Alleviating drought and water scarcity in the Mediterranean region through managed aquifer recharge

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Abstract
Drought and water scarcity can significantly impair the sustainable development of groundwater resources, a scenario commonly found in aquifers in the Mediterranean region. Water management measures to address these drivers of groundwater depletion are highly relevant, especially considering the increasing severity of droughts under climate change. This study evaluates the potential of managed aquifer recharge (MAR) to offset the adverse effects of drought and water scarcity on groundwater storage. Los Arenales aquifer (central Spain), which was unsustainably exploited for irrigation in the second half of the twentieth century, is employed as a case study. Two neighbouring zones within this aquifer are contrasted, namely, Los Arenales (LA) and Medina del Campo (MC). The primary difference between them in terms of water resources management is the wide-scale implementation of MAR systems in LA since the early 2000s. Several groundwater statistical methods are used. Groundwater-level trend analysis and average piezometric levels show in LA a faster recovery of aquifer storage and less susceptibility to drought compared to MC. On the other hand, standardised precipitation indexes and standardised groundwater level indexes of detrended groundwater-level time series, which do not include the effects of MAR, show that LA can be more negatively affected by drought and groundwater abstraction. The sharper recovery of piezometric levels in LA when considering MAR, and bigger drought impacts observed when the effects of this measure are removed, demonstrate that MAR can effectively alleviate the impacts of water scarcity and drought, providing an adaptation solution to climate change worldwide.

Keywords Artificial recharge · Groundwater statistics · Trend analysis · Standardised precipitation index · Standardised groundwater level index

Introduction
Groundwater is widely used to irrigate crops. Globally, groundwater contributes to irrigating around 300 million ha and accounts for 43% of the total irrigation water consumption (Siebert et al. 2010). A significant number of the aquifers that sustain this large quantity of irrigation are unsustainably developed and exhibit groundwater storage depletion (Alley 2002; Famiglietti 2014; Gleeson et al. 2012; Koohafkan and FAO 2011; Lall et al. 2020; Mustafa et al. 2017) and signs of water scarcity, i.e., an overexploitation condition in which water demand exceeds its natural availability (Hornbeck and Keskin 2014; Van Loon 2015; Van Loon and Van Lanen 2013). In addition to anthropogenic water scarcity, the available groundwater in agricultural socioeconomic contexts can be further decreased by droughts (Araya and Stroosnijder 2011; Halder et al. 2020; Hornbeck and Keskin 2014; Khan et al. 2008; Scanlon et al. 2012).

Drought has been defined by Tallaksen and Van Lanen (2004) as “a sustained and regional extensive occurrence of below average natural water availability”. This phenomenon originates when water availability decreases below the long-term average (Van Lanen and Peters 2000) as a result of natural climatic factors (Van Loon and Van Lanen 2013). There are four different types of droughts, of which meteorological drought is the first manifestation of water deficiency. Meteorological drought occurs when a large area is affected for
an extended period by decreasing rainfall, increasing evapotranspiration rates, or a combination of both (Heim 2002; IPCC 2021; Van Loon 2015). Subsequently, sustained water deficiency propagates to the soil. A lack of moisture results in agricultural drought (or soil moisture drought) that can potentially damage crops and terrestrial ecosystems (Brauns et al. 2020; Van Lanen and Peters 2000; Van Loon 2015). Finally, prolonged conditions of below-average water availability can impact groundwater levels and river discharge, causing hydrological drought, or more specifically, groundwater and surface-water drought (Van Loon 2015).

Since the second half of the twentieth century, the intensity and frequency of droughts have increased in some regions of the world, particularly in the Mediterranean (Senéviratne et al. 2012). In this region, the biggest economic impacts of droughts are related to the agricultural sector due to its high-water dependency (Isendahl and Schmidt 2006). For instance, a major drought in Turkey in 2007 resulted in economic losses of about 2.5 billion euros for agriculture. At the same time, imports of agricultural products increased by 60% (Divrak and Ayas 2010). In Spain, during the 1991–1995 drought, between eight and 12 million Spaniards living in urban areas faced water supply restrictions (Estrela and Sancho 2016; Llamas 2000). Furthermore, the 2016–2018 drought that affected the Iberian Peninsula caused crop damages of about 1 billion euros in the region of Castile and Leon (Spain) (CHD 2018). In Europe, the economic impact of drought amounted to 100 billion euros between 1976 and 2007 (European Commission 2012), and the availability of renewable freshwater resources per capita has decreased by about 24% between 1960 and 2010, especially in the south (EEA 2018).

