

# The dual role of irrigation in the groundwater budget under baseline conditions versus the 2022 drought: Lessons for future climate adaptation

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## ABSTRACT

Groundwater is facing shortage scenarios worldwide due to a changing climate, but systems governed by different recharge processes may react differently. Hence, understanding groundwater budget components is critical for sustainable resource management. This study analyzes seasonal groundwater level patterns from ca. 60 wells, investigating different hydrogeological contexts and water management practices. In the first phase, data under baseline conditions (2013–2021) are analyzed to identify the average seasonal patterns and the associated recharge and discharge processes. Successively, the 2022 data is compared with baseline data to quantify the effect of the hydrological drought. Results show that in surface-water-fed irrigation areas, the absence of surface water during the 2022 summer, related to winter snow scarcity in the Alps, caused significant disruption of the typical groundwater seasonal profile. The winter groundwater table decrease was more than twice the average decrease under baseline conditions, and the summer rise was the 30% of the average rise under baseline conditions. This is related to the missing recharge and the increased abstraction of groundwater to fill the lack of surface water for irrigation needs. Therefore, in a scenario of dryer summers linked to climate change, the plausible transition toward more efficient irrigation methods or groundwater irrigation could cause severe groundwater depletion and compensation measures will be needed. Conversely, in groundwater-fed irrigation areas, the increased irrigation needs during the 2022 summer determined a summer groundwater depletion 76% wider than the average summer depletion under baseline conditions. Here, mitigation actions to reduce abstracted volumes, such as transitioning to more efficient irrigation systems, could reduce groundwater vulnerability to climate change. On the other hand, aquifer systems governed by natural recharge and discharge processes showed a wider pluriannual variability associated with dry and wet years and resulted less vulnerable to single dry seasons than highly anthropic systems.

## 1. Introduction

Groundwater provides societies with tremendous social, economic, and environmental benefits and opportunities (UNESCO, 2022). Nevertheless, groundwater availability has been facing shortages worldwide in the last decades.

A recent study (Jasechko et al., 2024) highlighted that rapid groundwater-level declines are evident globally in the twenty-first century and that declines have accelerated over the past four decades in 30 % of the world's regional aquifers. Although generally considered more resilient than surface water to meteorological conditions, concerns about groundwater availability in relation to climate change are rising

worldwide (Atawneh et al., 2021; Bierkens & Wada, 2019; Ndehedehe et al., 2023). More specifically, drought effect on water availability can have direct impacts on human activities and natural ecosystems (Stephan et al., 2021).

IPCC reports that Global surface temperature will increase until at least mid-century under all emissions scenarios, and this will lead to changes in the climate system, including increases in the frequency and intensity of hot extremes and agricultural and ecological droughts. Projected changes in extremes are larger in frequency and intensity with every additional increment of global warming (IPCC, 2023; Stigter et al., 2023).

In the last 120 years, an increasing trend in the severity of

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agricultural and ecological droughts emerged due to amplified atmospheric evaporative demand, and increased drought severity is expected in areas in which models project reduced precipitation (southern North America and Central America, northern South America and the Amazon basin, southwestern America, the Mediterranean region, western and southern Africa and South Australia) but, more generally, in water-limited regions everywhere due to enhanced atmospheric evaporative demand (Vicente-Serrano et al., 2022).

A recent study at a global scale demonstrated that climate change is expected to have severe impacts on groundwater storage under the business-as-usual scenario (RCP8.5), highlighting that these effects are not only linked to projected changes in precipitations but also controlled by other hydrological processes (e.g., evapotranspiration and snow-melt) worsened by the impacts of over-pumping that could easily far exceed the natural replenishment (Wu et al., 2020).

In these scenarios, understanding the elements of the groundwater budget in specific areas is the cornerstone of sustainable resource management (Di Giovanni et al., 2023). Indeed, different recharge mechanisms can respond differently to global warming (Meixner et al., 2016), and a region's sensitivity to climate change depends on the recharge mechanisms governing a given aquifer system (Amanambu et al., 2020).

The analysis of groundwater level time series demonstrated to be key in deepening the understanding of the groundwater's response to natural and anthropic factors (Anand et al., 2020; Colyer et al., 2021; Egidio et al., 2022; Fronzi et al., 2024; Lasagna et al., 2020; Meggiorin et al., 2021; Noori & Singh, 2021; Obergfell et al., 2019; Pathak & Dodamani, 2019; Ronchi et al., 2018; Sakizadeh et al., 2019; Sartirana et al., 2022; Treviño et al., 2023).

More specifically, while most studies concentrate on long-term trends of groundwater levels, a focus on the seasonal patterns demonstrated to be able to provide precious insights into the anthropic and natural processes governing groundwater budget over time (Colyer et al., 2021; Lafare et al., 2016). Indeed, most of the groundwater budget elements can have a strong seasonality. In this regard Jasechko (2014) highlighted that the recharge of groundwater systems by meteoric water worldwide has a strong seasonal feature. On the other hand, also anthropogenic processes affecting groundwater can have strong seasonal differences. For example, agriculture, which has strong seasonal cyclicity, is regarded as one of the primary anthropogenic factors affecting the groundwater balance with multiple possible effects on groundwater worldwide, such as groundwater depletion in regions with primarily groundwater-fed irrigation or groundwater recharge from return flows where irrigation is fed by surface water (Dangar et al., 2021; Scanlon et al., 2023; Taylor et al., 2013).

Besides understanding the processes governing the groundwater budget under ordinary conditions, analyzing the groundwater response to critical situations, such as hydrological droughts, can provide valuable information on the groundwater budget elements and the response to water management policies. Hydrological droughts are defined as low-flow periods with streamflow or groundwater level deficits lower than "natural" conditions (Tramblay et al., 2020).

The year 2022 was one of the warmest years, with high temperatures in several regions worldwide. Many regions, such as the southwestern U. S., southern Europe, India and central South America suffered serious drought during that year, resulting in devastating impacts on social, agricultural, and ecological sectors (Liu et al., 2023; Weaver et al., 2023; Zhang et al., 2023).

In several European countries, 2022 was a critical year with a severe hydrological drought that resulted in enormous socioeconomic impacts (Faranda et al., 2023; Masseroni et al., 2024; Toreti et al., 2022). The drought conditions in Europe originated from a quasi-stationary high-pressure ridge extending from northern Africa to the British Islands and from the Azores to Italy, starting in winter 2021 (Avanzi et al., 2024). The simultaneous occurrence of dry and hot conditions during winter, as in 2022, generally causes the most severe snow droughts and,

consequently, the most severe summer streamflow droughts (Dierauer et al., 2018, 2019).

Global projections emphasize the critical need to study the mechanisms of groundwater recharge and discharge and their changes under water scarcity conditions. This is essential for planning sustainable water resource management that accounts for potential future water scarcity. Nevertheless, several areas worldwide report a lack of monitoring data or monitoring networks that are scarce and unevenly distributed in both space and time (Bhatti et al., 2017; Haaf et al., 2023; Lall et al., 2020). In most cases, regional monitoring networks hardly reach the detail needed to deeply understand the water budget at local scales, especially in highly heterogeneous areas. On the other hand, water suppliers collect groundwater and abstraction rate data, which are often neglected as they are associated with pumping wells. To the best of our knowledge, no previous work specifically addressed the challenges in exploiting groundwater level data from pumping wells. Therefore, finding a way to exploit groundwater dynamic data from water suppliers can become the new key to investigate groundwater vulnerability to climate change with high spatial and temporal resolution.

This work aims to investigate first the water budget under baseline conditions through the analysis of groundwater levels over time with a specific focus on seasonality and, successively, to explore the system response to the 2022 drought, highlighting the direct effects of meteorological conditions and the indirect effects mediated by human response to water scarcity, and to evaluate the vulnerabilities of different hydrogeological systems to climate changes. Furthermore, this work aims to investigate the potential of exploiting groundwater dynamic data collected from active drinking water wells that are crucial also for investigating areas such as the morainic amphitheaters, where no monitoring network is available, leading to a complete lack of data and previous knowledge of groundwater dynamics.

In this work, dynamic data from over 61 active drinking water wells are explored, and a preprocessing procedure is proposed aimed at extracting noiseless information from dynamic data representative of the aquifer conditions while discarding the effect of high pumping rates. The study area covers a wide range of hydrogeological settings and water management practices, including i) a plain area with intensive surface-water-fed irrigation, ii) a plain area with groundwater-fed irrigation, iii) two morainic amphitheaters with a multitude of small aquifers, and iv) alpine valleys.

To investigate the groundwater budget components, semi-static data under baseline conditions are analyzed through cluster analysis to extract seasonal patterns representative of recharge and discharge processes; to quantify the distortion from the typical seasonal patterns induced by meteorological conditions and water management the effect of the 2022 drought is explored through a specific focus. Furthermore, 22 years of meteorological data are analyzed to quantify precipitation and temperature anomalies.

