 mm per decade (drop with arrow symbol). Potential irrigation: wells within 2 km of a large agriculture area (1000 ha) with potential irrigation (watering can symbol). Urban area: those within 4 km of urban areas (more than 1500 ha) (buildings symbol). Background imagery from https://www.arcgis.com/home/item.html?id=c61ad8ab017d49e1a82f580ee1298931.

semi-arid climates exhibited the weakest correlation (mean correlation of −0.05). In temperate climates, recovery is influenced by variations in precipitation alongside other factors, while in semi-arid climates, recovery is more closely linked to aquifer management practices.

Rising wells in temperate climates were related to precipitation increases. Although significant trends in annual precipitation during the 1985–2014 period were not observed in this or previous studies[37], it is noteworthy that the decade 1995–2004 had higher precipitation than 1985–1994. Specifically, the median precipitation of 1995–2004 was higher by 16–73 mm across all clusters compared to the previous decade. Subsequently, we analysed the rate of precipitation change over the entire 30-year study period. Wells in rising clusters displayed a more pronounced increase of precipitation during the study period than the other groups (Fig. 2d), with an average increment rate of 20 mm per decade. Rising wells with higher than 20 mm increase per decade (47% of them) were located mostly in temperate climates (e.g., Po basin and eastern Portugal). In contrast, stable

