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Evaluating the feasibility of Managed Aquifer Recharge techniques as a drought mitigation strategy for the Seville water supply system (southern Spain)

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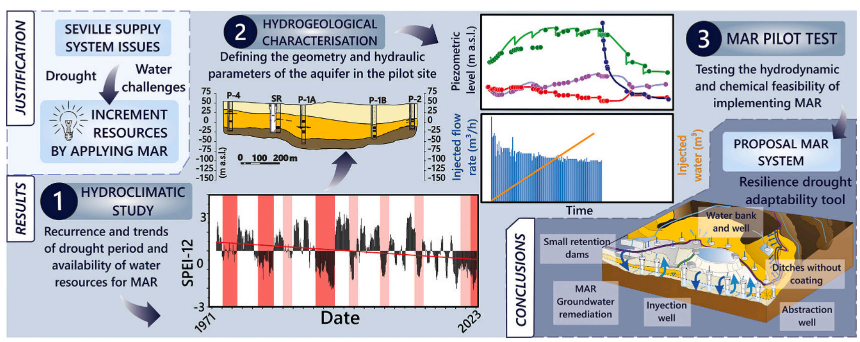
HIGHLIGHTS

- MAR viable drought solution and adaptable to semiarid regions globally
- Pilot tests ensure MAR design success and check eventual adverse groundwater impacts.
- The MAR infrastructure proposed improves the water supply system resilience.
- SPEI indices characterise drought recurrence and support MAR feasibility studies.
- The study shows MAR's role in global water management, addressing climate challenge.

GRAPHICAL ABSTRACT



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ABSTRACT

Managed Aquifer Recharge (MAR) is a recognised strategy for improving water security, particularly in regions facing increasing droughts and water demand due to climate change. However, gaps remain in assessing MAR feasibility through drought analysis, pilot testing, and resource availability evaluation. This study details a MAR pilot project in the Guillena-Cantillana Groundwater Body (GWB), part of the Niebla-Posadas aquifer, Seville, Spain, via storing released reservoir water for abstraction during dry episodes to evaluate its potential for mitigating supply system drought impacts. A hydroclimatic study using statistical analysis of the Standardised Precipitation Evapotranspiration Index (SPEI) revealed increasing drought trends and favourable wet periods for MAR implementation. The analysis of historical droughts and SPEI provided key insights into the duration of recharge and extraction periods, while trend analysis helped assess the long-term availability of water resources for MAR. The pilot test involved direct gravity injection of 4183 m^3 of surface water, with monitoring of water levels, electrical conductivity, pH, and concentrations of ions and metals to assess hydrodynamic and hydrochemical responses and provided data on recharge and abstraction rates. Results confirm that MAR via wells is technically and environmentally feasible in the study area, with no adverse effects on groundwater quality and sufficient aquifer recharge capacity. Hydrogeochemical modelling provided insights into recharge-groundwater interactions. This study highlights the value of hydroclimatic trend analysis, drought indices and pilot testing in MAR planning, demonstrating its potential to enhance Seville's water resilience and offer a transferable framework for similar confined aquifers worldwide.

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1. Introduction

Population growth, urban expansion, agriculture, and industry have intensified water demand and groundwater abstractions (Gleeson et al., 2012; Schipanski et al., 2023; UNESCO, 2022), particularly in semi-arid regions, where groundwater use has risen by 15–20 % in recent decades (UNESCO, 2024, UNESCO, 2022). Spain (southern Europe) has experienced a 15 % population increase over the last two decades (INE, 2023), driving higher water extractions. Simultaneously, rising global temperatures exacerbate drought recurrence, with climate models projecting a decline in annual precipitation and an increase in evaporation (Bellido-Jiménez et al., 2023; Calvin et al., 2023; WMO, 2023). These climatic changes impact groundwater recharge by reducing infiltration capacity (Babre et al., 2022). Meteorological droughts, defined as prolonged periods of below-average precipitation (WMO, 2023), significantly impact water availability (Araneda-Cabrera et al., 2021; Ionita et al., 2022; Isia et al., 2023). These events lead to hydrological droughts, reducing surface and groundwater resources (Hayes et al., 2011; Spinoni et al., 2019) and, in some cases, impact agricultural and urban supply demands, escalating into socio-economic droughts (Spinoni et al., 2015). In any case, drought periods require improving water efficiency and implementing conservation measures. Traditionally, drought mitigation relies on surface water storage (reservoirs, dams, ponds), which are highly vulnerable to evaporation losses (Kim et al., 2017). In response, water management strategies such as water recycling, desalination, and Managed Aquifer Recharge (MAR) have gained prominence (Gonzalez et al., 2020; Scanlon et al., 2016).

In this scenario, MAR, the induced and planned recharge in an aquifer for storage and subsequent use or environmental benefits, is a strategic approach to enhancing groundwater storage and quality, mitigating drought impacts by replenishing aquifers during periods of water surplus while minimising evaporative losses (Rawluk et al., 2013). Common MAR techniques include basins, induced riverbank filtration (34 % of MAR active sites worldwide) and pond infiltration (57 %), or injection wells (5 %) (Hiscock and Grischek, 2002; Rossetto et al., 2020; Sprenger et al., 2017). These methods allow the conjunctive management of groundwater and surface water by storing surpluses of surface resources in aquifers during wet years, which can be pumped for use in dry periods (Bouwer, 2002), making it a climate change adaptation strategy (Scanlon et al., 2023).

Successful MAR design and implementation require rigorous feasibility assessment, including hydrogeological and hydrochemical characterisation, aquifer geometry definition, and hydraulic property evaluation (Maliva, 2015; Page et al., 2011). A crucial aspect is understanding the availability of surplus surface water for recharge, which depends on hydrometeorological variability, including drought recurrence. Since drought quantification lacks a single measurable variable, indices such as the Standardised Precipitation Index (SPI) and the Standardised Precipitation-Evapotranspiration Index (SPEI) are widely used (Guttman, 1999; Hayes et al., 2011; Vicente-Serrano et al., 2010; WMO, 2023). SPI, the most commonly applied index, evaluates drought based on precipitation, while SPEI incorporates evapotranspiration, making it particularly effective in capturing temperature-driven drought intensification (Vicente-Serrano et al., 2010). However, despite the increasing application of hydroclimatic analyses in water resource studies, their integration into MAR planning remains limited (He et al., 2021; Henao Casas et al., 2022; Sufyan et al., 2024). This constitutes a significant research gap, given that the sustainability of MAR under changing climatic conditions is imperative for long-term water resource management, and drought indices could help assess whether sufficient water is available for recharge and identify optimal periods for injection and extraction. Additionally, MAR projects must address groundwater quality concerns, as surface water sources may introduce contaminants (Fakhreddine et al., 2015; Hiscock et al., 2024) and trigger hydrochemical interactions and operational challenges such as sediment clogging (Dillon et al., 2019; Pyne, 2015). MAR pilot tests and hydrogeochemical mixing models clarify the further chemical reactions between recharge water and native groundwater. However, existing literature predominantly focuses on built MAR systems (Dillon et al., 2019; Sprenger et al., 2017), often overlooking the critical role of pre-assessment studies in optimising system performance.

Despite favourable technical conditions, MAR adoption in Spain has been constrained by regulatory, environmental and economic factors (Fernández-Escalante, 2004), whereas countries like the USA and Australia have successfully integrated MAR into water management policies (Dillon et al., 2019). Seville (Southern Spain), with a metropolitan area hosting over 1.5 million inhabitants (INE, 2023), relies almost entirely on surface water, susceptible to climatic variations and pollution. Historical droughts (e.g., 1972–76, 1980–83, 1991–95) impacted the city's water supply, requiring emergency measures such as external resource capture, consumption restrictions, and public awareness campaigns (Del Moral Ituarte and Giansante, 2000). For all the above, the Seville water company (EMASESA, by its Spanish acronym, *Empresa Metropolitana de Abastecimiento y Saneamiento de Aguas de Sevilla*) have taken diverse actions to increase the supply guarantee in drought, but efforts have primarily focused on increasing surface water storage.

In recent years, EMASESA has initiated efforts to incorporate groundwater into the supply system through MAR and increase drought resilience, aiming to offset 10 % of its annual water demand (100 Mm^3) during drought periods. Within this background, EMASESA launched a project to study the feasibility of implementing MAR in nearby Groundwater Bodies (GWBs)[1] based on various scientific and technical criteria. This document presents the results of this research, which contributes to Seville's integrated water management through innovative strategies. The main objectives of this study are: (1) to assess climate change impacts on hydrometeorological conditions and surface water resources, an aspect not often covered in MAR scientific literature; (2) to evaluate MAR feasibility through pilot testing to design a sustainable solution, and (3) to outline key pre-implementation steps for a built MAR system. This innovative experience could serve as an example for other cities aiming to use groundwater resources based on a MAR system.

2. Material and methods

2.1. Study area

The selection process of the most MAR-suitable area in this study case includes all those GWBs close to the city of Seville (Fig. 1). The analysis, detailed in Supplementary Material Section 1, identified the Guillena-Cantillana GWB as the most favourable due to its hydrogeological characteristics, partial confinement, lower vulnerability to pollution and high abstraction pressures. In addition, this GWB is not in contact with any groundwater-dependent ecosystem of the Natura 2000 network and has infrastructure that could be used for the transport of recharge and recovered water. Previous studies have also highlighted its MAR potential, though they recommend further hydrogeological investigations and pilot tests (IGME, 1983; IGME-EMASESA, 2002).

The Niebla-Posadas aquifer, located at the northern edge of the Guadalquivir River Basin (Fig. 2A), outcrops in the Guillena-Cantillana GWB (106 km^2). The Iberian Massif bounds it to the north, the Guadalquivir alluvial aquifer to the south, and the Rivera de Huelva and Viar rivers to the west and east, respectively. The region has a subcontinental Mediterranean climate (Pita López and López Ontiveros, 2003), with

[1] Groundwater Body (GWB) is a distinct volume of groundwater within an aquifer or multiple aquifers that is delineated for water management and protection under the Water Framework Directive (WFD) (2000/60/EC). The WFD defines it as the fundamental unit for assessing and monitoring groundwater status across the European Union.

high seasonal temperature variations, mean annual temperatures of 17 °C, and precipitation averaging 565 mm/year, though highly variable (239 mm in 1994/95 to 1042 mm in 1996/97) for the period between 1982/83 and 2019/20 hydrological years.

In the study area, the outcropping materials are sands, sandstones and marls of the Upper Miocene age overlying a low permeable Paleozoic basement of the Iberian Massif (Fig. 2. B). The outcropping materials are included in a tertiary depositional series of marine origin of the Late Miocene (Tortonian-Mesinian) age that appears in an elongated NE-SW outcrop at the northernmost part of the Guadalquivir basin (Sierro et al., 1990; Viguier, 1974). These materials have a permeable detrital sequence, formed by conglomerates, sands, and sandstones, called Niebla Formation (Niebla Fm), that constitute the Niebla-Posadas aquifer, overlain by a confining layer of marls called Gibraleón Formation (Gibraleon Fm), and different alluvial and colluvial deposits of Quaternary age. The Niebla-Posadas aquifer is divided into several GWBs, one of which is the Guillena-Cantillana, the object of this study and is limited, on its NW boundary, by the Paleozoic materials of the Iberian Massif (impermeable substrate) and, to the SE, by the Gibraleon Fm, which confines and separates it from the aquifers formed by the Quaternary deposits (Fig. 2. B). The geometrical arrangement of the substrate and the lateral changes of lithological facies recognised in the sediments lead to variations in the thicknesses of the Niebla-Posadas aquifer (Fig. 3). The average thickness is between 20 and 30 m, although it can reach 70 m and even disappear in some areas. Similarly, hydraulic parameters range from unconfined conditions in the north to confined conditions in the south, with transmissivity values between 2 and 1000 m^2/day and storativity values between 10^{-2} to 10^{-3}–10^{-5} (IGME, 1983; IGME-EMASESA, 2002).

In the conceptual hydrogeological model (CEHIUMA-EMASESA, 2021; IGME-EMASESA, 2002), water recharge occurs primarily through direct rainfall infiltration in the unconfined sector, supplemented irrigation returns and infiltration from losing streams. Groundwater exploitation, mainly for irrigation and municipal supply, particularly in the towns of Guillena, Burguillos, and Villaverde del Río, has led to declines of up to 30 m, creating piezometric depressions (Fig. 2. B) and resulting in persistent water balance deficit—mainly for irrigation—exceeding available resources (CEHIUMA-EMASESA, 2021; CHG, 2022, CHG, 2015). Consequently, no natural outflows are currently occurring due to the abstraction to guarantee urban supply. This exploitation, evidenced by declining piezometric levels, makes the aquifer suitable for MAR.

Groundwater chemistry transitions from $Ca\text{-}HCO_3$ facies in the unconfined zone to Na-Cl facies in the confined sector, with increasing electrical conductivity along the NW–SE groundwater flow path (400–1500 μS/cm). However, in the Spanish Geological Survey database, there are wells located further to the SE, capturing the Niebla-Posadas aquifer outside the GWB, in which 22,445 μS/cm have been measured (IGME-EMASESA, 2002). Most of the agricultural activities occur within the confined sector, an area with low vulnerability to contamination. Despite this, NO_3^- concentrations occasionally reach values above 100 mg/L in the unconfined sector due to the use of fertilisers. In the confined sector, nitrate levels decline, coinciding with increases in NH_4^+ and NO_2^-, indicating redox processes (Ávila-Marín et al., 2023).