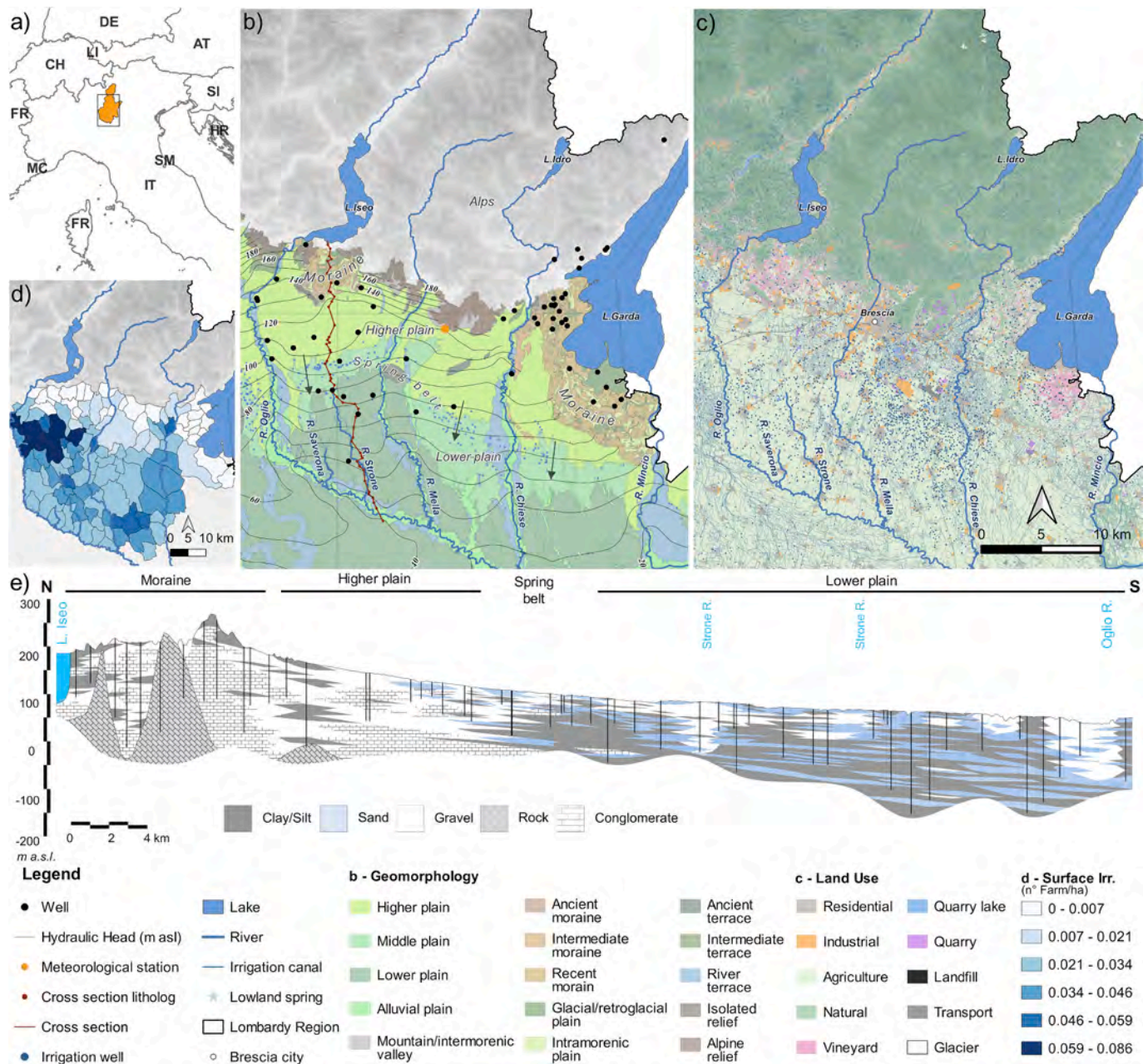
## 2. Materials and method

### 2.1. Study area

The present study covers an area of  $\sim 4000 \text{ km}^2$  within the province of Brescia in northern Italy (Fig. 1).

According to the Köppen classification, the study area falls in the "Cfa" climate group, which is characterized by a temperate continental climate with cold winters and humid, hot summers and an average temperature of  $12.5 \text{ }^\circ\text{C}$  (Faquese & Grossi, 2023). The rainfall regime, with a mean annual precipitation of  $\cong 900 \text{ mm}$ , is characterized by a bimodal trend with two maxima, with moderate prevalence of the autumn maximum over the spring one, and two minima, in winter and summer (Faquese & Grossi, 2023).

The land use is mostly agricultural (Fig. 1c). The most commonly used irrigation method is the surface irrigation method, where farmers flow water down small trenches running through their crops, but this



**Fig. 1.** A) study area; b) geomorphology, monitoring wells, meteorological monitoring station, cross-section trace, and water table contour map (september 2014; (Regione Lombardia, 2016)) with flow directions; c) Land use; d) Application of the surface irrigation method (surface water or groundwater fed) – number of farms that apply the surface irrigation method per hectare(municipal data available from ISTAT – <http://dati-censimentoagricoltura.istat.it/Index.aspx>); e) Cross-section (modified from Zanotti et al., 2022).

method is not practiced uniformly in the study area. In Fig. 1d, the number of farms applying the surface irrigation method is shown for every municipality, standardized by the municipality area (n° of farms per hectare); it is evident that the surface irrigation method is widely applied in the south-central plain, while it is rarer in the northernmost sector of the plain and in the moraine amphitheatres, mostly devoted to vineyards.

This area is denoted by a heterogeneous geological and hydrogeological setting (Fig. 1b), including an alpine area in the north, a plain area (part of the Po Plain) in the south, and two morainic amphitheatres along lakes Garda and Iseo (Marchetti, 2002; Vercesi, 1994; Zanotti et al., 2019). Lakes Garda and Iseo, together with Lake Idro, represent three of the main Italian lakes of the subalpine lakes district whose regime is dam regulated since the second half of the twentieth century,

mostly for hydropower and agricultural purposes (Hinegk et al., 2022).

In the study area, six main aquifer systems can be identified (Fig. 1b): i) Alpine area, ii) Lake Iseo morainic amphitheater, iii) Lake Garda morainic amphitheater, and a plain area which can be further divided into iv) higher plain, v) middle plain and, vi) lower plain. The transition from the higher to the lower plain is marked by a narrow area with numerous groundwater outflows (lowland springs), known as “the springs belt,” located in the middle plain (Bartoli et al., 2012; De Luca et al., 2014);

From a hydrogeological point of view, the Alpine area hosts alluvial river valley aquifers, usually unconfined, and mountain-blocked fractured aquifers whose main recharge sources correspond to precipitation and snowpack melt (Somers & McKenzie, 2020; Vercesi, 1994). Almost all the coastal territories of Lake Iseo, Lake Idro and the northern portion

of Lake Garda are included in the Alpine area.

The Iseo and Garda lakes morainic aquifer systems constitute incredibly complex hydrogeological environments where moraine and fluvio-glacial/-lacustrine deposits overlap. The land use is largely used for vineyards and, for residential destination. In particular, the area along the shores of Lake Garda is characterized by a strong summer tourist vocation. These systems include local unconfined aquifers of limited potential and deeper confined aquifers layered between silty/clayey aquitards with complex and long recharge mechanisms, which are difficult to determine due to the structural complexity of these aquifer systems (Bini & Zuccoli, 2004; Vercesi, 1994; Zanotti et al., 2022).

The higher plain (north) hosts a monolayer unconfined aquifer up to 100 m b.g.s, mainly composed of coarse sediments (sands and gravels – Fig. 1e). The land use is mainly agricultural (Fig. 1c) (crop/arable land), where corn cultivation, especially for cattle and pig feeding, dominates. Irrigation in this area is mostly fed by surface water through an extensive network of centuries-old irrigation canals (Fig. 1c) whose water comes from Subalpine lakes (lakes Iseo, Idro and Garda) and Alpine rivers (i.e. Oglio, Mella and Chiese rivers) with the exception of the northernmost sector where the irrigation is rarely practiced using groundwater.

In the higher plain, aquifer recharge occurs via irrigation return flow during the growing season, local precipitation, losing rivers and canals, and mountain-front recharge in the northernmost sector, while discharge is primarily related to outflows through the springs belt, well abstraction, gaining portion of Oglio River and outflow to the lower plain aquifers (Bonomi et al., 2008; Rotiroti et al., 2023). This sector constitutes the recharge area of both higher and lower plain aquifer system.

Nevertheless, the presence of the springs belt at the transition between the higher plain and the downstream lower plain intercepts and discharges the summer excess groundwater, preventing the increase of groundwater heads in the higher plain caused by irrigation during the growing season from being transferred to the lower plain aquifer. The spring's increased discharge transfers this excess downstream without excessively altering the groundwater level in correspondence and downstream the spring belt (Fumagalli et al., 2017; Rotiroti et al., 2019).

The lower plain hosts a multi-layer system of confined sandy aquifers separated by a vertical alternation of several layers of fine material (silt and clay – Fig. 1e) (Vercesi, 1994). Similarly to the higher plain, the land use in the lower plain is mainly agricultural, but here the main source for irrigation is the groundwater abstracted through irrigation wells (Rotiroti et al., 2019; Zanotti et al., 2019). Groundwater recharge for the lower plain aquifer system occurs solely through groundwater inflow from the higher plain aquifer due to the presence of superficial confining low-permeability layers that reduce or completely prevent surface infiltration. Discharges from the lower plain aquifers occur through gaining rivers and well abstraction (Vercesi, 1994).

The groundwater flow in the plain area is characterized by a NS direction in the higher plain and NW to SE direction in the lower plain (Regione Lombardia, 2016). The water table depth (Fig. S.1.1a) decreases from north to south, ranging from more than 40 m in the northernmost sector to less than 5 m in the medium-low plain.

Climate studies for northern Italy, indicate that this region is facing a concerning trend toward dry conditions (Baronetti et al., 2020). Projections for the twenty-first century (Baronetti et al., 2022) suggest this trend will persist and intensify. Most Global Climate Models (GCM) and Regional Climate Models (RCM) indicate an increase in drought severity, particularly under the high-emission scenario (RCP 8.5), with longer drought durations and a larger percentage of drought-affected areas expected by the latter part of the century (Baronetti et al., 2022; Raymond et al., 2019; Sofia et al., 2023). Significant temperature increases and escalating drought conditions will particularly impact the Alpine region, a crucial water source for the downstream plain areas.