The complex panorama posed by drought is expected to worsen in the following years due to climate change. According to the IPCC (2021), an increase of 0.5 °C in the mean global temperature will likely cause more severe and frequent droughts. In the face of this challenging situation, it is of paramount importance to formulate measures that can help cope with unsustainable groundwater development and drought in groundwater-fed irrigation. One of such measures is managed aquifer recharge (MAR), which involves the intentional recharge of aquifers for later use or environmental purposes (Dillon et al. 2009b; Maliva 2020). This technique has been shown to counteract the effects of unsustainable groundwater use and drought effectively (Fernández Escalante et al. 2016a; Pavetic et al. 2012; Scanlon et al. 2016, Scanlon et al. 2012; Thomas and Famiglietti 2015; Van Loon and Van Lanen 2013; Wendt et al. 2020a, b; Zhao et al. 2021).

Los Arenales aquifer, located in central Spain, encompasses an area with robust agricultural activity, where MAR, hydrological drought, and groundwater overdraft for irrigation have coalesced in the last 50 years. The present research aims to assess whether MAR has contributed to alleviating the effects of drought and groundwater scarcity in this aquifer. To this end, two neighbouring groundwater bodies within Los Arenales aquifer are compared in terms of their groundwater level evolution and their response to meteorological drought. Only one of the groundwater bodies has implemented MAR systems at a large scale. Several hydro statistical tools are employed, emphasising the Mann-Kendall test to assess linear trends, the standardised groundwater level index (SGI), and the standardised precipitation index (SPI).

**Background**

**Location and land use**

The study focuses on Los Arenales aquifer (central Spain) and the Douro River basin which covers a large extent of north-western Spain (Fig. 1). Geographically, this aquifer extends over the southern margin of the Douro River in a flat area that transitions to the south into the mountainous landscape of the Central System.

Under the European Water Framework Directive (European Parliament and Council of the European Union 2000), Los Arenales aquifer has been subdivided into several groundwater bodies, which constitute administrative delimitations for managing and controlling groundwater resources. Two of these groundwater bodies, Los Arenales (LA) (2,398 km²) and Medina del Campo (MC) (3,707 km²), (Fig. 1), are contrasted.

Agriculture is one of the main economic sectors in the area, representing 56% of the land use in LA and 88% in MC. In both regions, irrigation represents about 26% of agricultural land use and ~97% of groundwater abstractions. During the second half of the twentieth century, the site experienced a rapid decrease in groundwater storage as a result of the unregulated expansion of groundwater-fed irrigation. Between 1985 and 2002, groundwater levels decreased at a rate of 1.14 m/year in LA and 0.8 m/year in MC. At the end of the 1990s, the dramatic situation, which was also tangible in other aquifers of Spain (Llamas and Garrido 2007; Martínez-Santos et al. 2008; Van Loon and Van Lanen 2013), prompted farmers in LA to request the national government to implement MAR. This initiative resulted in Los Arenales MAR sites, which were officially inaugurated in 2002. Since 2002, groundwater levels have recovered in LA (0.35 m/year) while they continue to decrease in MC. These tendencies are also reflected in the groundwater exploitation index (the ratio between groundwater abstractions and available resources), which has been on average 0.9 in LA and 1.6 in MC since at least 2011. Several analyses have been conducted to elucidate the
mechanism behind such a marked difference. From 1985 to 2020, no divergence was visible between LA and MC in terms of the evolution of land use, cropping patterns, and precipitation. Additionally, groundwater levels show rising trends in wells located within the MAR areas in LA and the downstream zones. These pieces of evidence strongly suggest that the groundwater replenishment observed in LA is a major consequence of a double effect by MAR. First, this water management technique provides additional groundwater recharge. Second, the aggregation of farmers in irrigation communities that operate and co-manage MAR with the local authorities has enhanced groundwater governance and water demand control (Fernández Escalante and López-Gunn 2021; Giordano et al. 2021).

**Climate**

A Mediterranean continental climate characterises the site with annual potential evapotranspiration and precipitation around 1,130 and 395 mm, respectively. The wet season starts in October and extends till May. The interannual variability of precipitation and streamflow in the area is very high (González-Hidalgo et al. 2010; Llorente et al. 2018). For instance, the maximum and minimum annual precipitation between 1985 and 2020 differ from the average by about 50%.