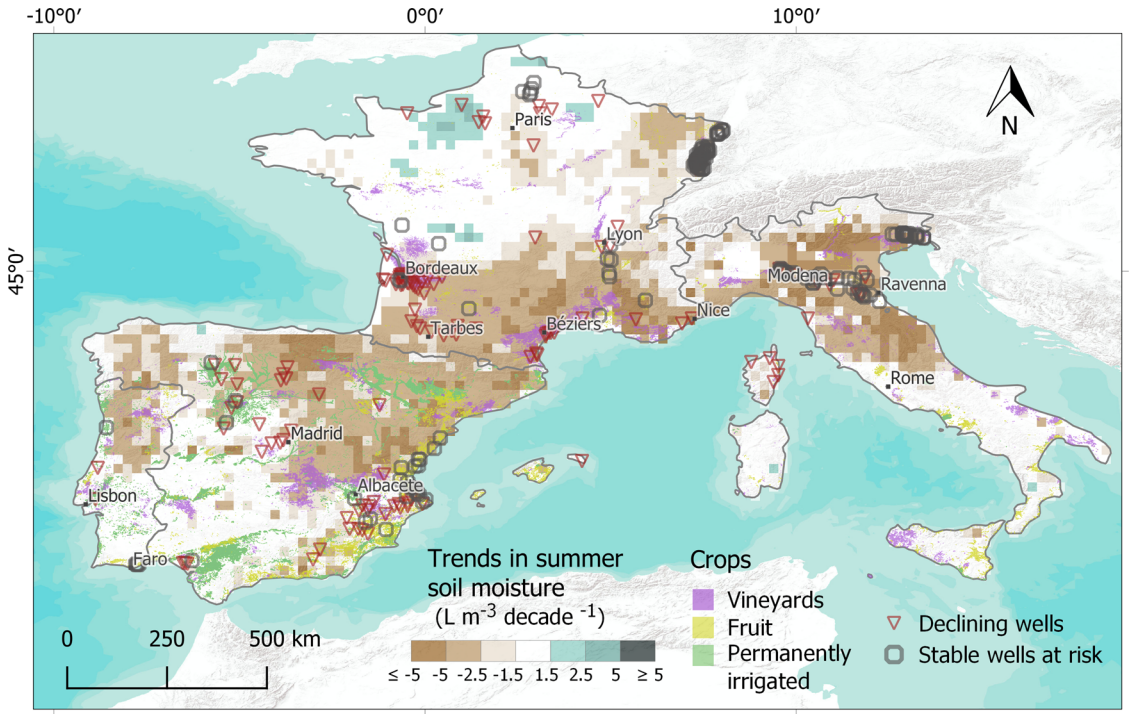


Fig. 3 | Role of soil moisture and crops. Wells with declining water levels (Clusters 7–9) marked in red triangles are generally located in areas with higher decreases in soil moisture across the region from 1950 to 2012 (Kurnik et al.[38]; Kurnik et al.[39])[35,36] as well as overlapping in some cases with vineyards and fruit orchards. Up to 21% of the stable wells (marked as grey rounded squares) located in irrigated areas experiencing a reduction in soil moisture of more than 1.5 L m^{-3} decade^{-1} or a decrease of 10 mm decade^{-1} in precipitation deficit, are considered at risk of climate-induced declines. Background imagery from https://www.arcgis.com/home/item.html?id=c61ad8ab017d49e1a82f580ee1298931.

and declining wells experienced comparatively lower increases in precipitation of 10 and 2 mm per decade, respectively.

In areas with wells, overall increases in annual potential evapotranspiration (PET), observed over the three decades, have often surpassed annual precipitation (P), leading to enhanced drier conditions as reflected in the precipitation deficit (P-PET). Particularly in regions around declining wells, negative trends of P-PET are more pronounced, averaging −3.1 mm per decade on average, compared to areas with stable wells (−1.2 mm per decade) and those with rising wells with an averaged net gain in P (6.7 mm per decade). This increase of drier conditions in P-PET contributes to reduced groundwater recharge rates and long-term groundwater level changes. Approximately 49% of all areas around wells had negative P-PET trends (66% of declining, 52% of stable, and 30% of rising wells).

We assessed the relationship between groundwater level changes and summer soil moisture trends during 1951–2012[38,39] (Fig. 3). Most of the study area, particularly northern Portugal, eastern Spain, southern France, and northern Italy, exhibited a consistent decrease of summer soil moisture during this period, with an average change of −1.5 L m^{-3} per decade. Notably, Clusters 8 and 9 (declining) were in areas with more substantial soil moisture losses, averaging −2.3 L m^{-3} per decade. In parallel, meteorological drought frequency per decade (1985–2014) (Table S3) also increased in the region, however, no significant differences among clusters were found. This underscores the association between groundwater level trends and long-term soil moisture declines rather than seasonal meteorological droughts.

Based on long-term average potential recharge estimates[40], which factor in precipitation, actual evapotranspiration and a groundwater recharge coefficient, the areas around stable wells exhibit an average recharge of 102 mm yr^{-1}. In comparison, areas around declining and rising wells report lower rates, at 61 and 64 mm yr^{-1}, respectively. This difference is particularly notable in the temperate climates, where the average potential recharge in Cluster 4 (stable) is the highest at 140 mm yr^{-1}, in contrast to Cluster 3 (rising), which had the lowest recharge of 78 mm yr^{-1}.

The distance between wells and the nearest stream in basins over 10 km² was on average 1039 m, with significant variability and no discernible statistical difference across well clusters. For streams receiving flow from at least one other stream (Strahler order 2 or higher), the average distance increased to 2390 m. Despite considerable variability, the distribution of distances remained consistent across cluster classifications (Fig. S5). The absence of stream-aquifer permeability data constrained our focus to distance analysis, precluding a deeper understanding of the interplay between groundwater levels and adjacent streams.

Anthropogenic drivers

Unlike wells with stable levels, wells exhibiting declining and rising levels were in closer proximity to agricultural lands potentially associated with irrigation activities (Fig. 2d). Specifically, Clusters 7 and 9, with declining levels, are mostly located in semi-arid regions and had the largest share of wells located within 1 km of irrigated lands (Fig. 2a). This suggests that groundwater is used predominantly for agricultural activities in semi-arid regions to meet the increasing crop irrigation demand. Note that the type of irrigation could have an impact on groundwater levels: irrigation from surface water could promote rising levels, while irrigation from groundwater would likely contribute to declining levels.

We observed a differentiated pattern based on climate in terms of proximity to urban areas. For temperate climates, wells were situated closer to cities compared to semi-arid climates. Temperate climate wells belonging to Cluster 8 (declining) had the closest proximity to cities (Fig. 2d), with a median distance of 1.5 km. This occurs since the majority of wells in France and Italy are located in temperate climates where a large proportion of groundwater use is attributed to urban domestic and industrial activities. In contrast, within semi-arid regions, wells in stable clusters were closest to urban areas, with a median distance of 25 km. The median distance between wells and urban areas exceeding 1500 ha in all climates was 14 km.