## 2.2. Available data

The local water supplier Acque Bresciane S.r.L. provided hourly raw data of the water head above the data logger (meters) and withdrawal rate (L/s) for 61 drinking water supply wells. The total data covers a maximum period of 10 years, from 2013 to 2022. In addition, the dataset containing static groundwater level data manually collected between 2013 and 2021 was provided. Since the data come from wells used for public supply, and the integrated monitoring network is constantly being improved and expanded, the available time series are characterized by different time spans. Finally, available supplementary structural information such as the well's elevation, well's depth, and data logger depth were provided by the water supplier for each well.

In previous studies (Zanotti et al., 2022), the classification of the groundwater body tapped by each well (Confined, Semiconfined, and Unconfined) was performed, evaluating the depth and extension of the first screen, lithostratigraphic data, geological information from the area, detailed cross-sections, and groundwater depth data. For nine wells, this categorization was not available.

Daily water level data of Lake Garda were downloaded from the web portal of Regional Agency for Environmental Protection of Lombardy (ARPA Lombardia, <https://www.arpalombardia.it/Pages/Meteorologia/Requested-data-metered.aspx>). In particular, the hydro-metric observations recorded by the monitoring station of Manerba del Garda – Dusanò (in the south-wester part of the Lake Garda) cover the period 2017–2022. Finally, from the same web portal, the datasets containing the historical series of daily precipitation and maximum and minimum temperature data from 2001 to 2022 were downloaded. These data were recorded by the gauging station in the city of Brescia (ITAS Pastori), where the longest time series were available.

## 2.3. Meteorological data analysis

Meteorological data were explored to identify the precipitation and temperature anomalies with a specific focus on 2022. The period 2001–2020 was considered as the reference period, and temperature and precipitation anomalies were expressed as percentage variations from the reference period average. Yearly anomalies were evaluated on the hydrological years (December – November). Furthermore, monthly anomalies in the 2021 and 2022 periods were evaluated and compared with the minima, maxima, 25th, and 75th percentiles of the monthly anomalies in the reference period. The multi-annual variability of the seasonal data was calculated: for each season, the cumulative precipitation, the average temperature, and dry days were calculated for every hydrogeological year of the considered time window.

## 2.4. Groundwater level data preprocessing

Data preprocessing started with the exclusion of data associated with sensor errors (e.g., negative values). Successively, the identification and the extraction of the static and/or semi-static trends were carried out. A first analysis of the availability of groundwater level data associated with a 0 L/s abstraction rate (Q) value revealed that the selection of these sole data would result in a substantial loss of data and in the elimination of several wells from the dataset since, in several cases, the wells are rarely completely switched off. Consequently, the data associated with a minimum flow rate, identified by a threshold value of 5 L/s, were selected. This threshold was chosen as the value that would allow maximum continuity along the time series while preserving proximity to static conditions and avoiding the effects of higher pumping rates. To investigate the effect of using data associated with a < 5 L/s discharge compared to the static data, a distribution analysis was performed on the daily maximum data through a Wilcoxon signed-rank test at a 95 % significance level. Results showed that 78 % of the wells had no significant difference between the distribution of static data and data associated with a < 5 L/s discharge. The remaining 22 % of the wells showed

a maximum difference of 0.47 m, which accounted for less than 2 % of the total time variability of the single wells. Only for two wells, average differences of 5.6 m and 6.5 m emerged, which accounts for 14 % and 15 % of the two wells' total variability. These average differences are mostly associated with sporadic data, whose effect is overcome by the monthly median calculation in the successive step. The procedure for the distribution analysis is thoroughly explained in the [supplementary material](#) (Section S.2).

Successively, to reduce the remaining noise in the data, the maximum daily values were extracted from the selected semi-static trend and the monthly medians were calculated. Monthly median groundwater levels were selected as robust values, less influenced by any possible remaining outlier. The figures in Section S.3 show several examples of the preprocessing on a variety of wells: from the raw data to daily maxima on data associated with an abstraction rate lower than 5 L/s and the monthly medians.

### 2.5. Groundwater level data analysis

As a first phase, the obtained time series were firstly standardized by subtracting the global mean for each well and then detrended by subtracting the yearly mean to remove the effect of interannual fluctuations, which could have masked seasonal variability, and to enable the comparison between time series with different time spans. Successively, seasonal profiles were extracted for each well as the twelve monthly medians. Figures in Section S.4 show examples of how subtracting the yearly mean allows for the extraction of meaningful seasonal profiles for a single well while using the original data could lead to noisy information.

To identify groups of wells with similar seasonal profiles and recurrent patterns, a hierarchical cluster analysis (HCA) was performed, considering the 12 monthly medians of the 61 available wells as different variables. Cluster analysis is an unsupervised pattern recognition technique that divides a large group of elements into smaller coherent groups, i.e., clusters (Triki et al., 2014; Zhou et al., 2007). Hierarchical clustering, in particular, was widely used for several groundwater analyses (Nourani et al., 2022; Pathak & Dodamani, 2019; Yin et al., 2022). In this study, HCA was performed using the Ward hierarchical method (Ward, 1963) with the squared Euclidean distance (Bloomfield et al., 2015) in the RStudio environment using the "hclust" function from the "stats" package (R Core Team (2021) Development Core Team, 2021).

Through the combined analysis of the groundwater level fluctuations, such as the seasonal minimum and maxima and the dynamic range (the difference between the maximum and minimum groundwater levels), the obtained clusters have been further grouped using a posteriori knowledge of the groundwater systems' hydrogeological conditions. This analysis was performed on data from 2013 to 2021, focusing specifically on years with baseline conditions representative of the natural seasonal trend of the groundwater level within the study area's meteorological regime.

To investigate how the seasonal variability is related to the total variability of the data for each well, the standard deviation of the original data (as monthly medians), and the standard deviation of the detrended data (i.e., subtracted annual mean) were calculated. The ratio between these two values indicates how much of the total variability is associated with the seasonal variability. This analysis considered only wells with at least two years of data before 2022.

### 2.6. 2022 Drought effects evaluation

To identify the different hydrogeological systems' responses to 2022 extreme conditions, the groundwater level trends from years before 2022 and the 2022 trend were compared. This analysis was conducted on a subset of 51 wells with the 2022 measurement available.

For the wells that fell into the clusters that showed a clear seasonal

profile (Groups A and C), a detailed analysis was carried out to quantify the distortion of the seasonal profile of 2022 compared to the seasonal profile of the reference years. Specifically, minimum and maximum groundwater levels have been identified for each year, and the average increase and decrease were calculated; successively, the 2022 decreases and increases were compared with the average decrease and increase and expressed as percentage anomalies. For the clusters where the pluriannual trend constitutes a major contribution to the total variability and seasonal patterns were less evident, a qualitative analysis through visual inspection was conducted.

## 3. Results

### 3.1. Meteorological data analysis

The year 2022 stood out for record-low precipitation and record-high air temperature, which resulted in a severe hydrological drought. Fig. 2 and a focus in Section S.5 summarize the elaborations of meteorological data at the weather monitoring station (Fig. 1); a twenty-year time window (2001 – 2020) was considered as reference period.

Fig. 2a combines the temperature and precipitation anomalies over the hydrological years (Dec-Nov) based on the reference period. Fig. 2b shows the monthly precipitation and temperature values for the reference period (boxplots and black line, respectively) and the 2022 data (red triangle and red line). Fig. 2c shows monthly precipitation anomalies as percentages: the grey bars indicate maxima, minima, 25th and 75th percentile of the percentage anomalies over the reference period, while red and blue bars indicate percentage anomalies of the 2021 and 2022 data. Fig. 2d reports the seasonal count of dry days.

This elaboration highlights how the hydrological 2022 year constitutes an absolute anomaly for both temperature and precipitation with respect to the reference period. Specifically, as shown in Fig. 2b and 2c, starting from December 2021 throughout the whole 2022, the precipitations were characterized by a severe negative rainfall anomaly and a deficit of precipitation of approximately – 48 % that reached the highest value in October 2022 with a rainfall deficit of – 99 % compared to the reference period. The driest season was spring, with a deficit equal to –75 % (Fig. 2c, Fig. 2d, and Fig. S.5.2). In addition to the precipitation deficit, an annual temperature anomaly of about + 1.5 °C was recorded compared to the 2001–2020 average of 14.4 °C (Fig. 2a). Positive temperature anomalies above 2 °C were recorded in February, May, June, October, and December, with a July peak of + 3.6 °C (Fig. 2b, Fig. S.5.1, and Fig. S.5.3).

