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Past innovations for future resilience: Hydrogeological appraisal of La Valduerna's Ag-MAR system

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Abstract

Ancestral water management systems, proven effective over centuries, offer valuable insights for developing innovative strategies to address global environmental change. Many of these systems represent resilient models that have withstood major climatic and social transformations. In Spain, several Agricultural Managed Aquifer Recharge (Ag-MAR) systems dating back to the Middle Ages remain operational. A notable example is found in the La Valduerna region (northwestern Spain), where farmers have traditionally used infiltration channels known as *zayas*, along with winter and flood irrigation, to recharge a shallow detrital aquifer. This practice involves diverting surface water during the wet season to promote infiltration and store groundwater for use during the dry months.

This study presents a comprehensive hydrogeological assessment of the La Valduerna Ag-MAR system, combining fieldwork, rainfall–runoff modelling, recharge estimation, 3D geological modelling, and numerical groundwater flow simulations. Results show that the aquifer has a limited storage capacity (9–12 hm³), while average natural recharge from rainfall infiltration (1–3 hm³/yr) is generally insufficient to satisfy irrigation demand (6–8 hm³/yr). Consequently, managed recharge through the *zayas* plays a critical role in maintaining groundwater availability, particularly during dry periods when river flows decline and water diversions must comply with ecological flow requirements.

Model simulations show that extending the operational period of the *zayas* or adding new channels could increase annual recharge by 100–200%. These findings confirm that Ag-MAR in La Valduerna is an effective Nature-based Solution (NbS), and that traditional water

management practices—some over six centuries old—should be recognized and supported by water planners. The study highlights how conjunctive use of surface and groundwater can be achieved simply and economically, using gravity, local materials, and existing infrastructure such as unlined irrigation channels and wells, common to irrigated regions worldwide.

Keywords: Agricultural Managed Aquifer Recharge (Ag-MAR), groundwater modelling, water scarcity, conjunctive use, nature-based solutions, irrigation channels (zayas).

1. Introduction

Nature inherently generates processes that facilitate water infiltration into aquifers, retention in soils, and filtration mechanisms that purify water before reaching rivers or the sea. When understood and replicated these processes form the basis of Nature-based Solutions (NbS), which aim to restore and enhance natural systems to address environmental challenges such as water scarcity, ecosystem degradation, and climate change (Cohen-Shacham et al., 2016; WWAP, 2018). NbS applied to water management include the protection and restoration of wetlands, riparian zones, and aquifer recharge areas, contributing to improved water retention and groundwater recharge (UN Environment, 2018). These approaches offer sustainable, resilient, and cost-effective strategies to improve water security.

The growing global acceptance of NbS has led managers, planners, and scientists to explore water management techniques that align with NbS principles. Agricultural Managed Aquifer Recharge (Ag-MAR) represents one such technique, involving intentional aquifer recharge through agricultural practices such as winter irrigation, flooding of irrigable areas, and infiltration via unlined irrigation channels (Bachand et al., 2014; Dahlke et al., 2018; Levintal et al., 2023). Ag-MAR can also be adapted to local conditions through the use of treated wastewater and wetland restoration (Neumann et al., 2009; Rushton et al., 2020; Morrisett et al., 2024). Initially developed in California and Nevada (Dokoozlian et al., 1987; Niswonger et al., 2017), its application is expanding across Europe (Facchi et al., 2020; Levintal et al., 2023), driven by its low cost, scalability, and dual benefits for hydrological regulation and environmental quality.

Ag-MAR contributes to sustaining groundwater-dependent ecosystems, increasing landscape resilience to climate extremes (Pavelic et al., 2012; Li et al., 2019; Scanlon et al., 2012), mitigating groundwater salinization and contamination (Casanova et al., 2016; Levintal et al., 2023), and reducing subsidence caused by overexploitation (CDWR, 2025). Its incorporation into international policy frameworks, such as the European Commission's Water Framework

Directive and recent proposals to promote MAR systems, underscores its strategic importance (European Commission, 2023; Sapiano et al., 2025).

In Spain, aquifer recharge through infiltration channels has been practiced since the Middle Ages. A well-documented example is the “acequias de careo” in Sierra Nevada (SE Spain), used to recharge aquifers in weathered hard rock areas (Martos-Rosillo et al., 2019; Civantos et al., 2023). Their efficiency has been demonstrated through hydrological, hydrogeochemical, and isotopic techniques (Barberá et al., 2018; Jódar et al., 2022b; Zakaluk et al., 2024), and recent studies show their positive impact on tree growth, drought resilience, and ecosystem service provision (Camarero et al., 2024; Aparicio-Ibáñez et al., 2025; Redrado, 2023; Vargas et al., 2025; Cabello et al., 2025; Cabello et al. 2026). These systems are socially embedded, operated by irrigation communities, and governed through evolving local institutions (Custodio et al., 2025).

This paper focuses on the *zayas* of La Valduerna, in León (northwestern Spain, Figure 1), a traditional Ag-MAR system that diverts water from the Duerna River into unlined channels known locally as *zayas*.

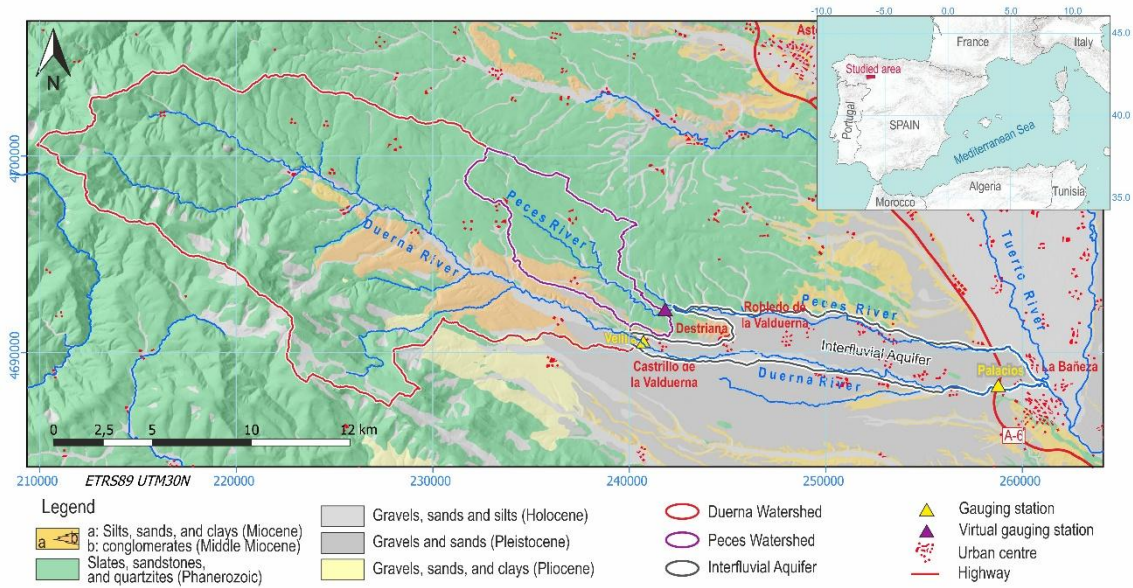
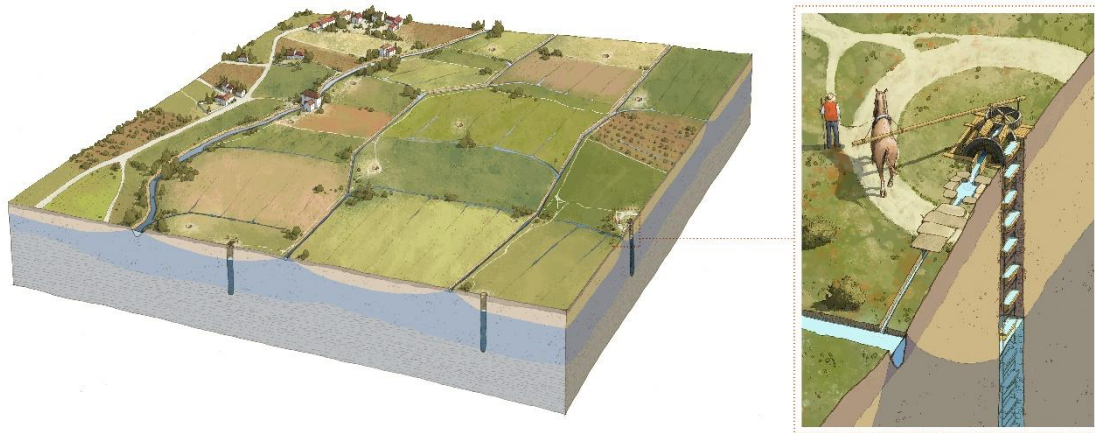


Figure 1. Location, simplified geological map and main points of interest.

During autumn and winter, water circulates through these channels to promote infiltration and recharge the unconfined aquifer. Additional recharge occurs through winter flooding of fallow fields and pastures. In late summer, when river flow decreases, groundwater previously recharged is extracted via wells, historically operated with horse-driven waterwheels (Figure 2), now replaced by suction pumps (Figure 3).