A series of droughts have been recorded in the Douro River basin since the second half of the twentieth century. The most significant ones occurred in 1948–1950, 1990–1995, 2001–2002, 2004–2005, 2007–2009, 2011–2013, and 2016–2018 (CHD 2018, 2007a, b; Del Pozo Garrido et al. 2006). The below-average water availability during these periods has combined with water scarcity to result in multidimensional impacts. These impacts include substantial crop damage (e.g., 70% loss of cereal crops in 2016–2018), urban water supply rationing (e.g., restrictions in Avila in 1993), drops in hydropower production (e.g., about 50% drop during the droughts of 2004–2005 and 2011–2013), surface water and groundwater quality issues (e.g., groundwater arsenic contamination in Sanchonuño and Segovia), and adverse environmental effects such as massive fish death and changes in bird reproduction and migration patterns (CHD 2018). Judging by the numbers, it is apparent that the frequency of droughts has increased in recent years.

Climate change will likely increase the frequency and impact of drought and water scarcity in the region. Climatic models and time series analysis suggest that by the end of the century, there will be a decrease in monthly, seasonal, and average Douro River discharge (Cruz-García et al. 2016; Guerreiro et al. 2017a). Furthermore, in the same interval, the basin will experience an increase in temperature (Amblar Francés et al. 2017), increase in the occurrence and intensity of multiyear drought (Guerreiro et al. 2017b; Llorente and Bejarano 2018; MAPA 2017), and prolongation of the dry periods (Guerreiro et al. 2016).
Hydrogeology and MAR sites

Los Arenales aquifer is subdivided into two main aquifers systems as a function of the hydrogeological characteristics. The first of these systems consists of shallow unconfined aquifers in Quaternary fluvial and eolian deposits with thicknesses around 10 m and up to 50 m in the Santiuste region (Fig. 2; Fernández Escalante et al. 2016a; Navarro Alvargonzález et al. 1993). In some areas the Quaternary deposits fill paleosurfaces, resulting in small basins with a bucket shape (Fernández Escalante et al. 2016b; Fernández Escalante 2004). Hydraulic conductivity and transmissivity are in the intervals of 25–75 m/day and 201–678 m²/day, respectively (Fernández Escalante 2004). The second aquifer system is deeper and comprises detrital sand and gravels from alluvial origin arranged in lenticular and elongated structures that are embedded in a predominantly silty and clayey matrix with varying degrees of permeability (Fig. 2; Antón et al. 2012; Fernández Escalante et al. 2016a; Navarro Alvargonzález et al. 1993). These sediments are part of the Paleogene and Neogene fill of the Douro River basin and have thicknesses between 500 and 1,000 m. Maximum depths are found towards the centre of the basin (IGME 2009; IGME 1980). The hydraulic conductivities and transmissivities of the deep system are typically 0.1–100 m/day and 0.5–1500 m²/day, respectively (IGME 2009).

Recharge in the shallow system originates from precipitation (Fig. 2; on average 11% of the annual precipitation), and to a minor extent, from irrigation returns and interactions with surface water bodies (IGME 1980). The deep aquifers are fed predominantly by vertical seeping from the shallow system. In the area, groundwater flow lines converge to the Douro River and have an overall north–northeast direction (Fig. 2). Based on the available literature, no significant hydrogeological differences exist between LA and MC.

The MAR systems in LA recharge the shallow aquifer system and cover broad surface areas (Fig. 1) through infiltration channels, ponds, basins, and wetlands. The sources of water for the intentional recharge are river water surpluses and, to a minor extent, reclaimed and rooftop water (Fernández Escalante et al. 2016a). Santiuste, El Carracillo, and Pedrajas-Alcazarén MAR sites were officially inaugurated in 2002, 2003, and 2012, respectively. Together, they provide ~5 Mm³/year and up to 22.25% of the local irrigation demands (Fernández Escalante and López-Gunn 2021).

Hydrological data

Groundwater level time series

Groundwater level data are obtained from the groundwater monitoring network of the Douro Water Confederation (CHD), which is the Spanish official body for water management in the Douro River basin. This network has 61 and 97 groundwater monitoring sites in LA and MC, respectively. For the present analysis, continuous data are needed during the maximum overlapping period among the monitoring sites. This requirement is met from 2001 to 2020 by narrowing down useful groundwater monitoring sites to eight in LA and 13 in MC (Fig. 1). Bimonthly groundwater level time series are resampled to a monthly frequency by linear interpolation (Sorensen et al. 2021; Wendt et al. 2020a, b). From 2011 to 2013, there is a data gap of around 1 year. For a given month within this gap, the missing values are estimated by computing the average between the previous and subsequent years (Shamsudduha et al. 2009). This procedure works reasonably well on the available data, given the high autocorrelation of the time series (~0.90 on average).