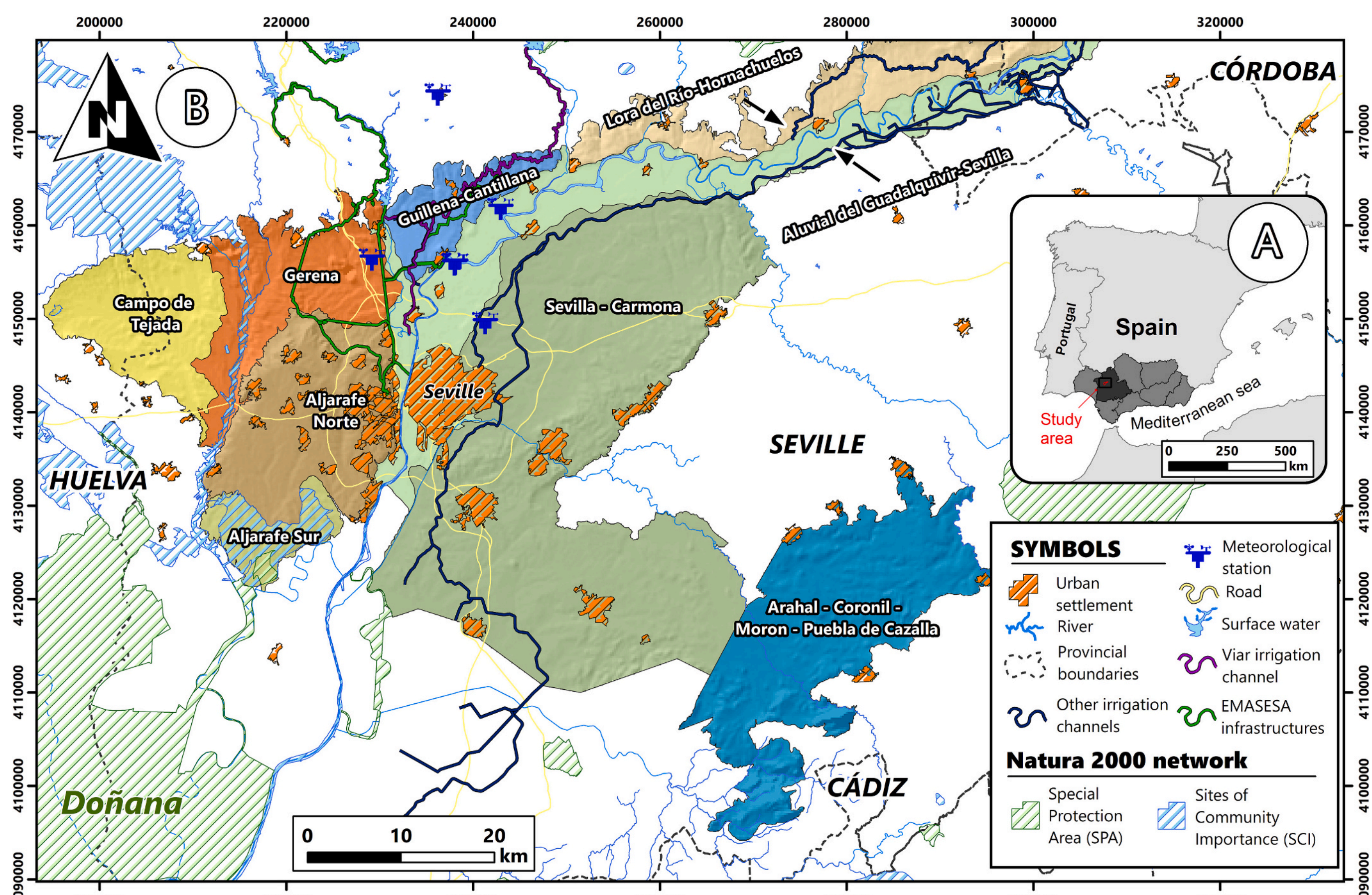

Fig. 1. Location of the Groundwater Bodies (GWB) with potential interest for the implementation of Managed Aquifer Recharge (MAR) in the surroundings of the metropolitan area of Seville (SW, Spain). The figure shows the Site of Community Interest (SCI) included in the Natura 2000 Network and some hydraulic infrastructures potentially useful to distribute MAR resources.

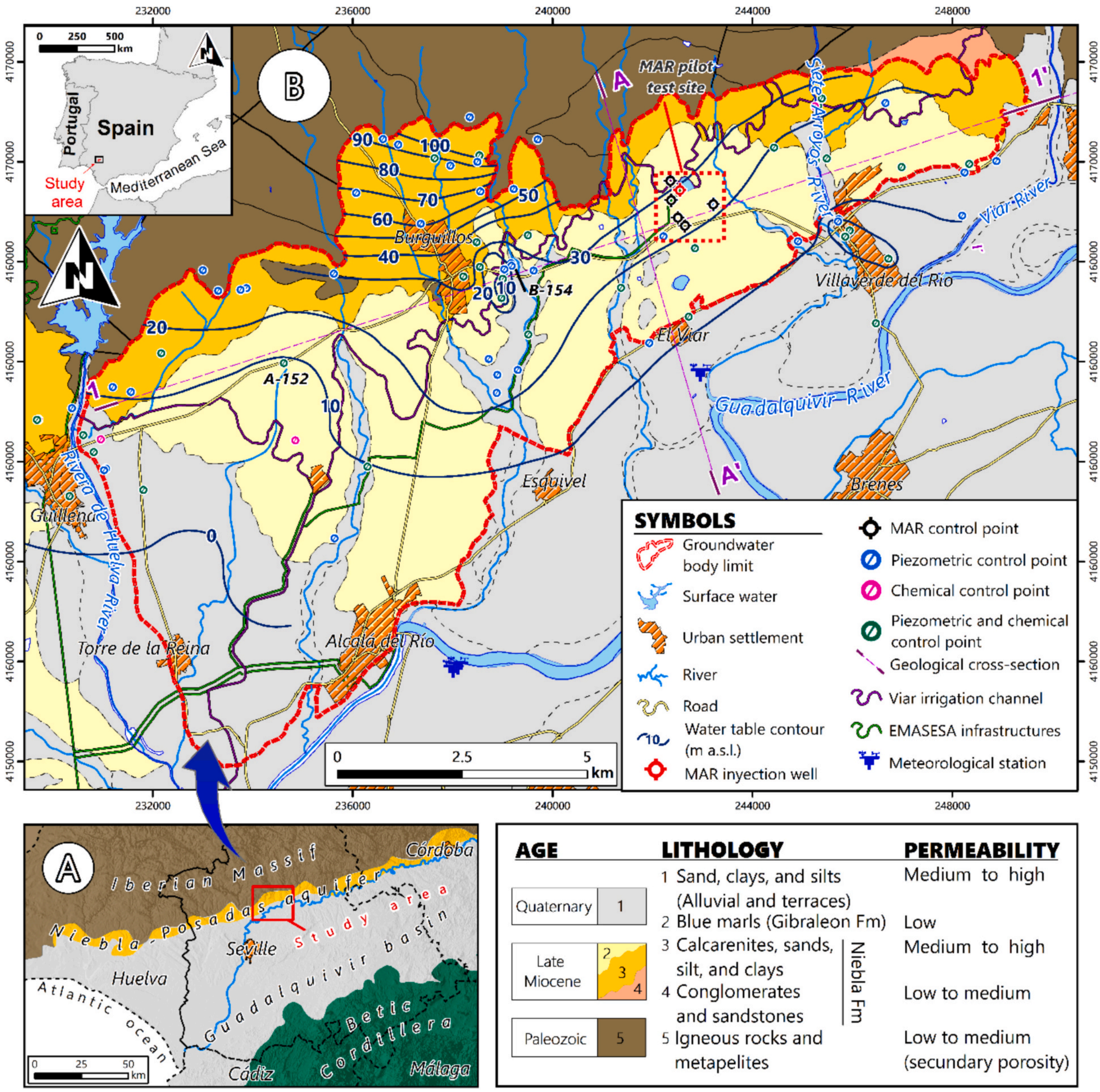

Fig. 2. (A) Regional geological context and location of the study area. (B) Geological and hydrogeological map. Including the cross-section direction shown in Fig. 3. Modified from Spatial Reference Data of Andalusia (DERA by Spanish acronym "Datos Espaciales de Referencia de Andalucía", (IECA, 2024) and continuous digital geological mapping (GEODE) of the Spanish Geological Survey (IGME) at scale 1:50.000 (Muelas and Crespo, 1976).

2.2. Hydroclimatic and hydrological study

To establish the hydroclimatic context, records of precipitation and maximum and minimum temperature over 51 hydrological years (1971/72–2022/23) were analysed using data from five meteorological stations (Fig. 1). These were operated by the Spanish Meteorological Agency (AEMET) and the Institute for Agricultural and Fisheries Research and Training (IFAPA). To determine the availability of surface water resources for MAR performance in the study area, the contributions to the Melonares reservoir have been analysed, which depends mainly on rainfall. This reservoir feeds the "El Viar" irrigation channel that crosses the Guillena-Cantillana GWB. Reservoir inflow data were compiled from EMASESA (2021) and Guadalquivir water authority (from Spanish Confederación Hidrográfica del Guadalquivir's -CHG) Automatic Hydrological Information System (SAIH), while pre-construction inflows (1971–2009) were simulated using the SIMPA model (CEDEX, 2019, CEDEX, 2017). Groundwater level data were obtained from IGME databases (1982–2020) and direct measurements (2020–2024).

Meteorological data were used to calculate the Standardised Precipitation Index (SPI) (Mckee et al., 1993) and Standardised Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) using the SPEI package in RStudio. Potential Evapotranspiration (PET) data used for the SPEI computation was calculated using Hargreaves and Samani (1985) method. The PET, SPI, and SPEI were calculated using the SPEI package in RStudio at a 12-month scale (SPEI-12 and SPI-12), allowing standardised comparisons across regions and periods. To detect significant climatic and hydrological trends over time, Mann-Kendall (MK) (Kendall, 1975; Mann, 1945) and Sen's slope (Sen, 1968) tests were conducted using the "trend" package in RStudio. The Mann-Kendall (MK) test was used to analyse the trend of the annual series of average temperature (AT), cumulative PET (CPET), cumulative precipitation (CP), and total inflows to the Melonares reservoir (Melonares INF), as well as the monthly data of the SPEI-12 and the SPI-12

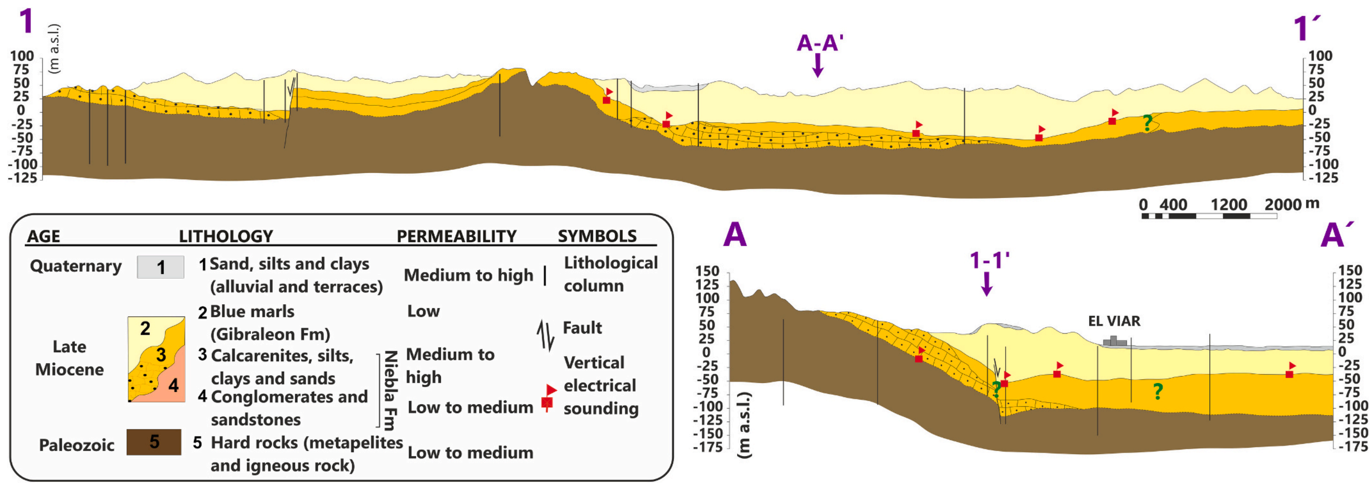

Fig. 3. Geological cross-sections 2–2′ and F-F′. See the situation in Fig. 2 (modified from CEHIUMA-EMASESA, 2021).

drought index. The analysed period comprises from 1971 to 2023. With a confidence level of 95 %, the MK test and Sen's slope (Ss) estimator were applied to evaluate the significance of the trends as well as the magnitude of the statistical changes. A summary of all data sources and methodologies is presented in Table 1. Detailed calculation equations for drought indices and trend analyses are provided in Supplementary Material 2.