Discussion

A recent study[19] that used GRACE satellite data to analyse groundwater storage trends across Europe from 2002 to 2020 found both rising and declining trends in all major climate zones in southwestern Europe. Our observations are consistent with these findings, although some discrepancies exist due to the observation scale differences. For instance, we found rising levels in the lower Po basin of Italy, while they observed declining trends in the whole Po basin. Similarly, we found a mix of declining, recovering, and rising wells in Spain, while they reported a positive trend in the Iberian Massif northwest of the Peninsula. Conversely, in southeastern Spain, decreasing levels were associated with drought and increasing groundwater pumping due to decreased surface water availability [22]. We similarly observed a combination of declining and rising groundwater levels in wells within this region. These findings highlight the importance of dense direct measurements for identifying detailed patterns of groundwater level fluctuations on a regional scale, reflecting the specific characteristics of the hydrogeology and patterns of use at the local scale as opposed to coarse satellite-based earth observation data.

Our finding that most wells have stable groundwater levels confirms that groundwater systems are more resilient to meteorological drought propagation than surface water resources[41,42]. What cannot be deduced, however, is whether stable groundwater levels will continue in the future in the face of projected drought conditions, which could exacerbate groundwater vulnerability[15,34]. This uncertainty is important, given the potential repercussions stemming from alterations in water storage dynamics. Such changes could adversely affect the biodiversity of groundwater-dependent ecosystems such as coastal lagoons and wetlands[42,43], as well as terrestrial vegetation[44,45].

Our study underscores the intricate interplay between anthropogenic activities and climatic factors in shaping declining and rising well levels across the region. Recognizing the challenge of reconciling localized impacts with our broader regional analysis, we present specific instances, such as the observed trends in Tarbes, France, and Medina del Campo, Spain, where substantial soil moisture reductions correlate with declining well levels, particularly in regions with irrigation (Fig. 3). These examples, characterized by a decrease in soil moisture content of 3.3 and 2.8 L m^{-3} per decade and groundwater level drops averaging 8.6 and 11.1 m from 1985 to 2014, respectively, serve to highlight the nuanced ways in which local climate conditions and management practices shape hydrological responses. Similarly, the contrast between the declining groundwater levels in the Segura basin's aquifers near Hellín, Spain, utilized for cereal and vineyard irrigation, and the near-stable levels in the Beauce aquifer in France, underscores the variability across regions. Such disparities, driven by differences in management such as increased abstraction permits in Hellín despite decreasing levels[46], and periodic abstraction restrictions in Beauce[47], reflect the localized nature of groundwater dynamics within the broader context of regional trends. By integrating these detailed observations, we aim to enrich our understanding of the diverse and complex nature of groundwater level changes at a regional scale, emphasizing that while climate fluctuations play a major role, human activities often emerge as a predominant driver of these changes, as also indicated globally[48]. This approach allows us to navigate the inherent challenge of integrating local impacts into a regional scale analysis, providing a more nuanced understanding of groundwater dynamics.

Anthropogenic influences on groundwater use were also evident in urban areas. For instance, a declining trend in water levels was observed around cities with populations ranging between 200–500 thousand inhabitants in temperate climates, such as Bordeaux, Lyon, Nice, and Modena. Conversely, rising groundwater levels in temperate climates with increased precipitation over the considered decades were found in areas where groundwater plays a limited role in irrigation, including the upper Po basin, the high Friulian plains in northeast Italy, and the Mata Nacional do Urso along the northwestern coast of Portugal.