Precipitation

Precipitation data are obtained from the meteorological networks of InfoRiego, a system providing irrigation recommendations to farmers in the Douro River basin, and AEMET, the Spanish meteorological agency. These networks have daily rainfall records in the selected analysis period (i.e., 2001–2020) at several stations in the study site (Fig. 1). Daily records are summed up to obtain monthly precipitation time series.

Methodology and preliminary analyses

The methodology used involves contrasting the groundwater and drought characteristics of LA and MC using three different statistical approaches.
1. Trend analysis: The significance of linear trends in groundwater level time series is assessed, and, when detected, their corresponding strength is estimated.

2. Average groundwater levels: The overall evolution of piezometric levels is calculated for the analysis period (2001–2020).

3. The standard groundwater level index: The response to drought events is evaluated by exploring SGI parameters.

These approaches are developed separately and subsequently integrated into the section ‘Discussion’ to provide a holistic panorama. In most analyses, the SPIs from selected meteorological stations are included as a proxy for meteorological drought.

**Trend analysis**

The Mann-Kendall (MK) test (Kendall 1970; Mann 1945) is a rank-based nonparametric test that allows assessing the statistical significance of a linear trend in a time series (Hamed 2008; Helsel and Frans 2006). This significance is evaluated in the selected monitoring sites using the trend-free pre-whitening (TFPW) procedure (Yue et al. 2002) of the MK test and the pyMannKendall package in Python (Hussain and Mahmud 2019). The aim of utilising the TFPW procedure is to decrease the probability of type I error, which in the context of this study occurs when determining a significant trend that, in reality, is not significant (Helsel and Hirsch 2002; Von Storch 1999; Yue et al. 2002). The strength (i.e., slope) of the significant linear trends is computed using the Theil-Sen estimator (Sen 1968; Theil 1992). In these analyses, groundwater levels are represented in meters above sea level. Therefore, an increasing trend will be due to rising groundwater levels, that is, the addition of groundwater to aquifer storage.

**Average groundwater levels**

Average groundwater levels for LA and MC are computed using the available data in the selected monitoring sites (Fig. 1) from 2001 to 2020.

**Groundwater drought analyses methods**

**The standardised precipitation index (SPI)**

The SPI is the most widely used indicator to characterise meteorological drought on different time scales (Edwards and McKee 1997; McKee et al. 1993). It compares rainfall over a cumulative period with the historical average, producing an index (Khan et al. 2008). In general, wet periods occur when the SPI > 0, while dry intervals are characterised by SPI < 0. The SPI for meteorological stations in the area is estimated at accumulation periods of 1, 3, 6, 9, 12, 24, 36, 48, and 60 months by employing the SPI generator from the US National Drought Mitigation Center (NDMC 2018).

**The standardised groundwater level index (SGI)**

The SGI (Bloomfield and Marchant 2013) is a nonparametric approach to estimating groundwater drought by comparing groundwater levels to the historical average. The SGI is a proxy for groundwater drought, as the SPI is similarly a proxy for meteorological drought. The SGI is calculated for the detrended residuals of the groundwater level time series. Detrending is carried out by subtracting the linear trend computed through the Theil-Sen estimator from the monthly groundwater levels. More details on the detrending and its rationale are presented in the following section (i.e., section ‘Preliminary analyses’).

**Preliminary analyses**

The aim of the preliminary analysis is to evaluate the possibility of isolating the aquifer’s natural response to drought by evaluating patterns in the groundwater level time series. Groundwater level time series can be well represented by an additive model resulting from three components, namely periodicity (or seasonality), a linear trend, and random noise (Khorasani et al. 2016; Shamsudduha et al. 2009).

The patterns of groundwater levels in Los Arenales aquifer over the course of a year are controlled by groundwater recharge and irrigation abstractions. For instance, as shown in Fig. 3a,b, every year, groundwater levels in LA and MC reach a maximum value in the first 6 months of the calendar year, coinciding with the end of the rainy season; subsequently, water heads decline steadily (Fig. 3) under the effects of irrigation abstractions, high evapotranspiration rates, and nearly null recharge as a consequence of very scant precipitation. The lowest point is reached in the last few months of the calendar year, around the period in which the rainy season starts.