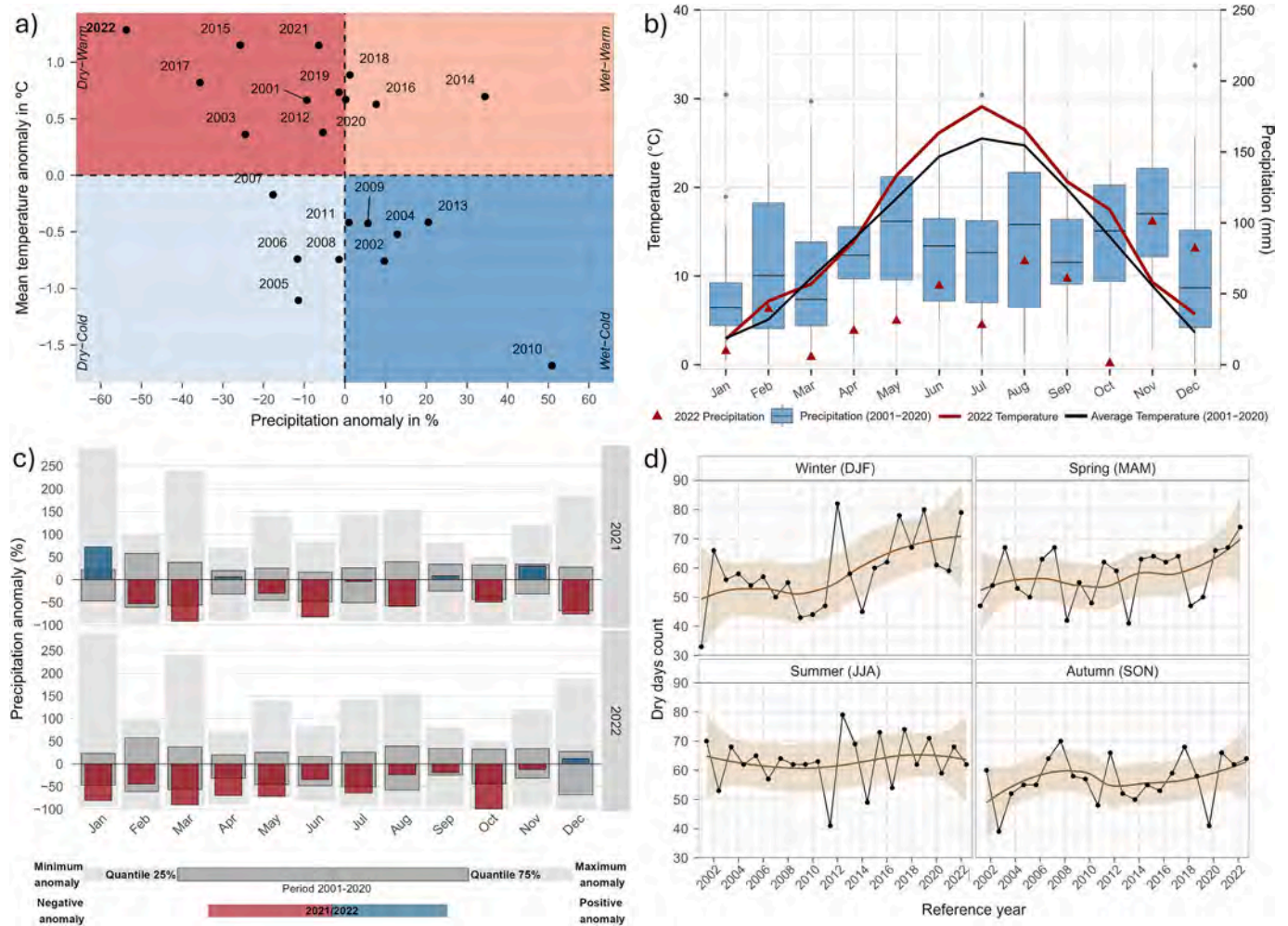
### 3.2. Analysis of groundwater levels under baseline conditions

The HCA resulted in the identification of 13 clusters. The spatial distribution and seasonal profiles are shown in Fig. 3, while Fig. 4 shows the monthly median of groundwater level for each well, color-coded by clusters. The 13 clusters have been grouped into 6 groups (A-F) based on similarities between seasonal maxima and minima. The areas where these groups are located can be considered hydrological units with comparable characteristics and where the groundwater level reacts to recharge and discharge in comparable ways.

In Table 1, the ratios between the standard deviation of the detrended monthly median (i.e., subtracted annual mean) and the standard deviation of the original monthly medians are reported as average over the different clusters.

The characteristics of each group are listed below, while focuses on single clusters are available in the [supplementary materials](#) (Section S.6).

Group A consists of 4 clusters, including 15 wells located in the higher plain, 4 wells in the intermorainic plains, and 2 wells located in the morainic deposits. All clusters exhibit a seasonal pattern with a minimum in Spring and a maximum during Autumn. The range of seasonal variability increases from A1 (2.6 m), to A4 (one well – 10.3 m).



**Fig. 2.** a) Precipitation and temperature anomalies over hydrological years (Dec – Nov) with respect to the reference period 2001–2020; b) Monthly precipitation and temperature over the reference period (boxplots and black line) and 2022 monthly precipitation and temperature (red triangles and red line); c) Precipitation anomalies (as percentages): grey bars indicate maxima and minima (light grey) and 25th and 75th percentile (dark grey) of precipitation anomalies over the reference period, while red and blue bars indicate 2021 and 2022 anomalies compared to the reference period; d) Seasonal count of dry days. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The A group seasonal profile, with its summer rising, can be generally associated with recharge from surface water linked to irrigation processes: irrigation return flow or leakages from unlined irrigation canals. The clusters highlight a difference between wells located in the outer limit of the morainic aquifer systems and in the northern part of the higher plain (A1 and A3), where the surface irrigation method is rarely applied and irrigation canals are sparser, and the southern sector of the higher plain (Cluster A2) where the surface irrigation method is prevalent, and a dense canal network is evident.

More specifically, wells in the northern sector (A1 and A3) generally show a wider pluriannual oscillation, with the seasonal oscillation constituting ca. 60 % of the total variability, while wells in the southern sector of the higher plain (A2) show a wider seasonal oscillation (3.8 m) constituting 85 % of the total variability (Table 1).

Group B includes 1 cluster, grouping 15 wells spatially dispersed in the study area. This cluster groups wells with the minimum seasonal oscillation in the dataset. The pluriannual variability (Fig. 4) is different among the wells in the cluster, ranging from very narrow (e.g., W33 and W34) to wider oscillations (e.g., W22 and W30). Within group B, 3 cases can be identified, characterized by specific hydrogeological settings that determine this narrow range of seasonal oscillation: a) proximity to the spring belt (middle plain), b) proximity to the Lake Garda shores, and c) morainic compartment and alpine valleys.

Group C represents wells tapping from lower plain and morainic aquifers that show a seasonal trend disrupted by a summer lowering. Group C includes three clusters (C1-C3) with a total of 14 wells, where C1 groups all the wells in the lower plain and a single well in the morainic compartment, C2 groups a set of neighboring wells in the southern portion of the Garda Lake morainic amphitheater and C3 only one well located in the morainic compartment. The range of the seasonal variability increases from C1 (2.5 m) to C3 (13.6 m). All the wells of group C show reduced pluriannual variability, and seasonal variability constitutes about 90 % of the total variability.

Group D (D1-D3) collects 7 wells in the morainic hills, showing a response to local precipitation. All group D clusters have a seasonal pattern with a maximum in Spring and a minimum in Summer or late Summer. All the wells in group D clusters show wide pluriannual variability (Fig. 4), and seasonal variability constitutes 54 % (D3) to 65 % (D1) of the total variability. For example, summer 2020, which was particularly wet, resulted in an average increase for most wells (Fig. 4). Well W51 appears to be the only exception since it is distinguished by a decreasing trend over all the available years dependent on local conditions.

Cluster E groups three wells tapping a small coarse aquifer in the Alpine valleys. The seasonal pattern, strictly correlated to the local geomorphological features, is characterized by the absence of an evident

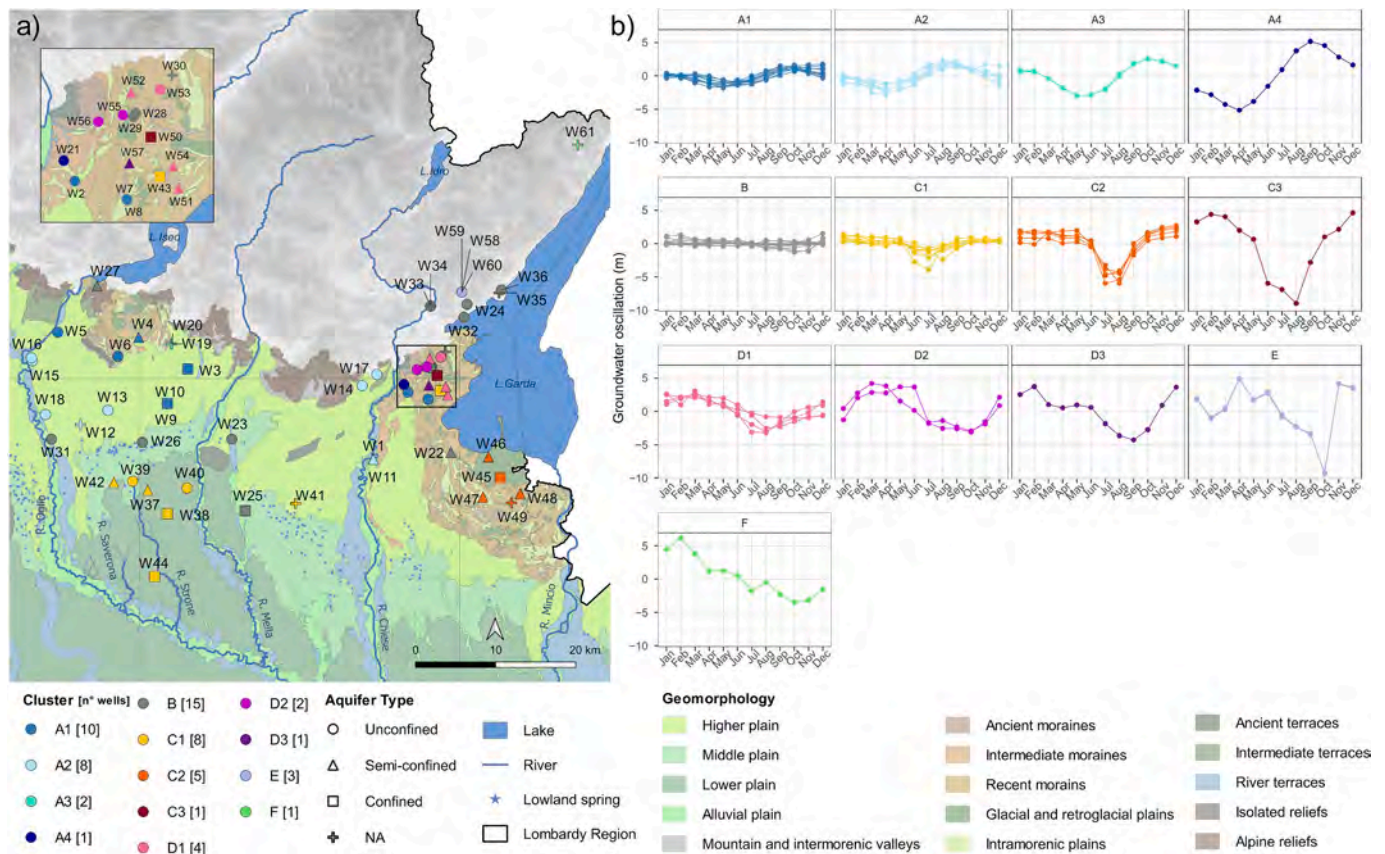


Fig. 3. A) spatial distribution of the wells color-coded by cluster, b) seasonal pattern of the wells, grouped by clusters.

maximum but shows a minimum in October. Due to the relatively lower elevation of the tapped alpine aquifer, liquid precipitation constitutes the year-round primary driver of groundwater recharge.