Soil moisture trends in the past show that despite stable precipitation patterns, rising temperatures and escalating evapotranspiration rates are responsible for a notable shift towards drier conditions[11]. Looking ahead, it is projected that agricultural droughts will become more frequent, prolonged and intense[49], profoundly affecting groundwater levels due to reduced infiltration and heightened irrigation demands to sustain crop yields. This impact is particularly relevant for summer crops such as maize, olive trees, fruits, and tomatoes[18,50]. This could lead to increased water abstraction in areas where groundwater levels are currently either declining or stable. Our analysis reveals that ~21% of wells currently classified as stable are located in areas at risk of climate-induced declines. We defined them as irrigated areas with drying conditions, that is areas exhibiting notable reductions in soil moisture, with losses exceeding 2.5 L m^{-3} per decade, or by a decrease in P-PET contributing to a deficit greater than 1.7 mm per decade—these figures represent the median values observed among declining wells in irrigated areas (Fig. 3).

Although the examined four countries maintain robust monitoring systems, there are notable gaps in the availability of continuous, long-term groundwater level records for entire basins. Data deficiencies are particularly prevalent in groundwater bodies within basins characterized by heavy abstraction pressures in addition to low measurement density. Moreover, critical information on aquifer characteristics—like aquifer type, well depth, and position within flow systems—essential for understanding their response to climate and human-induced changes is often incomplete or missing. These constraints not only impede our comprehension of aquifer dynamics (Supplementary Discussion) but also hold the potential to lead to erroneous decisions regarding groundwater allocation and exploitation. In the future, decision-making and research similar to this study would benefit from hydrogeological databases that consolidate existing but dispersed data on key variables such as degree of confinement, specific yield, and flow systems, making it accessible on a regional scale.

Furthermore, improved information on groundwater pumping quantity and patterns is essential for enhanced understanding of groundwater systems, especially under fragmented monitoring of driving factors[51,52]. The Mancha Oriental aquifer exemplifies the urgent need for comprehensive groundwater use monitoring. To address significant groundwater level declines[35], local farmers established a water user association that successfully restored groundwater storage through monitoring aided by remote sensing and individual cultivation plans[25,53]. This case underscores the crucial role of data access and monitoring in sustainable groundwater management, offering a model for similar regions.

The study's focus is on southwestern Europe, a region that represents a unique setting combining increasing water demand, long-term data availability, advanced science-based knowledge, and effective international governance, thus making it an ideal reference for other regions of the world facing similar groundwater challenges but with limited long-term data and a lack of effective management and well-developed governance structure. Enhanced understanding of groundwater systems necessitates the unimpeded accessibility of the scientific community and public at large to extensive spatial and temporal long-term in situ and earth observatory data across political boundaries.

Our analysis challenges the prevailing notion of declining groundwater levels in southwestern Europe. Instead, we uncovered a nuanced situation where declining trends are not widespread; rather, there is a diversity of groundwater level evolutions. Almost one-third of the analysed wells exhibited significant changes, including continuous depletion, rising levels, and even recovery after depletion. More than two-thirds of the wells experienced no significant groundwater level changes. Nonetheless, 21% of the stable wells face potential decline as projected drying conditions, such as soil moisture loss and aggravated precipitation deficit, increase irrigation demands. This emphasizes the need for heightened attention to groundwater levels and water use monitoring not just in traditionally depleted areas but also in regions where ongoing drying conditions may exacerbate the demand for groundwater use. Widespread groundwater depletion in this area could greatly impact food production, with far-reaching consequences for the entire European Union and beyond.

Methods

Data collection and processing

Groundwater levels. The study focuses on groundwater level time series data collected from public monitoring networks from southwestern Europe. The data from France, Portugal, and Spain were obtained through bulk downloads and scripts from centralized monitoring platforms (https://ades.eaufrance.fr/, https://snirh.apambiente.pt/, https://sig.mapama.gob.es/redes-seguimiento/index.html?herramienta=Piezometros). Time series from Italy were obtained by requests to subnational authorities and covered mostly the northern part of the country. After collection of the data, outliers were removed, and the data was collated. Annual instead of monthly data were used due to data gaps, with a focus on decadal changes rather than seasonal patterns. The period of 1985–2014 was selected because of the completeness of the data. At the time when the datasets were compiled (January 2020), Spanish data were only available up to the year 2017. Historically, the data density increased after the 1980s (Fig. 1b).