On an annual time scale, groundwater levels at the site seem to be controlled by annual precipitation predominantly. Lower annual precipitation, which in some cases represents meteorological drought, corresponds with lower annual groundwater levels (Fig. 3a,b). Groundwater level amplitudes are not necessarily correlated to annual precipitation magnitudes since low water availability triggers local anthropogenic reactions that impact groundwater levels to different extents that depend on the conditions of the entailed year (e.g., irrigation demands and storage in reservoirs). The correlation between annual groundwater level and annual precipitation is reflected in Fig. 3c. The residuals resulting from extracting the linear trend (red lines, Fig. 3a,b) from
the annual groundwater levels show a linear relation with annual precipitation.

The linear trends in time series (red lines, Fig. 3a,b) are caused by long-term water use practices that likely include MAR, irrigation abstractions, and irrigation returns (Hanson et al. 2004; Kendy and Bredehoeft 2006; Shamsudduha et al. 2009; Sishodia et al. 2016; Zwilling et al. 1989). Precipitation is discarded as a significant driver for long-term trends in groundwater levels by conducting the original MK test at 12 meteorological stations (the ones in Fig. 1 plus six in the vicinity) in the period 1985–2020, obtaining only one significant trend with a strength of −0.6 mm/year. Llorente et al. (2018) also found a lack of significant precipitation trends in MC over the last three decades.

In the face of these preliminary analyses, the aquifer’s response to drought is explored by detrending the groundwater level time series, which removes the linear trend (Gardner and Heilweil 2009; Hanson et al. 2004; Prinos et al. 2002). In doing so, the residuals should carry the aquifer response to the combined effect of meteorological drought (translating into hydrological drought) and additional groundwater abstractions aimed at buffering water scarcity. This detrending procedure results in a higher cross-correlation between the residuals (Fig. 4c,d) and the SPI (Fig. 4e,f). As stated by Van Lanen and Peters (2000), the direct application of conventional statistical tools (e.g., the SGI) to aquifers under the anthropogenic influence in locations such as the Mediterranean region could result in single long-term droughts (Fig. 4a,b). Subsequent analyses involving the SGI are performed on the residuals of the detrended time series.

**Drought parameters**

Drought is defined as a period in which the SGI < 0 with at least one occurrence of SGI < −1 (Bloomfield and Marchant 2013; Brauns et al. 2020). Several drought parameters are derived from the computed SGI time series. These parameters are the drought frequency, representing the number of droughts over a period (in this case, 2001–2020); the mean drought duration, which accounts for the average duration of
drought; the mean magnitude, which is the mean accumulation of negative SGI values during a drought; the maximum drought duration, which corresponds to the longest drought interval; and the total drought magnitude, which is the accumulation of negative SGI indexes over a given interval of time (2001–2020) (Liu et al. 2016). Additionally, the autocorrelation of the groundwater level time series (Bloomfield and Marchant 2013; Sorensen et al. 2021) and the maximum cross-correlation (Bloomfield and Marchant 2013; Lee et al. 2006; McCoy and Blanchard 2008; Yeh and Chang 2019) between the SGI and the SPI are evaluated.

### Results

#### Trend analysis

All the groundwater level time series analysed showed a statistically significant trend. In both groundwater bodies, half of the trends are positive, and the rest negative (Theil-Sen slope, Table 1). Overall, positive trends in LA had higher strength than negative ones, with an average of 0.13 m/year and a range between 0.6 and −0.3 m/year (Fig. 5). In MC, the average trend strength is nearly zero, and negative trends tend to be more pronounced. The maximum and minimum values are 0.2 and −0.8 m/year, respectively (Fig. 5). These results agree with previous studies by Henao Casas et al. (2021) and, to some extent, with the findings by Borowiecka et al. (2019). These authors found that the MK test has shown neutral to negative water level trends in MC and predominantly increasing trends in LA since the early 2000s.

Increasing trends in MC are in all cases related to surface irrigation areas and, therefore, probably result from irrigation returns. Good examples are monitoring sites 18, 19, and 20, located near the Adaja River Irrigation District, a large agricultural area that draws water from the Adaja River at Las Cogotas Dam since 2011. In LA, two of the monitoring sites with an increasing trend, namely 2 and 3, are in the vicinity of the Pedrajas-Alcazarén MAR area. In this case, the specific mechanism involved in the observed pattern is likely a combination of irrigation returns from the Cega River irrigation and the confluence of MAR from Santiuste and El Carracillo brought to the area by the general north–northwest groundwater flow direction. A similar situation can be attributed to monitoring site 1, located near the Douro River. The increasing trend in 7 is probably the result of MAR in Santiuste. Monitoring sites 5, 6, and 7 show a decreasing pattern and probably reflect irrigation abstractions. MAR in these sites does not have an impact given the north–northwest groundwater flow direction.
### Table 1 Summary of the results. CHD: Abbreviation in Spanish for the ‘Douro Water Confederation’