89 Figure 2. Illustration showing a panoramic view of the aquifer and the irrigable area of the
 90 Valduerna in the first half of the 20th century, when irrigation was done only by flooding with
 91 zayas and through wells with waterwheels at the end of summer

92 Historical records confirm the use of *zayas* since at least 1433, and linguistic evidence suggests
 93 even earlier origins of the term “*zaya*” because “*zaiga*” derives from the Arabic “*sāqiyah*”, the
 94 root of the Spanish word “*acequia*”. The system was traditionally managed by irrigators who
 95 maintained year-round flow, enabling aquifer recharge and powering water mills. However, in
 96 2017, the water resource planners, the Duero River Basin Authority (CHD) restricted water
 97 diversion to the irrigation season (from April 1 onward), prompting protests from farmers who
 98 argue that this policy reduces recharge capacity and compromises groundwater availability
 99 during critical periods.



Figure 3. Recreation of the Valduerna aquifer and its irrigable area at present

This study aims to evaluate the hydrological performance of the *zayas* system as a form of Ag-MAR, and to assess its potential integration into modern water management frameworks under changing climatic and regulatory conditions. Specifically, the objectives of this research are to demonstrate and validate this ancestral Ag-MAR system as an example of a Nature-based Solution (NbS), a practical water management tool, and a resilient response to both climate variability and centuries of social transformation. To achieve these goals, geological and hydrogeological data were collected in the field, hydrological modelling was conducted to assess the availability and seasonal distribution of surface water resources, and natural recharge through rainfall infiltration was quantified. Recharge via *zayas* was also evaluated, and a 3D geological model of the aquifer was developed to construct a groundwater flow model. This model was then used to propose improvements to the management of the system. Based on these results, adaptive water management strategies were formulated to reconcile ecological flow requirements in the river with the need to ensure groundwater availability for agriculture. The findings demonstrate that ancestral water management systems—some over six centuries old—can offer simple, cost-effective solutions for integrated surface and groundwater management, relying on gravity, local materials, and existing irrigation infrastructure such as unlined channels and wells, which are common in irrigated regions worldwide.

2. Study site

The irrigated area examined in this study is located in the region of La Valduerna, in the province of León, northwestern Spain. It encompasses approximately 2,000 hectares of irrigable land,

where the main crops—listed in order of importance—are cereals, maize, and potatoes. These lands are irrigated by unlined irrigation canals (zayas) that divert water from the Duerna River. By late summer, the flow of the Duerna River decreases substantially, and insufficient water is available for gravity-fed irrigation. As a result, irrigation is carried out using groundwater wells connected to sprinkler systems. Since 2017, water managers have prohibited the use of zayas diversion before April 1st, which has greatly limited aquifer recharge that previously occurred through seepage from the irrigation canals and by flooding agricultural fields during winter. This area lies above an unconfined alluvial aquifer situated in the lower reaches of two small rivers, the Duerna and the Peces, just before their confluence with the Tuerto River (Figure 1). The management and planning of water resources, both surface water and groundwater, in this region are overseen by CHD.

The Duerna River is 59.9 km long and originates in the Mount Teleno range, flowing toward the town of La Bañeza (León). Its catchment covers 298 km², with elevations ranging from 770 to 2,150 m a.s.l. The Peces River catchment is smaller, with an area of 38.3 km², a length of 13.1 km, and elevations between 889 and 1,206 m a.s.l. The average annual flow of the Duerna River for the last 20 years is 94.9 hm³ (CHD, 2021). The Peces River, which lacks a gauging station, typically exhibits intermittent flow and, in recent years, has remained dry for most of the year by the time it reaches the irrigated lands of La Valduerna.

Annual precipitation in the region varies significantly with altitude, ranging from approximately 900 mm at elevations near 2,000 m a.s.l. to 460 mm at 900 m a.s.l. Most precipitation occurs between December and May. The average annual temperature is around 12°C, with daily extremes ranging from -11°C to 40°C.

The geology of the catchment area includes the following formations, listed in chronological order (Figure 1), (i) Quartzites, slates, and sandstones from the Paleozoic; (ii) Slates, sandstones, and quartzites with interbedded limestones and dolomites from the Miocene; (iii) Gravels, sands, and silts from the Pliocene; (iv) Gravels and sands from the Pleistocene; and (v) Terraces, gravels, sands, and silts from the Holocene.

The Duerna River follows a general NW–SE orientation, aligned with a thrust fault where Ordovician quartzites and slates override Cambrian formations, placing Ordovician rocks on the left bank and Cambrian rocks on the right (Mata-González et al., 1981).

Riparian vegetation includes poplars, oaks, ash trees, alders, and mixed willow groves. The river hosts a rich macroinvertebrate community, with IBMWP (Iberian BioMonitoring Water Procedure) index values ranging from 200 to 250 (Alba-Tercedor & Sánchez-Ortega, 1988; Alba-

Tercedor, 1996; Alba-Tercedor & Pujante, 2000), making it one of the most biologically diverse rivers in the Duero basin and a key habitat for trout. Other notable species include the Eurasian otter (*Lutra lutra*), kingfisher (*Alcedo atthis*), and dipper (*Cinclus cinclus*) (CHD, 2015).

The Duerna–Peces Interfluvial Aquifer is located immediately downstream of the Duerna River gauging station near of Castrillo de la Valduerna, as indicated by a yellow triangle in Figure 1. This aquifer encompasses the main towns of the La Valduerna region. This aquifer consists of Holocene alluvial deposits associated with the Duerna and Peces rivers, composed primarily of sandstone and quartzite clasts with sandy intercalations (Vargas et al., 1984; Figure 1). These alluvial materials overlie Miocene silty and clayey sediments with sand.

The aquifer covers an area of approximately 44 km² and consists of permeable detrital formations with a thickness of less than 10 m (CHD, 2021). The maximum depth of the wells coincides with the geological contact between the alluvial deposits and the underlying low permeable Miocene clays. The aquifer is bounded by low-permeability Paleozoic metamorphic rocks to the west and northwest, by the Peces River to the north, and by the Duerna River to the south and east. Groundwater generally flow from west to east.

Numerous wells have been excavated within the aquifer, most of which are currently operated using suction pumps (Figure 3). Historically, groundwater was extracted using horse-driven waterwheels (Figure 2). The groundwater in this aquifer has high quality, with an average electrical conductivity of 96 $\mu\text{S}/\text{cm}$ and a nitrate concentration of 14 mg/L (CHD, 2021). It is used for both domestic supply and agricultural irrigation, particularly during the late dry season when the Duerna River is nearly dry near the town of Castrillo de la Valduerna (Figure 1).

3. Methodology

3.1 Data collection

a) Irrigation/recharge hydraulic infrastructure.

To represent and analyze the *zayas* system, a georeferenced database was developed using historical and cartographic sources, structured around three methodological approaches: remote sensing, direct field mapping, and collaboration with local irrigation communities. The remote sensing component involved comparative analysis of aerial imagery from the 1956 American flight and recent orthophotographs. Field mapping included on-site verification of *zayas* channels and well structures, which were digitized and integrated into a Geographic Information System (GIS). Collaboration with irrigation communities involved ethnographic

interviews and participatory mapping sessions, providing valuable local knowledge that enriched the spatial analysis.

b) Surface and underground data

To determine the geometry of the Holocene alluvial formation, data from geological mapping, well records, and two electrical resistivity tomography (ERT) profiles were used (CHD, 2021). The outcropping geological contacts of the alluvial basement were obtained from 1:50,000-scale geological maps (Vargas et al., 1984). The top surface of the alluvial formation was derived from a digital elevation model with 5-meter resolution (IGN, 2021). A total of 179 wells were used to reconstruct the geometry of the base of alluvial deposits. Given the relatively uniform thickness of the formation and its gradual spatial variation, it was assumed that the total depth of each well corresponds to the thickness of the alluvial layer.

c) Hydrometeorological data

Daily rainfall and temperature data were obtained from the ROCIO grid (5×5 km resolution) provided by the Spanish Meteorological Agency (AEMET; Peral et al., 2017), covering the period from 1952 to 2022. This dataset was complemented with records from the weather station located at the Duerna River gauging site (Figure 4), covering the period from 2022 to 2024.