2.3. Design and implementation of MAR pilot test. Simulation of MAR proposal system

Site selection considered hydrogeological characteristics, proximity to water infrastructure, and availability of public land to expedite permitting. The MAR pilot test was conducted in the Guillena-Cantillana GWB, between Burguillos and Villaverde del Río (Fig. 2), where the Niebla-Posadas aquifer is confined under the low-permeability Gibraleón Formation marls, in particular immediately to the SW of the Melonares raft (Fig. 4), which collects water for urban supply from the Melonares reservoir through the Viar channel (Fig. 4.B). In this area, the Niebla-Posadas aquifer is confined under the low permeability marls of the Gibraleon Fm. Previous studies (CEHIUMA-EMASESA, 2021) indicate that the materials that constitute the aquifer in this area are mainly permeable sands; their estimated thickness is about 20–40 m, and the decrease in the hydraulic head could be about 10–15 m. In addition, there are certain logistical advantages: 1) the proximity to the Melonares raft guarantees the availability of decanted water without fine sediments turbidity for recharge; 2) the raft is located on public property (owned by the CHG), so it is easy to obtain the necessary permissions to carry out the well drilling; and 3) there is an EMASESA pipeline that allows connection to the supply network to the city of Seville (Fig. 4). These characteristics are favourable for implementing MAR.

Table 1
Data sources and methodologies used for hydroclimatic and hydrogeological analyses. Standardised Precipitation Index (SPI) (Mckee et al., 1993) and Standardised Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010).

Data type	Period covered	Source	Methodology / notes
Precipitation and temperature	1971/72–2022/23	AEMET, IFAPA	Data from five meteorological stations near the study area.
Reservoir Inflow	2009–2018	EMASESA (2021)	Measured inflows to Melonares reservoir.
	2018–2023	CHG (SAIH)	Automatic Hydrological Information System data.
	1971–2009	SIMPA Model (CEDEX, 2019, CEDEX, 2017)	Simulated inflow before dam construction.
Groundwater level	1982–2020	IGME (Spanish Geological Survey)	Historical piezometric records.
	2020–2024	Field measurements	Direct well measurements.
Drought Indices (SPI, SPEI)	1971/72–2022/23	Calculated	SPI (Mckee et al., 1993); SPEI (Vicente-Serrano et al., 2010) using RStudio.
Potential Evapotranspiration (PET)	1971/72–2022/23	Calculated	Hargreaves and Samani (1985) method in RStudio.
Trend Analysis	1971–2023	Calculated	Mann-Kendall test (Mann, 1945; Kendall, 1975) & Sen's slope (Sen, 1968) in RStudio.

In the context of this research, the CHG is the regulatory authority responsible for granting permits and overseeing the implementation of MAR projects within the basin. The CHG mandates specific criteria for MAR pilot tests, such as suitable well and piezometer locations, limits on recharge volumes (20,000 m^3 in this study), and monitoring hydrochemical parameters to ensure groundwater quality. Six wells were drilled in the pilot site before the MAR pilot test, with depths between 64 and 98 m (Fig. 4), of which five are control points piezometers (P-1A, P-2, P-3, P-4, and P-1B) and the remaining one is the recharge injection well (SR). Control points were placed upstream and downstream of the SR (250–730 m away) following CHG criteria to monitor the potential hydrodynamic and hydrochemical effects of the MAR pilot test on the aquifer. Before the MAR pilot test, a pumping test was carried out in the SR well to assess the yield capacity and to determine hydraulic parameters such as transmissivity (T) and storage coefficient (S). The pumping test lasted 23 h and consisted of several steps with progressively increasing pumping rates (3.5, 5, 7, 8, 9, and 10 L/s).

The origin of the water for recharge is another critical issue in recharge experiments, as well as its quality and quantity. In the study area, no large treatment plants facilitate access to regenerated or treated water. Subsequently, surface water is the only viable possibility. Some options include surface runoff generated upstream of the Niebla-Posadas aquifer or surplus dammed water released from the Melonares and El Pintado reservoirs and transported through the Viar irrigation channel (Fig. 4.A). In both cases, resource availability depends mainly on rainfall because total inflows to the Melonares reservoir come from surface runoff water and releases from the El Pintado reservoir (Fig. 4.A). The

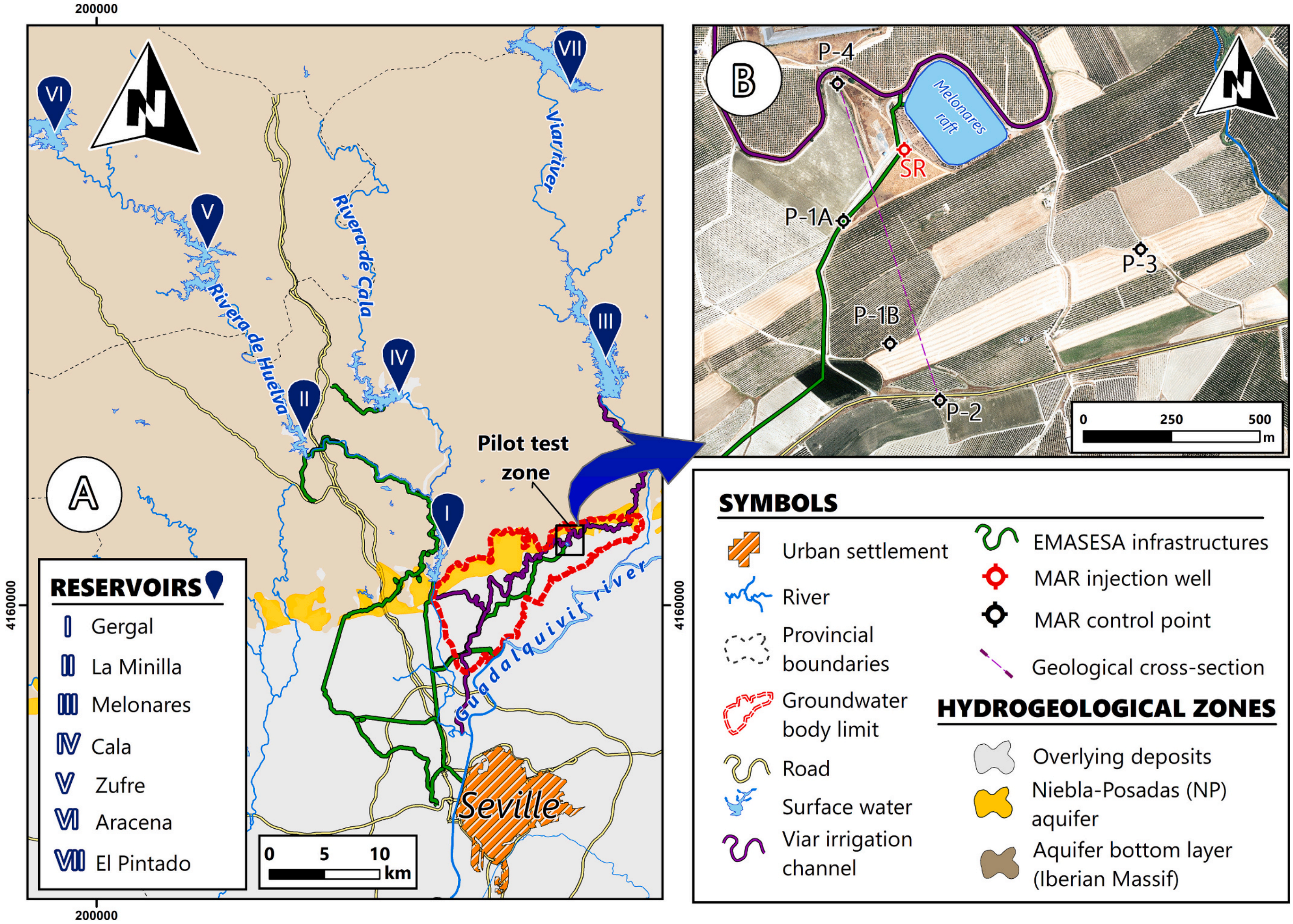

Fig. 4. (A) Schematic of Seville water supply system, location of the Guillena-Cantillana GWB and MAR pilot test site and reservoirs involved in the supply system. (B) Mean features of the MAR pilot test.

possibility of using other sources, such as urban runoff, has not been considered because it would require preliminary analysis and treatment, and urban areas near Guillena-Cantillana GWB are small.

A flow meter and a pressure manometer were installed in the SR well to monitor the input flow and pressure during the test, ensuring compliance with the allocated water volume. Geological control during well drilling provided information on the lithological column, hydrogeological characteristics, and hydraulic head position. During the pumping test and MAR pilot injection test, the piezometric level was measured in the control points with a water level meter -OTT. In addition, Odyssey water level loggers and CTD divers from Schlumberger were installed in the control piezometers to obtain a record of the hydraulic head of the aquifer.

On 10 May 2023, at 10:00 a.m., the MAR pilot test began and was concluded five days later. During these days, no precipitation was recorded, and average temperatures ranged between 21 and 25 °C (according to the information obtained from the nearest meteorological stations described in Section 2.2). The water of recharge was supplied by gravity from the Melonares raft, taking advantage of the difference in height between the water intake, 9 m above the ground, and the water level in the SR well, which was 33–34 m below the ground surface. Thus, the manometric pressure at the water entrance to the well was close to 1 bar. However, the hydraulic pressure on the groundwater should initially be over 4 bar, given that the total water column on the piezometric level test was 42–43 m before the MAR pilot started.

During the study period (2020–2024), the pumping test and one day before starting the MAR pilot test, groundwater samples were taken in the recharge well (SR) and other wells in the confined zone of the aquifer to determine the background hydrochemical condition in the environment of the test pilot site. In addition, samples of the water used in the MAR action (RW) were taken daily during the MAR test between 10 and 15 May 2023. After the recharge operation, the SR was sampled weekly in May and monthly from June to December 2023 based on CHG requirements. Electrical conductivity (EC) measurements of the water samples were also carried out on each sampling using an EC meter equipped with a thermometer (WTW Model Cond3310) with an accuracy of ±1 μS/cm. The EC values were measured at a reference temperature of 20 °C.

The analysed compounds include the priority substances for which the European Water Framework Directive (WFD) has established limit values based on environmental quality standards (EQS) and drinking water standards (DWS) and those included in the groundwater quality standards for urban supply in Spain (CHG, 2022; European Commission, 2008, European Commission, 1998; Ministerio de Medio Ambiente, y M. R. y M, 2009). Among the analysed chemicals were some active substances of the pesticides included in WFD (Atrazine, Dieldrin, Simazine, and Terbuthylazine) and the Spanish legislation (Trichloroethylene and Tetrachloroethylene), some heavy metals (As, Cd, Hg, Pb), ammonium (NH_4^+), chlorides (Cl^-), fluorides (F^-), nitrates (NO_3^-), phosphate (PO_4^{3-}), and sulphate (SO_4^{2-}). Chemical analyses were carried out in the laboratory of EMASESA certified according to the Spanish standardisation association in ISO 9001. In addition, pH, alkalinity, and other heavy metals (Mn and Fe) were measured in the Centre of Hydrogeology of Malaga University (CEHIUMA).

In the pilot test, the recharge water from the Melonares raft (Fig. 4. B) flowed through a pipeline recharge well (SR), where it was introduced by gravity. The pipeline takes water from the upper part of the decanting raft to prevent water from entering the borehole with a high turbidity level. According to previous reports (CEHIUMA-EMASESA, 2021) and samples taken during the field campaigns carried out prior to the tests (between 2020 and 2024), the waters of the Melonares reservoir have low mineralisation (EC between 145 and 319 μS/cm at 20 °C), bicarbonate-calcium facies and medium-low hardness values (total hardness between 6.59 and 13.83 °F). Nitrate concentrations are also low (0–7.59 mg/L). The excellent quality of the water in the Melonares reservoir has a significant influence on the water in the regulating raft (Table 2). Moreover, during its journey through the Viar irrigation channel, no negative effects have been detected in the water; in fact, it usually improves its quality since some dissolved metals, such as manganese and iron, are oxidised and precipitate before reaching the reservoir, decreasing its concentration to values below 100 and 200 μg/L, respectively (CEHIUMA-EMASESA, 2021). In addition, a decrease in the turbidity from 4 to 8 NTU of the reservoir water to below 1 NTU in the channel and of Melonares raft is measured. For these reasons, the water from this raft was suitable for MAR and has been selected as the source for the pilot test (Table 2).

Finally, based on the results of the pilot test (section 4.2) and the data collected for the hydroclimatic analysis (Table 1), the operation of a proposed MAR system has been simulated from 2009 to 2023 (172 months) to estimate the total water volume available to Seville's supply system if MAR had been operational since the construction of the Melonares reservoir. The spreadsheet-based simulation algorithms were implemented using Excel and applying conditional formulas to automate decision-making based on the evolution of the reservoir's stored volume and the SPEI index. Recharge from the Melonares reservoir was assumed to occur only when the reservoir volume exceeded 90 % of its capacity (or 80 % if the previous month's SPEI was >1, indicating moderate humidity). Conversely, abstraction from the MAR system for urban supply was initiated only when the reservoir volume fell below 60 % or when the SPEI value of the previous month was less than −1 (indicative of moderate drought). Further details on the volumes used are specified in sections 4.2, 4.3 and 4.4.