| Groundwater monitoring site | CHD code | Groundwater Body | Well depth (m) | Nearest meteorological station (code) | Theil-Sen slope (m/year) | Autocorrelation of groundwater level time series | Maximum cross-correlation SGI-SPI | Drought frequency | Mean drought duration (months) | Maximum duration (months) | Maximum drought magnitude | Mean drought magnitude | Maximum drought duration (months) | Maximum drought magnitude |
|-----------------------------|----------|------------------|--------------|--------------------------------------|------------------------|-----------------------------------------------|---------------------------------|------------------|-------------------------------|------------------------|---------------------|-----------------------------|------------------------|-----------------------------|
| 1                           | PC0245001| LA               | 72           | 2422                                 | 0.262                  | 0.88                                          | 0.4                             | 14               | 7.4                           | 23                     | 6.02                | 23                          | 84.29                  |
| 2                           | PZ0245004| LA               | 217          | VA03                                 | 0.611                  | 0.98                                          | 0.27                            | 9                | 11.7                          | 41                     | 9.39                | 41                          | 84.50                  |
| 3                           | PZ0245005| LA               | 150          | VA03                                 | 0.564                  | 0.96                                          | 0.6                             | 11               | 9.7                           | 24                     | 7.67                | 24                          | 84.35                  |
| 4                           | PZ0245011| LA               | 331          | SG01                                 | -0.294                 | 0.89                                          | 0.32                            | 12               | 8.8                           | 29                     | 7.03                | 29                          | 84.36                  |
| 5                           | PZ0245013| LA               | 117          | SG01                                 | -0.146                 | 0.99                                          | -0.04                           | 6                | 17.5                          | 78                     | 14.06               | 78                          | 84.37                  |
| 6                           | PZ0245017| LA               | 564          | SG01                                 | -0.207                 | 0.96                                          | -0.01                           | 6                | 18.0                          | 61                     | 14.12               | 61                          | 84.73                  |
| 7                           | PZ0245031| LA               | 450          | SG02                                 | 0.336                  | 0.91                                          | 0.7                             | 12               | 8.6                           | 26                     | 6.94                | 26                          | 83.25                  |
| 8                           | PZ0245036| LA               | 525          | SG02                                 | -0.105                 | 0.86                                          | 0.44                            | 10               | 10.3                          | 41                     | 8.38                | 41                          | 83.76                  |
| 9                           | PZ0247009| MC               | 70           | VA06                                 | 0.103                  | 0.86                                          | 0.59                            | 16               | 6.44                          | 17                     | 5.19                | 17                          | 83.10                  |
| 10                          | PZ0247016| MC               | 300          | VA02                                 | -0.041                 | 0.80                                          | 0.38                            | 21               | 4.86                          | 15                     | 3.90                | 15                          | 81.97                  |
| 11                          | PZ0247005| MC               | 190          | VA06                                 | -0.035                 | 0.84                                          | 0.61                            | 15               | 6.73                          | 25                     | 5.54                | 25                          | 83.09                  |
| 12                          | PZ0247010| MC               | 302          | VA06                                 | -0.130                 | 0.87                                          | 0.67                            | 12               | 8.50                          | 26                     | 6.91                | 26                          | 82.97                  |
| 13                          | PZ0247021| MC               | 250          | VA02                                 | -0.468                 | 0.84                                          | 0.24                            | 23               | 3.91                          | 10                     | 3.27                | 10                          | 75.27                  |
| 14                          | PZ0247027| MC               | 200          | VA03                                 | 0.097                  | 0.91                                          | 0.28                            | 8                | 12.25                         | 37                     | 10.44               | 37                          | 83.54                  |
| 15                          | PZ0247029| MC               | 590          | VA02                                 | -0.575                 | 0.86                                          | 0.32                            | 14               | 7.64                          | 24                     | 6.03                | 24                          | 84.36                  |
| 16                          | PZ0247041| MC               | 539          | VA03                                 | 0.254                  | 0.97                                          | 0.35                            | 7                | 15.00                         | 42                     | 12.09               | 42                          | 84.66                  |
| 17                          | PZ0247043| MC               | 536          | VA03                                 | -0.796                 | 0.89                                          | 0.55                            | 14               | 7.64                          | 19                     | 6.03                | 19                          | 84.37                  |
| 18                          | PZ0247050| MC               | 501          | SG02                                 | 0.883                  | 0.97                                          | 0.04                            | 7                | 15.14                         | 57                     | 12.06               | 57                          | 84.45                  |
| 19                          | PZ0247051| MC               | 200          | 2444                                 | 0.019                  | 0.84                                          | 0.19                            | 17               | 14.43                         | 53                     | 11.71               | 53                          | 81.97                  |
| 20                          | PZ0247053| MC               | 250          | 2444                                 | 0.074                  | 0.83                                          | 0.33                            | 15               | 6.80                          | 19                     | 5.45                | 19                          | 81.77                  |
Average groundwater levels