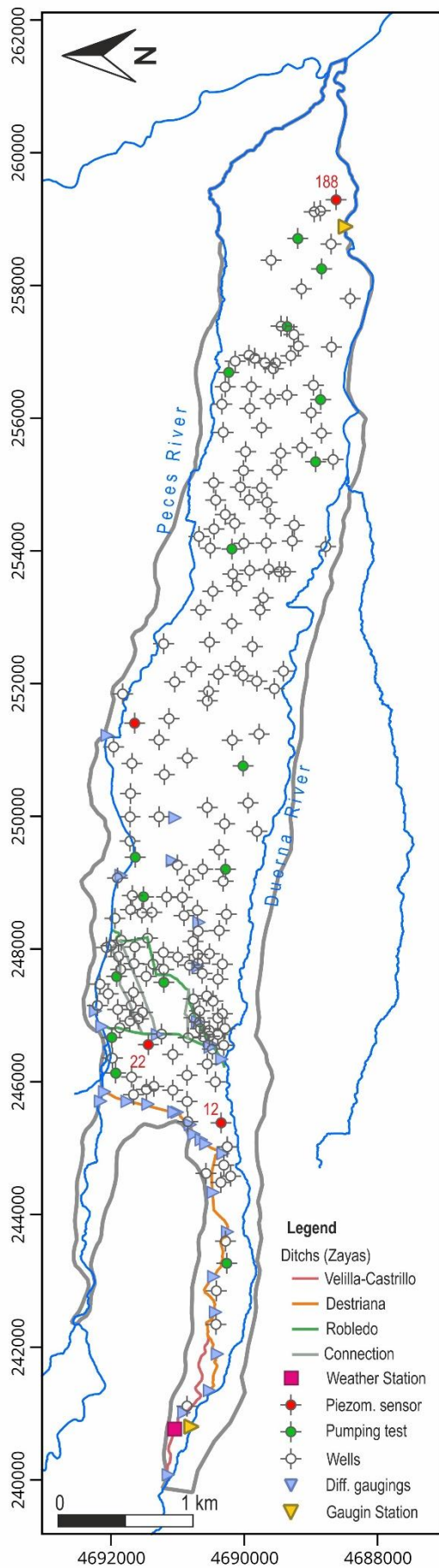


Figure 4. Map showing the location of wells, wells with associated pumping test data, wells with pressure sensors, meteorological and gauging stations, flow monitoring points (Diff. gaugings), and the main zayas

The piezometric study included from 75 to 78 sampling points during with 11 monitoring campaigns. The first campaign took place on November 18, 2023, and the last one on May 19, 2025. In addition, four Level Logger pressure sensors (Solinst) and one Barologger were installed, recording hourly measurements from April 2024 to May 2025. All monitoring wells were georeferenced using a LEYCA GPS and marked to ensure consistent reference points throughout the monitoring campaigns.

3.2. Precipitation-runoff model

A rainfall–runoff model of the Duerna River was developed using data from its gauging station at Velilla (Figure 1), with the aim of calibrating the model to support the simulation of the Peces River, which lacks a gauging station. The objectives of this modelling effort were to estimate the flow of the Peces River upstream of the irrigated area and to generate average annual hydrographs, thereby identifying the most suitable periods for diverting water from both rivers without compromising the ecological flow requirements defined by the CHD.

To develop the precipitation–runoff model, the HBV Light code (Seibert, 2005) was selected. The original HBV model was developed by the Swedish Meteorological and Hydrological Institute (SMHI) (Bergström, 1976; Bergström, 1995). The upstream catchment area of the Velilla gauging station on the Duerna River covers 245 km², which was subdivided into eight elevation zones at 200-meter intervals. The model operates on a daily basis. The simulation period included an initial warm-up phase of eight hydrological years (October 2005 to September 2013), a calibration period of six years (October 2013 to September 2019), and a validation period of three years and three months (October 2019 to December 2022). Parameter uncertainty was assessed using a Monte Carlo sampling approach, whereby thousands of parameter sets were randomly generated within physically plausible ranges. Model performance was evaluated for each realization using the Nash–Sutcliffe Efficiency (R_{eff} in HBV-Light), and the ensemble of acceptable simulations was used to quantify the uncertainty associated with model calibration and its propagation to the simulated streamflow (Beven and Binley, 1992; Beven, 2006).

The HBV model was configured in its standard form, which includes three groundwater storage reservoirs, with saturated zone storage located in the upper reservoir (“Three GW boxes, STZ

distributed”; Seibert, 2005). The Peces River Basin does not have a gauging station, and no river-discharge time series are available to calibrate its HBV model. Given the geological and geomorphological similarities between the Duerna and Peces River basins, the HBV parameter set used to simulate the hydrodynamic response of the Peces Basin is the same as the one calibrated for the Duerna Basin for the same time interval (October 2013 to December 2022).

3.3. Evaluation of *zayas* channels’ contributions to groundwater recharge.

To assess the recharge capacity of the main *zayas* in the Valduerna recharge system, an infiltration tests were conducted in April 2024. In this tests water was diverted through the three principal *zayas* of the irrigation system: Velilla, Castrillo, and Robledo (Fig.4). Diverted flow rates were monitored at the inlet and outlet of each channel to estimate the volume of water infiltrated along their course. While the three main *zayas* are equipped with flow gauges at their inlets, outlet measurements—where the channels discharge into the Peces River—were obtained using saline-type flow meters (EasyFlow, JDC Electronic SA). During the tests, the middle reach of the Peces River was dry, functioning as a losing stream. All water discharged from the Duerna River infiltrated shortly after entering the riverbed without being part of the continuous surficial flow. Given that rainfall recharge between April 1 and May 13, 2024 amounted to only 27 mm (spread over 9 rainy days), it is reasonable to attribute aquifer recharge during this period entirely (100%) to the operation of the “*zayas*.”

Before, during and after the diverting water into the *zayas*, several piezometric campaigns—each covering 78 wells—were conducted to measure changes in groundwater levels. The rise in the piezometric level has made it possible to estimate the volume of the saturated aquifer. Once this volume was determined and given the storage coefficient values obtained with considerable detail in the alluvial deposits on the right bank of the Duerna River (Suringar, 1985), it was verified whether the volume of water recharged by the *zayas* was consistent with the measured piezometric rise.

3.4. 3D Geological modelling

To construct the 3D geometry of the alluvial aquifer, well data and interpretations from electrical resistivity tomography (ERT) profiles were integrated into the Skua-GOCAD software (Emerson E&P Software, 2021). Skua-GOCAD is an advanced platform for geological and reservoir modelling, capable of generating 3D models that incorporate diverse data sources, including geological maps, borehole logs, and geophysical measurements (Mallet, 2002).

3.5. Numerical groundwater model

To develop the numerical groundwater flow model of the aquifer, the most recent version of the software developed by the United States Geological Survey (USGS), MODFLOW—specifically MODFLOW 6 (Langevin et al., 2017)—was used, along with its graphical user interface, ModelMuse (Winston, 2019). The model boundaries correspond to the limits of the unconfined aquifer, delineated to the north by the Peces River, to the south by the Duerna River, and to the east and west by the high-permeability fluvial lithologies that characterize the aquifer (Figure 1). The model was spatially discretized into 100×100 m cells (Figure 5) and temporally into daily time steps, covering the period from October 2010 to September 2020.

The model was first calibrated under steady-state conditions, assuming constant inflows and outflows. These results were then used to build a transient model recalibrated using data from 62 selected piezometric measurements. Boundary conditions were implemented using the following MODFLOW 6 packages (Hughes et al., 2017; Fig 5): RIV (river boundary conditions for the Peces and Duerna rivers), RCH (recharge from both natural infiltration and the *zayas*), and WELL (pumping from 73 wells).

Once the model was calibrated and validated, the transient model was used to simulate two alternative management scenarios aimed at improving water resource availability: (i) Management Simulation 1: adding a new *zaya* to the east of the existing ones, and (ii) Management Simulation 2: extending the operational period of the *zayas* from April 1 to January 1. Additionally, the aquifer's renewal period (RP)—defined as the ratio between total storage capacity and annual recharge (ψ/R ; Margat et al., 2006)—was estimated. Natural recharge by infiltration of precipitation water (R) was calculated using a soil water balance approach based on daily precipitation and potential evapotranspiration, the latter estimated using the Hargreaves equation (Hargreaves and Samani, 1985). Climatic data processing was performed using TRASERO (Padilla and Delgado, 2013), a software tool for hydrological time series analysis. Groundwater reserves were estimated using the aquifer geometry derived from the 3D geological model, piezometric data, and porosity values for the study zone (Suringar, 1985). MODPATH (Pollock, 2016) was also used to calculate groundwater transit time from the western to the eastern boundaries of the aquifer.

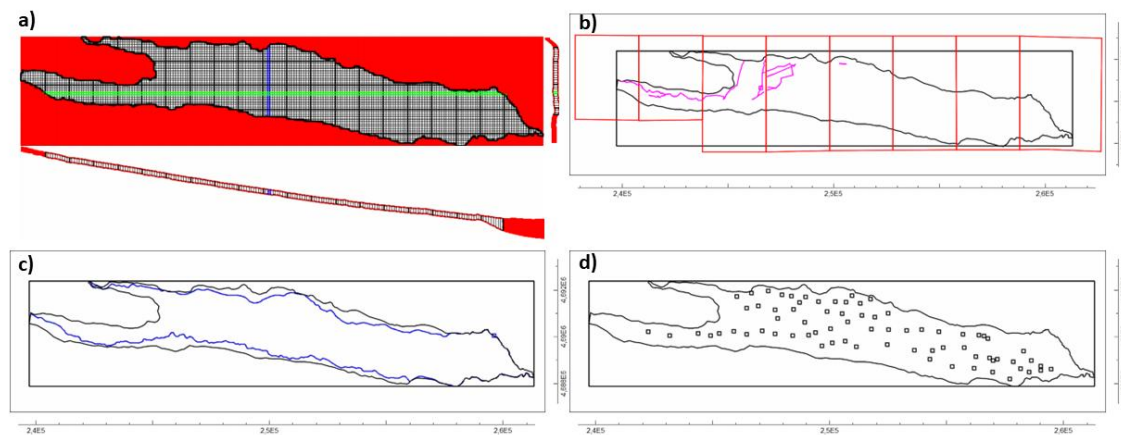


Figure 5. Illustration of the principal components incorporated in the groundwater model, depicting: a) aquifer mesh discretization, featuring two 2D profiles (with the NS location indicated in blue and the EW location highlighted in green); b) configuration of the recharge package (fuchsia lines denote infiltration channels, and red rectangles indicate rain recharge zonification); c) representation of the river package for the Duerna and Peces rivers (illustrated with blue lines); and d) elements of the well package (each well represented by a black rectangle).