Cluster F includes only one well located in a small Alpine valley. As cluster E, cluster F well tap a small coarse aquifer. However, its seasonal pattern, with no specific maxima or minimum, results mostly from a general decreasing trend, and due to the reduced amount of available data, a specific seasonal pattern does not emerge.

### 3.3. Analysis of groundwater level response to the 2022 drought

The different hydrogeological compartments have shown a peculiar response to the 2022 drought.

For group A, the analysis of the 2022 response was conducted on 17 wells having 2022 data (Fig. 5, focus in Section S.7). For each well, the 2022 spring decrease and summer increase were compared with the average decreases and increases in the previous years. It results that during 2022, over the whole A group, spring decrease was 111 % higher than the average decrease measured in years before 2022, while the 2022 summer increase was 69 % lower than the average increase (Fig. 5). More specifically, considering only the Higher Plain aquifer, the 2022 winter decrease was 89 % wider than the usual decrease, while the 2022 summer increase was 71 % lower than the usual increase.

Moreover, in the typical seasonal profile of group A, the spring minimum is reached in April-May, while in 2022, 60 % of wells (9 wells) reach the minimum in summer (July-August) during the irrigation season (Fig. S.7.1). Differently, three wells (W5, W14, and W17) reach the minimum in the typical period, while they reach the maximum in July or August, i.e., 1–2 months before the typical maximum. For these three wells, the analysis was conducted using a reference period of one year (2021) since it was the only complete year available.

Well W21 (cluster A4) represents the only exception within group A;

indeed, the 2022 increase was only 6 % lower than the average measured in years prior to 2022, while the decrease was 44 % wider than the average decrease. As described in Section S.6, well W21 taps a smaller and highly responsive aquifer, which plausibly shows a response even to a small amount of recharge. Therefore, this peculiar behavior compared to group A could be attributable to the local management of irrigation water, where even a small amount could determine the groundwater table rise, also sustained by August and September rain.

For group C, the 2022 response analysis was conducted on 11 wells with 2022 data. In 2022, group C displayed the typical profile but with an exacerbated summer minimum (Fig. 6, focus in Section S.7). The 2022 summer decrease and subsequent increase were compared to the average decreases and increases in previous years (Fig. 6 and Fig. S.7.2). Results show that, globally, the 2022 summer decrease was 76 % higher than the average decrease (Fig. 6). As a result, the lowest groundwater level throughout the available series was recorded in 9 wells. For most of the wells, the increase after the summer minimum led to the restoration of normal conditions, while for 2 wells (W41 and W44), the 2022 increase was lower than the average of the years before 2022.

For group B, 2022 data are available for 12 wells. Group B is characterized by a steady groundwater level with the narrowest groundwater level oscillation throughout the study area. The reduced amplitude of the oscillations is also confirmed in 2022. In the spring belt, 2022 data are available only for the eastern sector (W23 and W25), which shows a 2022 response comparable to group C. Their 2022 trend is characterized by a decrease during the summer period that determined an unprecedented minimum. As for group C, this response to the 2022 conditions is attributable to the increased summer groundwater demand.

Group B wells in the morainic compartment, primarily influenced by the recharge effect of rainy periods, exhibited different responses to the reduced amount of precipitation due to local hydrogeological factors.

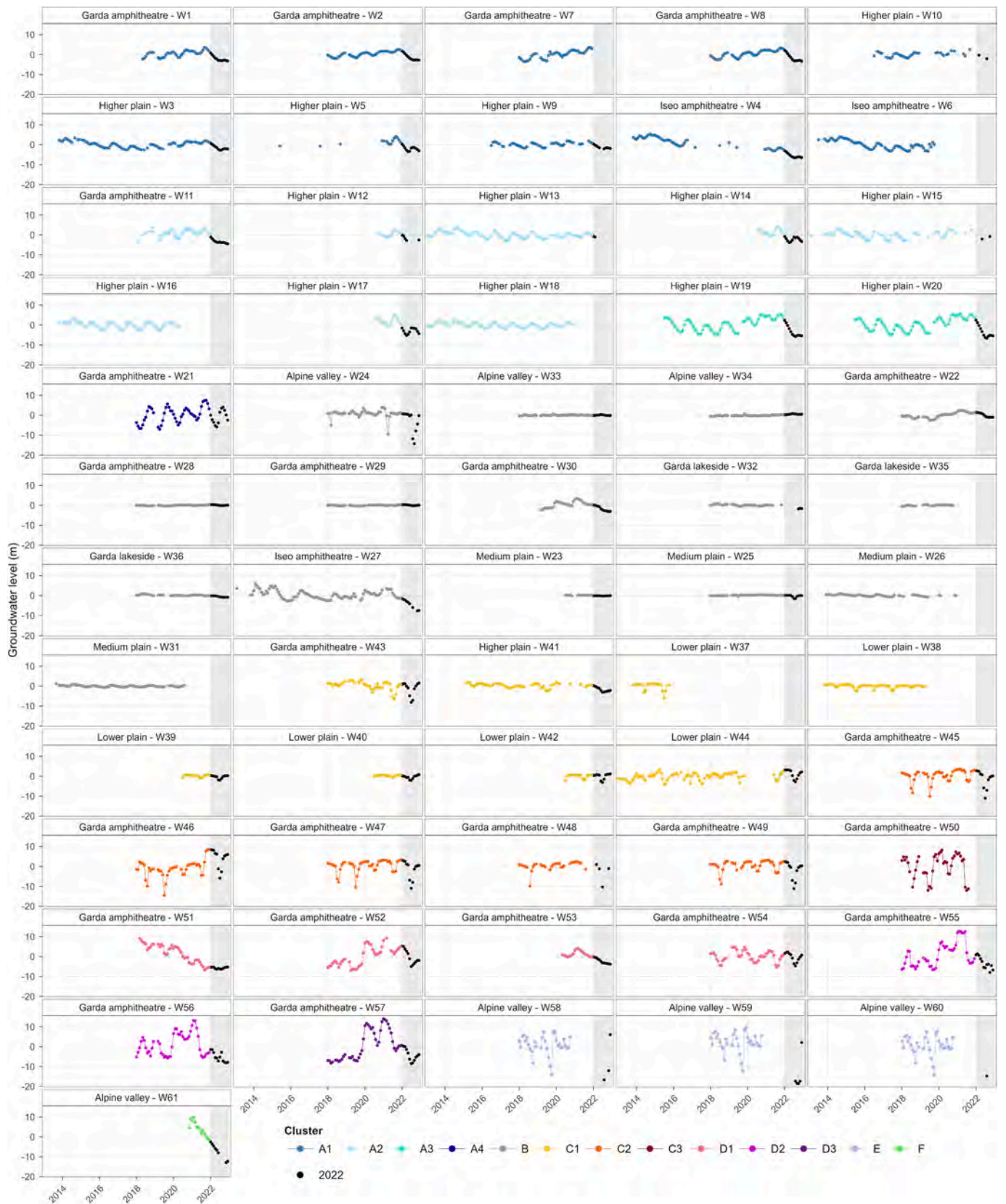


Fig. 4. Groundwater level time series (monthly median) color-coded by cluster. Data for 2022, excluded from the cluster analysis, are represented as black dots over the grey-shaded area.

**Table 1**

Average ratio between the seasonal variability and the total variability calculated, respectively, as the standard deviation of detrended data (annual mean subtracted) and the standard deviation of original data.

Cluster	Average of sd. Detrended/ sd. Total
A1	62.81 %
A2	84.70 %
A3	63.88 %
A4	92.63 %
B	76.57 %
C1	87.68 %
C2	92.45 %
C3	92.32 %
D1	59.05 %
D2	75.01 %
D3	53.76 %
E	99.24 %
F	n.d.

However, in 2022, a significant decrease in groundwater level was observed within all wells' trends, with 8 wells recording historical groundwater level minima within the available time series (Fig. 4 and Fig. S.8.1). Wells in the alpine valleys constitute exceptions: in well W33 the level increased comparably to the previous years, and in well W34, the groundwater level growing trend started in 2020 is also maintained during 2022 (in both cases the range is limited to a few cm), while well W24 shows a marked decrease in 2022 (ca. 1 m).