2.4. Hydrogeochemical modelling

Forward geochemical modelling was performed using the USGS programme PHREEQC interactive 3.7 for Windows (Appelo and Postma, 2005) to identify the governing hydrogeochemical processes at the MAR pilot test site. A geochemical model aims to determine which set of hydrogeochemical reactions and to what extent (in terms of moles of reaction) can explain observed changes in water composition in a system, including the mixing of different water types. In this study, specifically, the model was used to calculate the results of conservative mixing between recharge water and groundwater and subsequently to explain which reactions could identify further changes in water composition, as observed in samples from groundwater post-pilot test. The theoretical mixing concentrations of solutes not influenced by processes besides mixing in the water (m_{mix}) were calculated using eq. (1). This computation is based on mixing fractions of recharge water and groundwater calculated using Cl^- concentrations as a conservative ion (eq. (1)) and the actual end-member concentrations of recharge water and groundwater (Appelo and Postma, 2005):

$$m_{mix} = f_{Cl^-}\cdot m_{Cl^-PRE} + \left(1 - f_{Cl^-}\right)\cdot m_{Cl^-RW} \tag{1}$$

where the concentrations of ion Cl^- for groundwater and recharge water are denoted as $m_{Cl\text{-}PRE}$ (aquifer pre-pilot test) and $m_{Cl\text{-}RW}$ (recharge water), respectively, and the Cl-based fraction of infiltration water in abstracted water is denoted as $f_{Cl\text{-}}$, calculated as:

$$f_{Cl^-} = \frac{m_{Cl^-POST}\cdot m_{Cl^-RW}}{m_{Cl^-PRE}\cdot m_{Cl^-RW}} \tag{2}$$

where measured concentrations of Cl in groundwater post-pilot tests are denoted as $m_{Cl\text{-}POST}$.

In the model, concentrations of all other solutes were calculated based on the assumption of conservative mixing, i.e., without reactions (eqs. (1) and (2)). The differences between the measured concentrations and these calculated conservative mixing concentrations were assumed to be the result of reactive processes in the aquifer that need to be monitored in future MAR pilot tests. The model also calculated saturation indices for key minerals (siderite, calcite, dolomite, hematite, and goethite) based on previous studies of the Niebla-Posadas aquifer (Scheiber et al., 2016, Scheiber et al., 2015) to explain changes in water composition.

Table 2
Summary of the hydrochemical compounds determined and parameters measured from samples taken from the Melonares reservoir (EMASESA, 2021), Viar irrigation Channel, and Melonares raft (both sampled from June 2016 to May 2023), source of the recharge water used in the Managed Aquifer Recharge (MAR) pilot test conducted in this study. -N.M- No measured.

Water sampled	WFD limit value	Melonares reservoir (EMASESA, 2021)			Viar irrigation channel			Melonares raft		
Parameter (unit)		n	Mean	SD	n	Mean	SD	n	Mean	SD
EC (μS/cm)	2500	657	216	26	24	256	23.94	9	268	1.67
pH	No limit	657	7.73	0.54	24	7.99	0.81	4	7.97	0.75
Dissolved oxygen (mg/L)	No limit	657	5.66	3.67	24	7.63	1.34	4	7.75	1.21
Temperature (°C)	No limit	657	14.9	5.00	24	18.3	3.16	4	15.7	6.5
ORP (mV)	No limit	657	144	109	24	117	22.5	4	110	23.1
Turbidity (N.T.U.)	No limit	656	4.64	4.64	24	1.10	1.7	4	0.85	1.60
TOC (mg/L)	No limit	68	5	0.64	24	4.40	0.45	4	4.20	0.31
TSS (mg/L)	No limit	130	4.12	2.66	N.M			N.M		
Na^+ (mg/L)	No limit	271	10.9	1.41	24	13.1	2.11	4	11.7	1.75
NH_4^+ (mg/L)	No limit	656	<2	0.23	24	0.00	0.00	9	<0.15	0.00
Ca^{2+} (mg/L)	No limit	271	25.7	3	24	27.9	1.3	4	27.9	1.30
Cl^- (mg/L)	250	498	10.5	1.26	24	13.1	1.66	9	15.7	0.50
F^- (mg/L)	1.5	432	0.15	0.01	24	0.91	0.82	9	<0.2	0.00
NO_3^- (mg/L)	50	616	<2	1.201	24	0.40	0.59	9	3.10	0.11
PO_4^{3-} (mg/L)	No limit	640	<2	0.06	24	0.00	0.00	9	<0.2	0.00
SO_4^{2-} (mg/L)	250	498	10.6	1.32	24	11.2	1.34	9	16.0	0.00
Fe (μg/L)	No limit	656	219	301.9	24	160	169	4	160	169
Mn (μg/L)	No limit	656	267	562.4	24	51.2	87.87	4	51.2	87.9
As (μg/L)	10	103	2.49	2.11	24	0.75	0.72	9	1.37	0.21
Cd (μg/L)	5	130	13.2	12.26	N.M			9	0.10	0.00
Hg (μg/L)	1	26	0.006	0.015	N.M			9	<0.02	0.00
Pb (μg/L)	10	130	0.18	0.34	24	0.11	0.21	9	<1	0.00

3. Results

3.1. Hydroclimatic study

Fig. 5 presents the calculated SPEI-12 index for the study area (1971–2023), alongside total and cumulative rainfall, simulated (1971–2009) and observed inflows (2009–2023) to the Melonares reservoir, groundwater level evolution (1982–2024), and reservoir the storage percentage (total reservoir capacity of 185.6 million m^3 or Mm^3) since its construction in 2009. It also highlights major drought periods in the Seville metropolitan area (1972–1976, 1980–1983, 1991–1995) classified as socio-economic droughts, and hydrological droughts (1985–1987, 1998–1999, 2004–2006, 2010–2012), in which the cumulative annual precipitation did not generate sufficient resources to supply the population these years (CEDEX, 2019, CEDEX, 2017; EMASESA, 2021), though stored resources prevented adverse socio-economic impacts.

Fig. 5 plots the SPEI-12 instead of the SPI-12 because the first index reproduces the historical drought periods more closely. Both drought indices show fluctuations between wet and dry meteorological periods, and the drought periods are detected in both cases, but the SPI-12 values are more marked (Fig. 6). This can be seen in the dry episodes of 1980–1983, 1998–1999, and 2004–2006 or in the wet periods of 1987–1989 and 1994–1996, where the SPI-12 values are extremely low and high, respectively (Fig. 6). The SPEI-12 index show wetter episodes in 1986–1990, 1995–1997, and 2009–2010, and dry periods in 1980–1983, 1990–1995, and 2020–2023, partly coinciding with drought periods reflected in the literature. However, the historical drought period from 1972 to 1976 that SPEI-12 does not distinguish. The SPEI-12 index detected 6 months of extreme drought in the study area (spread over 1995, 1999, 2019, and 2023), 28 months as severe drought, and 83 months out of 624 months as moderate drought. Thus, almost 19 % of the months of the study period are in a state of meteorological drought (Fig. 5).

The annual rainfall distribution and the annual and monthly accumulated precipitation are similar to the SPEI-12 evolution (Fig. 5), with increases in wet periods and decreases in dry ones. Groundwater levels have generally declined since the late 20th century (Fig. 5). During the first years of the 21st century, the downward trend in piezometric levels continues but is less pronounced. Groundwater level variations are related to the historical wet and drought periods (1980–83, 1985–87 and 1991–95) shown by the SPEI index. During the wet periods, slight rises in groundwater levels can be observed but do not recover to the level at the beginning of the period.

The total inflows to the Melonares reservoir (8–364 Mm^3/y, average 116 Mm^3/y) show a similar temporal evolution to rainfall and SPEI-12. However, although both variables depend mainly on precipitation, there are years in which the relationship between the SPEI-12 drought index and total inflows is not clear. Periods of meteorological drought (1985–1987, 2012–2013, and 2016–2017) saw unexpectedly high inflows, according to the SPEI-12. Reservoir storage remained stable (>80 %) from 2009 to 2019, except in the meteorological drought episodes of 2010–2012 and 2016–2017. From 2019 to 2023, the total volume of dammed water decreased to 80 Mm^3, which is about 43 % of its capacity. The evolution of the dammed water volume is similar to accumulated monthly precipitation, although delayed in time. The decrease in the storage volume of the last years coincides with the current meteorological drought period (2020−2023) calculated by the SPEI-12. However, hydrological and socio-economic droughts do not always align with meteorological droughts, as prolonged low SPEI-12 values

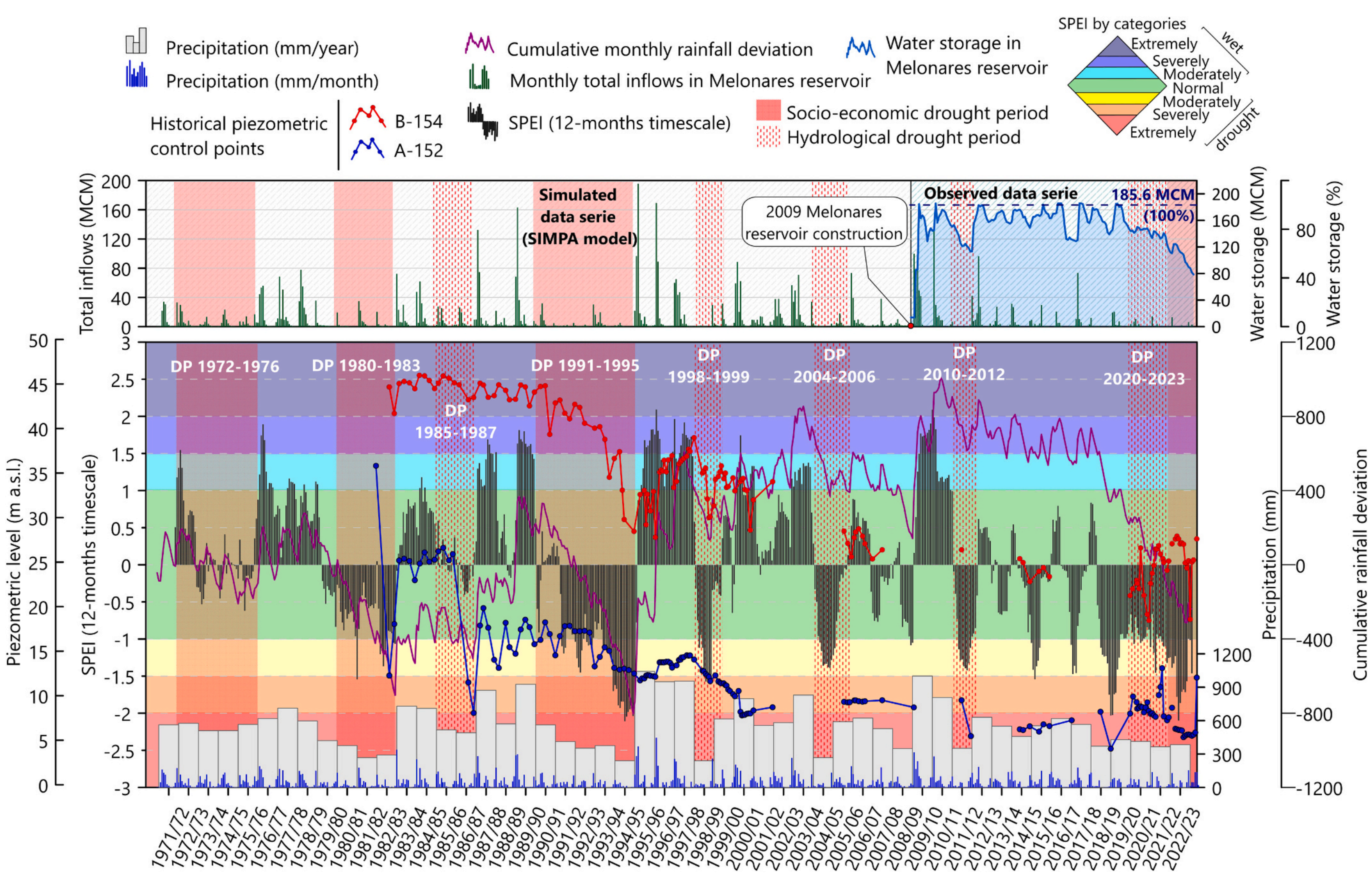

Fig. 5. Time evolution of the SPEI drought index, total and cumulative monthly and annual precipitation, total inflow and Melonares reservoir storage (Mm^3 and %) from 1971/72 to the 2022/23 hydrological years. It also includes the historical evolution of the groundwater level from 1982 to 2024 at the available piezometric monitoring points (See location in Fig. 2).