4. Results

4.1. Historical irrigation-recharge infrastructure

Since the 17th–18th centuries, approximately 100 buildings, including mills, small factories, and sawmills, have been documented as using water power from both the Duerna River and the “*zayas*,” indicating that the irrigation channels were already in operation by that time. Written records of their use date back to 1433, and some archaeological and linguistic theories suggest that the term *zaiga* (from which *zaya* derives) may originate from the period of Islamic occupation of the Iberian Peninsula (8th–15th centuries), placing the likely origin of the *zayas* around the year 1150.

Figure 6 illustrates the evolution in the number of canals and wells between 1956 and 2025: in 1956, there were 503 km of canals and 650 wells, while in 2025, only 246 km of canals and 179 wells remain. Historically, inhabitants of La Valduerna diverted water from the Duerna River through the Velilla, Robledo, and Castrillo “*zayas*,” which transported surface water across the interfluvial aquifer before reconnecting with the Peces River. As water flows through the channels, current irrigators manually open and close the gates to allow water to flood their fields, providing surface irrigation for crops.

The water diverted through the *zayas* and the rivers infiltrates by gravity, recharging the unconfined aquifer and functioning as a true Agriculture Managed Aquifer Recharge (Ag-MAR) system during the wetter months of the year. This system uses the aquifer as a natural reservoir, allowing water to be extracted during the dry season (June to September) through 179 shallow wells. The extracted groundwater is primarily used for supply and for sprinkler irrigation of cereals and potatoes, making La Valduerna a living example of conjunctive water use through traditional recharge techniques.

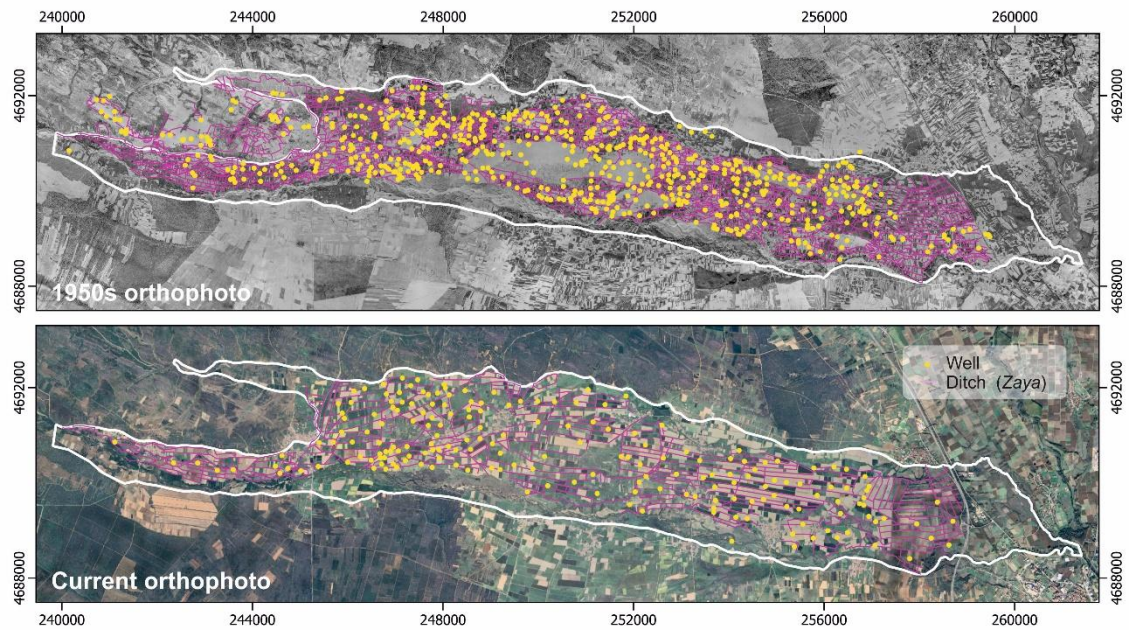


Figure 6. *Zayas* and wells spatial distribution over Duerna -Peces Aquifer a) in 1956 b) in 2025.

4.2. Precipitation-Runoff model

The Duerna River model was calibrated by minimizing the error between observed and simulated flow hydrographs, using model efficiency (R_{eff} ; Seibert, 1997) as the objective function. A final efficiency value of 81.9% was achieved. Figure 7a presents the results for the Duerna River, including observed flows, simulated flows during the calibration period (October 2013–September 2019), and validation period (October 2019–September 2022), along with the confidence interval derived from Monte Carlo analysis [10%, 90%]. Figure 7b shows the simulated flow and corresponding confidence interval for the Peces River model.

Regarding the water balance distribution, contributions to total basin discharge from surface runoff, subsurface flow, and groundwater were 12.5%, 11.7%, and 75.7%, respectively. For the Peces River, the corresponding values were 8.4%, 2.3%, and 89.1%, respectively. Both rivers exhibit a strong groundwater component, accounting for 75–90% of the hydrograph.

Figures 7a and 7b display the average annual hydrographs for the Duerna and Peces rivers (black dashed lines), based on daily data aggregated monthly. Figure 7a also includes the annual variation in the ecological flow thresholds established by the CHD (brown dashed line). During dry years, represented by the 20th percentile of flow, the most suitable period for diverting river water for Ag-MAR is between December and June, as indicated by the overlap between the Monte Carlo confidence interval (yellow area) and the ecological flow thresholds.

The results shown in Figures 8a and 8b represent the average water resources available over the 10-year modelling period, amounting to 81.31 hm³/year for the Duerna River and 3.72 hm³/year for the Peces River. Based on these findings, it is essential to adapt the operational schedule of the *zayas* recharge system to prevailing climatic conditions—particularly by taking advantage of wetter years, such as 2023–2024, when the recharge season could begin as early as January. Adjusting the timing of water diversion through the *zayas* may be key to preventing water scarcity during the summer months. In this context, recharge rates function as a form of water savings, helping to secure water availability throughout the hydrological year.

From an ecological perspective, the hydrological model confirms that advancing the aquifer recharge period to the winter months, using the *zayas* channels, would have minimal impact on the ecological flow of the river.

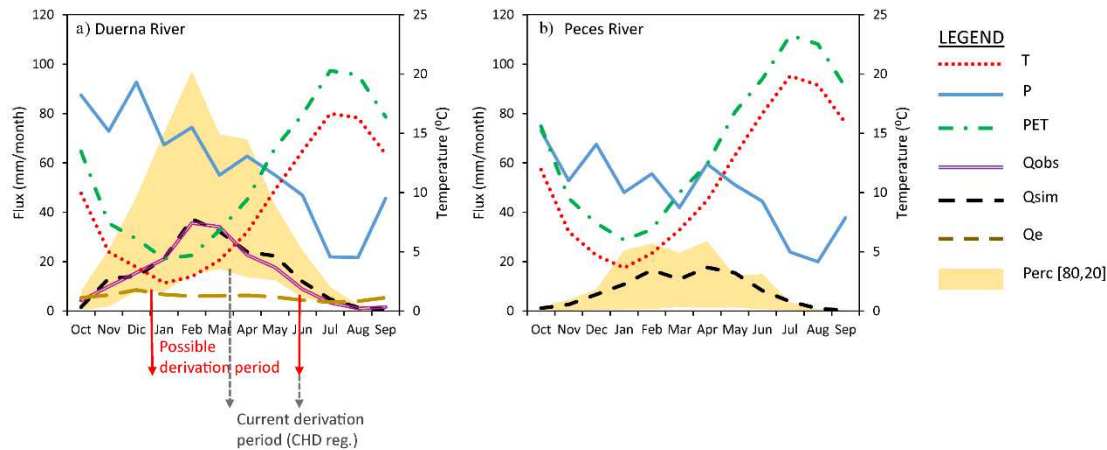
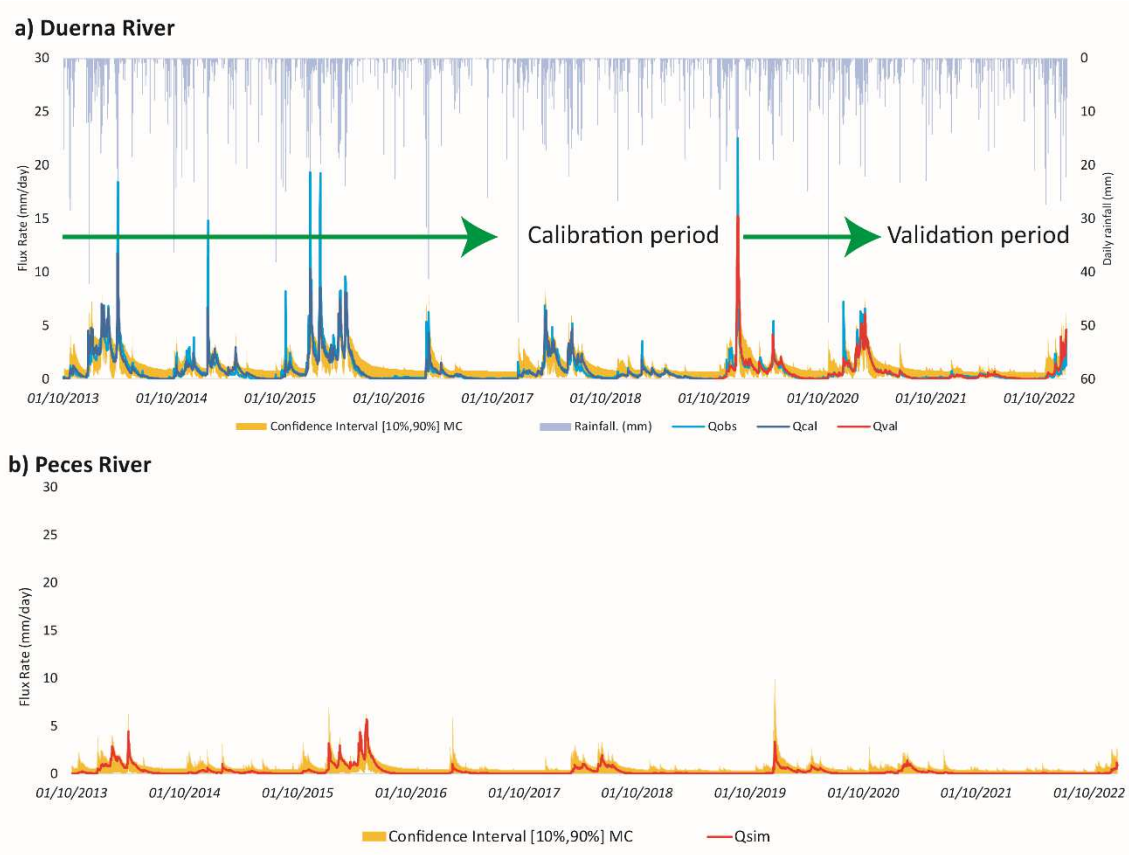