W32, W35, and W36 wells, located along the Lake Garda shores, confirmed the pressure balance between these portions of the aquifer and the lake. The groundwater level trend of the three wells is indeed equal to the trend of the water level of Lake Garda, which showed a 2022 minimum typical of surface water bodies (Section S.6).

All 7 wells of Group D have 2022 data. During 2022, the effect of the drought period is highlighted by a general decrease in the groundwater level in all the wells. Group D's response to 2022 is not homogeneous (Fig. 4, focus in Section S.8). For wells W52, W53, W54 and W57 (assuming W53 to have a similar time series to his neighboring well W52) 2022 response does not determine an unprecedented condition, as opposite to Groups A and B, while for wells W55 and W56 the 2022

response induce a minimum which is respectively 1.4 m and 2.4 m lower than the minimum of the previous years. Well W51 is characterized by a decreasing trend in all the available years.

Due to a lack of data, analysis could not be performed for Cluster E and Cluster F (Fig. 4, focus in Section S.8).

#### 4. Discussions

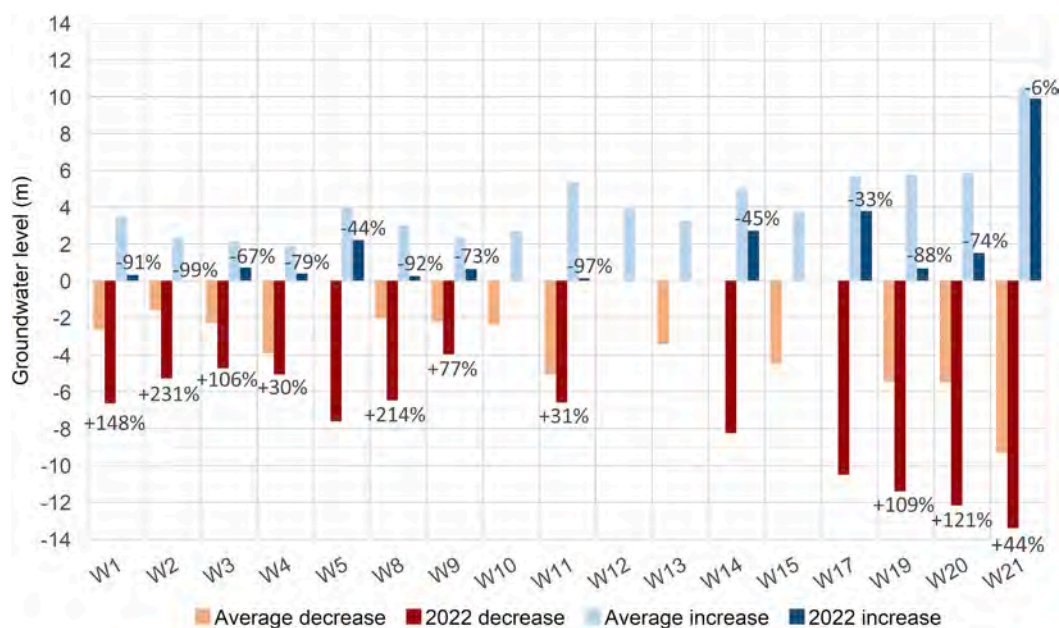
##### 4.1. Groundwater recharge and discharge of the different aquifer systems under baseline conditions

###### 4.1.1. Higher plain aquifer – Surface-water-fed irrigation areas

The higher plain aquifer system is characterized by a highly permeable unconfined aquifer mainly composed of coarse sediments. All the wells tapping this aquifer system fall into the A group, showing a groundwater level rise during summer, which is a dry season in terms of precipitation. The A group seasonal profile, with its summer rising, can be generally associated with recharge from surface water linked to irrigation processes: irrigation return flow or leakages from unlined irrigation canals (Zucaro et al., 2011).

A narrower seasonal oscillation is evident in the north-western area and at the border of the morainic area (cluster A1 – 2.6 m), where irrigation canals are sparser (Fig. 1c), and irrigation methods rarely include the surface irrigation method (Fig. 1d), with an exception for the well in cluster A3 which shows a wider variability, associated with the specific geological setting. For these wells, the seasonal variability only determines a portion of the total variability (ca. 60 %), and wide pluriannual oscillations are evident. Therefore, in these areas, the contribution of local precipitation and recharge from upstream formations (mountain-front recharge) is significant and determines a wider pluriannual variability (Fig. 4, Table 1) compared to downstream wells. A narrow oscillation (cluster A1) is also evident for the confined and semi-confined wells of the higher plain (W3, W10), showing a seasonal pattern comparable to all wells in group A. The presence of fine material layers precludes aquifer direct contact with the surface, but their local extension does not prevent the interaction between these aquifer portions with the overlying unconfined aquifers of the higher plain.

Conversely, wells in the southern and eastern portions of the higher plain (cluster A2), where the canal network is denser (Fig. 1c) and where the most common irrigation method is surface irrigation (Fig. 1d), show



**Fig. 5.** Average winter/spring groundwater level decrease (orange bar), and summer increase (light blue bar) compared to 2022 winter/spring decrease (red bar) and increase (blue bar). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

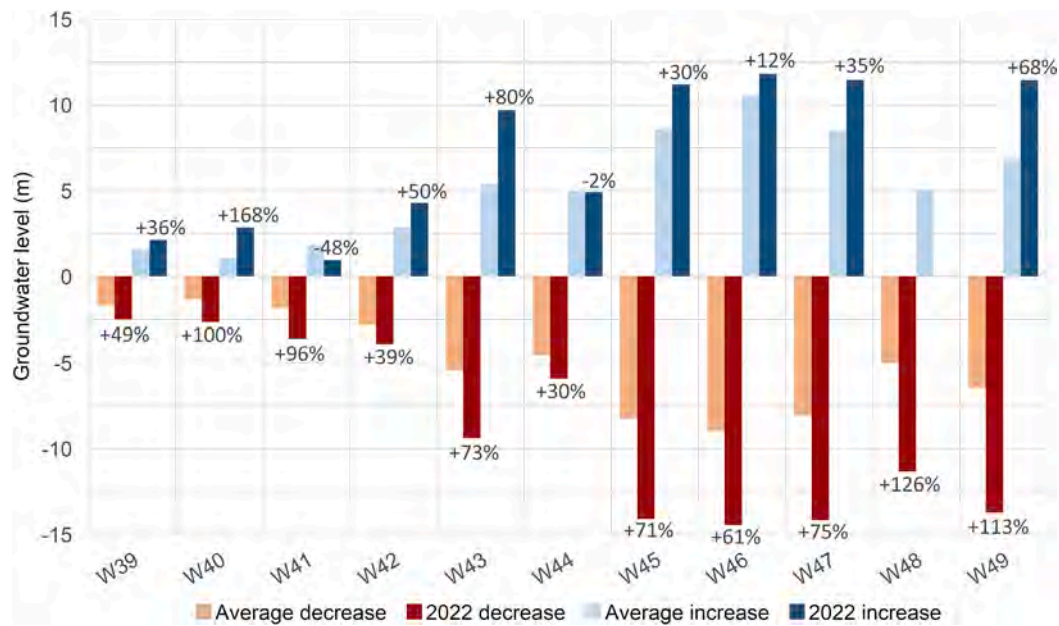


Fig. 6. Average summer groundwater level decrease (orange bar), and autumn increase (light blue bar) compared to 2022 summer decrease (red bar) and increase (blue bar). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

wider seasonal oscillations (3.8 m). Here, the seasonal variability is much wider than the pluriannual variability, constituting 85 % of the total variability. Therefore, results confirm that the recharge in the higher plain is primarily influenced by irrigation return flow and leakages from the surface water network, while the variability associated with dryer or wetter years is reduced. Indeed, the infiltration of excess irrigation water together with losses during the distribution of water flowing along the unlined irrigation canals network has been estimated, through an isotopic approach, to constitute around 60 % of the groundwater's recharge in the area while the remainder is from local precipitation and recharge from upstream (Rotiroti et al., 2019, 2023).

#### 4.1.2. Middle plain aquifer – Springs belt

The wells at the transition between the higher plain and the lower plain, show groundwater levels constant throughout the year and over different years (group B). In this area the decrease in grain size from coarse to fine sediments, and the consequent change in the aquifer transmissivity, force the groundwater level close to the ground level, constraining the groundwater head oscillations (De Luca et al., 2014). Therefore, the stability of the groundwater trend is mostly associated with the lower permeability of the aquifer system. In the western part of the area, downstream to the intensively irrigated areas, a seasonal pattern is associated with recharge from surface water irrigation, although the variability is significantly lower than upstream. In the eastern part, no seasonal pattern is evident.

#### 4.1.3. Lower plain aquifer – Groundwater-fed irrigation areas

The lower plain aquifer system hosts a multilayer system of super-imposed confined aquifers. All the wells in the lower plain fall into the C1 cluster, showing a constant pluriannual trend with significant summer decreases. Here, recharge is only from groundwater inflow from the higher plain, while irrigation water's and rainwater's infiltration is highly reduced due to diffuse sub-horizontal layers of clay and silt that preclude the aquifers from direct interaction with the surface. Contrary to the higher plain, the main source of irrigation comes from the groundwater extracted through the numerous irrigation wells displayed in the lower plain (Fig. 1c). Irrigation thus not only has minimal to no impact in recharging lower plain aquifer but, combined with the summer increase in domestic water demand, contributes significantly to the discharge from the aquifer system.

#### 4.1.4. Morainic aquifers

The morainic aquifer systems show a wide variety of seasonal patterns, strongly linked to the high heterogeneity of the geology settings.

South of Lake Garda, a group of wells marking a specific area and tapping confined and semiconfined aquifers that constitute cluster C2 is evident. These aquifers experience a significant drop in groundwater levels during the summer. The area is largely used for vineyards, which do not require intensive irrigation.