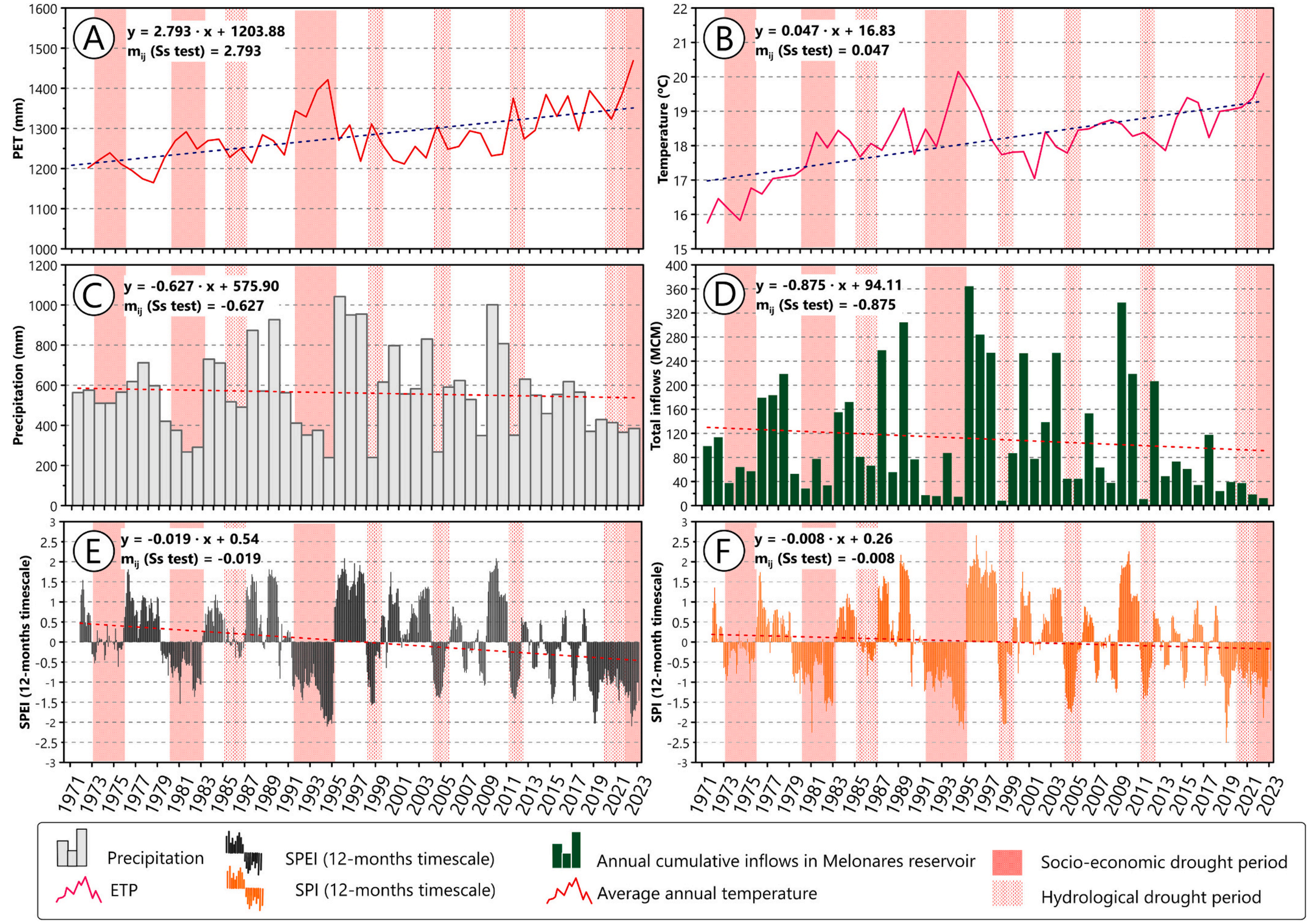

Fig. 6. Trend analysis results from the Sen's slope (Ss) test applied to (A) annual PET, (B) average annual temperature, (C) annual precipitation, (D) total annual inflows to Melonares reservoir, (E) SPEI and (F) SPI drought index (12 months) at the study area from 1971 to 2023.

(<−1) are needed to impact inflows and storage significantly. Thus, there is no effect on the total inflow and the stored water volume in the Melonares reservoir, or if any, it recovers quickly (Fig. 5).

Table 3 summarises the results of the trend tests performed. The MK test applied to the SPEI-12 ($Z = -7.16$) and the SPI-12 ($Z = -3.31$) shows a statistically significant decreasing trend of values, indicating a rise in the number of drought months and, therefore, a higher recurrence of dry periods. However, total inflows ($Z = -1.60$) and CP ($Z = -0.45$) show no statistically significant trends (p-value $> \alpha = 0.05$ and Z similar to 0). CPET ($Z = 4.87$) and the mean annual temperature ($Z = 5.52$) show significant increasing trends.

Table 3
Main statistical results derived from Mann-Kendall (MK) and Sen's slope tests used to analyse the trends of the annual average temperature (AT), cumulative PET (APET), precipitation (AP), and total inflows to the Melonares reservoir (Melonares INF), the SPEI-12 and the SPI-12 drought index at the study area from 1971 to 2023.

Time series	n	Z	Kendall's Tau (τ)	p-value	S	Sen's slope m_{ij} (Ss)
AT	51	5.52	$8.25 \cdot 10^{-2}$	<0.05	$1.62 \cdot 10^{4}$	0.047
CPET	51	4.87	$7.04 \cdot 10^{-2}$	<0.05	$1.38 \cdot 10^{4}$	2.793
SPI-12	612	−3.31	$-8.91 \cdot 10^{-2}$	<0.05	$-1.69 \cdot 10^{4}$	−0.008
SPEI-12	612	−7.16	$-1.93 \cdot 10^{-1}$	<0.05	$-3.65 \cdot 10^{4}$	−0.019
CP	51	−0.45	$-4.47 \cdot 10^{-2}$	0.65	$-5.70 \cdot 10^{2}$	−0.627
Melonares INF	51	−1.60	$-1.06 \cdot 10^{-2}$	0.97	$-2.07 \cdot 10^{2}$	−0.875

In addition, Fig. 6 shows the Ss test applied between time and the climatic variables such as (A) annual PET, (B) average annual temperature, (C) annual precipitation, (D) total annual inflows to Melonares reservoir, (E) SPEI-12 and (F) SPI-12 drought index at the study area from 1971 to 2023. The Ss test showed significant trends in the same parameters as MK did (Fig. 6. A, B, E y F). The slope (m_{ij}) of the Ss test shows an annual increase of 2.79 mm for PET (A), 0.047 °C of the annual temperature (B), and an annual decrease of −0.019 and − 0.008 values for SPEI-12 (E) and SPI-12 (F), respectively. Besides, the dry periods identified in the drought indices not only coincide with years of low rainfall but also those with significantly higher values of potential evapotranspiration and mean temperature (Fig. 6. A and B).

3.2. Defining the geometry and hydraulic properties of the aquifer in the pilot site

The lithological columns of the drilled wells have permitted us to draw up a schematic geological cross-section of the geology of the area (Fig. 7). All piezometers were drilled through the Miocene aquifer until reaching the low permeability Paleozoic substratum. The lithological column data used correspond to the P-1A, P-1B, P-2, and P-4 control points and the SR well (Fig. 4. B). The information in the geological cross-section indicates that the Paleozoic basement is deeper between P-1A and P-1B, probably due to erosion before the deposition of the Niebla Fm or to tectonic displacement. Furthermore, the thickening of the Niebla Fm can be observed in the area where the Paleozoic is depressed (or deeply buried). In addition, calcarenite sections were observed in all

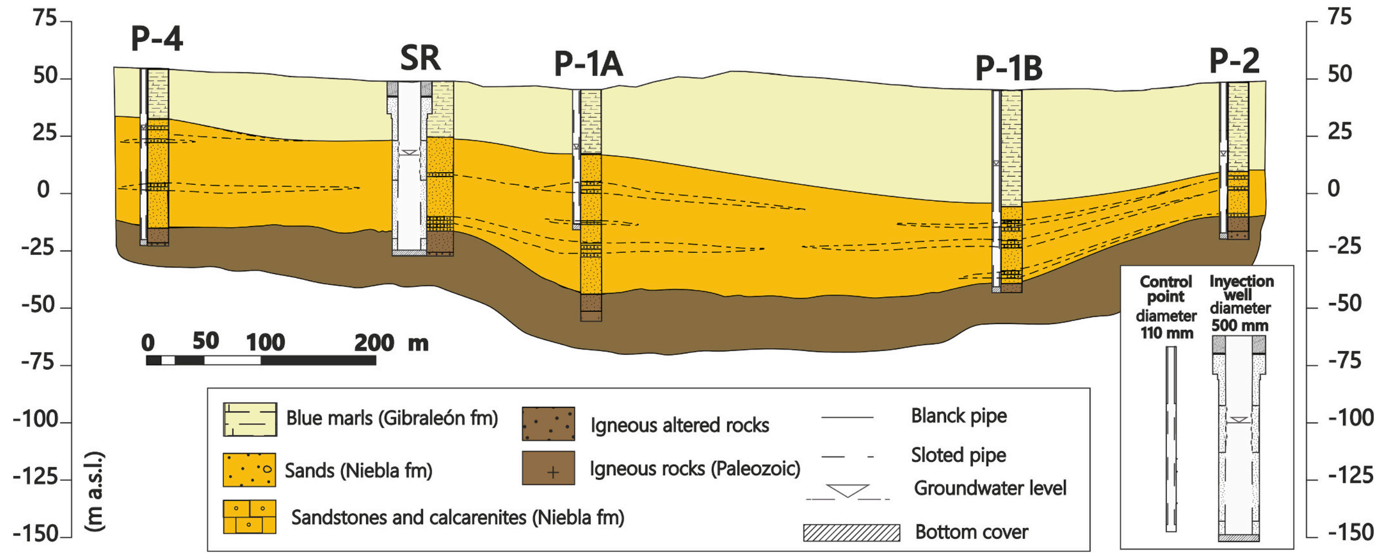

Fig. 7. Geological schematic cross-section made from the columns of the P-1A, P-1B, P-2, and P-4 MAR control points and the injection well (SR). See the cross-section direction in Fig. 3. B.

the drilled wells, which could be related to the variations in the original sedimentation of the basin. Although it is not possible to say for certain, there may be some lateral continuity between some of these calcarenite sections, as suggested in the sketch in Fig. 7.

The specific yield capacity observed during the pumping test was 0.38 L/s·m. The test results showed the stabilisation of the dynamic groundwater level at a rate of around 9–10 L/s, suggesting that the yield capacity (and recharge) flow rate could be of that order. The piezometric control carried out at the control points during the pumping test also permitted the calculation of some hydraulic parameters. Transmissivity data vary between 40 and 80 m^2/day. However, in the SR, where the yield test was carried out and the closest control point (P-1A), the results are 40–45 m^2/day. The storativity values are between $1.1 \cdot 10^{-4}$ and $4.6 \cdot 10^{-4}$, typical of a confined aquifer. The recovery after the pumping test was monitored for 29 h, during which a large part of the recorded descent recovered (26.13 m out of 33.88 m). The transmissivity value obtained from the recovery test is 60 m^2/day, of the same order of magnitude as those estimated during pumping.

3.3. MAR pilot test

In total, 4183 m^3 of water was introduced into the aquifer, with an average recharge rate of 34.9 m^3/h (9.7 L/s) (Fig. 8). The recharge flow rate at the beginning of the period was 50–60 m^3/h, but it decreased below 40 m^3/h during the first day of the test. On the following days, the recharge flow rate kept progressively descending until it stabilised near 30 m^3/h on the last day of the test.

Immediately after the water injection ceased, the groundwater level in the SR well rapidly decreased (Fig. 8), and 7 min after the end of the MAR pilot test, the piezometric level was already at a depth of 14 m (36 m a.s.l.). After 28 h, the groundwater level measured was 33.74 m deep (16.26 m a.s.l.) similar to the 33.8 m depth measured at the start of the test. The recharge test led to a slight rise in piezometric levels at control points P-1A, P-3, and P-4 (0.42–2.12 m), with recovery occurring within 12 and 120 h (Fig. 8). In contrast, the other two monitoring points showed no significant response. These variations align with the distance and position of each point relative to the natural groundwater flow.

3.4. Hydrochemical control

Table 4 shows the results of the chemical control during the MAR project. The temporal evolution of these parameters during the execution of the MAR pilot test is shown in the supplementary material. As no pesticide-active substances included in WFD (CHG, 2022) have been detected in any of the samples analysed, they have not been included in Table 4.

Table 4 shows a total of 91 groundwater samples taken from control points situated in the confined zone at different depths and distances from the recharge area and SR and analysed. For the average concentrations determined, fluoride is the only parameter that consistently exceeds the WFD limit across the aquifer. Other parameters, including EC, chloride, nitrate, sulfate, arsenic, and lead, remain below the WFD limits.

Regarding the parameters included in the quality standards for urban supply (RD 1514/2009), the aquifer water extracted in the pumping test has between 2.4 and 3.1 mg/L of NO_3^-, much lower than the 50 mg/L limit. All indicators, except for the F^-, are below the maximum permissible limit for the substances for which the CHG has defined threshold values. During the MAR pilot test, the parameters analysed in the surface water used for recharge (RW) were consistently below the WFD maximum admissible limit (CHG, 2022). The only exception was total lead (Pb), which reached a concentration of 26 μg/L in the first water sample right after installing the recharge pipe and sampling tap. In the following days, the concentration of Pb fell below the detection limit in all the samples analysed. Subsequently, the high concentration seemed to be an isolated episode that was not representative of the quality of the water used for recharge. Thanks to the mixing with the water used in the recharge, the mineralisation of groundwater decreased from 730 μS/cm the day before the start of the test to 360 μS/cm one day after the end of the test.

After the MAR operation ended, the chemical quality of the groundwater in the SR well continued to be monitored monthly (Table 4). The most relevant changes in groundwater quality include the increase in EC up to 752 μS/cm in December, close to the initial conditions. In every case, the concentrations of the priority substances for which the WFD has established threshold values and those included in the groundwater quality standards are below the maximum permissible limit.