Figure 7. a) Monthly average of temperature (T), precipitation (P), potential evapotranspiration (PET), observed flux rate (Qobs), simulated flux rate (Qsim), ecological flux rate (Qe) and Monte Carlo confidence interval (Perc [20,80%]) for the Duerna River basin. b) Monthly average of temperature, precipitation, potential evapotranspiration, observed flux rate, simulated flux rate, ecological flux rate and Monte Carlo confidence interval [20,80%] for the Peces River basin.



365

366 Figure 8. **a)** Daily rainfall (mm; grey columns), daily flow discharge (mm) measured at Velilla de
367 La Valduerna gauging station (Qobs; blue dots line), hydrogram calculated for the calibration
368 period (Qcal, dark blue line), hydrogram calculated for the validation period (Qval, red line) and
369 confident interval [10,90%] of 5000 simulations with Monte Carlo interpolation (yellow band).
370 **b)** Daily flow rate (mm) calculated with HBV for Peces Basin from October 2013 to December
371 2022.

372 **4.2. Piezometric levels evolution**

373 Temporal (Figure 9) and spatial (Figure 10) variations in the groundwater level were analysed
374 across the entire aquifer for the period between November 2023 and May 2025. Since the
375 beginning of the study period, fluctuations of approximately 4–5 m were recorded in most of
376 the aquifer, while in the lowest area variations were closer to 1 m (Figure 8). The highest water
377 levels occurred in spring 2024, and the lowest were observed between August and October
378 2024.

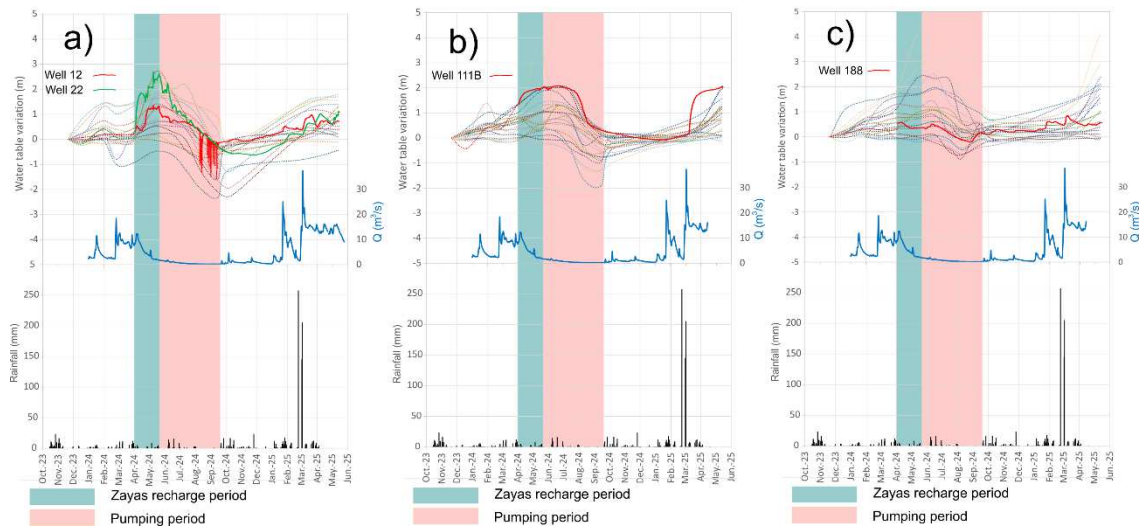


Figure 9. Temporal evolution of variations in water table depth in the three zones into which the aquifer has been divided: a) Upper Area; b) Middle Area; c) Lower Area (see Figure 10). The rainfall at station Velilla de la Valduerna and changes in the flow of the Duerna River at gauging station are included, and recharge period in the zayas and the pumping operation period in the wells is indicated.

In 2024, winter and spring precipitation began influencing the flow of the Duerna River in January, with an initial rise in discharge followed by a more pronounced and sustained peak at the end of February and again between March and April. The wettest period ended in early April, and on April 1st, induced recharge began through water distribution via the “zayas.” At that time, the most significant rise in piezometric levels was observed in the Upper and Middle zones, despite the *zayas* being located only in the Upper Zone (see Figure9a). The peak rise in the Upper Zone was recorded in May, after a month without precipitation, followed by a decline that began in June (Figure 9c). In the Middle Zone, the rise was more gradual and sustained, without a distinct peak, and the decline began in late July (Figure 9b). In the Lower Zone, piezometers at higher elevations showed behaviour similar to those in the Middle Zone, while piezometers at lower elevations—such as monitoring well 188—exhibited much smaller fluctuations, with minimal influence from the *zayas*, which were clearly impactful in the Upper and Middle zones (Figure 9c).

The onset of pumping was clearly recorded at monitoring well 12, which is directly influenced by a nearby production well. Groundwater extraction for crop irrigation—particularly for potatoes and maize—typically begins in May and gradually increases, peaking in July and August when water demand is highest. Following the cessation of pumping, groundwater levels began to gradually recover in the Upper Zone (well 12) and in the Lower Zone, with minimal influence

from autumn precipitation. In contrast, recovery in well 22 was delayed until December 2024, similar to the Middle Zone, where monitoring well 111B continued to decline until the onset of winter precipitation in January 2025.

In 2025, precipitation in February—and especially in March—was exceptionally abundant, and the *zayas* were not activated. This may explain why the rise in groundwater levels in the Upper Zone was lower than in the previous year. Conversely, in the Middle Zone, a sharp increase in groundwater levels occurred in response to March precipitation, rapidly reaching the maximum levels observed the previous year.

Figure 9 presents two piezometric maps of the Duerna–Peces aquifer. The first corresponds to the post-recharge period following the use of *zayas*, when groundwater levels were at their highest (May 15, 2024). The second represents conditions at the end of the irrigation season, after intensive groundwater abstraction (September 2024), when levels were at their lowest. Groundwater flow is predominantly east–west, with a piezometric gradient ranging between 0.6 and 0.8 ‰. Only two localized drawdown cones were identified: one in the northern sector, at a well located near the aquifer’s impermeable boundary, and another in the eastern sector, associated with intensive pumping for maize irrigation. In both maps, the orientation of equipotential lines in the eastern part of the aquifer—where the water table lies close to the surface—suggests some groundwater discharge toward the Duerna and Peces rivers.