LA has attested a slight (~2 m) recovery of groundwater levels between 2001 and 2020 (Fig. 6a), while on the other hand, during the same period, groundwater levels in MC have decreased by about 4 m relative to the level in 2001. Figure 6b, includes the study site’s average SPI 12, i.e., the SPI with an accumulation period of 12 months. This accumulation period is considered a good proxy for meteorological drought (Bloomfield and Marchant 2013; WMO 2012; Yeh and Chang 2019). A comparison of the average groundwater level curves with the SPI 12 (Fig. 6b) reveals that the meteorological droughts in the periods 2004–2005, 2008–2009 and 2014–2015, have a more detrimental effect on MC than on LA. For instance, the valley amplitude in groundwater levels due to the droughts of 2004–2005 and 2007–2009 are 1.4 and 3 times larger in MC than in LA. The droughts in the Douro River basin that resulted in socioeconomic and environmental losses and that were reported by the CHD (Fig. 6, red shades in the background) (CHD 2018, 2007a, and b) are represented by the SPI 12 estimated.

Groundwater drought analysis

The drought parameters (Fig. 7a and Table 1) show that, compared with MC, LA is subject to less frequent hydrological droughts (an average of ~10 vs 13, from 2001 to 2020) but with a longer mean duration (on average ~12 vs 9 months) and magnitude (on average approximately 9 vs 7). Concerning the maximum drought duration (Fig. 7b), LA shows higher maximum, minimum, and average values (40 vs 29 months). These patterns are, to a reasonable extent, explained by the higher autocorrelation of the groundwater level time series in LA (0.93 vs 0.87 in MC) (Fig. 7c and Table 1), which results in greater inertia of the system and the need for more time to reverse a trend (Bloomfield and Marchant 2013). This inertia could, in turn, be related to the hydraulic connection between surface water and groundwater in the area (IGME 2008) and the increasing number of
recovered wetlands in LA, which have consistently reappeared since the early 2000s. As Van Loon and Van Lanen (2013) noted, wetlands can slow the response of catchments and groundwater to environmental changes.

Total drought magnitude (Fig. 7d) shows a wider range in MC and is, on average, smaller than in LA. This means that the total impact of meteorological drought and water scarcity between 2001 and 2020 has more negative effects in LA, but to a minor extent.

Wendt et al. (2020a) have demonstrated that a decrease in drought frequency and an increase in drought duration and magnitude characterise aquifers in which groundwater abstraction and drought-related water deficit are more significant than recharge. Under this assumption and considering that climate is very similar throughout the area, the SGI-related parameters indicate that LA would represent a region in Los Arenales aquifer with more intense groundwater exploitation and drought impact than MC. Notice that this analysis excludes the groundwater level trends and thus, to a great extent, some anthropogenic impacts such as MAR, irrigation returns, and some of the groundwater abstractions.

**Discussion**

Linear trend analyses through the Mann-Kendall test show that groundwater levels at all monitoring sites have a significant trend. The slope strengths through the Theil-Sen estimator are on average higher in LA (Fig. 5) and indicative of storage increase. This indication is also found in the average groundwater level time series (Fig. 6), which shows an increase of about 2 m in LA between 2001 and 2020.

The drought parameters computed from the SGI of the detrended groundwater level time series show that, without the linear trends caused by MAR and other water use practices, LA represents a groundwater body where the abstraction and drought-related water deficit are higher with respect to recharge. This fact is reflected primarily in the lengthening of drought and a higher total drought magnitude in relation to MC.

However, the average groundwater level curves (Fig. 6) reveal that LA has recovered its groundwater levels in a more significant quantity and is less sensitive to meteorological drought. These observations lead to the conclusion that some water management measures implemented exclusively in LA (and that is contained in the linear trends removed in the drought parameter analysis) probably account for the overall better status of this groundwater body compared to MC. To the authors’ best knowledge, the only significant measure implemented in recent years that could explain the differences between the two regions of Los Arenales aquifer is MAR. Therefore, the implementation of this technology in LA is proving its attributes to cope with hydrological drought and water scarcity.