The summer decrease is more plausibly associated with increased groundwater extraction for domestic use during hotter months, worsened by the increase in the population due to tourist flow for summer holidays in the locations close to Lake Garda and by the limited lateral extent of the aquifers, which result in significant fluctuations in groundwater levels.

Another group of wells is clearly evident, in the north-west portion of the Lake Garda amphitheater, and it constitutes group D. This group shows a direct response to local precipitations with a maximum during spring due to winter and spring precipitations and a minimum at the end of summer linked to dry summers and increased summer water demand. The reduced dimensions of the tapped aquifers and the fragmentation of the superficial impermeable layer determine a direct response of the aquifer to precipitations. The seasonal variability of these wells is only a small component of the total variability since pluriannual variations are higher than seasonal variations. This further supports the interpretation of group D as wells strongly linked to local precipitations, affected by rainy or dry months, but mainly by the cumulative effect of wetter or dryer years.

Several other wells in the morainic aquifers system show different behaviors, falling into the A, B, or C groups. Three wells fall in the A group (clusters A4 and A1), with a summer increase associated with a summer recharge. Also in this case, since summer is the dry season, this recharge could be associated with surface water and irrigation processes. These territories have agricultural land use, but no dense river network is present. In this case, further analysis, such as isotopic analysis, could provide a conclusive validation of the recharge by irrigation hypothesis.

7 wells of the lakes Garda and Iseo moraine fall in the B group. The reduced amplitude of the seasonal pattern oscillation is related to the limited thickness of the tapped shallow aquifers, which are generally discontinuous and have low productivity. Despite local differences,

aquifers with these characteristics are thereby affected by limited groundwater level oscillation that responds to particularly rainy periods (Severi et al., 1994). Local precipitation constitutes the main input of these systems (Bini & Zuccoli, 2004). This means that seasonality is not evident, while a wider variability is associated with pluriannual precipitation trends.

A peculiar situation emerges for the wells along the Lake Garda shores, which present a strong similarity with the Lake Garda hydro-metric level as a result of the pressure balance between the aquifer and the lake (Fig. S.6.1).

Two moraine wells in clusters C1 and C3, with a marked summer groundwater level drop, tap confined aquifers in mostly residential areas. In this case, similarly to cluster C2, the increase in summer withdrawals is more plausibly associated with domestic uses, also in relation to summer tourist flow, exacerbated by the reduced dimensions of the aquifer.

#### 4.1.5. Alpine aquifers

Wells in the alpine valleys show various behaviors: 3 wells in group E, 1 well in group F and 3 wells in group B (W24, W34 and W33), each characterized by a peculiar trend due to the geological and hydro-geological feature of the specific watershed (e.g. size and altitude) and aquifer (e.g. size, shape, lithology).

#### 4.2. The 2022 hydrological drought

Results indicate that 2022 constitutes both a temperature and precipitation anomaly, showing: a) lack of winter precipitation, starting from December 2021, determining reduced local recharge, but mostly reduced snow accumulation in the Alps, which led to a water deficit in spring at the beginning of the irrigation season, and b) dry spring and summer, with anomalous high temperatures, which increased the irrigation needs and determined high evapotranspiration, reducing net recharge percentage. The combination of dry and hot conditions had significant repercussions on water reserves. Studies on the Italian Alps highlight that the warm and dry winter conditions caused a severe snow drought, with a snow water equivalent reported 88 % lower than the 2011–2021 period (Avanzi et al., 2024), with a March SWE anomaly in 2022 reaching the lowest value in the last century (Colombo et al., 2023).

Spring snow melting constitutes one of the main water sources of the subalpine lakes (ANBI Lombardia, 2023; Cochand et al., 2019; Crespi et al., 2021). Therefore, in 2022, the lack of winter snow in the alpine region led to a reduced inflow in the alpine lakes, leading to a water deficit of more than –30 % in the lakes' water volumes (ANBI Lombardia, 2023).

The subalpine lakes constitute the reservoir for rivers and irrigation canals in the downstream plain during summer. Therefore, the reduced availability of surface water in the subalpine lakes and in the downstream rivers (–60 % at the regional scale) led to a severe lack of surface water resources for irrigation purposes.

In addition, the particular meteorological conditions of 2022, and particularly the high temperatures, have led to an increase in net irrigation needs that, at a regional level, has recorded an increase of 32 % compared to the period 2016–2021 (ANBI Lombardia, 2023). Increased evapotranspiration has been proven to worsen storage anomalies during summer droughts (Teuling et al., 2013).

It was demonstrated (Montanari et al., 2023) that the 2022 hydrological drought in the Po plain (N Italy) was the worst event in the past two centuries (30 % lower than the second worst), being part of an increasing trend in severe drought occurrence in the area. Bonaldo et al. (2023) highlight that persistent negative rainfall anomalies like the ones that characterized the 2022 event, though unlikely to become a typical feature of future climate, could remarkably increase their frequency, particularly in severe climate change conditions, and rising temperatures will magnify their impacts. Local studies on Northern Italy indicate

that droughts are expected to increase by about 50 % by the mid-21st century and by approximately 80 % by the late 21st century (Sofia et al., 2024). More specifically for the city of Brescia, in the study area of the present study, climate change projections on groundwater resources indicate that a temperature increase has to be expected across all climate scenarios, while changes in precipitation patterns are predicted with winter increase and summer decrease leading to water scarcity by the middle of the century (Faquese & Grossi, 2023).

#### 4.3. Groundwater recharge and discharge changes due to the 2022 drought

##### 4.3.1. Higher plain aquifer – Surface-water-fed irrigation areas

In the higher plain, 2022 determined a drastic change in the typical seasonal pattern. All the wells tapping the higher plain aquifer system reached an unprecedented minimum and exhibited a wider spring decrease (up to + 148 %) and a narrower summer increase (up to –97 %) and shifts in the time distribution of minima and maxima compared to the reference period. This modified seasonal pattern is also evident in the northwest area where, under normal conditions, wells show a reduced seasonality and a wider pluriannual variability.

Since the seasonal pattern is attributable mainly to recharge provided by surface water irrigation, it emerged that the vulnerability of this aquifer system is not directly linked to the lack of summer rainfall. Rather, the system's groundwater scarcity was determined by the winter conditions (reduced rain and snow precipitation and higher winter temperatures decreasing snow accumulation) that largely determine the availability of surface water resources, especially in the lake's reservoirs. Specifically, the reduced availability of surface water resources resulted in a significant reduction of the total derived volumes for irrigation purposes from the Oglio and Chiese rivers (–36 % and –53 %, respectively (ANBI Lombardia, 2022, 2023)).

Furthermore, irrigation management played a crucial role in groundwater recharge: the lack of surface water led to an increased abstraction of groundwater to fulfill irrigation needs. Indeed, data shows that, at the Lombardy region scale, the groundwater volume abstracted in 2022 for irrigational purposes was double the average volume of groundwater extracted in 2016–2021 (ANBI Lombardia, 2023). Therefore, 2022 modified seasonal patterns show the joint effect of surface water scarcity for irrigation and increased groundwater abstraction for irrigation purposes.

##### 4.3.2. Lower and middle plain aquifers – Groundwater-fed irrigation areas

In the lower plain, groundwater levels in 2022 showed a drastic increase in the typical summer lowering (from 30 % to 100 % – Fig. 6); in most cases, the successive rising led to the restoration of baseline conditions. Since the main driver of summer decrease is water abstraction for irrigation purposes, which in this area is mostly based on wells, the response to the 2022 climatic conditions could be linked primarily to the increased summer temperature, which led to an increased net irrigation need for crop yield. The same response is visible in the middle plain, where 2022 data show a significant decrease during summer, plausibly associated with increased demand and groundwater abstraction.

##### 4.3.3. Morainic aquifers

The southeast part of the morainic amphitheater (cluster C2), which has a seasonality similar to the lower plain, also shows a 2022 response similar to the one of the lower plain, with a significantly wider groundwater level decrease during the 2022 summer compared to previous years (from 61 % to 113 %) but in several cases, the autumn rising did not restore the groundwater level of the previous winter.

In the northern part of the morainic amphitheater (group D), the shorter time series limits the interpretation of the 2022 response due to high multi-annual variability. This contrasts with groups A, B, and C, where the seasonal pattern is the primary component of variability. In this case, longer time series would allow for a more solid comparison of

2022 effects with respect to a baseline calculated over several years. Nevertheless, group D's 2022 response generally does not determine dramatic unprecedented conditions (Fig. 4, focus in Section S.8).

Morainic wells that showed seasonal profiles assimilable to those in the plain (groups A, B, and C) also show a general 2022 response similar to plain wells, but the limited amplitude of the aquifers determines some peculiarities. The well W43 with the C profile has a widened summer decrease, but it restores the original conditions during autumn; the well W21, in group A, shows a widened winter decrease, but the summer rise is similar to the average rise of the previous years, which seems to indicate that even small amount of recharge can determine a rise in this small aquifer. The morainic wells in group B (W30, W28, W29 and, W22) confirm narrow oscillations and 2022 does not determine a global groundwater level minimum.

#### 4.3.4. Alpine valleys

In the alpine valleys, 2022 data are available only for wells falling in the B group. The two neighboring wells W34 and W33, showed increased groundwater levels in 2022 (less than 40 cm, compatible with the total variability of the wells). These wells tap an alpine valley aquifer with an ample watershed. Since no recharge from precipitation was available, this increased groundwater level can plausibly be associated with a mountain front recharge that was able to perdure for several dry months. Also in this case, chemical and isotopic analysis could provide more robust insights into the recharge processes of this valley.