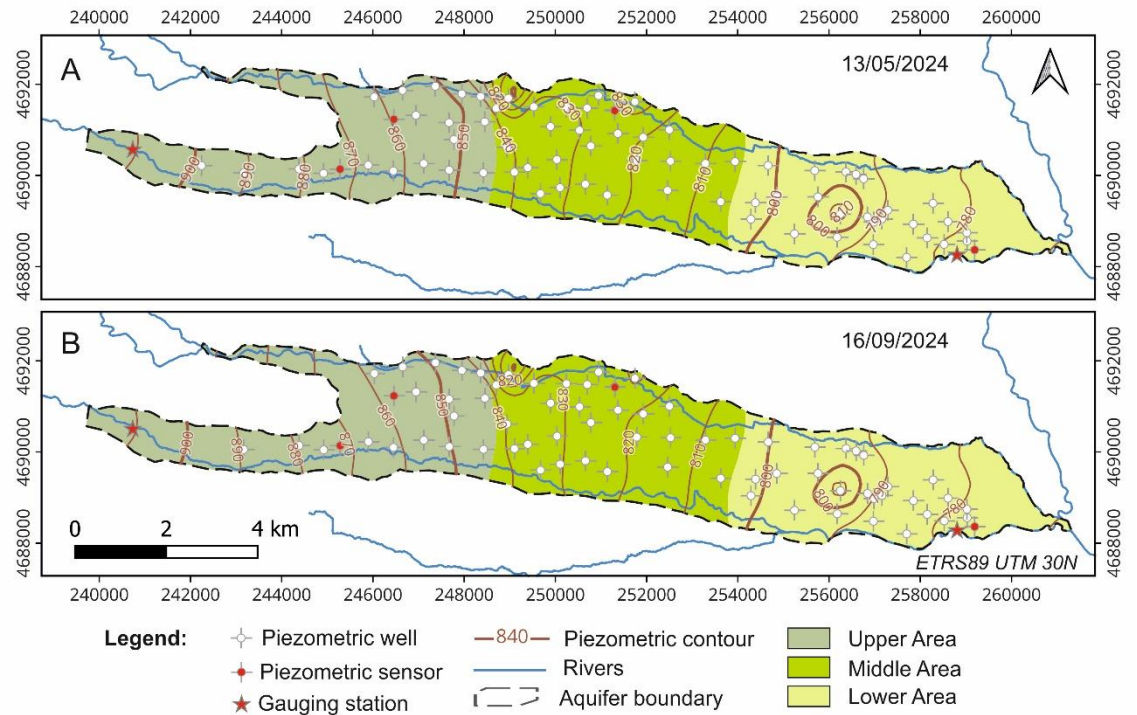


Figure 10. Piezometric map of the Duerna-Peces aquifer piezometric with measured levels on 13 May 2024 and 16 September 2024. The location of the monitored wells with pressure sensors (red spots), gauging station (red star) and the three different areas of aquifer behaviour.

4.3. Evaluation of recharge from *zayas*

Flow rates along the *zayas* were measured during the April 2024 field campaign to quantify the system's recharge potential. Figure 11 illustrates the spatial distribution of the measurement points, as well as the variation in flow from the Duerna River diversion to its confluence with the Peces River. Additional measurements were taken along the Peces River to assess changes in flow downstream of the *zayas* discharge points.

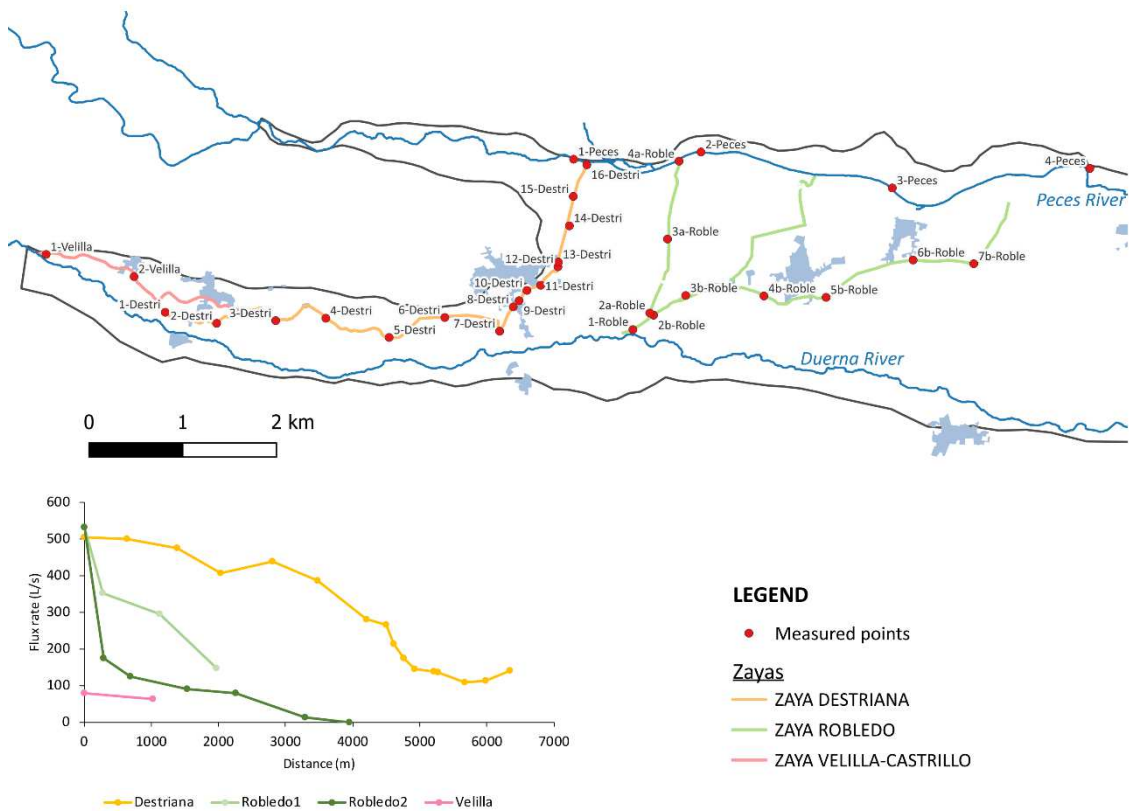


Figure 11 Flow rate along the *zayas* channels during field campaign in April 2024.

To quantify the aquifer response after the activation of the *zayas*, piezometric surfaces from April 1st to May 13th, 2024 were compared, resulting in an average groundwater level increase of 0.47 m across the 44 km² extent of the aquifer.

Figure 12 presents the daily volume of recharged water, totalling approximately 1.5 hm³ over a 43-day period.

To assess the consistency between the volume of water infiltrated through the zayas during the test period and the observed rise in the piezometric level, the volume of saturated material was divided by the volume of water recharged via the zayas. This calculation provided a specific yield of 7.8%, which is close to the average value determined on the right bank of the Duerna River (7.9%). It was obtained from a sampling campaign of alluvial deposits conducted during a gold prospecting survey (Suringar, 1985).

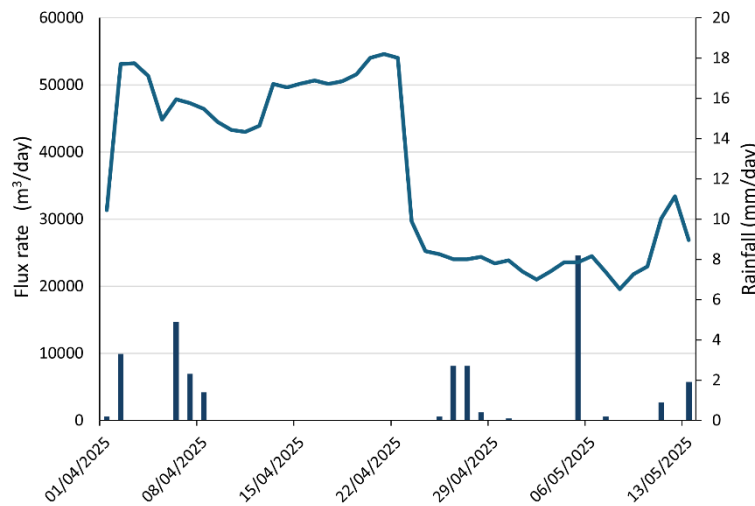


Figure 12. Flow rate of *zayas* channels and rainfall records during recharge test from 1st April 2024 to 13th May 2024.

4.4. 3D Geological model

The three-dimensional (3D) model of the La Valduerna alluvial aquifer characterizes Holocene alluvial deposits primarily associated with the Duerna and Peces rivers. These deposits unconformably overlie Miocene sediments.

The model covers an area of approximately 44 km², with an average alluvial thickness of 8 m and a mean dip of 1.2° (Figure 13). The thickness of the alluvial unit is remarkably consistent throughout the model, with no significant variations indicative of faulting or the presence of a depocenter. The northern boundary of the model corresponds to the termination of the alluvial formation, where an erosional unconformity with the Miocene sediments is observed, roughly following the course of the Peces River. The eastern boundary is defined by the limit of the alluvial outcrop, while the southern boundary follows the course of the Duerna River and the outcropping Miocene formation. The western boundary coincides with the confluence of the Duerna and Peces rivers. Overall, the model reflects a stable depositional environment with limited tectonic influence on the Holocene alluvial deposits.