3.5. Hydrochemical modelling

The injection of Recharged Water (RW) used during the pilot test, which is an aerobic freshwater that contained low concentrations of As, Fe, Mn, and nutrients (e.g., NO_3^{2-}), into the anaerobic groundwater

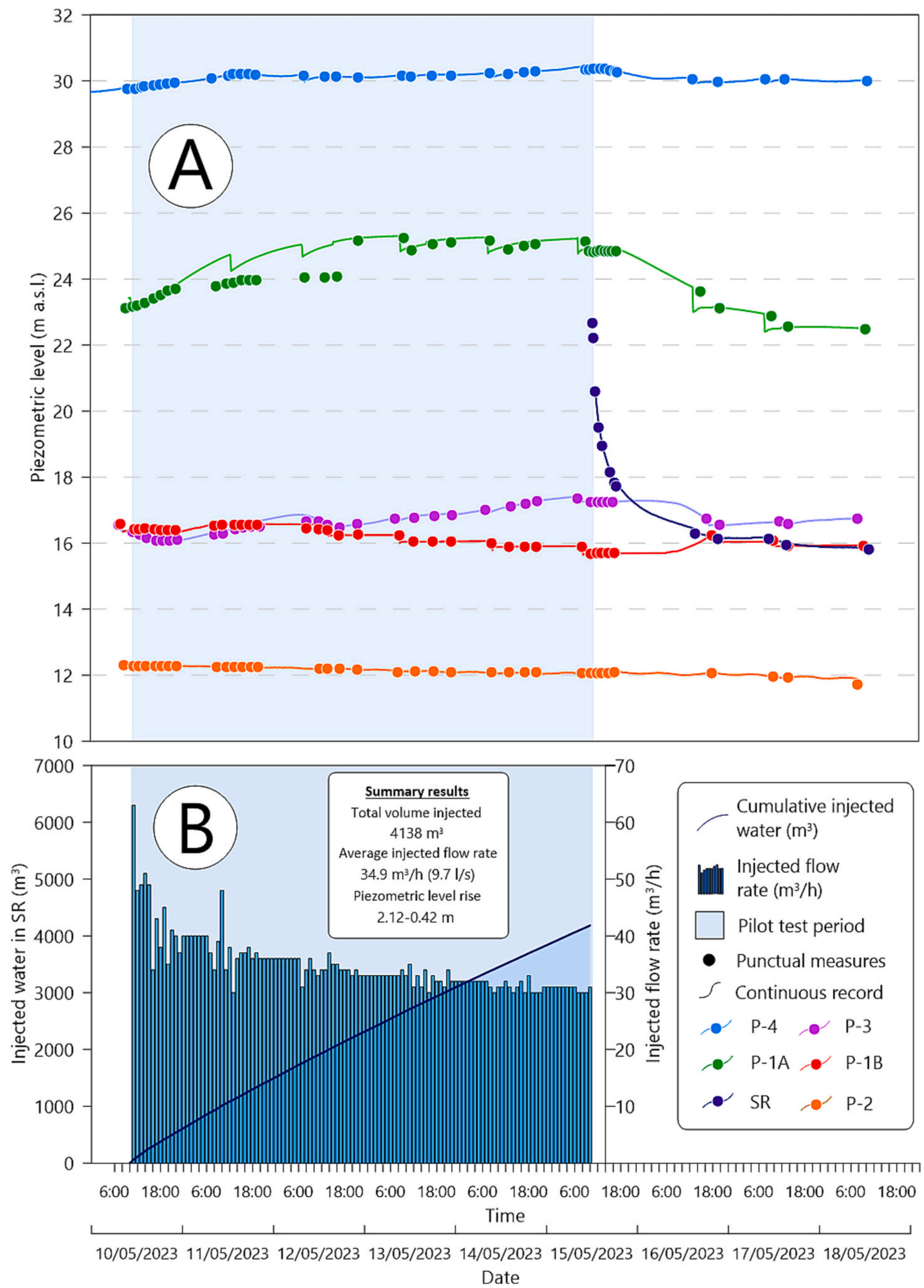

Fig. 8. (A) Evolution of the groundwater level in the control points and the SR well and (B) of the injected flow rate during de MAR pilot test.

resulted in mixing water and, likely, the triggering of hydrogeochemical reactions. The results of the model have been compared to the post-pilot test abstracted water, as shown in Table 5, and its differences have been attributed to chemical reactions. Based on eqs. (1) and (2), the Cl^- concentration in the resultant water was between the RW and the post-pilot test groundwater, agreeing with a mixing ratio of 10.1 % RW with 89.9 %, respectively.

In Table 5, the following parameters show lower concentrations than expected according to both mixing models: alkalinity, Ca^{2+}, Mg^{2+}, NO_3^{2-}, Na^+, SO_4^{2-}, and O_2. On the contrary, some parameters, pH, As, Fe, and Mn, show higher values than expected. The saturation indices (SI) of siderite, calcite, and dolomite are practically in equilibrium with the medium in the samples taken prior to the MAR pilot test (Table 5). However, in the mixing model, the saturation index value in siderite indicates sub-saturation (SI < 0), while the saturation index of calcite and dolomite remains stable. The sample taken right at the end of the pilot test shows a super-saturation with respect to the siderite. Additionally, the high SI values for hematite and goethite across all samples (both observed and simulated) confirm that groundwater is over-saturated with respect to these minerals, rendering their dissolution unlikely.

4. Discussion

4.1. Recurrence of drought period and availability of water resources for MAR implementation

In the case study, SPI-12 and SPEI-12 differ slightly (Fig. 6) because the latter index includes evapotranspiration losses in its calculation and is temperature-dependent (Hargreaves and Samani, 1985). Global air temperature has risen over the last 150 years (WMO, 2023) and is projected to increase further (Mathbout et al., 2023), exacerbating

Table 4
Hydrochemical summary of groundwater samples from the confined zone of the Niebla-Posadas aquifer (sampled from 2020 to 2023), in the recharge well (SR) and from recharge water (RW) (sampled from May 2023 to January 2024) analysed during the study. The limit values set by Confederación Hidrografica del Guadalquivir (CHG) to comply with the European Water Framework Directive -WFD- are shown (CHG, 2022). -EC- electrical conductivity. -ND- No determined.

Water sampled	WFD Limit value	Control points in the confined aquifer		Pre-pilot test SR		RW		Post-pilot test SR	
		$n = 91$		$n = 4$		$n = 9$		$n = 12$	
Parameter (unit)		Mean	SD (σ)	Mean	SD (σ)	Mean	SD (σ)	Mean	SD (σ)
EC (μS/cm)	2500	729	263	720	10	268	1.67	554	232
pH	No limit	7.71	0.74	7.4	0.51	7.7	0.23	7.8	0.27
NH_4^+ (mg/L)	No limit	0.63	0.62	<0.15	0	<0.15	0	0.22	0.06
Cl^- (mg/L)	250	63.2	120	30	1	15.7	0.5	34.3	13.5
F^- (mg/L)	1.5	4.04	2.41	0.8	0	<0.2	0	0.53	0.24
NO_3^- (mg/L)	50	3.94	6.33	2.75	0.35	3.1	0.11	<2	0
PO_4^{3-} (mg/L)	No limit	<0.2	6.1	<0.2	0	<0.2	0	<0.2	0
SO_4^{2-} (mg/L)	250	62.9	47.1	81	1	16	0	88.5	63.3
As (μg/L)	10	1.61	1.5	3.5	0.5	1.37	0.22	4.34	2.77
Cd (μg/L)	5	ND	ND	0.1	0	0.1	0	<0.1	0
Hg (μg/L)	1	ND	ND	<0.02	0	<0.02	0	<0.02	0
Pb (μg/L)	10	1.46	2.36	7	0	<1	0	1.6	0.85

Table 5
Average chemical composition of the samples taken from Melonares raft, Niebla-Posadas aquifer in the confined zone, and those from the pilot test carried out in the Guillena-Cantillana GWB. The table also includes the results from the mixing model between the recharge water (RW) and the pre-pilot test groundwater, and between the groundwater in the confined zone of the aquifer and the water from the Melonares raft, as well as the saturation index (SI) of the main mineral species involved in the geochemistry of the aquifer.

Water sampled	Pre pilot test	RW	Conservative mixing (model)	Post pilot test	Change
Parameter (unit)			Mixing model (90:10)		
pH	7.4	7.7	7.4	7.8	0.4
Alkalinity (mmol/L)	6.5	2.6	6.6	3.0	−3.6
As (μmol/L)	0.01	0.02	0.01	0.02	0.01
Ca^{2+} (mmol/L)	2.1	0.8	1.9	1.1	0.8
Cl^-(mmol/L)	0.9	0.4	0.8	0.8	0.0
Fe (μmol/L)	14.7	0.0	13.2	44.8	31.6
K^+ (mmol/L)	0.1	0.1	0.1	0.1	0.0
Mg^{2+} (mmol/L)	1.0	0.4	0.9	0.5	−0.4
Mn (μmol/L)	1.0	0.0	0.9	1.8	0.9
NO_3^- (mmol/L)	0.2	0.3	0.2	0.1	−0.1
Na^+ (mmol/L)	1.5	0.7	1.4	1.0	−0.4
Pb (μmol/L)	0.007	0.0002	0.006	0.003	−0.003
SO_4^{2-} (mmol/L)	0.8	0.2	0.8	0.3	−0.5
O_2 (mmol/L)	0.2	0.5	0.7	0.2	−0.5
$SI_{Calcite}$	0.3	−0.2	0.3	0.2	
$SI_{Siderite}$	0.4	−2.9	−9.1	1.1	
$SI_{Hematite}$	9.6	12.1	19.3	13.2	
$SI_{Goethite}$	3.8	5.1	8.6	5.6	
$SI_{Dolomite}$	0.4	−0.6	−0.3	−0.4	
PCO_2	−1.8	−2.6	−1.9	−2.6	

drought conditions, particularly in semi-arid regions (Hyung-Il et al., 2023). In the study area, temperature and PET have increased significantly, with statistical analyses showing upward trends of 2.79 mm/year and 0.047 °C/year in temperature (Table 4 and Fig. 6). Similar trends have been observed in southern Spain (Tomás-Burguera et al., 2021; Vicente-Serrano et al., 2014), and future models predict even greater increases (Bellido-Jiménez et al., 2023). Given PET's impact on water resources and its exclusion from SPI-12 calculations, SPEI-12 better reflects historical drought periods (Fig. 5).

Despite their differences, SPEI-12 and SPI-12 show an increase in the recurrence of drought events, with a stronger negative trend in the MK and Ss tests (Fig. 6 and Table 3). The descending rate is higher in SPEI-12 due to the ascending trend of PET. However, annual precipitation does not show a statistically significant trend, reflecting that the long-term average precipitation remains stable throughout the years (Fig. 6). Therefore, negative trends of the drought indices, mainly the SPI-12, are explained if the temporal distribution of rainfall events and their intensity varies, which could affect the distribution of meteorological drought periods. Based on general circulation models worldwide, some authors conclude that while annual precipitation amounts are likely to remain unchanged, there is likely to be greater variability in rainfall patterns, with a rising incidence of high-intensity storms and longer periods of drought (Ionita et al., 2022; Norwine and John, 2007). In the study case, during some years within the normal range (1985–1987 and 2012–2013) and even periods of meteorological drought (2016–2017), the inflows to the reservoir are higher than expected for the SPEI-12 values (Fig. 5). These contributions are primarily attributed to months of abundant rainfall interspersed with months of low rainfall. This uneven temporal distribution of rainfall results in low SPEI-12 values reflecting cumulative water deficit over time. However, the occurrence of short, intense rainfall events during these months can generate runoff, leading to inflows in the reservoir.

Analysis of historical drought periods and SPEI-12 values from the hydroclimatic study indicates that, on average, droughts occur every 4.5 years and last approximately 2.5 years (Fig. 5) in the study area. This information is crucial for designing MAR operations, as it helps determine the duration of recharge periods and the expected timeframe for groundwater abstraction during droughts. By understanding these patterns, MAR strategies can be optimised to ensure a sustainable balance between recharge and extraction, enhancing resilience against future dry periods.

Although drought periods could affect the reservoir's inflow, the uneven distribution of rainfall would explain why statistical analyses indicate no significant long-term decline (Table 3 and Fig. 6). Thus, if rainfall trends continue, the inflows to the reservoir would remain steady on a multiannual basis, and there would be surface water available in the future for MAR, ensuring groundwater storage in new periods of drought. The occurrence of drought affects surface resources, but it also generally leads to increased stress on groundwater resources (Babre et al., 2022). In this case, the increasing trend in temperature and PET (Fig. 6) and the enhanced variability in the temporal distribution of rainfall events (Fig. 5) could negatively affect the natural aquifer recharge (Berghuijs et al., 2024). These temporal changes in climatic variables would lead to a decrease in direct infiltration inflows from precipitation, which would mean that the large groundwater level declines (up to 30 m) observed would be more difficult to recover even if pumping ceased (Fig. 2).