Conversely, well W24, located in a small valley on the slopes towards the lake, shows an unprecedented minimum in 2022, 15 m below the groundwater level at the beginning of 2022. Therefore, as for the data under baseline conditions, 2022 data also showed diverse responses in different alpine valleys; here, more data are needed to investigate local recharge and discharge, also based on watershed amplitude, altitude, and exposition.

### 4.4. Aquifer vulnerability to climate change and adaptation measures

#### 4.4.1. Higher plain aquifer – Surface-water-fed irrigation areas

Results indicate that in areas with surface-water-fed irrigation, such as the higher plain, climate change adaptation strategies to preserve agricultural productivity will have a decisive impact on groundwater availability, plausibly stronger than climate change itself. Implementing actions to improve the efficiency of irrigation processes, like canal lining operations, and transitioning to more efficient irrigation techniques, such as sprinkling or micro irrigation, would lead to a drastic reduction in groundwater recharge.

Currently, in Italy, local authorities favor the transition from traditional surface irrigation systems to water-saving techniques such as spray, drip, or micro irrigation techniques in response to European and Italian directives. Previous studies (Fabbri et al., 2016; Pool et al., 2021, 2022) highlight that the infiltration due to irrigation could strongly decrease considering the climate changes, up to disappearance due to the complete transition to these irrigation systems. The potential decrease of the infiltration related to the joint effect of climate change and irrigation policies could represent a social, economic and environmental issue, including the decreased inflow of the middle plain springs related to the progressive recharge reduction.

Furthermore, results clearly demonstrate that, in the most extreme case, switching from surface water irrigation to groundwater irrigation would have the double effect of reducing recharge and introducing a new system output. Indeed, groundwater irrigation has been proven to exacerbate drought conditions' effects on groundwater storage (Liu et al., 2022).

In these scenarios, compensation measures will have to be implemented to restore groundwater recharge and guarantee the social and ecosystem services that it provides (such as the downstream springs). Examples of mitigation measures could be managed aquifer recharge systems, such as forested infiltration areas, exploiting the high flow

conditions in wetter seasons.

#### 4.4.2. Lower plain – Groundwater-fed irrigation areas

Conversely, in areas characterized by groundwater-fed irrigation, such as the lower plain, results indicate that vulnerability to climate change is mostly mediated by human abstractions: higher temperatures are expected to lead to increased water needs for irrigation and domestic purposes both in terms of extracted volumes and longer abstraction periods. Recent studies (Amanambu et al., 2020; Russo & Lall, 2017; Whittemore et al., 2016) have shown that groundwater levels can respond faster to changes in abstraction rates driven by human response to climate variability than to direct changes in recharge, also driven by climate variability. Unlike the high plain areas, in the lower plain, mitigation actions such as the transition to more efficient irrigation methods or the reduction of aqueduct losses could contribute positively to the resilience of groundwater resources, reducing anthropic pressures and extracted volumes.

#### 4.4.3. Middle plain

The transition zone in the middle plain shows recharge processes strongly connected to the irrigation excess in the higher plain. Still, results also indicated a summer decrease related to increased abstractions in 2022, similar to the lower plain. Therefore, in the middle plain, vulnerability in terms of water scarcity is linked to two aspects: 1) reduced recharge from upstream in case of changes in irrigation processes and surface water availability and 2) increased abstraction linked to increased irrigation and domestic needs due to higher temperatures. In this area, groundwater not only constitutes a valuable resource for human needs, but it also guarantees environmental services by feeding the multitude of springs vital for downstream agriculture and ecosystems.

#### 4.4.4. Morainic aquifers

Results in the southern sector of the Garda morainic amphitheater (cluster C2) indicate a water budget and a vulnerability profile similar to the one in the lower plain, governed by human abstractions. Similarly to the lower plain, in this area, the main driver of water scarcity during climate change could be increased abstractions for domestic use, exacerbated by the limited extension of the aquifers. Similarly, mitigation measures that reduce the extracted volumes in the future are necessary to preserve the water resource.

The wells in the northeast sector of the Lake Garda morainic amphitheater (group D), which show a wider pluriannual variability compared to the seasonality, seem to indicate that in a hydrogeological context where the main recharge and discharge components are natural, groundwater can be resilient to single dry seasons. This is the opposite of environments where the water budget is highly governed by human water resource management, where anthropic impacts can exacerbate the effects of dry seasons. Nevertheless, longer time series could produce more robust conclusions in this highly variable region.

As regards single aquifers with peculiar situations that resulted similar to plain regions (groups A, B, or C), vulnerability to climate change can be deduced by association with respect to the groups they belong to, with parallels to what was deduced for groups A, B, and C. A significant aspect, however, lies in the reduced extension and productivity of these aquifers, which can potentially make them more vulnerable as the volumes involved are much lower than those of plain systems.

#### 4.4.5. Alpine valleys

Data were insufficient to draw robust conclusions about alpine valleys, but they highlighted the importance of local studies since vulnerability profiles are strictly connected to the amplitude and altitude of the aquifers and their watershed, other than human consumption and the presence of surface water bodies.

#### 4.5. Methodological approach pros and cons

This work is based on dynamic data collected from active wells. This is unconventional since, in most cases, hydrogeological investigations are based on static data, which are considered more representative of the aquifer conditions. Here, the authors propose a method for data preprocessing that led to the extraction of significant information from dynamic groundwater level data. Exploiting dynamic data from active wells could help fill the gaps in ordinary monitoring networks in other regions worldwide.

Indeed, data from water suppliers are usually monitored and archived for management purposes, and therefore, they can be used for research purposes without additional costs. These data usually have a high temporal resolution (hour/minutes), which means that the selection of static/semi-static data could lead to a lower resolution (days/months), which is still significant for hydrogeological evaluations.

Exploiting dynamic data allowed us to investigate territories where the lack of regional monitoring networks has always prevented any kind of hydrogeological characterization. In this case, for example, no previous data are reported on the moraine aquifer system, which still constitutes a strategic territory for Italian wine production, tourism, and a residential area.

In this case, the limitations of the work are mostly related to the data being scattered among the database time span: different time spans were available for different wells. This prevented the application of typical analyses, such as trend analysis, which would have led to results that were not comparable between different wells.

On the other hand, the evaluation of seasonal patterns was applied here by subtracting yearly means, which allowed data from different years to be compared both within the same well and different wells.

While most time series studies focus on long-term trends, the seasonal analysis applied here allowed for a detailed understanding of the groundwater budget and a more precise quantification of the drought effects. Indeed, in most cases, the drought effects were not evident as significant global minima over the time span, but they were most likely associated with dramatic changes in the seasonal patterns, showing the complete lack of seasonal recharge or the exacerbation of seasonal depletion.

#### 5. Conclusions

The present work provides valuable support to researchers and water managers, offering tools for more effective groundwater management in the context of climate change, particularly in regions where irrigation plays a central role.

The analysis investigated groundwater levels across diverse hydrogeological settings, analyzing seasonal patterns to understand recharge and discharge dynamics under baseline conditions while assessing the response of groundwater resources to the 2022 drought with implications for similar contexts facing water scarcity challenges, which afflicted several countries.

The main outcomes of the study highlighted the dual role of irrigation on groundwater budget, based on the irrigation water source (i.e., surface water or groundwater fed irrigation).

Indeed, in regions with surface-water-fed irrigation, surface water scarcity under hydrological droughts can rapidly induce a groundwater depletion related to a) the missing recharge from irrigation return flow and b) the increased groundwater abstraction to compensate for the lack of surface water. In these regions, the transition toward more efficient irrigation practices, such as sprinkling or micro irrigation, would determine a significant reduction of aquifer recharge and would require compensation measures such as managed aquifer recharge during wet seasons.

On the other hand, in regions with groundwater-fed irrigation, increased temperatures and the associated increased irrigation needs lead to increased groundwater depletion during irrigation season. In

these regions, the aquifer balance could benefit from mitigation actions aimed at reducing groundwater abstractions, such as more efficient irrigation practices or consumption reduction.

Differently, aquifer systems governed by natural recharge and discharge processes can be more characterized by pluriannual variability associated with dry and wet years and, therefore, less sensitive to single dry seasons than highly anthropic systems.

The main limitations of this study arise from the varying time spans of the available data, which prevented the application of standard analyses, such as trend analysis, while still allowing for the comparison of seasonal patterns.

The results of this work highlighted that analyzing groundwater seasonal patterns provides a deep understanding of groundwater dynamics and enables precise quantification of drought season effects, offering new findings that long-term analyses like trend analysis cannot describe in such detail and that can be applied in any similar hydrogeological context.

Furthermore, if properly preprocessed, dynamic data from active wells can be valuable sources for investigating aquifer dynamics. They can also be useful for obtaining time series data in regions where monitoring networks are missing or insufficient.

#### CRediT authorship contribution statement

**Agnes Redaelli:** Data curation, Formal analysis, Visualization, Investigation, Writing – original draft. **Tullia Bonomi:** Conceptualization, Supervision, Validation, Resources, Funding acquisition, Project administration, Writing – review & editing. **Davide Sartirana:** Writing – review & editing, Visualization, Conceptualization. **Gianfranco Sinatra:** Resources. **Marco Rotiroti:** Conceptualization, Supervision, Validation, Funding acquisition, Project administration, Writing – review & editing. **Chiara Zanotti:** Data curation, Formal analysis, Visualization, Investigation, Methodology, Conceptualization, Supervision, Validation, Funding acquisition, Project administration, Writing – original draft.

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#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Chiara Zanotti reports financial support was provided by Acque Bresciane S.r.l. SB. Marco Rotiroti is Associate Editor of the Journal of Hydrology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhydrol.2025.133211>.

#### Data availability

The authors do not have permission to share data.

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