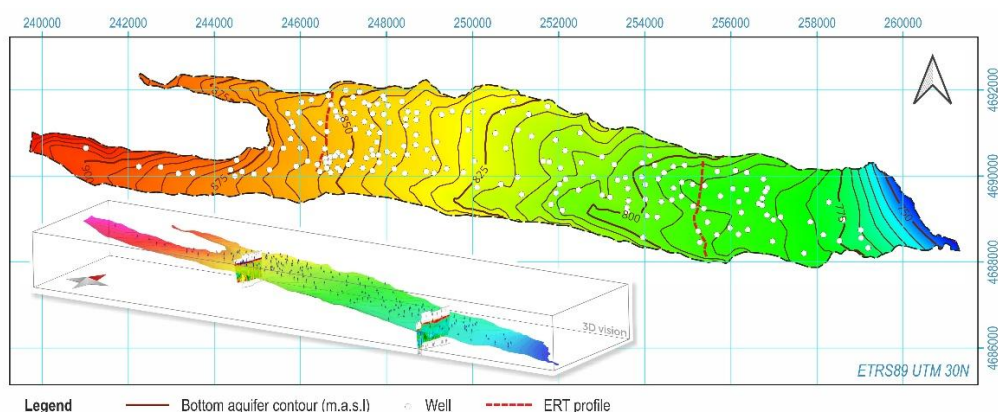


Figure 13. 3D geological model results.

4.5. Numerical groundwater model of Duerna-Peces Interfluvial Aquifer

When running the model in the transient state piezometric values showed minimal variation throughout the study period (Figure 14), consistent with measurements taken onsite during 2023–2024 (Figure 10). The spatial distribution of groundwater levels also remained stable, with higher values at the western end of the aquifer—reaching approximately 910 m a.s.l., and gradually decreasing eastward, down to a minimum of 775 m a.s.l., following the topographic gradient.

Model calibration yielded excellent results, with an R^2 value of 0.99 (Figure 14) during dry and wet season and also before and after recharge test. The resulting water balance components (Table 1) were consistent with the conceptual model of the area, particularly highlighting recharge as the most variable element across hydrological years. Average annual recharge from rainfall infiltration was estimated at 3.57 hm³/year. The highest recharge occurred during the wet year of 2015–2016, reaching 7.89 hm³/year, while the driest year, 2018–2019, yielded only 1.58 hm³/year. Additionally, the estimated renewal period ranged from 1.7 to 2.5 years, and the calculated groundwater transit time across the aquifer was 44 years.

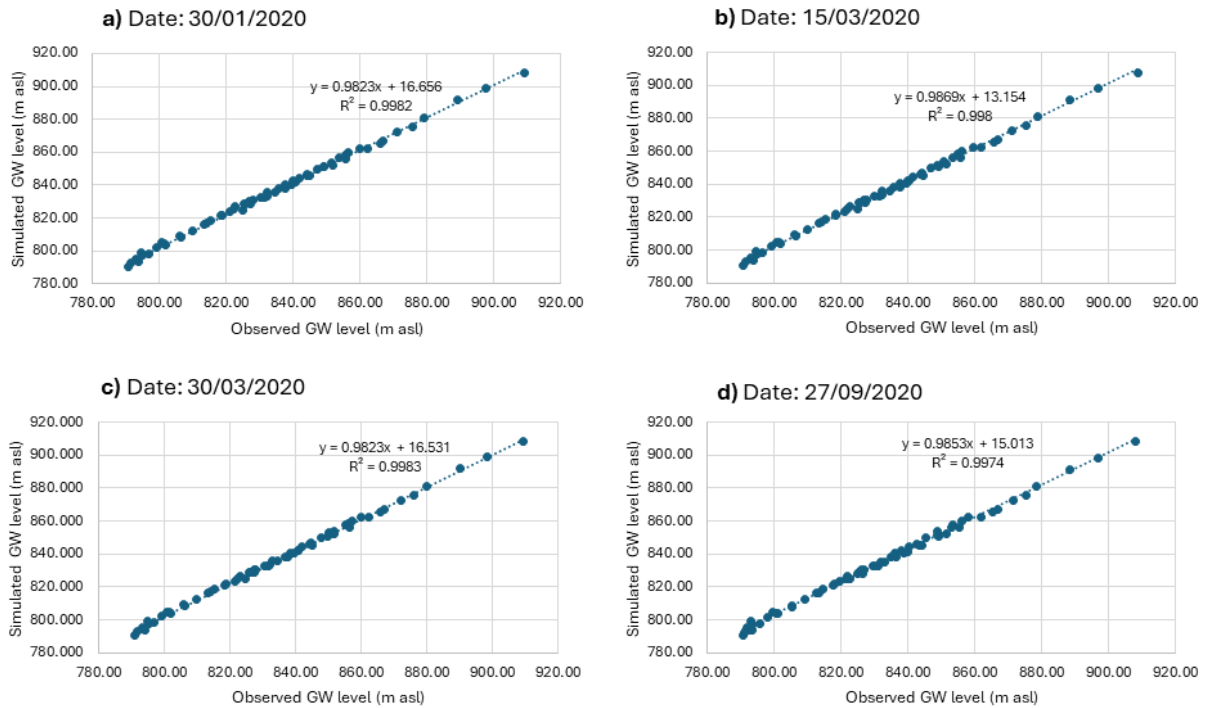


Figure 14. Calibration plots of the transient model: a) winter season (recharge), b) before the recharge test, c) after the recharge test, d) summer season (dry period).

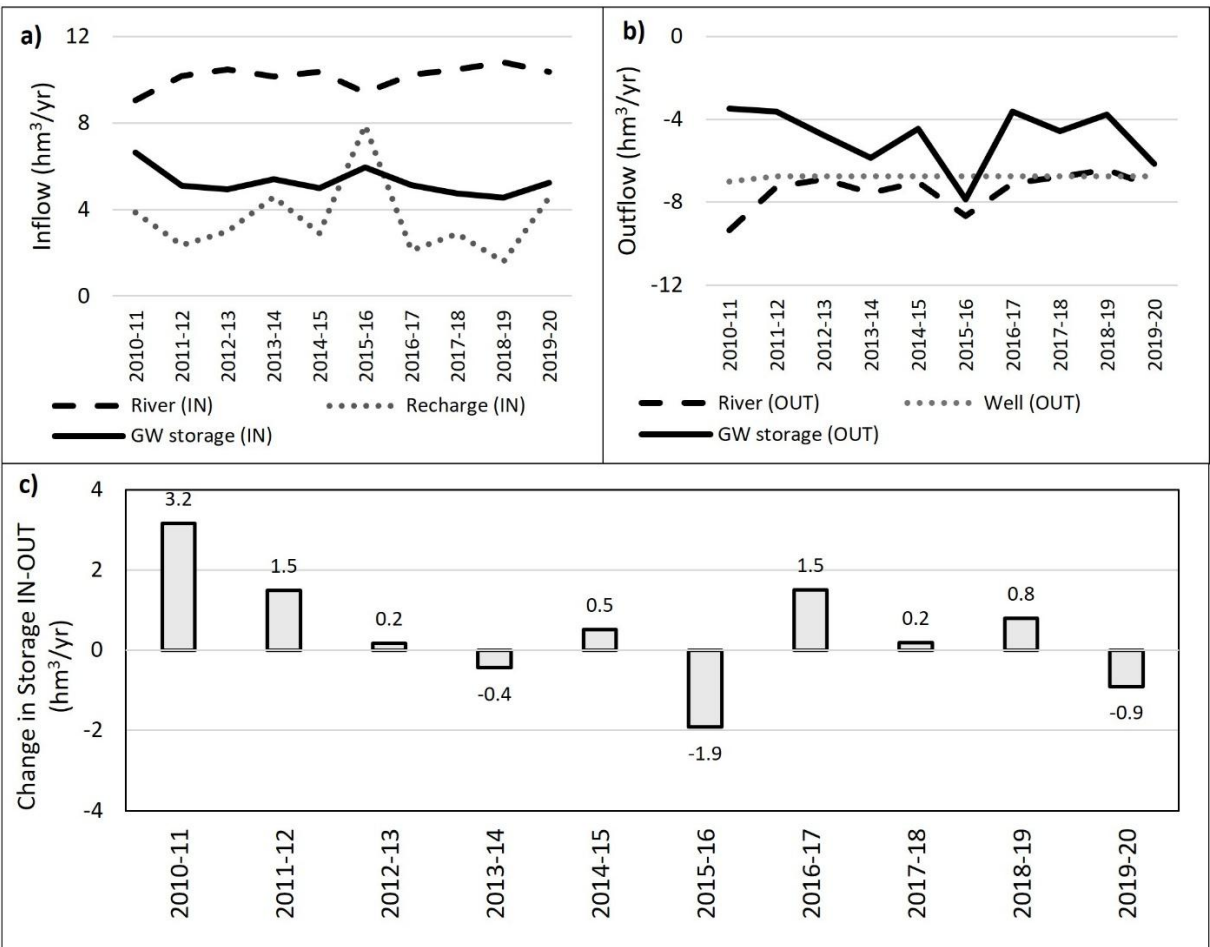


Figure 15. a). Inflow water budget (hm^3/yr) represented as lines. Inputs include contributions from the Duerna River (dotted line), recharge from rainfall and *zayas* channels (dashed line), and groundwater storage (black line). b). Outflow water budget include discharge to the Duerna and Peces Rivers (dashed line), extraction from shallow wells (dotted line), and changes in groundwater storage (black line). c). Yearly changes in Storage (Inflow-Outflow) represented as columns.