As the increasing trends in temperature and PET in the metropolitan area of Seville affect the surface resources used for the city supply, it is necessary to take management measures, including other resources, such as groundwater storage by MAR. Since the inflows to the Melonares reservoir do not show any pluriannual reduction trend, surface water will remain available for MAR. Furthermore, if the episodes of drought decrease the recharge of the Niebla-Posadas aquifer, the replenishment of its water table will be hindered. Therefore, a desaturated aquifer volume will be available to implement MAR as a solution to improve Seville's supply system in view of the difficulties in management caused by climatic trend variations. Furthermore, increasing trends in PET directly impact the effectiveness of MAR systems by influencing aquifer recharge dynamics and increasing evaporation losses from open recharge infrastructures, such as infiltration ponds. These factors highlight the importance of selecting the MAR technique, considering site-specific climatic conditions and mitigation strategies to ensure the long-term sustainability of MAR.

4.2. MAR pilot test

Some variations in depth of the Paleozoic basement, similar to those observed between points 1-A and 1-B, have been reported by García-Castellanos et al. (2002). Such variations result from the activity of *syn*-sedimentary faults with small dips that generate preferential depositional zones that are particularly interesting for implementing MAR as they tend to generate thick deposits. Concretely, the pilot test sector shows good potential for MAR because the aquifer formation shows sandy *facies* and great thicknesses (Fig. 7).

The slight variations of the piezometric level (or their absence) recorded during the pilot test (Fig. 8), together with those observed during the pumping test, suggest that the area of influence of the recharge well (SR) is limited and unevenly distributed. This is consistent with the relatively low recharge volume of the test (4183 m^3) or preferential flow paths, which may have contributed to the weak hydraulic response. Despite this, a head change was detected at the P-3, 710 m away from the injection well, it was not noticed at the P-1B and P-2 control points, 730 and 560 m away from the SR well, respectively. This difference would be caused by 1) the fact that the direction of groundwater flow is toward the SE (Fig. 2), where P-3 is located; 2) the anisotropy of the medium, with calcarenitic levels of less permeability that can partially hinder the aquifer connection; and 3) the possible existence of pumping in the vicinity of the control points, as suggested by the declines recorded after the test in P-1B, P-2, P-3, and P-4 (Fig. 8). The quick groundwater level recovery observed in the SR well, together with the stabilisation of the recharge flow rate around 30 m^3/h (8.3 L/s) and the response at the nearest control points, would suggest that the recharge operation could be maintained for a longer time with that rate, slightly lower than the operating flow rate from the pumping tests (9–10 L/s).

The results obtained from the pilot test are moderate (720–840 m^3/day) compared with other MAR systems using wells, where recharge rates are generally higher, above 1000 m^3/day per well (Bouwer, 2009; Lluria et al., 2018; Mäkinen et al., 2018; Pyne, 2015). Literature on MAR pilot testing is generally extended (Page et al., 2011), but the best part of pilot test literature has focused on free sedimentary aquifers, with results ranging from 43 m^3/day per well (Alam et al., 2020) to 1000 m^3/day via an induced bank lagoon (Hiscock et al., 2024). Despite the disparity of recharge rates and the differences in the characteristics of the other pilot cases (e.g., hydrogeological setting, methods, duration), the test results are close to the highest reported values. Besides, it should be recalled that the receptor is a semi-confined aquifer (Storativity between 10^{-2} and 10^{-4}); therefore, the results can be considered satisfactory even if they are slightly lower than other definitive MAR systems. Implementing MAR techniques in semi-confined and confined aquifers is more challenging than in free aquifers as they have lower hydraulic parameters. Even recharge methods are limited in the confined sector to injection by well, which is less effective than others, like infiltration banks, and more costly to implement and maintain (Pavelic et al., 2007; Sprenger et al., 2017). Despite these issues, there are successful examples of MAR in semi-confined detrital aquifers worldwide (Dillon et al., 2019; Scanlon et al., 2016). In Spain, the most relevant cases are those of the lower Llobregat basin (Queralt, 2020), located near Barcelona (NE, Spain) and the Aquifer Storage and Recovery System (ASDR) at the CLC mine (Baquero et al., 2016). However, their function is environmental, to prevent the aquifer from marine intrusion and to protect its quality and quantity, respectively, and not mainly for human supply.

The chemical composition of groundwater at the SR well exhibited some variations before and after the MAR pilot test. Still, they have not adversely affected groundwater quality. According to Table 4, the water introduced into the aquifer did not cause any harmful effects on groundwater. In any case, there has been some dilution during the first months after the MAR pilot test, as reflected in the variation of the EC values, from 710 μS/cm before the trial to 346 μS/cm at the end (Table 4). Similar improvements in water quality in the aquifer due to dilution are reported in other MAR studies (García-Menéndez et al., 2021; Hiscock et al., 2024) on a short and large scale. The recharge water (RW) from the Melonares reservoir is of high chemical quality (Table 4), suggesting that continued MAR operations using this source could enhance local groundwater conditions (Mäkinen et al., 2018), at least in the area surrounding MAR infrastructure.

However, hydrochemical changes must be carefully monitored, particularly in relation to fluoride (F^-) concentrations. The aquifer exhibits naturally elevated F^- levels (Table 5), likely due to water-rock interactions rather than anthropogenic contamination(Podgorski and Berg, 2022; Shaji et al., 2024). F^- enrichment in groundwater commonly results from the dissolution, particularly in semi-confined detrital aquifers with extended groundwater residence times. During the MAR pilot test, F^- concentrations remained stable, indicating that the introduction of recharge water did not trigger significant mobilisation. Nevertheless, long-term MAR operations should incorporate regular monitoring of F^- levels and saturation indices to ensure that geochemical equilibrium is maintained and potential desorption processes are minimised.

Clogging is a major issue in MAR, especially in well injection (Page et al., 2014; Pavelic et al., 2007). Despite the good quality of Melonares reservoir water, the observed reduction in injection flow rate (Fig. 8) suggests potential clogging, warranting further investigation. While turbidity (4.64 N.T.U.) and total suspended solids (TSS, 4.12 mg/L) indicate a low risk of physical clogging (Martin, 2013), this is mitigated by sedimentation in the Viar channel and settling basin, lowering turbidity to below 1 N.T.U. The connection pipeline at the upper part of the Melonares raft reduces suspended particles, decreasing clogging potential. Chemical clogging is also a concern due to significant levels of Fe and Mn, which can precipitate in the aquifer when oxidised by dissolved oxygen (5.66 mg/L). The results of the hydrochemical assessment show an increase in Fe and Mn content during the pilot test, which is not explained by the conservative mixing model (Table 5). This variation in Fe content may be due to the dissolution of siderite present in the aquifer, as indicated by the negative value of its saturation index in the sample taken after the MAR pilot test. On the other hand, the other Fe mineral saturation indices indicate a supersaturation and, therefore, a possible precipitation of these minerals if the pH and ORP conditions are suitable. These dissolution and precipitation processes that control the Fe content could potentially lead to clogging and need to be taken into account in an eventual MAR system. High concentrations of Fe and Mn must be controlled and treated during the extraction of water for use in the water supply. In addition to Fe and Mn, clogging can be caused by the mobilisation of other metals. Although the concentrations in the recharge water and the confined zone of the aquifer (Tables 2 and 5) of metals such as As and Pb are generally low, the mobilisation of metals during MAR implementation is widely documented around the world

(Arthur et al., 2005; Pavelic et al., 2005). This mobilisation can occur in anoxic environments due to the influx of oxidised water, as is the case. Although no significant increase in the concentration of metals has been observed during the pilot test, the presence of these metals in the Niebla-Posadas aquifer (Scheiber et al., 2016) makes it necessary to monitor the concentration of these elements and the ORP and pH of the aquifer during the following MAR tests to design of water pre-treatment measures if such a need is confirmed. Additionally, moderate total organic carbon (TOC, 5 mg/L) could theoretically support microbial growth, contributing to biological clogging, but the risk is low given the little content measured. In the following pilot tests, the content of biological contaminants and micro-organisms must be carefully monitored. Pre-treatment, such as filtration or, principally, oxidation control, can reduce these risks.

4.3. Proposal of MAR system and inclusion in the supply network

The increasing variability of wet and dry periods, along with rising potential evapotranspiration, supports the use of aquifers for water storage, especially in semi-arid regions (Dillon et al., 2019). For all these reasons, in the coming years, an increasingly important development of large regional-scale MAR (Bouwer, 2009; Lluria et al., 2018) is, therefore, to be expected globally in the face of increasingly severe drought conditions (Scanlon et al., 2016). Additionally, MAR systems generally offer a more cost-effective solution than building new reservoirs. The economic analysis of MAR systems involves various cost factors (Berbel et al., 2017; Page et al., 2010; Pulido-Velázquez et al., 2008), from the initial construction to the long-term operation, including pretreatment and maintenance of the infrastructure. The cost per cubic meter of

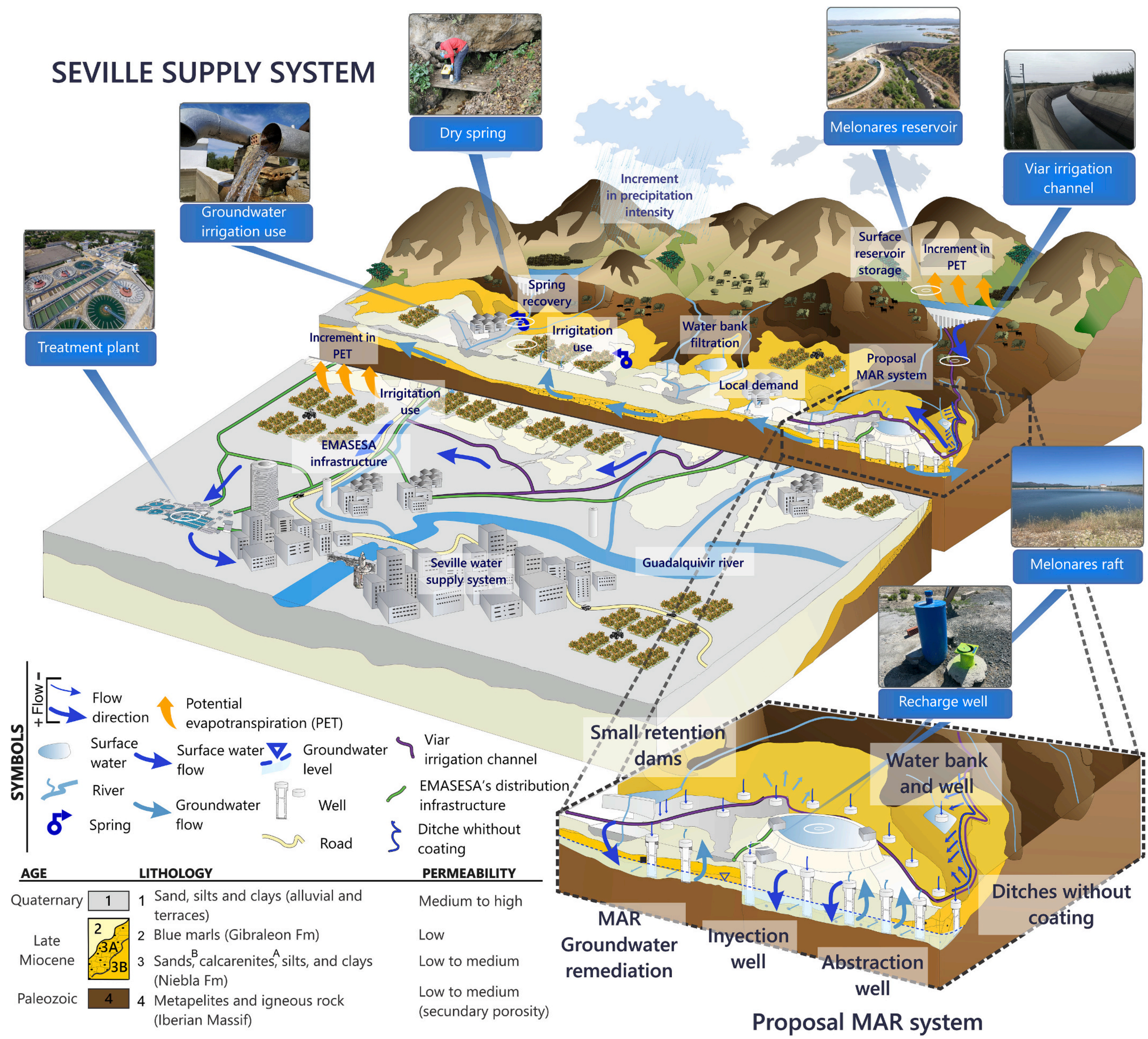

Fig. 9. Proposal of definitive MAR system and its inclusion in Seville's water supply network. Some alternative proposals include ditches without coating or constructing small dams in intermittent stream flow.

recharge for well injection systems ranged from \$0.20–0.30 for large-volume systems to \$0.75–1.05 for small systems (Gonzalez et al., 2024). The cost per cubic meter for dam water ranges from \$0.72 to 2.78 (Gonzalez et al., 2024), which is higher than most MAR systems and similar to some small ones, highlighting MAR's long-term economic advantages. Desalination, another alternative, is a challenge for Seville due to its distance from the coast (70 km) and the environmental and cost problems of pipeline construction, such as the Doñana Natural Park, if the shortest route were chosen (Fig. 1). Past efforts to use water from the Guadalquivir River during drought periods (Fig. 7) have faced significant acceptance issues over quality concerns.