Wendt et al. (2020a, b) also proved that the application of MAR in the Central Valley of California (USA), an area with intensive agriculture and frequent drought events, translated into positive short-term effects on groundwater levels.
These effects were found in sites with a consistent improvement over time in groundwater storage, proving that MAR can constitute an asset against water scarcity and drought in heavily stressed aquifers.

The present study could provide stakeholders with a good example of the beneficial effects of MAR in the face of drought and water scarcity. If suitable conditions for the technique are present, agricultural regions around the world suffering from the impacts of drought and intensive abstractions (some examples can be found in Cruz et al. 2021; Hossain et al. 2021; Liu et al. 2016; Martínez-Santos et al. 2008; Mustafa et al. 2017; Pathak and Dodamani 2019) could benefit from MAR. However, this technology can cope with climate variability and water scarcity to some extent. Other measures tailored for particular social, economic, and environmental conditions are needed to mitigate further aquifer depletion, including water demand control, increase in groundwater-fed irrigation efficiency, and the conjunctive use of surface and subsurface water resources (Aeschbach-Hertig and Gleeson 2012; Dillon et al. 2009a; Fernández Escalante and López-Gunn 2021; Henao Casas et al. 2021; Scanlon et al. 2016; Van Loon et al. 2016).

Furthermore, this research illustrates that MAR has good potential as an adaptation measure to climate change. Although other authors highlight the adaptive potential of MAR (Aeschbach-Hertig and Gleeson 2012; Clifton et al. 2010; Dragoni and Sukhija 2008; Green et al. 2011; Taylor et al. 2013; Wilby and Dessai 2010), few studies in the reviewed literature have proven this point explicitly with real-world case scenarios. Areas such as the Mediterranean, prone to more frequent extreme events under climate change projections (IPCC 2021; Seneviratne et al. 2012), could take advantage of this technology to buffer drought and floods.

The results align with previous studies that have shown that detrending, which involves extracting linear trends from groundwater level time series, can help in removing some human impacts on groundwater levels (Gardner and Heilweil 2009; Hanson et al. 2004). The detrending is particularly beneficial when analysing drought parameters, contributing to avoiding SGI time series with single long-term droughts (Fig. 4a, b) that might not be related to meteorological water deficit.

However, the utilised SGI series are still strongly influenced by anthropogenic activity, which is verifiable by the low cross-correlation coefficient between the SGI and the SPI (Table 1), and the considerable deviation of the mean drought duration in terms of typical values in gravel/sand aquifers (6–7 months; Brauns et al. 2020). This result is not surprising. Van Loon and Van Lanen (2013) found that in Spanish basins, the effect of abstraction on groundwater resources can be up to four times the impact of drought. Future studies at the same site could greatly benefit from groundwater abstraction data.

Conclusions

The comparison between two groundwater bodies in Los Arenales aquifer indicates that managed aquifer recharge (MAR) is an effective solution to counteract the adverse effects of drought and water scarcity on groundwater storage. The Mann-Kendall tests show significant trends for all the groundwater monitoring sites evaluated. In the groundwater bodies of Los Arenales (LA) and Medina del Campo (MC) half of the trends are negative and half positive. In LA, increasing trends have more substantial slopes, 0.13 m/year on average, and are likely the result of managed aquifer recharge (MAR) and irrigation returns. On the other hand, trends in MC have more significant negative slopes and an average value of −0.05 m/year. Positive trends in MC are related to irrigation returns. In all cases, negative trends are likely caused by irrigation abstractions. The average groundwater level in LA shows a rise of about 2 m between 2001 and 2020. In contrast, MC shows a decreasing trend that amounts to 4 m in the same period.

An analysis of the standardised groundwater level index in detrended groundwater level time series, which do not include the effect of managed aquifer recharge (MAR), indicates that LA experiences less frequent (10 vs 13 in 2001–2020) and longer droughts (~12 vs 9 months), which accounts for longer maximum drought duration (40 vs 29 months), and greater total (84 vs 82 in 2001–2020) and mean (nine vs seven) magnitude.

Increasing patterns in the groundwater level time series that hold the recovering effect of MAR, and finding worse drought parameters when the same time series are detrended and lose the additional recharge from MAR, indicate that this water management measure accounts for the more significant storage recovery observed in LA.

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