Table 1. Summary of the main hydrological components controlling groundwater availability in the Duerna-Peces aquifer. Values derived from recharge experiments, groundwater modelling and hydrogeological characterization performed in this study.

<i>Water-budget component</i>	<i>Value</i>
<i>Mean annual natural recharge from precipitation infiltration</i>	$3.57 \text{ hm}^3 \text{ yr}^{-1}$
<i>Natural recharge range</i>	$1.58\text{-}7.89 \text{ hm}^3 \text{ yr}^{-1}$
<i>Recharge through zayas during the field experiment (43 days)</i>	1.5 hm^3
<i>Irrigation groundwater abstraction</i>	$6\text{-}8 \text{ hm}^3 \text{ yr}^{-1}$
<i>Aquifer storage capacity</i>	$9\text{-}12 \text{ hm}^3$
<i>Aquifer renewal period</i>	$1.7\text{-}2.5 \text{ years}$
<i>Groundwater transit time</i>	44 years
<i>Additional recharge in Management Simulation 1</i>	$1.2\text{-}2.4 \text{ hm}^3 \text{ yr}^{-1}$
<i>Additional recharge in Management Simulation 2</i>	$2.0\text{-}4.3 \text{ hm}^3 \text{ yr}^{-1}$

In the Management Simulation 1, annual recharge increases ranged from 1.2 to 2.4 hm^3 (Table 1), while in Management Simulation 2 (Table 1), additional recharge varied between 2.0 and 4.3 hm^3 , depending on the hydrological year.

5. Discussion

The results obtained from field monitoring, recharge tests, and surface-groundwater modelling allow a comprehensive assessment of the Duerna-Peces aquifer water balance (Table 1). Average natural recharge derived from rainfall infiltration is relatively limited compared with groundwater abstractions for irrigation, while aquifer storage capacity remains modest. Consequently, aquifer sustainability largely depends on managed recharge through the *zayas* system. By diverting excess river flows during the wetter months and storing them underground for later use, the aquifer effectively functions as a natural reservoir. This conjunctive use strategy reduces the temporal mismatch between water availability, concentrated in winter and spring, and irrigation demand, concentrated during summer

Observed data indicate that the Duerna River Basin contributes an average of 76.4 hm^3/year (2013–2022) as it traverses the Duerna–Peces aquifer. This estimate was validated by the rainfall–runoff model developed for this study. However, it is lower than the value reported by

previous studies (84.8 hm³/year) for the period 2013–2024 (CHD, 2021). Streamflow records at the Velilla gauging station (Figure 1) confirm that, during dry periods, discharge from the Duerna River is insufficient to meet irrigation demand. Similarly, the hydrological modeling of the Peces River shows that this stream lacks significant resources to support summer irrigation under average precipitation conditions.

Recharge tests revealed that the three main zayas can infiltrate monthly volumes exceeding 1.4 hm³. The resulting rise in groundwater levels is consistent with storage coefficient values of 7–8%, as previously reported for the area (Suringar, 1985). Monthly piezometric monitoring confirmed that recharge through the zayas exerts a measurable influence on the Upper and Middle zones of the aquifer, with observed water-level rises of 2 to 3 m. This effect is also evident in the westernmost piezometers of the Lower Zone. Conversely, groundwater pumping induces declines of approximately between 2 and 5 m across the aquifer—a significant drawdown given its limited saturated thickness.

Hydrogeological modeling confirms that natural recharge from rainfall infiltration is minimal (1–3 hm³/year) and that pumping is offset by water capture from the Duerna River and artificial recharge via the zayas. The 3D geological model and piezometric data indicate a limited storage capacity (9–12 hm³), making artificial recharge essential to meeting water-resources demands, particularly during dry years. Irrigation demand is estimated at 6.7 hm³/year. Groundwater flow simulations suggest that extending the operational period of the zayas (starting earlier) or constructing additional infiltration channels could increase annual recharge by 100–200%, without compromising downstream ecological flow thresholds. These findings demonstrate that the numerical groundwater model developed for the interfluvial aquifer is a robust tool for water resource management and regulatory decision-making.

The comparison between recharge and abstraction estimates highlights the strategic importance of the zayas. Average annual irrigation demand (approximately 6–8 hm³ per year) exceeds natural recharge during most hydrological years, indicating that precipitation alone could not guarantee groundwater availability throughout the irrigation season. Under these conditions, managed aquifer recharge represents an essential component of the water budget rather than a supplementary resource. The recharge test carried out in spring 2024 demonstrated that significant volumes can be transferred to groundwater storage over relatively short periods, supporting the role of the zayas as an efficient and low-cost recharge infrastructure.

Ensuring long-term sustainability of the Duerna–Peces aquifer and effective management of its ancestral Ag-MAR system require coordinated measures between users and water planners. Establishing a structured user representative group would facilitate direct communication with the CHD, reducing conflicts and streamlining requests. This approach—groundwater user associations—has proven successful in other Spanish regions (Custodio et al., 2024), such as the acequias de careo system in Sierra Nevada (Martos-Rosillo et al., 2025; Jódar et al., 2022b). The user community should be supported by scientific and technical advisors to promote informed decision-making and sustainable resource management. Furthermore, CHD should allow the recharge period through zayas and flood irrigation to be advanced to winter months, as practiced prior to 2017.

Preservation and enhancement of the zayas system must be prioritized, recognizing its historical resilience to climatic, social and economic changes; and its significance as cultural heritage. The proven effectiveness of these ancestral infiltration channels in promoting aquifer recharge at minimal cost and through community-based management underscores the importance of their maintenance and conservation. Comparable ancestral systems have been documented in Sierra Nevada (Spain), such as the acequias de careo, and in the Peruvian Andes, with the amunas, both recognized as Nature-based Solutions (NbS) that enhance aquifer recharge, ecosystem services and drought resilience (Jódar et al., 2022a; Ochoa-Tocachi et al., 2019). These systems share key attributes with the zayas: gravity-driven operation, use of local materials, community governance and low maintenance costs.

These findings align with broader research on modern Ag-MAR systems in California and Nevada, where winter flooding of agricultural lands has proven effective in enhancing groundwater storage and streamflow resilience (Levintal et al., 2023; Morrisett et al., 2024). Despite their demonstrated effectiveness, Ag-MAR systems remain underutilized outside the United States. In California’s Central Valley, Ag-MAR has been integrated into groundwater sustainability plans under the Sustainable Groundwater Management Act (SGMA), supported by regulatory frameworks, monitoring tools, and financial incentives (Waterhouse et al., 2021; Medellín-Azuara, 2024). In contrast, most regions worldwide lack robust institutional mechanisms for their adoption. Recent European Commission reviews emphasize the need for stronger policy integration, long-term monitoring and financial instruments to scale NbS in agricultural landscapes, although this process remains in its early stages (Pistocchi, 2022; Santos, 2025).

5. Conclusions

This study provides a comprehensive hydrogeological assessment of the traditional Agricultural Managed Aquifer Recharge (Ag-MAR) system of La Valduerna, demonstrating its effectiveness as a long-standing and operationally robust mechanism for enhancing groundwater storage under current climatic and regulatory conditions. The zayas channels, in use since at least the 15th century, contribute substantially to seasonal aquifer replenishment through gravity-driven infiltration and low-cost infrastructure maintained by local water users.

Quantitative evidence from piezometric monitoring, infiltration measurements, hydrological and hydrogeological modelling, and 3D geological reconstruction confirms that artificial recharge is essential for sustaining groundwater levels in this shallow detrital aquifer, where natural recharge remains limited. Model simulations indicate that extending the operating period of the zayas or incorporating additional infiltration channels could significantly increase annual recharge while respecting ecological flow constraints.

The findings support recent international recommendations promoting the integration of ancestral water-management practices as Nature-based Solutions, demonstrating that traditional systems can be aligned with modern groundwater management objectives when supported by hydrological evidence. The La Valduerna Ag-MAR system represents a transferable example of cost-effective conjunctive use, particularly relevant for regions facing seasonal water scarcity, declining aquifer storage, and rural socioeconomic pressures.

The water balance analysis demonstrates that groundwater abstraction for irrigation frequently exceeds natural aquifer recharge. Consequently, managed aquifer recharge through the zayas is not merely a complementary practice but an essential component of groundwater sustainability in La Valduerna, allowing seasonal storage of surplus winter flows for subsequent use during summer irrigation periods.

Overall, this work highlights the relevance of historically rooted Ag-MAR systems for contemporary groundwater sustainability strategies, underscores the need for regulatory adjustments to optimize recharge timing, and provides a scientific basis for the preservation and potential replication of similar community-managed recharge infrastructures in comparable hydroclimatic settings.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Nuria Naranjo-Fernández, Almudena de la Losa-Román, Carolina Guardiola-Albert, Guiussepe Massone, José Ángel Ventura, José María Ruíz-Hernández, Carlos Marín-Lechado, Antonio González-Ramón, Jorge Jódar-Bermúdez, Blas Ramos-Rodríguez, Sergio Martos-Rosillo. The first draft of the manuscript was written by Nuria Naranjo Fernández, Sergio Martos-Rosillo and Antonio González-Ramón (Cap 4.2) and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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