The exploitation of the Niebla-Posadas aquifer and the results of the hydroclimatological analysis (Fig. 5 and Fig. 6) could be used to design and implement MAR in the Guillena-Cantillana GWB. The outcome obtained from the pilot test shows the feasibility of MAR through wells in the confined sector of the aquifer, at least in its northernmost part (closer to the natural recharge area, in the free sector), where the storativity values are higher. Thus, a permanent MAR system (Fig. 9) could be proposed through wells in areas of the aquifer with similar hydrogeological characteristics. The objective of the MAR system is to supply approximately 10 % of the total annual demand (100 Mm^3/y) during drought emergency periods, equivalent to 10 Mm^3/y. Since these dry episodes have an average duration of 2.5 years, injecting 25 Mm^3, distributed over less than the 4.5 years between one drought period and the next, would be necessary. Therefore, the annual injection flow of the proposed MAR system should be above 5.5 Mm^3/y.

EMASESA's supply system has a surface water reservoir capacity of 641 Mm^3, of which 185.6 Mm^3 corresponds to the Melonares reservoir (Fig. 9). The average annual inflows during the working period of this dam (2009 to 2023) are 113.7 Mm^3/y, while the simulated period from 1971 to 2009 accounts for 116 Mm^3/y. The annual abstractions from Melonares reservoir to cover water demands are around 32.7 Mm^3/year, including the ecological flow (3.4 Mm^3/y) and human supply (29.3 Mm^3). Since the calculated evaporation losses over the water table in the reservoir area are about 20 Mm^3/y (EMASESA, 2021), water releases downstream the dam, where no consumptive uses of water exist, are over 60 Mm^3/y on average. These data and the steady evolution of its storage throughout most of its working period (Fig. 5) show enough water resources available in the Melonares reservoir to carry out MAR without compromising its main uses. Thus, in wet and average hydrometeorological conditions, MAR would recharge the aquifer with 5.5 Mm^3/y of surface water, storing part of the volume that would otherwise be released downstream. Consequently, this MAR system would increase water reserves for urban water supply in periods of hydrological drought, when the wells would function as abstraction points to avoid socio-economic impacts. Rainfall variability could affect recharge availability, as the reservoir relies on surface runoff. The Melonares reservoir, often near 100 % capacity (Fig. 5), faces management challenges due to more frequent intense rainfall. Implementing MAR at a continuous low flow rate would have minimal impact on total resources while creating storage, improving regulation, and keeping the reservoir below full capacity to capture extreme runoff events.

The pilot test recorded a recharge rate of 30 m^3/h in the SR well, allowing for 0.25 Mm^3/y of recharge if operated continuously. To meet the target of 5.5 Mm^3/y, 20–25 injection wells with similar characteristics would be needed. However, it should be noted that the admission capacity of each well would vary according to the permeability, transmissivity and storativity characteristics of the drilled materials. Besides, the estimates consider a constant and uninterrupted recharge flow rate, which is difficult to achieve for various reasons, including periods of lack of available water resources for recharge or problems related to infrastructure maintenance (Maples et al., 2020). Well placement should consider proximity to existing infrastructure that allows the distribution of water resources (Fig. 9). In this sense, the Viar irrigation channel is interesting, as its route coincides with the contact between the Niebla-Posadas aquifer and the marls, where recharge is favourable (Fig. 9). A network of 15–20 wells, spaced 0.5–1 km, distributed in the NE zone of the study area along the irrigation channel (Fig. 9) could achieve 3–5 Mm^3/y of recharge. The chosen distance of 550–750 m, similar to that between the SR and the control points where no rise in the groundwater level was recorded, between 550 and 750 m, ensures minimal influence of each recharge well of the MAR system on the nearest wells. Alternatively, wells could also be located near the EMASESA infrastructures but always close to the geological contact mentioned above. However, if the minimum drill distance deduced from the tests (0.5–1 km) is maintained, it would not be possible to locate by the Viar channel the 20–25 wells necessary to exceed the 5.5 Mm^3 required to meet the needs in an average drought period. During droughts, at least 10 extraction wells, positioned 0.5–1 km downstream of the injection wells, would be required. In total, 30 wells, each extracting at 10 L/s, would enable the recovery of 25 Mm^3 over 2.5 years. Additionally, to meet the demand of the supply system, other MAR actions are necessary, such as surface recharge using water banks (CEHIUMA-EMASESA, 2021), ditches without coating or constructing small dams in intermittent stream flow (IGME-EMASESA, 2002). However, these MAR features should be located in the free sector of the aquifer (Fig. 9). In any case, before carrying out any of these actions, it would be necessary to conduct detailed feasibility studies and pilot tests for their adequate design and planning.

4.4. Simulation of the proposal MAR system for the period 2009–2023

Fig. 10 shows the simulation of the volume of MAR water stored in the Niebla-Posadas aquifer in the Melonares reservoir and the total volume included in the supply system. In addition, the evolution of the actual volume in the Melonares reservoir, the SPEI index and the monthly rainfall for the entire simulated period are shown for comparison. Induced recharge of water from the Melonares reservoir was only carried out when the criteria were met (90 % of the dam capacity, or at least 80 % if the SPEI value of the previous month was >1. If this is the case, a maximum of 0.46 Mm^3 would be injected that month, which is the estimated maximum capacity that the 20 ASR wells would have at an average flow rate of 30 m^3/h. For recharge, priority is given to water released from the reservoir to the river, but if there are no releases or if they are <0.46 Mm^3, water from the reservoir would be used if its use for supply is not compromised (29 Mm^3/y). The criteria for MAR implementation are met in 71 months or 41 % of the simulation period. Similarly, a maximum of 0.78 Mm^3 would be pumped if the abstraction criteria were met that month, which is the maximum capacity that 30 wells would extract at an average flow rate of 10 L/s. In the simulation, the pumped volume is subtracted from the water retrieved from the reservoir for urban supply that month. Both criteria are met in a total of 13 months, equivalent to 8 % of the simulated period, and 12 of them occur in the last two years.

The volumes resulting from the simulation are moderate but quite encouraging. MAR system total volume stored in the aquifer would be 22.52 Mm^3 at the end of the simulation period. The simulated volume reached its maximum in June 2020 when the cumulative volume was 31 Mm^3, although it was reduced in the latter part of the period due to drought conditions (Fig. 10). The evolution of the water storage in Melonares and its simulation considering the MAR system are alike. During most of the study period, the simulated volume was lower than the actual volume because some of the water in the reservoir was used to recharge the aquifer when there were insufficient releases. However, at the end of the period, both values converge, and even in the last months, the simulated volume is higher than the actual volume. According to these considerations, if the MAR management system had been implemented, the total accumulated volume in the system (surface and groundwater) would be 20 Mm^3 higher than the volume available at the end of 2022/2023.

The simulated MAR system alone would not be sufficient to sustain the entire water supply system, which was never the objective. However,

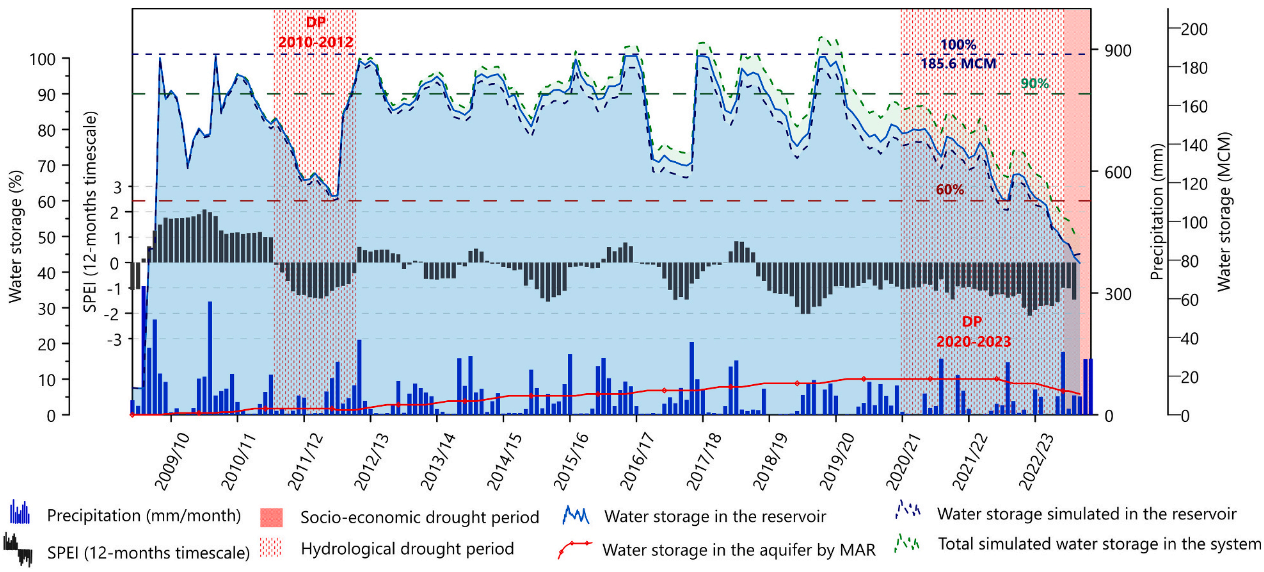

Fig. 10. Results of the simulations of the volume of water stored in the Niebla-Posadas aquifer, in the Melonares reservoir, and the total volume included in the supply system if the Managed Aquifer Recharge (MAR) proposal system had been implemented since the construction of the Melonares reservoir in 2009 until 2023. The evolution of the actual volume in the Melonares reservoir, the SPEI index, and the monthly rainfall for the entire simulated period are shown. -Mm^3- millions of cubic meters.

31 Mm^3 would have been recharged before the start of the drought period in the 2020/21 hydrological year, which is sufficient to supply 10 % of the water demand in Seville according to calculations for the average duration of the drought period (2.5 years). These findings underscore its potential to enhance the resilience of Seville's water system. Furthermore, the simulation suggests that incorporating additional recharge infrastructures (e.g. infiltration ponds and basins) could further increase recharge volumes. Future work should focus on additional pilot tests and advanced hydraulic modelling to estimate recharge rates, storage efficiency, and recoverability at larger scales.

5. Conclusions

This study demonstrates the feasibility of implementing a MAR system in Seville's water supply network to mitigate drought impacts. Based on hydroclimatic and hydrogeological analyses, as well as a pilot test in the Guillena-Cantillana GWB, a sustainable approach for underground storage of released reservoir water has been proposed. The key findings include:

The hydroclimatic trend analysis, partly based on drought indices (SPI-12 and SPEI-12), revealed an increase in the recurrence of drought periods, exacerbated by rising temperatures and ETP, which last on average 2.5 years and occur every 4.5 years, affecting Seville's water supply system.

The study of the aquifer geometry and hydraulic parameters confirms sufficient storage capacity and technical feasibility for MAR implementation.

The MAR pilot test demonstrated the feasibility of sustaining a moderate recharge flow rate of approximately 30 m^3/h (8.3 L/s) over extended periods, as evidenced by the recovery of groundwater levels and the stable flow rate in the SR well—an essential step toward scaling up MAR.

Simulation of the proposed MAR system during the period 2009–2023 suggests it could store up to 20 Mm^3 annually, covering 10 % of Seville's demand during drought periods (nearly 4.5 years).

The pilot test results and hydrochemical modelling indicated the need to mitigate clogging caused by biological, chemical, and physical factors as a key challenge in MAR. While pre-treatment can help mitigate these issues, further pilot tests are necessary to assess the long-term effectiveness of these solutions. Water quality control of groundwater and recharge water is critical to minimise clogging and, thus, to maintain system efficiency over time.

Despite these challenges, MAR presents a viable, long-term strategy to enhance Seville's water resilience by integrating surface and groundwater resources and offering a sustainable solution against drought.

This study contributes to Seville's (S Spain) water resource management by demonstrating the potential of MAR to address increasing demand and hydroclimatic challenges. It provides valuable insights into MAR implementation in confined and semi-confined aquifers, demonstrating its potential to strengthen water security when strategically planned and executed. The hydroclimatic analysis presents a novel framework for assessing MAR feasibility, incorporating long-term data on precipitation, temperature, and drought indices (SPEI-12 and SPI-12) to identify increasing drought recurrence and its implications for water availability. This methodology offers a transferable approach for optimising MAR in regions facing similar challenges, supporting drought resilience planning. While the proposed MAR system for Seville serves as a model for integrating surface and groundwater management, its implementation in other regions requires site-specific adaptations due to variations in groundwater systems and regulatory frameworks.

The results show a potential for the application of MAR in the Seville supply system. However, with a single pilot test and with a moderate recharge volume, it is challenging to design a MAR system. For this reason, future research is based on several pilot tests, including different types of recharge infrastructures (infiltration basins), different recharged volumes, and locations with a diversity of hydraulic parameters (storativity and transmissivity). Other future research should focus on evaluating the long-term impacts of climate change on the MAR system, exploring advanced pre-treatment technologies to optimise water quality, avoiding clogging and mobilisation of heavy metals. Addressing these gaps is crucial for adapting MAR methodologies to other semi-arid regions facing similar challenges, improving their drought resilience and water resource management. Despite its technical and economic challenges, integrating MAR into Seville's water supply system would significantly enhance drought resilience, ensuring additional water reserves and reducing reliance on dammed surface water offering valuable lessons for global water management in an era of increasing environmental pressures.

CRediT authorship contribution statement

J. Ávila-Marín: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **J. M. Gil-Márquez:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **B. Andreo:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors 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.scitotenv.2025.179636.

Data availability

Data will be made available on request. The databases used are reflected in the study methods.

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