This study compiled the most comprehensive, long-term groundwater level database (12,398 wells) to date in the four southwestern European countries (Portugal, Spain, France, and Italy). The analysis primarily considered water table depth (WTD) for practical groundwater assessment rather than head above mean sea level. In cases involving confined aquifers, the relevant data were interpreted by piezometric levels rather than WTD.

In examining the completeness of our dataset, we determined that 80% of the observation wells used for trend clustering possessed complete datasets throughout the three decades in question (1985–2014), boasting an average of 96% of annual records. To evaluate the likelihood of seasonal data gaps influencing annual groundwater level trends, we analysed monthly data completeness for the same period. We found that 62% of wells had at least 70% monthly data coverage, with only 3% showing seasonal skewness in their gaps, predominantly in spring and autumn. For the 28% of wells with less than 70% monthly data coverage, gaps were more prevalent and typically of greater duration. Despite this, seasonal bias in data gaps was observed in only 2% of these wells, thereby reducing the risk of seasonal bias impacting the annual trend analysis.

Ancillary data. Ancillary data utilized in this study to provide additional context and information included various variables from multiple sources. Precipitation data from the E-OBS dataset (https://doi.org/10.24381/cds.151d3ec6) were used to assess alterations in recharge and to estimate drought presence. Potential and actual evapotranspiration time series, obtained from the Global Land Evaporation Amsterdam Model (GLEAM v3.7a), aided in understanding evaporative demand changes affecting recharge and drought presence. The CORINE Land Cover 2018 dataset was employed as a surrogate for anthropogenic pressures on groundwater since it is concerned with land covers associated with irrigated agriculture and urban water usage. Köppen-Geiger climate classification maps were used to differentiate temperature and precipitation regimes. The IHME1500 dataset, alongside national geology surveys, provided information on hydrogeology, which is crucial for understanding groundwater flow and storage. The European Irrigation Map for the year 2010 (EIM2010) was utilized to estimate irrigated areas and to assess irrigation intensity. EuroGeoSurveys' Potential Groundwater Recharge dataset provided estimates of the influx of water into groundwater stores. Trends in summer soil moisture in Europe[35,36] served as proxies for decadal recharge change. These ancillary datasets were preprocessed to match observation wells based on their spatial locations, enabling comprehensive analysis and interpretation of the groundwater system. Further details are available in the Supplementary Information.

Trend detection and clustering. We used the Mann-Kendall-Hamed Rao modification to detect trends in the groundwater level time series[54] for wells with at least ten years of measurements ($n = 7155$ wells) using the Python package pyMannKendall[55]. Decadal trends (1985–1994, 1995–2004, 2005–2014) were also calculated for wells with at least 30 years of observations ($n = 1038$). The trend detection results, along with the magnitude of the trend, measured as Sen Slope, were the inputs for *k*-means clustering that grouped wells based on similar WTD evolutions. The number of clusters was determined by comparing the elbow method and silhouette coefficient[56].

Drivers analysis. The relationship between anthropogenic and climate variables was examined for each well. A total of 33 variables were analysed to assess their potential impact on groundwater levels (Supplementary Tables S2, S3, Figs. S3–S7). These variables encompassed numerous factors such as average values, trends, and decadal changes in precipitation, potential evapotranspiration, and actual evapotranspiration. Additionally, wet days per year, cross-correlation between annual precipitation and WTD, climate classification, potential recharge, elevation, hydrogeology, drought and summer drought frequency trends, as well as distances to different land uses, including urban areas and potentially irrigated fields, were considered. Furthermore, we considered the areas dedicated to irrigation of specific crops such as vineyards, cereals, rice, citrus, and olives. To determine the key drivers distinguishing the identified clusters, a Random Forest analysis was conducted (Fig. S4) to prioritize variables of highest importance for further analysis.

Cross-correlation analysis employing a moving time frame, with a maximum period of 3 years, was employed to establish the correlation between annual groundwater level time series and annual precipitation data obtained from the nearest E-OBS gridded dataset[57]. Utilizing the same dataset, we extracted information on the number of wet days per year, defined as days with precipitation exceeding 0.1 mm[58], to calculate the average count of wet days as well as the rates of changes during the 1985–2014 period.

Meteorological drought influence was evaluated by analysing the distribution of wells in relation to drought events per decade using SPEI-3 months[10] (Table S3).

Soil moisture trends were determined from the soil moisture balance model in the upper soil horizons for summers (June–August) between 1951 and 2012. The soil moisture balance was previously validated with measured soil moisture depth between 5 and 90 cm[36,37]. We selected this dataset for its comprehensive temporal coverage and validation against in situ measurements, enabling a robust analysis of long-term influences on groundwater levels within our study period of 1985–2014.

The Euclidean distance from each well to the closest urban or irrigation area was calculated using the QGIS plugin NN Join[59]. Urban areas were defined as having at least 1500 ha of continuous pixels classified as continuous urban fabric, discontinuous urban fabric, industrial, or commercial units in the CORINE database[60]. In this same database, irrigated areas were defined as at least 1000 ha of continuous pixels classified in CORINE as permanently irrigated, rice fields, vineyards, fruit trees, berry plantations, annual crops associated with permanent crops, and complex cultivation patterns.

In a similar way, the distance from each well to the nearest stream was estimated using the global river network HydroRivers[61]. Initially, distances were computed considering all streams to establish a baseline proximity. Subsequently, to emphasize the significance of larger rivers, the stream database was refined to include only those streams with a Strahler order greater than 1.

Data availability

The groundwater level data from Portugal, Spain and France that support the findings of this study are available from the following repositories: https://snirh.apambiente.pt/, https://sig.mapama.gob.es/redes-seguimiento/index.html?herramienta=Piezometros, and https://ades.eaufrance.fr/, respectively. Data from Italy are not provided because the data agreement prevents public sharing of the data. Interested parties can contact the regional water authorities of Italy directly to gain access to the data. Data presented in Figures are available at https://doi.org/10.6084/m9.figshare.26069383.

Code availability

All analysis was made with standard statistical analysis in Python using packages. Python version 3.9.18, packages used: pyMannKendall[55] v1.4.2 for trend detection; SciKitLearn[62] v1.1.3 for clustering and random forest classification.

Received: 9 January 2024; Accepted: 5 July 2024;
Published online: 18 July 2024

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Acknowledgements

This work was developed under the scope of the InTheMED project. InTheMED is part of the PRIMA program funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 1923. The study was also supported by the OurMED PRIMA Program project funded by the European Union's Horizon 2020 research and innovation under grant agreement No. 2222. The collection of measured groundwater data was supported by the Sustain-COAST project under the EU PRIMA 2018 program, co-funded by the German Federal Ministry of Education and Research (BMBF, Germany, Grant number 01DH19015) and the Italian Ministry for Universities and Research (MUR, Italy, CUP number J84D18000180005). We thank the editors Rahim Barzegar and Joe Aslin, and reviewers Steffen Birk, Eric Rosa and an anonymous reviewer for their valuable comments and suggestions for improving the manuscript. We acknowledge the E-OBS dataset from the EU-FP6 project UERRA and the Copernicus Climate Change Service, and the data providers in the ECA&D project (https://www.ecad.eu). This publication has been prepared using the European Union's Copernicus Land Monitoring Service information; https://doi.org/10.2909/960998c1-1870-4e82-8051-6485205ebbac.

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Conception of the work: R.C.G.S., J.J.G.H. and S.J. Acquisition of data: R.C.G.S., J.J.G.H. and S.J. Design of analysis, data analysis and produced figures: R.C.G.S., R.R., E.H., J.J.G.H. and S.J. Results discussion: R.C.G.S., R.R., N.K.C., D.A.B., E.H., D.L., P.P.R., D.B., M.R., J.J.G.H. and S.J. R.C.G.S. wrote the first manuscript. Editing: R.C.G.S., N.K.C. D.A.B., M.R., J.J.G.H. and S.J. All authors read, improved, and approved the final manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-024-01554-w.

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Peer review information *Communications Earth & Environment* thanks Steffen Birk, Eric Rosa and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Rahim Barzegar and Joe Aslin. A peer review file is available

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